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Review article

Heavy metals in food crops: Health risks, fate, mechanisms, and management

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ABSTRACT

Food security is a high-priority issue for sustainable global development both quantitatively and qualitatively. In recent decades, adverse effects of unexpected contaminants on crop quality have threatened both food security and human health. Heavy metals and metalloids (e.g., Hg, As, Pb, Cd, and Cr) can disturb human metabolomics, contributing to morbidity and even mortality. Therefore, this review focuses on and describes heavy metal contamination in soil–food crop subsystems with respect to human health risks. It also explores the possible geographical pathways of heavy metals in such subsystems. In-depth discussion is further offered on physiological/molecular translocation mechanisms involved in the uptake of metallic contaminants inside food crops. Finally, management strategies are proposed to regain sustainability in soil–food subsystems.

1. Introduction

Heavy metal pollution has spread broadly over the globe, perturbing the environment and posing serious health hazards to humans. The root causes of this problem are generally held to be the rapid pace of urbanization, land use changes, and industrialization, especially in developing countries with extremely high populations, such as India and China (UN-HABITAT, 2004). Since the industrial revolution and economic globalization, the diversity of environmental contaminants has increased exponentially, with countless anthropogenic sources. Therefore, the diverse and emerging issues of food security have become a global concern, particularly their inextricable association with human health (Clarke, 2011; Säumel et al., 2012; Toth et al., 2016; Rai, 2018a).

Several hazardous heavy metals and metalloids (e.g., As, Pb, Cd, and Hg) are classified as non-essential to metabolic and other biological functions. Those metals are deleterious in various respects (Gall et al., 2015), and they have therefore been included in the top 20 list of dangerous substances by the United States Environmental Protection Agency and the Agency for Toxic Substances and Disease Registry (ATSDR) (ATSDR, 2007; Xiong et al., 2016a, 2016b; Khalid et al., 2017; Rai, 2018a). Certain heavy metals, such as Cu, Fe, and Zn (and even Cr (III)), are essential components of metabolic processes, including cytochromes and enzymes, inextricably linked to the metabolic functioning of biota (Marschner, 2012). Nickel is an integral component of urease, although it can cause human health risks at excessive levels (Zhuang et al., 2009; Marschner, 2012). Thus, soil–food crop/vegetable systems provide a classic example of abiotic-biotic interactions in the environment.

Soil is the fundamental sustenance of food crops, and it can be greatly perturbed by heavy metals from point sources (e.g., energy-intensive industries, such as thermal power plants and coal mines, and chlor-alkali chemical industries, such as goldmines, smelting, electroplating, textiles, leather, and e-waste processing) and non-point sources (e.g., soil/sediment erosion, agricultural runoff, and open freight storage). In addition to their human health implications, heavy metals adversely affect soil biota through microbial processes and soil–microbe interactions (Gadd, 2010; Gall et al., 2015; Rai, 2018a). Beneficial soil insects (especially in agriculture), invertebrates, and small and large mammals are all affected (Gall et al., 2015; Bartrons and Peñuelas, 2017; Rai et al., 2018). For example, medicinal plants used for traditional human health care should be examined for heavy metal contamination to prevent adverse effects, as demonstrated by the Chinese medicinal plant Feng dan (*Paeonia ostii*) (Shen et al., 2017). Many medicinal plants have been shown to bioaccumulate various metals (e.g., Cd, As, Cr, Cd, Cu, Pb, and Fe) when grown near smelting or other

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industrial areas (Hamiani et al., 2015; Bolan et al., 2017; Kim et al., 2017a, 2017b; Kohzadi et al., 2018). Greenhouse vegetables are also highly contaminated with heavy metals such as Cu, Zn, Mn, Pb, and Cd (but not Fe) compared to open field vegetables, possibly due to less illumination (Li et al., 2017a, 2017b).

A better understanding on the soil-food crop transfer mechanisms is prerequisite for devising the effective remediation technologies. To meet this goal, this review first describes diverse sources of heavy metal contamination in soil system and their significance to human health risks with respect to the basic processes governing such pollution and the associated consequential dietary intake of contaminated crops. Interestingly, this review attempts to provide a general view on the global geographical pattern of heavy metal sources in agro-ecosystems in relation to anthropogenic factors and processes. In this respect, it also covers information about heavy metal contamination in soil–food crop subsystems on all inhabited continents. Furthermore, the environmental and human health implications of those subsystems are discussed in detail to help elucidate the physiological/molecular mechanisms involved in the uptake of metallic contaminants inside food crops. Lastly, the review discusses state-of-the-art remediation approaches (e.g., eco-remediation and the use of chemicals, biochar, and nanoparticles) to help properly manage heavy metals in the environment. These management approaches are inextricably linked with human health welfare by suppressing or minimizing the transfer of metallic contaminants from soil to food crops (soil-crop systems).

2. Sources of heavy metals in soil–crop systems

The primary sources of heavy metals in the soil environment and agriculture are atmospheric deposition, livestock manure, irrigation with wastewater or polluted water, metallo-pesticides or herbicides, phosphate-based fertilizers, and sewage sludge–based amendments (Chary et al., 2008; Cai et al., 2009; Luo et al., 2009; Mansour et al., 2009; Gall et al., 2015; Lv et al., 2015; Elgallal et al., 2016; Woldetsadik et al., 2017; El-Kady and Abdel-Wahhab, 2018). In addition to natural sources, conventional/emerging anthropogenic contaminants pose major human health risks through the dietary intake of food crops contaminated by root transfer from soil to plant tissues or direct atmospheric deposition onto plant surfaces (Samsøe-Petersen et al., 2002; Zhuang et al., 2009) (Fig. 1). Particulate matter (PM) emitted by industries and vehicles ultimately accumulates in soil and the food chain (Rai, 2016a, 2016b; França et al., 2017). Coal-fired power plants are one major source of Hg contamination in soil. Li et al. (2017a, 2017b) reported that the long-term consumption of lettuce, amaranth, water spinach, cowpea, and grains (e.g., rice) grown in Hg-contaminated soils (e.g., close to thermal power plants in China) is deleterious to human health. Likewise, several strong source processes (e.g., wastewater as an irrigation source, sewage sludge as a soil amendment for food crops, and PM pollution/deposition on soil/plants) pose a grim scenario for global food safety.

A reliable strategy and stable treatment systems are urgently needed to address the issue of increasing wastewater generated by domestic and industrial processes due to the expanding human population. Indeed, many countries do not have adequate water resources to sustain their agricultural needs. To ensure agricultural productivity, inadequately treated wastewater and sewage sludge are extensively applied to food crops; however, the quality and safety of food crops grown in soils irrigated with poorly treated reclaimed water cannot be guaranteed (Rai and Tripathi, 2007; Jaramillo and Restrepo, 2017). Sewage sludge is produced in large quantities as a soil amendment for agriculture (e.g., 70, 30, and 6 million tons in Japan, China, and USA, respectively) (Kelessidis and Stasinakis, 2012; Bourioug et al., 2015; Gall et al., 2015), but negative environmental and public health repercussions have been reported from using uncertainly or partially treated effluent and sewage sludge in that way (Sipter et al., 2008; Toth et al., 2016; El-Kady and Abdel-Wahhab, 2018).

Sludge from distilleries and the chemical, electroplating, textile, and leather industries is often found to contain significantly high concentrations of heavy metals (e.g., Fe, Cu, Cr, Pb, Ni, and Mn) (Ram Chandra and Kumar, 2017). Pandey (2006) showed that Cd, Cr, Cu, Ni, and Zn from electroplating effluent could have drastic effects, such as stunted growth, necrosis and chlorosis in leaves, and plant death. Another study in China revealed that Pb-acid battery production factories emitted metals bound in PM that were then deposited in soils and crops in the agro-ecosystem (Liu et al., 2014; França et al., 2017). Phosphogypsum from phosphate fertilizer waste can generate diverse heavy metals in soil and crops. The soil was enriched mostly with Cd and Cr, whereas the Pb bioavailability was highest in tomatoes and green peppers (Al-Hawati and Al-Khashman, 2015). However, the daily intake of metals (DIM) and health risk index (HRI) in that investigation were < 1, indicating that the health risks might not be too serious, though the concomitant interactions of metals through dermal and inhalation exposure could exacerbate the vulnerability of humans, particularly children, to disease. Soil can act as an interface with other abiotic compartments of the environment, so severe soil pollution can lead to the contamination of sediment-groundwater and coastal zones (Facchinelli et al., 2001; Khan et al., 2010; Yang et al., 2017a, 2017b, 2017c; Rai et al., 2018; Yang et al., 2018).

Indoor cultivation of crops in a controlled environment is not an absolute way to ensure food safety. Vegetables grown in greenhouses have also been found to be contaminated with heavy metals, mostly through anthropogenic sources. Indoors, the source identification of heavy metals can be performed using advanced statistical and geospatial tools (Facchinelli et al., 2001; Acosta et al., 2011; Xu et al., 2015; Fan et al., 2017). In China, greenhouse vegetables were more sensitive to Cd contamination than crops in open farmlands (Liu et al., 2011a, 2011b). The results of a principal components analysis showed that Cr, As, and Ni are mainly released by weathered rocks, whereas metallic contaminants such as Hg and Pb are generated by industries, vehicular fumes and PM, and wastewater reuse for irrigation (Liu et al., 2011a, 2011b). The identification of soil contaminants and their sources is essential research because of their tight links to human health (Velea et al., 2009; Khan et al., 2010; Rai, 2012).

The use of nanotechnology in several sectors (e.g., medicine, energy, environment, and agriculture) has environmental repercussions through the unregulated release of nanoparticles (NPs) and associated toxic metals (Xiong et al., 2017; Rai et al., 2018a). Food crops should be subjected to an impact assessment for nano-toxicity (e.g., CuONPs) because the presence of NPs can lead to adverse effects on both crop physiology (especially reduced photosynthesis) and human health (Xiong et al., 2017).

3. Global geographical pattern of heavy metal contamination in soil-food crop system

This section provides an overview of the global scenario for heavy metal contamination of food crops in relation to their broad anthropogenic sources, including the ecotoxicological effects on human health (Tables 1 and 2). Indeed, the bioaccumulation of heavy metals in food crops and its effects on human health are of great concern worldwide. However, information on geographical trends may help us understand that the extent of their effect on human health problems may vary across country, along with the source of metallic contaminants, which has been reviewed scantily.

The rapid pace of population growth and industrialization have caused land-use changes across the Asian sub-continent and compelled sustained efforts to enhance the agricultural productivity of limited geographical areas to produce adequate quantities of food. Unfortunately, to meet that objective, wastewater, treated effluent, and sludge contaminated with heavy metals have frequently been used as low-cost sources of irrigation in parts of Asia and Africa, which has caused food quality, and hence health, to deteriorate.

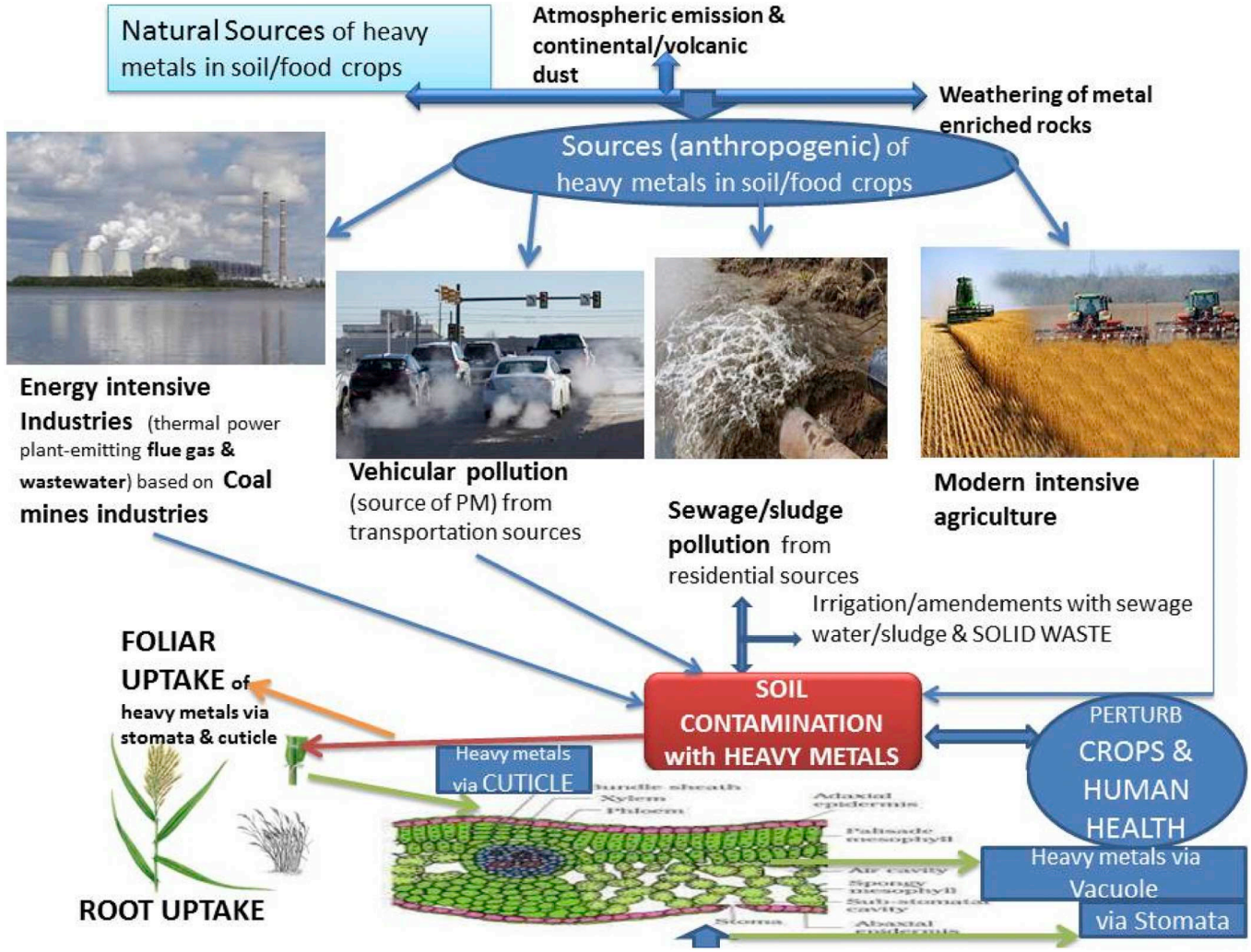

Fig. 1. Natural and anthropogenic sources of heavy metal contamination in food crops and mechanisms of their entrance (through stomata/cuticle) with resulting impacts on biota and humans.

In this respect, both highly populated countries (e.g., India and China) and underdeveloped countries (e.g., Nigeria and Zambia) have soil–crop subsystems affected by wastewater irrigation and sludge amendment patterns, with food safety and ecotoxicology consequences. Several case studies in Africa have confirmed that geographical source pattern of soil contamination with heavy metals (Eliku and Leta, 2017; Woldetsadik et al., 2017; El-Kady and Abdel-Wahhab, 2018). Likewise in India, long-term wastewater irrigation has been shown to contaminate food crops with heavy metals (concomitantly changing the physiology and biochemistry of crop plants) and pose health hazards (Rattan et al., 2005; Rai and Tripathi, 2008; Ghosh et al., 2012; Garg et al., 2014; Saha et al., 2015; Chabukdhara et al., 2016).

China has also focused intensively on ecotoxicological, environmental, and food safety because of its extremely high population and need to expand farmlands as a result of rapid industrialization (especially mining and smelting) and urbanization. In the Chinese context, wastewater is used as source of irrigation in certain regions in line with geographical pattern applicable to Asian/African continent (Song et al., 2015; Zhang et al., 2015; Junhe et al., 2017). According to a survey of food safety and human health concerns (regarding heavy metal contamination), 10% of Chinese territory is contaminated with Cd (7.75% as the highest contribution), Hg, Cu, Ni, and Cr (the lowest contribution). As a result, several case studies in China were carried out to describe the health risks caused by heavy metal contamination of food crops, especially cereals such as rice, as a result of wastewater irrigation (Cui et al., 2004; Liu et al., 2005; Zheng et al., 2007; Zhuang et al., 2009; Liu et al., 2011a, 2011b; Wang et al., 2012a, 2012b; Chang et al., 2014; Li et al., 2014; Song et al., 2015; Zhang et al., 2015; Junhe et al., 2017). Food safety and human health concerns have also been investigated intensively in Bangladesh (Shaheen et al., 2016; Sultana et al., 2017), Pakistan (Khan et al., 2010, 2013), South Korea (Kwon et al., 2017), and Hong Kong (Hu et al., 2013).

Interestingly, unlike in Asia and Africa, the sources of heavy metals in American, European, and Oceanic countries are usually found to be PM and modern intensive agricultural practices. Therefore, the geographical patterns pertaining to heavy metals sources in these regions vary significantly from Asian/African perspective. For example, extensive case studies of food crop samples from North and South America have found that the metal concentrations are attributable to the use of Cu-based fungicides and fertilizers in agriculture and PM originating from vehicles and industrial sites (Lucho-Contantino et al., 2005; ATSDR, 2007; França et al., 2017; McBride et al., 2014; Garrido et al., 2017). Further, the presence of heavy metals in industrially processed food stuffs/pharmaceuticals were noted in several developed countries of these regions (e.g. Spain, Belgium, England, and USA) which may impose serious human health risks (Gonzalez-Martin et al., 2018).

Food safety is major issue of concern in south-American context (e.g. Brazil and Argentina) due to increasing concentrations of heavy metals and other industrial environmental contaminants (Arisseto-Bragotto et al., 2017). Heavy metals (e.g., Pb, Cu, and Zn) derived from

Table 1
Heavy metal contamination from diverse sources in global food crops.

No.	Food crops (cereals, fruits, vegetables, etc.)	Country where investigated	Sources of heavy metal contaminants affecting food chains	Metal concentrations recorded in food crops (dry weight)	References
1.	Brassica sp., Chenopodium sp., leafy and root vegetables, grains	India	Sewage effluent (inadequately treated)	Cu 1.7–12.9 mg/kg Pb 0.13 mg/kg Zn 7.25–24.6 mg/kg Cr 0.08–0.38 mg/kg Pb 0.02–0.013 mg/kg Cu 0.16–0.85 mg/kg Zn	Rattan et al. (2005)
2.	Rice, wheat, soybean (*Glycine* max), corn (*Zea mays*), potato	Brazil	Industrial/modern intensive urban agriculture	Below the standard limits hazardous to human health	Branco Corguinha et al. (2015)
3.	Grain, maize (*Zea mays*), green cabbage, *Brassica juncea* L, radish (Raphanus sativus L), turnip, *Brassica napus*, spinach, cauliflower, and lettuce	China	Sewage effluent (inadequately treated using a biological approach)	Cr 0.08–0.38 mg/kg Pb 0.02–0.013 mg/kg Cu 0.16–0.85 mg/kg Zn 0.16–0.53 mg/kg	Khan et al., 2008a
4.	Lettuce (*Lactuca sativa*); a leafy food crop/vegetable	Spain	Air (PM) from industries and vehicles	< 0.02 mg Ni/kg, < 0.008 mg Hg/kg, 0.005 mg As/kg and < 0.005 mg Cd/kg	Ercilla-Montserrat et al. (2018)
5.	Brassica sp., food grains, and leafy vegetables	China	Both sewage and industrial waste (from smelter) drained into river water used for irrigation	Cr 0.01–0.19 mg/kg Pb 0.12–0.23 mg/kg Cu 0.15–0.86 mg/kg Zn 0.42–0.95 mg/kg	Liu et al. (2005)
	Soybean	Argentina	Industrial (battery) waste in soil	Metals (Pb & Zn) well above permissible limits	Rodriguez et al. (2014); Blanco et al. (2017)
6.	*Triticum aestivum* (wheat), *Lycopersicum esculentum* L. (tomato), radish, spinach, brinjal, carrot, *Capsicum annum*, *Allium sativum* (garlic), *Coriandrum sativum* (coriander), and okra	Pakistan	Metal-contaminated groundwater	Cr > 0.18 mg/kg Pb 0.91–3.96 mg/kg	Khan et al. (2013)
7.	Rice and other paddy crops and vegetables	Australia (food crops imported from Bangladesh, India, Pakistan, Thailand, Italy, Canada and Egypt)	Arsenic- and metal-contaminated groundwater	Rice: Cr 15–465 μg/kg Pb 16–248 μg/kg Cu 1.0–9.4 mg/kg Zn 10.9–24.5 mg/kg Cd 8.7–17.1 μg/kg Co 7–42 μg/kg Mn 61–356 μg/kg Ni 61–356 μg/kg Pb 670–16,500 μg/kg Vegetables: Cr 27–774 μg/kg Pb 35–495 μg/kg Cu 1–29 mg/kg Zn 17–183 mg/kg Cd 3–370 μg/kg Mn 3–140 μg/kg Ni 151–10,035 μg/kg Pb 35–495 μg/kg	Rahman et al. (2014) [see also Tripathi et al. (1997), Alam et al. (2003), Islam et al., 2017; Yang et al., 2018]
8.	French beans (*Phaseolus vulgaris*), beetroot (*Beta vulgaris*), and kale (Brassica oleracea var. acephala)	Australia	Urban stormwater	Cr 0.00078–0.049 mg/kg Pb 0.001–0.11 mg/kg Cu 0.016–0.66 mg/kg Zn 0.038–0.145 mg/kg	Tom et al. (2014)
9.	Spinach	India	Sewage wastewater (inadequately treated)	Cu 0.09 mg/kg Cr 2.9 mg/kg Pb 3.1 mg/kg Zn 10 mg/kg Ni 3.2 mg/kg	Chary et al. (2008)
10.	Radish	China	Inadequately treated wastewater	Cu 0.34 mg/kg Cr 0.03 mg/kg Pb 0.07 mg/kg Cd 0.012 mg/kg Zn 2.48 mg/kg Ni 0.07 mg/kg	Song et al. (2009)
11.	Industrially processed food stuffs (e.g. candy) and pharmaceuticals	United States of America (USA), Spain, Portugal, Belgium, England, and Chile	Industries/food processing industries/modern pesticides based agriculture	Cr (0.10–17.7 ppm), Ni (0.01–7.01 ppm), Cu (0.01–6.44 ppm), Zn (0.01–6.44 ppm) Pb (0.03–7.21 ppm)	Gonzalez-Martin et al. (2018)

(*continued on next page*)

Table 1 (*continued*)

No.	Food crops (cereals, fruits, vegetables, etc.)	Country where investigated	Sources of heavy metal contaminants affecting food chains	Metal concentrations recorded in food crops (dry weight)	References
12.	Potato/other foodstuffs	Egypt	Inadequately treated wastewater	Cu 0.83 mg/kg Cr nil Pb 0.08 mg/kg Cd 0.02 mg/kg Zn 7.16 mg/kg	Radwan and Salama (2006); El-Kady and Abdel-Wahhab (2018)
13.	Potato	China	Inadequately treated urban wastewater	Cu 1.03 mg/kg Cr 0.03 mg/kg Pb 0.067 mg/kg Cd 0.015 mg/kg Zn 3.77 mg/kg Ni 0.054 mg/kg	Song et al. (2009)
14.	Radish	India	Diverse contamination sources	Cu 5.96 mg/kg Cr nil Pb nil Cd nil Zn 22.5 mg/kg Ni nil	Arora et al. (2008)
15.	Cauliflower	China	Urban wastewater	Cu 0.6 mg/kg Cr 0.02 mg/kg Pb 0.03 mg/kg Cd 0.014 mg/kg Zn 5.45 mg/kg Ni 0.68 mg/kg	Song et al. (2009)
16.	Amaranthus	India	–	Cu 1.4 mg/kg Cr 2.4 mg/kg Pb 2.9 mg/kg Cd nil Zn 8 mg/kg Ni 3.1 mg/kg	Chary et al. (2008)
17.	Chinese cabbage	China	Pot experiment with exogenous supply of Cd	Cd 0.12–1.70 mg/kg	Junhe et al. (2017)
18.	Lettuce (*Lactuca sativa*)	United States (Florida)	–	As 27.3 mg/kg However, reduced by 21%	de Oliveira et al. (2017)

industrial waste in food crops of Argentina (e.g. soyabean) were reported to impose human health hazards (Rodriguez et al., 2014; Blanco et al., 2017). Nevertheless, in Brazilian perspective, other case study on several food stuffs (e.g., potoato, wheat, corn, soybeans, and rice) demonstrated that the concentrations of metals/metalloids (e.g., Cd, Pb, and As) in these food crops does not impose human health implications (Branco Corguinha et al., 2015).

In line with those American results, European countries also face heavy metal contamination of food crops and pollution, with PM (Peris et al., 2007; Antisari et al., 2015; Ferri et al., 2015; Memoli et al., 2017) and industrial activities (Hough et al., 2004; McGrath and Zhao, 2015; Jusufi et al., 2017; Antoniadis et al., 2017; Trebolazabala et al., 2017) commonly listed as the prime sources. However, in Barcelona city of Spain, the concentrations of metallic contaminants in airborne PM were below the permissible limits to make less contribution to food contamination like an experimental food crop (lettuce) to support the generally safe conditions for human consumption (Ercilla-Montserrat et al., 2018).

Also, in Oceania (including Australia and New Zealand), PM from the industrial and transport sectors and unsustainable agricultural and environmental hazards are blamed for the heavy metal contamination of food crops (Rahman et al., 2014; Ashrafzadeh et al., 2018). Those case studies illustrate the geographic variations and socio-economic scenarios that account for remarkably different sources and extents of heavy metal pollution in soil–crop systems and the resulting human health implications.

4. Health effects and risks from metals in food crops

Because most heavy metals in soil can accumulate in crops, they can be transferred to other media through the food chain. The bioconcentration factor (BCF) of several heavy metals in the crop–soil interface, particularly in major global staple crops such as wheat and corn, has been documented (Wang et al., 2017a, 2017b, 2017c) (Table 1).

The ingestion of vegetables contaminated with heavy metals causes serious human health issues, such as gastrointestinal cancer, fragile immunological mechanisms, mental growth retardation, and malnutrition (Iyengar and Nair, 2000; Turkdogan et al., 2003; Carrizales et al., 2006; Khan et al., 2008b; Hu et al., 2013; Gress et al., 2015; Dickin et al., 2016; El-Kady and Abdel-Wahhab, 2018). The soil–plant transfer factor (TF) of metals and metalloids is an important criterion to assess global human health concerns (Rattan et al., 2005; Rothenberg et al., 2007; Khan et al., 2008a; Woldetsadik et al., 2017). Human health hazards are closely linked to the intake of metal-contaminated food crops (Table 2). Heavy metals can accumulate in human bones or fatty tissues through dietary intake, thereby leading to the depletion of essential nutrients and weakened immunological defenses. Certain heavy metals (e.g., Al, Cd, Mn, and Pb) are further suspected to cause intrauterine growth retardation (Iyengar and Nair, 2000; Turkdogan et al., 2003; Khan et al., 2010; Rai, 2018a).

Lead contamination adversely affects mental growth, causing neurological and cardiovascular diseases in humans, especially children (Navas-Acien et al., 2007; Zhou et al., 2016; Al-Saleh et al., 2017). Certain heavy metals, especially Pb and Cd, have carcinogenic effects (Trichopoulos, 1997) and can also lead to bone fractures and malformation, cardiovascular complications, kidney dysfunction, hypertension, and other serious diseases of the liver, lung, nervous system, and immune system (Klaassen et al., 1999, 2009; Jarup, 2003; Zhou et al., 2016; Zhuang et al., 2009; El-Kady and Abdel-Wahhab, 2018). Excessive levels of As in soil, food crops, and groundwater can cause cancer, dermal problems, respiratory complications, and many other

Table 2
Health risks from the dietary intake of foodstuffs contaminated with heavy metals and metalloids.

S. No.	Heavy metals and metalloid	Sources of metallic contamination	Route/medium of exposure	Dose response details/ toxicity limits	Health risks Acute, chronic, critical		References
1	Mercury	Non-surgical tools, dental amalgams, chemical/chlor-alkali industries, energy-intensive industries such as thermal power plants	Methyl mercury enters the food chain through biomethylation; adversely affects the health of plants and humans	10 μg/L (in whole blood); 20 μg/L (in urine)	Inorganic Hg leads to lung damage; kidney damage, proteinuria, allergy, and amalgam disease Organic Hg perturbs central nervous system (CNS) coordination and the health of plants	Neuropsychological symptoms; hypersensitivity (pink disease), nephrotic syndrome, historical Minamata disease on sea coast of Japan & Iraq killed thousands of people	Jarup (2003); Heaton et al. (2003), Soghoian and Sinert (2008); Guzzi and La Porta (2008); Peralta-Videa et al. (2009); El-Kady and Abdel-Wahhab (2018)
2.	Cadmium	Soil amendments with fertilizer and sewage sludge, Ni-Cd batteries, alloys, cigarette smoking	Food crops in non-smoking population; smoking; Fe status also affects gastrointestinal absorption	NOAEL (food): 0.01 mg/kg/day; RfD (mg/kg/day): 0.01×10^{-2}	Adversely affects kidney functioning through increased secretion of low molecular weight proteins (β2-macroglobulin & α1-macroglobulin) & enzymes (*N*-acetyl-β-D-glucosaminidase), pneumonitis (oxide fumes), inhibition of sex hormones (progesterone & estradiol), endocrine disruption	Proteinuria in humans, kidney damage, human carcinogen (group I) causing lung & breast cancer, long-term exposure can result in itai-itai due to conjunction of osteomalacia & osteoporosis as evidenced in Japan	WHO (World Health Organization) (2001); Jarup (2003); Hough et al. (2004); Henson and Chedrese (2004); Brama et al. (2007); Zhang et al. (2008); Soghoian and Sinert (2008); Peralta-Videa et al. (2009)
3.	Lead	Mining & smelting, paint, thermal power plants, crude petrol	Air/particulate deposition on food crops, occupational exposure	NOAEL:25 μg/dL; RfD (mg/kg/day): 0.35×10^{-3} [toxic limit] Pb ≥ 70 μ/dL	Encephalopathy, nausea & vomiting, adverse impact on CNS, circulatory, & cardiovascular systems, children are vulnerable to problems with learning and concentration	Accumulation of erythrocyte protoporphyrin through inhibition of ferrochelatase, anemia, abdominal pain, nephropathy, possible human carcinogen	Ma (1996); Jarup (2003); Hough et al. (2004); Soghoian and Sinert (2008); Peralta-Videa et al. (2009); El-Kady and Abdel-Wahhab (2018)
4.	Copper	Irrigation with contaminated wastewater	Intake of contaminated food	LOAEL: 10 mg/kg/day	Can affect renal & metabolic functions	Excess protein droplets in epithelial cells of the proximal convoluted tubules in rats	Hough et al. (2004)
5.	Chromium	Electroplating/ chrome plating industries, dye industry, sewage wastewater/ sludge	Intake of food contaminated by wastewater & soil amendment with industrial sludge	Toxic limits in humans not specified clearly	Kidney/renal dysfunction/failure, Cr (VI) is more health hazardous than Cr (III) due to rapid absorption, hemolysis & gastrointestinal hemorrhage	Collapse/dysfunction of respiratory system through lung cancer & pulmonary fibrosis	Dong et al. (2007); Soghoian and Sinert (2008); Peralta-Videa et al. (2009)
6.	Nickel	Ni-Cd batteries, wastewater	Intake of contaminated food	NOAEL: 5 mg/kg/day; RfD: 0.05×10^{-1}	Can affect renal functioning, integral component of urease enzyme in kidney	Remarkable decrease in body & organ weights	Hough et al. (2004)
7.	Arsenic (metalloid)	Inorganic As in contaminated groundwater, smelting of non-ferrous elements, thermal power plants using fossil fuels (coal), particulate deposition, minor sources include arsenical pesticides & wood preservatives	Contaminated drinking water & foodstuffs	Dose-response: 100 μg/L As can lead to cancer & 50–100 μg/L can lead to skin cancer [toxic limits] 24-h urine: ≥50 μg/L, or 100 μg/g creatinine	Multi-organ dysfunction, encephalopathy, bone marrow depression, hepatomegaly, melanosis, "rice-water" diarrhea, severe neuropathy, long QT syndrome, peripheral vascular disease (black foot disease of Taiwan)	Cancer in the lungs, kidney, bladder, and skin (hyperkeratosis & pigmentation); changes can occur from drinking As-contaminated water; diabetes & cardiovascular diseases	Jarup (2003); Soghoian and Sinert (2008); Peralta-Videa et al. (2009); Islam et al., 2017; El-Kady and Abdel-Wahhab, 2018
8.	Zinc	Irrigation with contaminated wastewater (industrial & sewage)	Contaminated foodstuffs	LOAEL: 59.3 mg/kg/day; RfD: 1.00 × 10 mg/kg/day	Respiratory problems	Significant decrease (47%) in erythrocyte superoxide dismutase concentration in adult females	Hough et al. (2004)

Note/Abbreviations: No observed adverse effect level (NOAEL); lowest observed adverse effects level (LOAEL); RfD: reference dose (RfD, milligrams per kilogram per day) defined as the maximum tolerable daily intake of a specific metal that does not result in any deleterious health effects.

diseases in the cardiovascular, gastrointestinal, hematological, hepatic, renal, neurological, developmental, reproductive, and immune systems (Chiou et al., 1995; Kapaj et al., 2006; Hartley and Lepp, 2008; Hu et al., 2013; Lin et al., 2013; Liu et al., 2013; Zhou et al., 2016; Islam et al., 2017; El-Kady and Abdel-Wahhab, 2018). Cd contamination in food crops and its effects on human health have also been extensively reported (Yang et al., 2018).

Excess Zn levels in the human body can affect the concentration levels of high-density lipoproteins and disturb the immune system (Zhou et al., 2016). Likewise, excess Cu intake can induce liver damage and other gastric-related problems in humans (Gaetke and Chow, 2003; Rahman et al., 2014; Zhou et al., 2016). Heavy metals (e.g., Cr, Cu, and Zn) in soil can cause non-carcinogenic human health hazards such as neurologic complications, headaches, and liver disease (US EPA, 2000; Liu et al., 2013). Cr(VI) is more hazardous than Cr(III) and other ionic forms in terms of its stability. As such, the former form is suspected to have enhanced potential to cause lung cancer compared with the latter form (Park et al., 2004; Liu et al., 2013). Cd is highly carcinogenic, typically ingested by humans through contaminated food crops, especially rice, and causes postmenopausal breast cancer (Hiroaki et al., 2014).

The inhalation of soil and dietary intake of fruits, crops, and vegetables contaminated with metals or metalloids can lead to gastrointestinal cancer (Turkdogan et al., 2003). The concentrations of heavy metals were measured in several leafy (e.g., lettuce and spinach) and non-leafy vegetables (e.g., radishes and carrots) to determine the bioavailability of the metals in the human gastrointestinal tract (Intawongse and Dean, 2006). The soil–plant TF was significantly high for Mn, followed by Zn, Cd, Cu, and Pb. Interestingly, the bioavailability in the human gastrointestinal tract was independent of the type of heavy metal and plant.

Health hazard indices are derived to assess the human health risks that result from the dietary intake of food crops contaminated with various types of heavy metals. In a study on health risks, especially heavy metal–induced cancer, Cr, Pb, As, Hg, and Cd had target hazard quotient (THQ) values > 1 in food crops, and Pb and Hg were found to cause gastric and liver cancers, respectively (Zhao et al., 2014). Health risk studies on the intake of food crops in a developing country were conducted to assess 30 agro-ecological zones in terms of health indices. The results revealed that the consumption of vegetables contaminated by heavy metals (especially Mn and Cu) was more deleterious to human health than the consumption of contaminated fruits (Shaheen et al., 2016). Obiora et al. (2016) reported that vegetables grown near a Pb-Zn mine were contaminated with heavy metals, especially Pb and Mn, which can lead to Alzheimer's disease and manganism. In a study that emphasized the systematic health risks of a mixture of Pb and Cd, rather than the effects of specific metals in isolation, Cui et al. (2005) found renal dysfunction in a population of people who ingested foods contaminated with multiple metals.

5. Soil–plant metal transfer and health risk assessment indices

Indices of soil–plant metal transfer and health risks have been proposed to describe the translocation of heavy metals in soil and plant systems (plant uptake factors) and to assess the extent of risk from the dietary intake of vegetables and other food crops (Yang et al., 2018). This section discusses the different indices used to determine the ecotoxicological effects and health risks from the intake of contaminated food crops.

5.1. Soil–plant transfer indices

5.1.1. Bio-concentration factor

Although the enrichment factor (EF) was initially proposed to quantify the soil–plant transfer of heavy metals, other terms, such as BCF and the plant uptake factor, are also widely used in environmental biogeochemistry (Wang et al., 2006a, 2006b; Khan et al., 2010; Brioschi et al., 2013; Chang et al., 2014; Yang et al., 2018). The BCF is an important parameter for the soil–plant transfer of hazardous contaminants such as heavy metals. Several studies have demonstrated that the highest *BCF* values are found in leafy vegetables, followed by tuberous ones, whereas the lowest values are found in horticulture crops and fruits (García et al., 2009; Melgar et al., 2009; Liu et al., 2012; Chang et al., 2014; Yang et al., 2018). Transfer factor (TF)/metal transfer factor (MTF) are similar terms used in place of BCF in documented literatures (Rashed, 2010; Khan et al., 2013). In some case studies using the TF, food crops and medicinal plants were found to affected by heavy metals in the atmosphere, which has serious human health implications (Jarup, 2003; Cui et al., 2004; Chary et al., 2008; Cao et al., 2010; Street, 2012; Amaya et al., 2013; Sahoo and Kim, 2013; Gall et al., 2015; Kohzadi et al., 2018).

$$BCF = \frac{Concentration\ in\ crop/vegetable}{Concentration\ in\ soil}$$

5.1.2. Pollution load index (PLI)

The PLI can be used to assess the extent of heavy metal pollution (Rashed, 2010).

$$PLI = (CF_1 \times CF_2 \times CF_3 \times ??? \times CF_n)^{1/n}$$

where C is the concentration of a metal in soil divided by its background or baseline value (concentration in unpolluted soil/control/reference) to obtain CF. The PLI is scored using a scale from 1 to 6: 0 = none, 1 = none to medium, 2 = moderate, 3 = moderate to strong, 4 = strongly polluted, 5 = strong to very strong, and 6 = very strong (Rashed, 2010).

5.2. Diverse health risk assessment indices

The transfer of contaminants from food crops to humans has also been widely studied in terms of health risk (Cui et al., 2004; Hough et al., 2004; Chary et al., 2008; Khan et al., 2008b; Zhuang et al., 2009; Gall et al., 2015; El-Kady and Abdel-Wahhab, 2018) using indices such as the *HRI*, hazard index (*HI*), hazard quotient (*HQ*), *DIM*, and daily dietary index (*DDI*).

$$HQ = [W_{plant}] \times \frac{[M_{plant}]}{R_f D \times B}$$

$HQ < 1$ is safe, whereas $HQ \geq 1$ could pose a health risk (Chary et al., 2008).

In the preceding equation, W_{plant} is the dry weight of the contaminated plant material consumed (mg/day), M_{plant} is the concentration of the metal in the vegetable(s) (mg/kg), R_fD is the food reference dose (the maximum acceptable oral dose of a toxic substance) of the metal (mg/day), and B is the human body mass (kg).

$$DDI = \frac{X \times Y \times Z}{B}$$

DDI reflects the daily amount of a metal consumed by an individual.where X is the metal concentration of a given vegetable, Y is the dry weight of the vegetable, Z is the approximate daily intake, and B is the average body mass of consumers.

$$DIM = \frac{C_{metal} \times C_{factor} \times D_{food}}{B_{average\ weight}}$$

where C_{metal} is the heavy metal concentration in plants (mg/kg), C_{factor} is the conversion factor (typically 0.085 to convert fresh vegetable weight to dry weight), D_{food} is the daily intake of vegetables, and $B_{average\ weight}$ is the average weight of the consumers (Rattan et al., 2005; Oves et al., 2012).

$$HRI = \frac{DIM}{R_f D}$$

$HRI < 1$ is safe, whereas $HRI \geq 1$ could pose a health risk over multiple metals (Oves et al., 2012). *HRI* can be calculated using *DIM*, with R_fD being the food reference dose.

5.2.1. Potential ecological risk index (RI)

This parameter reflects the sum of the risk factors for all hazardous heavy metals in a soil sample and the biotic responses (Chabukdhara et al., 2016).

$$C_f^i = \frac{C_n}{C_{nr}}$$

$$E_r^i = T_r^i C_f^i$$

$$RI = \sum E_r^i$$

where C_f^i is a single-metal pollution factor, C_n is the concentration of the given metal in the sample, C_{nr} is the reference value of the metal, E_r^i is the potential ecological risk index of the individual metal, and T_r^i is the toxic factor of the individual metal (5 for Pb and Cu, 1 for Zn, 30 for Cd, 2 for Cr, and 6 for Ni). T_r^i is assumed to be 6 (Gan et al., 2000). *RI* can be low (< 50), moderate (50–100), considerable (100 − 200), and intense/high (> 200) (Chabukdhara et al., 2016).

5.2.2. Incremental lifetime cancer risk (ILCR):

The ILCR was proposed by Liu et al. (2013) to assess the carcinogenic potential of metallic contaminants in the environment.

$$ILCR = CDI \times CSF$$

where *CDI* is the chronic daily intake of a chemical carcinogen (mg/kg), and *CSF* is the cancer slope factor.

6. Mechanisms

An explicit understanding of the routes and mechanisms by which heavy metals pose a risk to human health through the consumption of grains and vegetables enables the adoption of suitable strategies to manage and mitigate heavy metals for the benefit of local people, farmers, researchers, pedologists, and policy makers (Oves et al., 2012). Therefore, this section describes the multifaceted mechanisms involved in the pathways of metals, their adverse effects, and the physiological and molecular stress tolerance mechanisms of crop plants.

6.1. Pathways and transport of metals in crop plants

Heavy metals are transferred from soil pores to plants in ionic forms, which can vary by metal (McLaughlin et al., 2011). The biospeciation of heavy metals can also vary by food crop. Vegetables such as iceberg lettuce, cherry belle radishes, Roma bush beans, and Better Boy tomatoes all accumulate heavy metals with different concentrations in the roots, leaves, and fruits (Cobb et al., 2000). Pb uptake in lettuce was higher than that in tomatoes and beans, and Cd and As uptake in the same plants was lower than Zn uptake (Cobb et al., 2000). Pb, Cd, Cu, Zn, and As bioaccumulated in 22 vegetables grown in China in the following decreasing order: leaves > stalk/root/solanaceous > legume/melon vegetables. The THQ reached 5, indicating that all the vegetables had a high potential to cause severe health risks upon ingestion (Zhou et al., 2016).

Plant roots play the most vital role in the uptake and translocation of heavy metals. The entry of metals into a root depends on its anatomy (especially the cell wall) and environmental adaptability. For example, Zn uptake in mangrove seedlings adversely affected their environmental adaptability through radial oxygen loss (Cheng et al., 2010). Heavy metals enter the roots from the soil through the intake of water mixed with minerals and nutrients and then bind to low-methyl-esterified pectins, whose levels increase under metal stress (Krzeslowska, 2011). Pb binds to the cell wall of the root primarily through esterified pectins, as demonstrated in the protonemata of a moss plant (*Funaria hygrometrica*), and can be remobilized (Krzeslowska et al., 2010). Polysaccharides (with –COOH, –OH, and –SH functional groups assisting in binding heavy metals to the root) in the root cell walls of food crops also play an important role in the avoidance and tolerance of metal stress. Polysaccharide remodeling under heavy metal stress in food crops results in perturbations of the structural integrity of the cell membrane and organelles (especially chloroplasts and mitochondria), enzyme inactivation through the replacement of integral components or binding to the sulfhydryl or carboxyl group, and nucleic acid conformation changes.

Proper investigation of the mechanisms involved in the foliar uptake of heavy metals is also necessary to manage health risks. As demonstrated in a series of studies by Schreck et al. (2012, 2013, 2014) on Pb uptake by *Lactuca sativa*, foliar uptake of the heavy metal occurred mainly via adsorption to the cuticle or stomatal pores (Fig. 1). Heavy metals are transported from the roots to the aerial parts of the plant through xylem loading, whereas foliar transport involves the phloem vascular system. With regard to the mechanisms of heavy metal uptake in crops, foliar translocation has been studied less than the root uptake mechanism (Shahid et al., 2016).

6.2. Metal stress tolerance mechanisms and metal fate in crop plants

The toxicity of heavy metals in crop plants is minimized by the plants' ability to avoid (e.g., exocytosis) or tolerate stress. Avoidance is a basic strategy used to prevent heavy metals in the roots from entering the shoots and leaves by neutralizing their toxic effects in root cells (Krzeslowska et al., 2010). Thickening of the root cell wall by inducing peroxidase activity through lignin synthesis is one avoidance strategy under metal exposure (Probst et al., 2009). The root apoplast can also act as a dynamic physical barrier to restrict the entry of heavy metals into the symplast. The plasma membrane acts as a physiological barrier against metals through several mechanisms, including lipid peroxidation (Ovečka and Takáč, 2014). The induction of the biological activities of metal transporters, such as metallothioneins (by scavenging reactive oxygen species [ROS]) and phytochelatins, under heavy metal stress imparts tolerance to crop plants, though the role of phytochelatins in minimizing the bioaccumulation of heavy metals in plants can also have adverse effects. For example, the heterologous expression of wheat TaPCS1 increased Cd accumulation in the shoots instead of the roots, thereby producing more toxicity in the crop (Wang et al., 2012a, 2012b; Ovečka and Takáč, 2014).

Previous studies have reported the detailed fate of heavy metals in food crops through molecular homeostasis, physiological and biochemical alterations, and intracellular compartmentalization (Babula et al., 2008; Clemens and Ma, 2016; Yang et al., 2018). Heavy metals can cause breaks in DNA strands, molecular cross linkage, mutations of genetic materials, oxidative stress and damage by ROS and free radicals, and functional and structural membrane disintegration, which all ultimately increase the phytoavailability of heavy metals and inhibit the growth of crop plants (Fig. 2). All those biochemical, physiological, and genetic changes in plants are inextricably linked with human health and the food chain (Fig. 3).

Heavy metals also cause drastic physiological changes and adverse effects on different growth stages, particularly germination and seedlings (Fig. 3). Heavy metals adversely affect the enzymes (e.g., acid phosphatases, proteases, and α-amylases) and protein profiles involved in germination. For example, heavy metals reduced the starch content, limited the nutrient level, inhibited the PSII of the chloroplast, and induced the expression of heat shock proteins and proline (Rai, 2016a; Seneviratne et al., 2017).

In relation to the seed growth of food crops, the effects of heavy metals have been studied mostly in rice (He et al., 2014; Rizwan et al.,

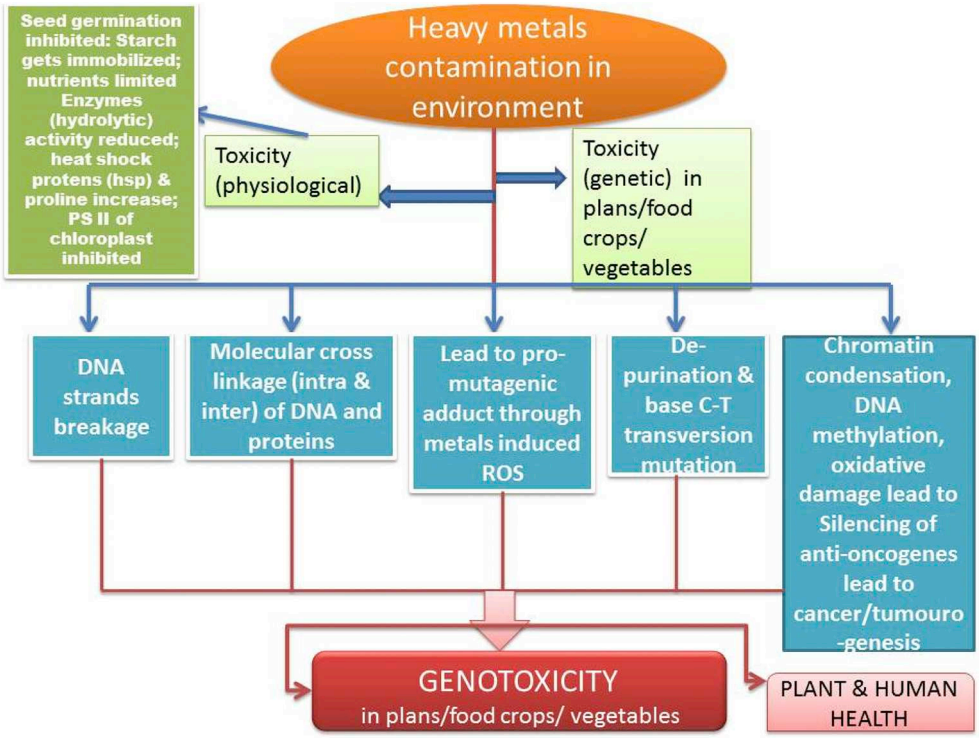

Fig. 2. Eco-toxicological impacts (in terms of physiology and molecular alterations) of heavy metal contamination in food crops and ultimately on human health.

2017), and Cd is one of the most investigated contaminants (Prodanovic et al., 2016). However, scanty research has focused on multi-metal toxicity in food crops (Kim et al., 2012; Rizwan et al., 2017; Seneviratne et al., 2017). Chatterjee and Chatterjee (2000) found that among Co, Cu, and Cr, Co was the most toxic to cauliflower (*B. oleracea*) in terms of adverse effects on biomass and physiological activities (e.g., foliar Fe, chlorophylls [a, b], protein, and catalase activity). Those metals also impeded the translocation of essential elements (e.g., P, S, Mn, and Zn) from the roots to the shoots, with Cr demonstrating the lowest phytotoxicity.

Heavy metals and metalloids generally enter the cells of food crops via metal transporters/chelators such as phyto-siderophores (Guerinot, 2000; Shenker et al., 2001; Perfus-Barbeoch et al., 2002; Eide, 2004; Babula et al., 2008; Rai and Tripathi, 2008; Rai et al., 2010; Rai et al., 2018) (Fig. 4a). Heavy metals and metalloids cause oxidative stress in plants (Supalkova et al., 2007) by converting cysteine into reduced

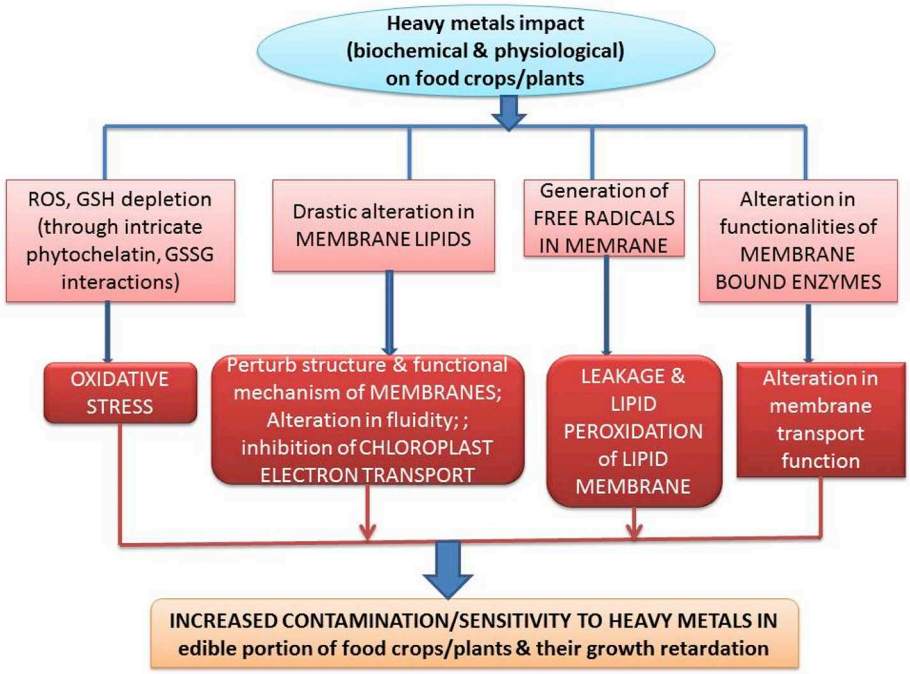

Fig. 3. General physiological and biochemical mechanisms of heavy metal contamination in food crops.

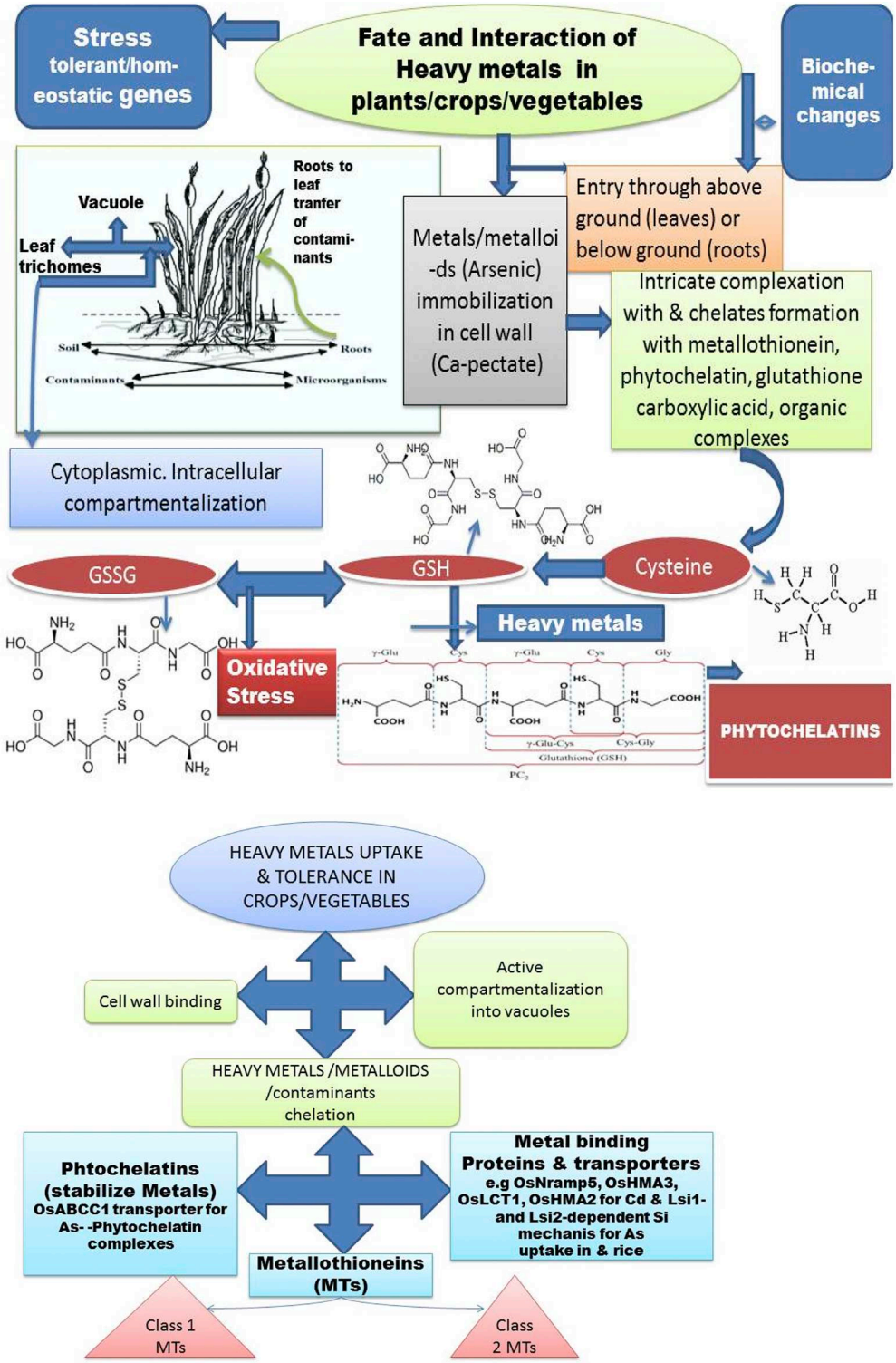

Fig. 4. Elucidation of molecular basis (cascade of stress tolerant biomolecular weapons) of heavy metals: (a) Upper: bioccumulation/interaction with food crops and (b) Lower: stress tolerance of food crops consequent on bioaccumulation of heavy metals.

glutathione (GSH) and oxidized glutathione (GSSG) (the ratio of GSH/GSSG = oxidative stress or ROS generation) (Babula et al., 2008) and forming phytochelatins (Supalkova et al., 2007, 2008; Babula et al., 2008). An inexplicit tolerance toward heavy metals can develop through heavy metal homeostasis and stress-tolerant genes such as ZRT and IRT like protein (ZIP) transporters (Fig. 4) (Weber et al., 2004; Babula et al., 2008; Clemens and Ma, 2016). Furthermore, heavy metal transporters such as ATP-binding cassettes, cation exchangers, natural resistance-associated macrophages, and cation diffusion facilitators are associated with heavy metal uptake in food crops (Assunção et al., 2003; Zhao and McGrath, 2009; Rascio and NavariIzzo, 2011; Shahid et al., 2016).

Heavy metal contamination in vegetables such as *R. sativus*, *Colocasia esculenta*, and *Brassica nigra* cultivated in soil irrigated with treated effluent or wastewater alters their biochemical parameters. For example, high TF and EF values in those vegetables were reported by

Gupta et al. (2010). The levels of total chlorophyll and total amino acids decreased, whereas those of soluble sugars, total protein, ascorbic acid, and phenol increased. Furthermore, metal toxicity and behavior in the soil were influenced by soil pH, carbonate contents, and contamination levels (Waterlot et al., 2017).

Salinity stress can also affect the extent of heavy metal contamination in food crops and change their physiological and biochemical characteristics (Li et al., 2010). An increase in metal contamination in certain vegetables (highest in water spinach, followed by amaranth, leaf mustard, Chinese flowering cabbage, green capsicum, and tomato) reduced their biomass and chlorophyll content; by contrast, the level of peroxidase, known to be an anti-oxidative enzyme, initially increased at low concentrations of the metallic contaminants. Tomato, the food least contaminated by metals, became increasingly tolerant to salinity stress with an increase in heavy metal concentrations.

Molecular biology tools can be used to elucidate the mechanisms of heavy metal toxicity in food crops. Biotechnological and molecular insights could improve understanding of heavy metal uptake in food crops. In several food crops, root-associated metal transporters assist in the sequestration of hazardous elements, such as Cd, and minimize their bioaccumulation in seeds after their transfer from the root to the stem. OsHMA3 in rice (a global food crop used to prove the bioaccumulation of Cd) leads to the sequestration of Cd in root vacuoles, minimizing its translocation into shoots and seeds. Similarly, the GmHMA3 transporter in soybeans induces Cd sequestration in the root endoplasmic reticulum, thereby limiting Cd translocation to the shoots and seeds through a single-point mutation (*Glycine* max) (Wang et al., 2018a, 2018b, 2018c). The overexpression of PtoEXPA12 facilitated the expression of cell wall proteins such as expansin in tobacco plants, enhancing Cd accumulation and having phytoremediation implications (Zhang et al., 2018). In addition, the mis-sense mutation of genes responsible for cellulose biosynthesis (i.e., rice bc13 [*brittle culm13*]) remarkably reduced Cd bioaccumulation in the food grains (Song et al., 2018).

The biomethylation of As and Hg causes the formation of health-hazardous forms more toxic than their inorganic forms. The molecular mechanisms of As toxicity in food crops have been investigated (Chao et al., 2014; Sánchez-Bermejo et al., 2014; Clemens and Ma, 2016). Molecular approaches underlying As(III) uptake in rice are mediated through Lsi1- and Lsi2-dependent Si uptake pathways (Fig. 4). As a model plant for molecular investigations, *Arabidopsis thaliana* has been used extensively to investigate the mechanism of As tolerance. A previous study revealed the role of plant arsenate reductases in preventing the root–shoot translocation of As. Moreover, innovations in instrumentation tools, such as NanoSIMS and synchrotron X-ray fluorescence, have contributed to a precise understanding of the compartmentalization of sub-cellular As and other trace metals in rice crops (Moore et al., 2014; Clemens and Ma, 2016). As(III) S-adenosylmethionine methyltransferase genes in bacteria could cause As methylation in rice crops (Clemens and Ma, 2016). However, As(III) methyltransferases have not yet been reported in genomes (Ye et al., 2012; Clemens and Ma, 2016). The toxicity of As in food crops and the subsequent human health risk are mainly attributed to rice intake (Clemens and Ma, 2016; Islam et al., 2017).

Phyto-chelation and immobilization by lignocellulose and other components of plants and the storage of heavy metals in the vacuole are key processes in the tolerance for heavy metals. Phytochelatin is a ligand/complexing agent responsible for imparting As tolerance, and the OsABCC1 transporter is responsible for transporting As-phytochelatin complexes into the vacuole (Ma et al., 2008; Song et al., 2014; Clemens and Ma, 2016). OsNramp5, OsHMA3, OsLCT1, OsHMA3 (a P1b-type of ATPase), and OsHMA2 transporters assist in the retention and intervascular transfer of Cd in paddy crops (Fig. 4) (Fujimaki et al., 2010; Miyadate et al., 2010; Ueno et al., 2010; Uraguchi et al., 2011; Ishikawa et al., 2012; Sasaki et al., 2012; Clemens and Ma, 2016). Therefore, molecular research approaches in crop plants should be identified to develop stress-tolerant varieties and reduce the concentrations of heavy metals and metalloids in the edible parts of food crops (Clemens and Ma, 2016).

6.3. Source appointment of metals in food crops: genotoxicity and health risks

In determining the health risks from Cd-Zn interaction in vegetables, multiple soil factors, such as pH, can contribute to high Cd contamination in radishes (Yang et al., 2017a, 2017b, 2017c, 2018). From a different perspective, the concentrations of several heavy metals in vegetables, especially in *Allium cepa* (among *Allium sativum*, *Solanum lycopersicum*, and *S. melongena*), were 50-fold higher when they were watered with treated effluent than when they were watered from a tube-well source, making them a health hazard to adults and children (Noor-ul-Amin et al., 2013). Thus, source compartmentalization can affect metal bioaccumulation in food crops.

PM possesses an intricate, complex mechanism in food crops and is of particular research interest. Phyllosphere interactions were analyzed using scanning electronic microscopy coupled with energy dispersive X-ray (SEM-EDS). Particulates from the atmosphere contain heavy metals and can deposit them directly onto the leaf parts of vegetable crops (e.g., cabbage, lettuce, and spinach) in urban home gardens (Hu et al., 2012; Schreck et al., 2012, 2013; Xiong et al., 2014).

Vehicular air pollution can thus have genotoxic effects on urban forestry and gardens (Rai, 2013, 2016a, 2016b; Spósito et al., 2015; Amato-Lourenco et al., 2017). In urban home gardens in densely populated cities, vegetables and other food grains can carry serious human health risks, as demonstrated by genotoxicity studies in Sao Paulo, Brazil (Amato-Lourenco et al., 2016, 2017). In that context, genotoxicity studies to assess air pollution were performed by estimating the micronucleus frequencies for early tetrads in screened utility plants, such as *Tradescantia pallida* (also known as Trad-MCN) (Rai, 2016b; Spósito et al., 2015; Amato-Lourenco et al., 2017). An energy-dispersive X-ray fluorescence spectroscopy analysis indicated that the frequency of Trad-MCN was significantly correlated with air pollution and the integral chemical constituents of road dust/PM. Furthermore, the frequency of Trad-MCN was negatively associated with traffic point distance and other natural and anthropogenic barriers; thus, biomonitoring of atmospheric pollution through genotoxicity studies can assist in selecting proper agriculture sites to maximize human health (Amato-Lourenco et al., 2017).

7. Management of heavy metals in the soil–crop system

Food safety is a global priority for better human health, and it is threatened by anthropogenic sources of heavy metals such as wastewater irrigation, sludge application, and industrial effluents. Therefore, heavy metal remediation of soil could prevent the transfer of heavy metals in the soil–crop system. The mechanisms of the translocation of heavy metals from soil to crops are well understood. Remediation efforts should be directed toward reducing metal concentrations in soil to minimize the subsequent transfer to crops.

Remediation technologies should be environmentally friendly, rapid, and cost-effective. The remediation of heavy metals in soil can be conducted through physical, biological, ecological, and chemical approaches (Fig. 5). Innovations in nanotechnology could assist in the remediation of metallic contaminants. The H-G concept integrates human health risk assessment methods with geospatial technologies to evaluate geographical indicators, provide rapid and accurate assessment of problematic soil sites, and develop suitable remediation measures (Zou et al., 2017). Moreover, judicial land use policy alterations and land-use shifts should be applied to locate agricultural fields distant from municipal and industrial sources of heavy metals. Multifaceted strategies for raising organic food without chemical applications are beneficial to human health and have gained much popularity at the

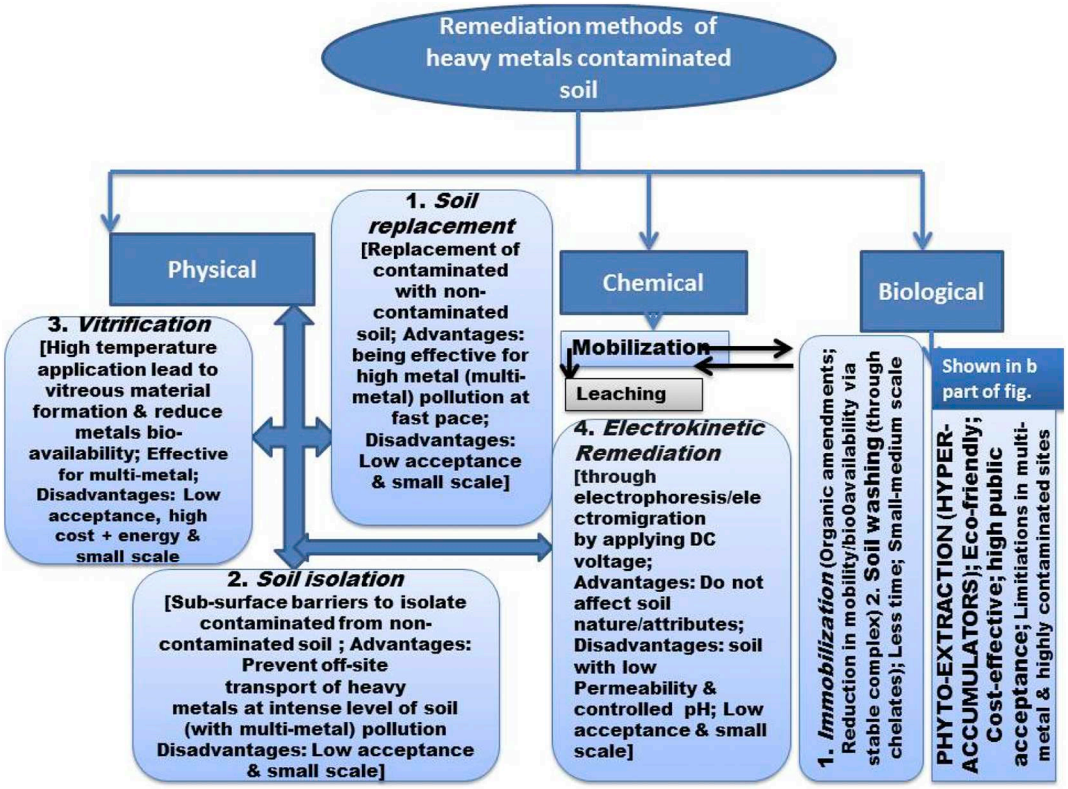

Fig. 5. Glimpses of existing tools on remediation of heavy metals in soil-food crops sub-system to mitigate human health risks.

global level. However, those methods are expensive and cannot be afforded everywhere (Rock et al., 2017).

7.1. Source reduction

Reducing the sources of heavy metals is an effective strategy for improving human welfare. Avoiding inadequately treated effluent and sewage sludge could significantly reduce the heavy metal accumulation in food crops. Air-quality management could result in less PM deposition in the soil and reduce the contamination of food crops. Massaquoi et al. (2015) conducted a comparative assessment between sites irrigated with clean water and those irrigated with inadequately treated wastewater. The concentrations of metals (especially Cd) in the soil and in hair samples from people who ate food grown in wastewater-irrigated fields were significantly higher than those in the soil and in hair sampled from people who ate food grown in fields irrigated with clean water. McLaughlin et al. (1999) reported that contamination with heavy metals such as Cd can be effectively minimized by reducing the input sources of contamination; meanwhile, plant breeding and agronomic advances can regulate soil–food crop transfer.

Heavy metals can be managed by reducing the use of treated effluent or by adequately treating sewage before it is used for irrigation. In Algeria, heavy metal contamination of vegetables (e.g., tomatoes, potatoes, and cucumbers) was reduced by ~85% simply by avoiding inadequately treated wastewater (Cherfi et al., 2015). In a few districts in Pakistan, food grains and vegetables, particularly wheat, irrigated with wastewater were contaminated with hazardous heavy metals such as Cd and Pb, posing serious health concerns (> 1 HRI) (Khan et al., 2015a, 2015b). Those authors strongly advocated for the adequate pretreatment of wastewater and using it away from home gardens, which are used to raise food crops that are directly consumed by local residents.

Land use optimization promotes food safety. Road-side food crops are prone to metal contamination (e.g., Pb in the leaves of *Amaranthus dubius*) through PM deposition on their leaves (Nabulo et al., 2006). Roadside dust/PM originating from heavy urban traffic also acts as a pathway for heavy metals in crop plants, which should not be grown within 30 m of a roadside (Liao et al., 2016). Severe human health risks have been predicted as a result of eating food crops (sugarcane, rice, and 30 vegetables) contaminated by heavy metals after being planted near an acidic mining drainage area. The presence of As, Cd, and Pb in those crops was mainly attributed to atmospheric PM deposition (Liao et al., 2016).

Adequate regulation of environmental parameters such as pH and organic matter is important even in greenhouses. Root vegetables and fruit crops were the least affected by heavy metals and thus more suitable for production in greenhouses than leafy vegetables (Hu et al., 2017; Zhang et al., 2017a, 2017b). The health risks in greenhouses have been mainly attributed to Hg and Pb (Fan et al., 2017). In case studies on vegetables in China (Xu et al., 2015; Fan et al., 2017) and Europe (Facchinelli et al., 2001; Acosta et al., 2011), the sources of heavy metals in greenhouses were primarily anthropogenic. Xu et al. (2015) revealed that As, Cd, Cr, and Hg contamination in plants was derived from anthropogenic sources; however, the Pb contamination might have originated from a natural source. In another case study of greenhouse-grown vegetables in Nanjing, China, heavy metals, including As, Cd, Cu, Hg, and Zn, originated from the application of massive amounts of low-grade fertilizer (Fan et al., 2017). The presence of certain hazardous metals, such as Hg, in a greenhouse for vegetable production could be attributed to the application of insecticides, and the presence of As, Cd, Cr, and Pb might also derive from anthropogenic sources (Xu et al., 2015). Interestingly, the source of Hg in greenhouses was identified through multivariate statistical and geospatial analyses (Facchinelli et al., 2001; Xu et al., 2015). Livestock manure can also bring Cd and As into such controlled environments (Li et al., 2009; Xu et al., 2015).

7.2. Eco-remediation

Biochar application is considered to be a potent eco-remediation strategy to alleviate heavy metal contamination in soil and confer multifaceted benefits. Biochar derived from waste could effectively sequester heavy metals by altering the physicochemical conditions of soil and reducing the phytoavailability of hazardous elements (Jiang et al., 2012; Khan et al., 2014; Gul et al., 2015; Igalavithana et al., 2017; Peng et al., 2018). Composting and biochar can act as ecological solutions to improve the soil nutrient cycle, cation exchange capacity, and humification and effectively reduce soil metal concentrations (as revealed by the measure-monitor model) (Beesley et al., 2014; Wu et al., 2017). Li et al. (2018) found that biochar combined with metal-resistant bacteria such as *Pseudomonas chenduensis* remarkably reduced Cd bioavailability in contaminated paddy soil.

The consumption of foodstuffs containing As is a global health concern (Beesley et al., 2013; Qiao et al., 2018). However, no regulatory As standards have been established for farmlands or home gardens (de Oliveira et al., 2017). As a low-cost, eco-friendly tool, biochar amendment has gained increasing popularity for As removal from soil related to food crops and drinking water (Beesley and Marmiroli, 2011; Beesley et al., 2013; Chen et al., 2016; Wang et al., 2017a, 2017b, 2017c; Peng et al., 2018; Qiao et al., 2018). However, the success of biochar in As removal is not uniform because of variation in biochar acidity. Several researchers observed biochar to play a negligible role (Beesley and Marmiroli, 2011; Beesley et al., 2013; Peng et al., 2018; Qiao et al., 2018), whereas others reported success in using biochar to reduce As from even the anoxic environment of a paddy soil (Chen et al., 2016; Wang et al., 2017a, 2017b, 2017c; Qiao et al., 2018). Considering the negligible role that biochar played in removing As from a multi-metallic soil environment, a meta-analysis of the effects of biochar on the phytoavailability of heavy metals and their transfer in food crops has been conducted (Peng et al., 2018).

Biochar changes the ionic nature and pH of a soil, which could explain its limited success in As removal. The sorption of negatively charged arsenate and arsenite onto biochar (pH 7–7.5) is constrained by the net negative charge on most biochar surfaces (Beesley and Marmiroli, 2011; Li et al., 2018). Interestingly, the alkalinity of biochar caused an increase in soil pH, which enhanced As release, resulting in poor As removal efficiency from using the biochar treatment system (Qiao et al., 2018).

Using biochar in conjunction with Fe remarkably enhanced As removal (Chen et al., 2016). The oxidation of Fe (from Fe^0 to Fe^{3+}) derived from low-cost Fe ores led to the reduction of As (from As^{5+} to As^{3+}), thereby increasing the As removal potential of biochar. The combination of Fe(III) and biochar stimulated the microbial community, especially *Geobacter* and *Clostridium*, and their transcriptional activities play a vital role in removing As from soil (Qiao et al., 2018). Thus, biochar amendment could be quite effective in As remediation from soil–crop subsystems because of a shift in microbial communities, especially Fe(III)-reducing bacteria (Chen et al., 2016; Wang et al., 2017a, 2017b, 2017c; Li et al., 2018; Qiao et al., 2018). An integrated approach to phytoremediation and chemical and organic amendments could also reduce the bioavailability of free As in plant–soil systems. A combination *Pteris vittata* (a fern) (Ma et al., 2001; Gonzaga et al., 2008; Lessl et al., 2014) and organic or chemical amendments such as biochar and activated carbon significantly reduced the As hazard in soil (de Oliveira et al., 2017). In leafy vegetables such as lettuce (*L. sativa*) and *P. vittata*, activated carbon reduced the phytoavailability of this metalloid by around 22%.

The maximum health hazard of Cd and Pb in the edible portions of food crops was more affected by biochar amendments than that of Zn, Ni, Mn, Cr, and Co (Rizwan et al., 2016; Peng et al., 2018). Augmenting greenhouse soil slightly contaminated with Cd with biochar reduced the edible biomass of lettuce, adversely affecting the nutritional content of the vegetable; however, greenhouse soil heavily contaminated with Cd was effectively remediated through biochar amendment, which enhanced Cd complexation (Zhang et al., 2017a, 2017b).

Despite numerous advantages associated with biochar amendments in soil-crop sub-systems, there exists certain disadvantages/limitations. In the context of plant-soil systems, multifaceted factors (e.g. physicochemical properties of biochars/soil and metals speciation) are important (Ahmad et al., 2014; Wu et al., 2017; Wang et al., 2018a, 2018b, 2018c; Chen et al., 2018). Further, récipes of biochar like feedstock type, temperature used for pyrolysis, and types of heavy metals can play a pivotal role (Ahmad et al., 2014; Wu et al., 2017; Chen et al., 2018). Unfortunately, it has been suggested that biochar is less effective in heavy metals decontamination in soil, when compared to organic contaminants remediation from aquatic ecosystems (Zhang et al., 2013; Ahmad et al., 2014; Wu et al., 2017). Moreover, in case of a few metals, biochar amendment can enhance their mobility in soil. Therefore, metals stablization mechanisms, if made through specific biochar, need to be elucidated for better remediation (Ahmad et al., 2014). Henceforth, physico-chemical and biological characteristics of contaminated soil and concentrations of heavy metal in soil need to be investigated for enhancing the effectiveness of biochar.

It is noted that most of the metals decontamination tested with the use of biochar are conducted at laboratory/greenhouse and pilot scale. Hence, further researches are needed to shift this ecofriendly-remediation approach to large-scale field trials (Zhang et al., 2013; Ahmad et al., 2014). Designer biochar approach is needed for site-specific metals remediation of soil. Also, in the context of biochar amendements, time-specific retention and release of metals over time in soil-crop systems need to be adequately investigated for their sustained application at field scale (Zhang et al., 2013; Ahmad et al., 2014; Wu et al., 2017; Wang et al., 2018a, 2018b, 2018c).

Immobilization of heavy metals with biochar and its potentiality in soil remediation is also inadequately addressed (Nejad et al., 2018). Nanoscale materials can remarkably increase the active sites and surface properties of biochar (Ho et al., 2017), which should be investigated in further, for effective heavy metals eco-remediation from soil. Although fortification of biochar with nanoscale materials (e.g. magnetic zerovalent iron) is promising (Zhu et al., 2017; Ho et al., 2017), such approaches are in their infancy stage in context of heavy metals removal.

Phytoremediation is a green strategy that comprises phytoextraction, rhizofiltration, phytodegradation, phytostabilization, and phytovolatilization for heavy metals in soil–food crop subsystems. The phytotechnologies are particularly applicable to wetland plants (Rai, 2018a, 2018b). Algal biomass (*Anabaena azollae*) and water ferns (e.g., *Pteris* sp. and *Azolla pinnata*) also assisted in metal remediation through extracellular binding to exopolysaccharides, biosorption, and bioaccumulation (Rai, 2007, 2012, 2018a) (Fig. 6). Phytoremediation can help vegetables grow free of heavy metals and boost human health across different agroclimatic zones worldwide (Saif et al., 2017). Metallophytes or hyperaccumulators are terrestrial and wetland plants that can phytoextract metals from soil (Wenzel, 2009; Haferburg and Kothe, 2010; Gall et al., 2015). Moreover, using phytotechnologies to remediate metals is cost-effective and eco-sustainable, unlike traditional chemical technologies (Tang et al., 2012; Gall et al., 2015). The role of phytotechnologies in addressing food safety issues linked with human health has been investigated (Yoon et al., 2006). Among different native plants used experimentally in Florida, USA, *Phyla nodiflora* was found to be efficient in the phytostabilization of Cu and Zn, and *Gentiana pennelliana* was effective for Pb, Cu, and Zn. The heavy metals in the effluent from the sponge iron industries accumulates significantly in macrophytes and wetland plants; thus treated effluent would be suitable for irrigating agricultural fields (Gupta et al., 2008).

A critical global survey/bibliometric analysis of soil pollution from 1999 to 2012 found that the problem of heavy metal contamination and its associated bio/phytoremediation was the most investigated research issue (Guo et al., 2014). Although physicochemical methods are quick

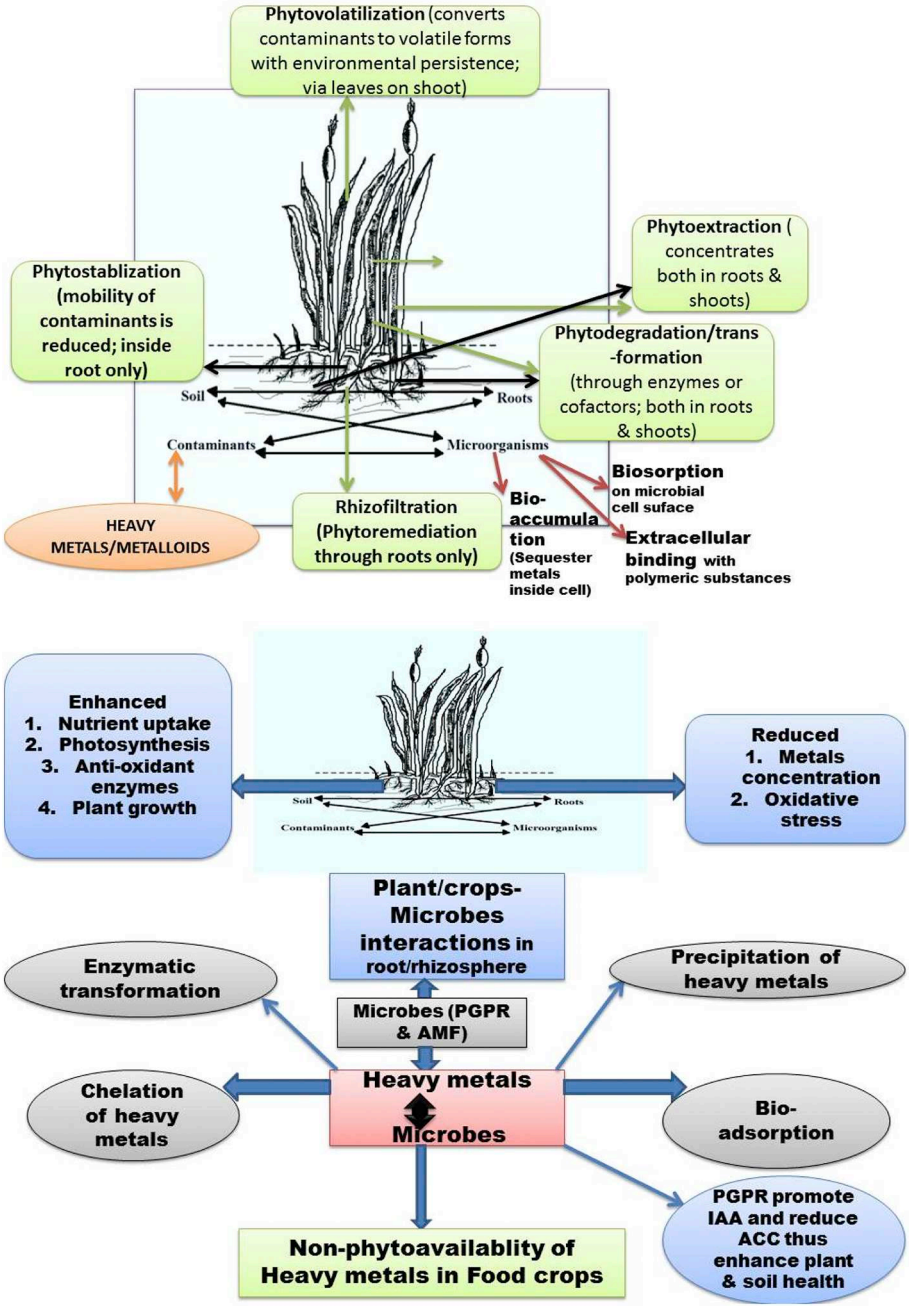

Fig. 6. Elucidation of different eco-remediation steps/methods: (a) Upper: Role of phyto-technologies/phytoremediation in soil-food crops sub-systems to manage human health risks (Modified from Rai et al., 2018) and (b) Lower: Role/utility of plant/food crops-microbe interactions, especially PGPR, in crops health and heavy metal eco-remediation.

and effective for highly contaminated sites, they are not cost-effective and can alter the physical, chemical, and biological properties of soil; thus, such methods could induce secondary pollution (Mahar et al., 2016; Ashraf et al., 2017). In contrast, biological remediation (using plants or microbes) is a cost-effective, solar-based, and eco-friendly method that maintains natural soil attributes through biostimulation, bioaugmentation, composting, bioleaching, bioremediation, land aeration, bioventing, and bio/phytoremediation (Hasegawa et al., 2016; Kang et al., 2016; Rai, 2018a). Nonetheless, at highly contaminated sites with intense metal pollution, phytotechnologies are less efficient and more time-consuming than chemical technologies. Microbe-assisted soil remediation has made remarkable advances (Zubair et al., 2016; Ashraf et al., 2017; Rai, 2018a); therefore, microbial phytotechnologies for metallic soil pollution have widely been applied.

Gold mining is a leading source of heavy metal contamination, especially, Hg, Pb, and Cd, in soil and food crops. Phytoremediation using three potent plants, *Erigeron canadensis*, *Digitaria ciliaris*, and *Solanum nigrum*, can mitigate the carcinogenic potential of Hg and Pb (Xiao et al., 2017). Transmission electron microscopy revealed a high propensity for heavy metal hyperaccumulation in the roots of *Parthenium hysterophorus*, *Cannabis sativa*, *S. nigrum*, and *Ricinus communis*. Using such plants can assist in the ecological restoration of soils contaminated with anthropogenic heavy metals (Ram Chandra and Kumar, 2017).

Despite immense potential of phytoremediation, we cannot overlook several disdavantages associated with its application. Especially, in the context of soil-crop systems, these limitations need to be addressed for wider applicabililty/acceptability of phyto-technologies (Liu et al., 2018). To this end, biomass disposal issue (especially edible plants) and certain operating mechanisms (e.g. phytovolatilization) can transfer the metallic contaminants from one environmental compartments to other (Muthusaravanan et al., 2018). Also, a wide cultivation of certain identified metals accumalotor plant germplasms should be encouraged with farmers awareness and cooperation, which is an essential prerequisite, while in reality lacking with phytoremediation technology (Yadav et al., 2018). Further, through an integrated participatory approach of remediation biologists, soil scientists and farmers, it will be possible to prepare certain site-specific management practices for sustainable utilization/safe disposal of metals contaminated biomass. In this respect, phyto-mining/bio-ores, biomass based energy, and utilization of biomass for small-scale industries (e.g. use of biomass in bricks with impermeable coating) can be some approaches, which in-turn would help increase the economic returns of phytoremediation. Another limitation of phytoremediation lies in the feasibility of remediation at very high metals concentrations or their slow pace of metals decontamination from heavily polluted soils (Yadav et al., 2018; Rai et al., 2018a). However, this limitation is being addressed through gene manipulation tools which may enhance the metals-stress tolerance ability of plants and plant-microbe interactions (Nahar et al., 2017; Fan et al., 2018; Muthusaravanan et al., 2018). Nevertheless, sustained future researches in the field of plants genetic engineering are warranted to enhance the phytoremediation potential of heavy metals contaminated soil.

In China, scientific crop rotation systems for three types of oil crops assist in the eco-remediation of heavy metal–contaminated soil through phytoextraction. Yang et al. (2017a, 2017b, 2017c) found that an oilseed-rape-sunflower rotation exhibited the maximum remediation efficiency for carcinogenic Cd. Vegetables grown in Cd-contaminated sites in China were thus effectively remediated. For example, in the case of eggplant (*S. melongena*), intercropping of Cd phytoremediators/hyperaccumulators belonging to separate agro-climatic regions, including *S. nigrum* and *Solanum photeinocarpum*, was used. A drastic shift in the biochemical and physiological parameters was observed, and antioxidant enzyme activity in the eggplant was enhanced by intercropping (Yi et al., 2017).

Certain metals, such as Zn, are required in small dietary quantities for adequate functional metabolism, and they are sometimes added to soil-crop systems, such as in *Chenopodium album*, through chemical amendments with $ZnSO_4$ or organics (Ray et al., 2017). Adding a beneficial microbial community to soil can also assist in heavy metal remediation. Plant growth–promoting bacteria (PGPR) enhanced the phytoremediation potential of hazardous heavy metals in food crops such as rice, maize, and wheat (Belimov et al., 2015; Hassan et al., 2016; Ashraf et al., 2017). Plant–microbe interactions can greatly reduce the bio/phytoavailability of heavy metals in crops (Fig. 6). However, those crops should not be compared with hyperaccumulators, which play a remarkable role in heavy metal phytoremediation. PGPR in the roots and rhizosphere greatly reduce heavy metal stress in plants by secreting organic acids, thereby producing siderophores, 1-aminocyclopropane-1-carboxylic (ACC)-deaminase, phytohormones, chelation, immobilization, and enzymatic transformation (Madhaiyan et al., 2007; Sharma and Archana, 2016; Rizwan et al., 2017; Vimal et al., 2017). The application of PGPR also promoted the concentration of indole-3-acetic acid (IAA), which is assumed to be a precursor of auxin (a growth hormone). On the contrary, PGPR acted as a sink for ACC, which is an immediate precursor of ethylene (a hormone responsible for aging and senescence) (Hayat et al., 2010; Bücker-Neto et al., 2017). Thus, PGPR plays an immense role in boosting plant growth and soil health. In this context, the role of arbuscular mycorrhizal fungi in reducing heavy metal stress is also worth mentioning (Fig. 6) (Hu et al., 2016; Wu et al., 2016; Rizwan et al., 2017).

In mitigating the adverse effects of heavy metal contamination in food crops, the combination of PGPR (*Neorhizobium huautlense* T1–17) with biochar demonstrated synergistic effects not only in reducing the Cd and Pb uptake into the edible parts of Chinese cabbage and radishes but also in increasing their edible biomass (Wang et al., 2016). This PGPR (T1–17) combination also increased the soil composition/ratio of IAA-producing bacteria (Wang et al., 2016). Furthermore, PGPRs such as the H3 strain of *Bacillus megaterium* can reduce the concentrations of Cd and Pb in green vegetables (i.e., *Brassica sp.*), improve soil quality, and improve the protein and vitamin C content of the vegetables (Wang et al., 2018a, 2018b, 2018c). Adding the Cd/As-resistant bacteria *Ralstonia eutropha* Q2–8, *Rhizobium tropici* Q2–13, and *Exiguobacterium aurantiacum* Q3–11 to soil reduced the bioaccumulation of metalloid contaminants in food crops, increased their edible biomass, reduced the diethylenetriaminepentaacetic acid–extractable concentrations of Cd in rhizospheric soils, and improved soil organic matter (Wang et al., 2017a, 2017b, 2017c).

7.3. Chemical and physicochemical strategies

Chemical strategies, although less preferable than biological processes, are used to restore soil sites contaminated with heavy metals. The complexation of metals in soil makes them less available to food crops and can thus lower the health risks (Udom et al., 2004). Scholars have focused on developing green chemicals (e.g., ferrate) for soil remediation (Rai et al., 2018, 2018a). Feasible chemical measures, for example using synthetic zeolites with the augmentation of alkaline clay, are effective for remediation of heavy metal–polluted soil. Several studies have demonstrated the use of red mud, silicon calcium fertilizer, magnetite, hydrous manganese oxide, maghemite, hematite zeolite, and amended biochar to remove heavy metals from soil (Gu et al., 2011; Chang et al., 2013; Feng et al., 2013; Balakhnina et al., 2015; Yao et al., 2017; Rai et al., 2018a). Innovative instruments such as SEM–EDS and X-ray powder diffraction revealed that the uptake of As and Cd in vegetables was reduced because the metals were inactivated as silicates, phosphates, and hydroxides inside the soil (Yao et al., 2017). In a 3-year field experiment on spring barley (*Hordeum sativum*), Mandzhieva et al. (2017) found that soil–plant systems can cope up with Zn and Pb, and chalk and manure amendments (containing glauconite or natural zeolite, chalk, and manure) reduced the presence of weakly mobile elements and heavy metals in both the soil and *H. sativum*.

Wheat, an important global food grain, can be contaminated with heavy metals of particular human health concern. The phytoavailability of Cd ($\geq$54.13%) and Pb ($\geq$42.14%) was considerably reduced in soils amended with single superphosphate, triple superphosphate, and calcium magnesium phosphate sepiolite in conjunction with $ZnSO_4$; however, the reduction was less pronounced when used with Zn fertilizer (Guo et al., 2018). For leafy vegetables, chemical amendment (phosphate containing diammonium phosphate and hydroxyapatite) decreased the phyto-availability of Pb and Cd (Waterlot et al., 2017). In that study, phosphate amendment more effectively regulated the phyto- and bio-availability of Pb than Cd.

Metalloids (i.e., As) of global concern provoke reduced chlorophyll and elevated lipid peroxidation in the seedlings of *Spinacia oleracea* (spinach), causing high toxicity; however, adding Ca and EDTA minimized the toxicity to both the plant itself and the humans who eat it (Shahid et al., 2017). In contrast to the positive studies just described, a few studies have demonstrated that chemical amendments to soil produce a neutral response in heavy metal remediation. In a study on the productivity of rice, wheat, and sorghum, the activity of soil *exo*-enzymes and the safety of heavy metal concentrations in cereal grains grown in chemically treated (acid washing/amendments) industrial soil were the same as those grown in untreated industrial soil, with short-term human health risks being absent in both cases (Kim et al., 2017a, 2017b). Similarly, fewer non-carcinogenic health risks were reported in

rice in northern India (Yadav et al., 2017).

7.4. Nanoparticle techniques

NPs are a remarkable research hotspot for ensuring soil security as an integral component of agro-nanotechnology and for reducing the bioavailability of heavy metals (Shalaby et al., 2016; Rai et al., 2018a). The phytosynthesis of nano-scale materials and recent advances in plant molecular biology through genetic and protein engineering have also been highlighted for their regulated biosynthesis in environmental remediation (Kostal et al., 2005).

Nano-tools for soil remediation might be cost-effective. NPs and green chemicals are mainly used for the sustainability of agriculture and human health (Rai et al., 2018a). Moreover, nano-sensors are applied in food safety analyses, especially in evaluating the extent of contamination in food crops (Kuswandi et al., 2017). Tools for making metal-contaminated wastewater and sludge less hazardous for food crops must be developed, as demonstrated in the case of pesticide formulation through diverse nano-technologies or formulations (Hazra et al., 2017). Upon adsorption, biochar nanosheets remarkably reduced the bioavailability of carcinogenic metals in wheat grown in contaminated soil near industrial establishments (Yousaf et al., 2018). However, silica NPs inhibited gene expression linked with the synthesis of Cd transporters (OsHMA3) in rice, resulting in increased Cd toxicity (Cui et al., 2017). Therefore, an explicit understanding of the fate and adverse effects of NPs in the environment and food crops is required.

8. Conclusions

Environmental contaminants, food safety and security, and human health are inextricably linked. The concentrations of heavy metals in the environment have increased significantly in recent decades. The sources of heavy metals in food crops vary in the developing and developed world. The deposition of PM on food crops and the use of industrial effluents and sewage sludge as fertilizers are the primary contamination sources in soil–crop systems in developed countries. However, in developing countries, irrigation with inadequately treated effluent or sludge is the main contamination source for food crops. Heavy metal transfer from soil to crop systems is complex and uses multifaceted mechanisms. Multi-metal toxicity in food crops requires specific attention to determine the actual metal toxicity. The human health risks have been widely investigated on a global scale, but only a few of those works have used proper epidemiological methods. To prevent health risks, existing remediation options focus on reducing the concentration of heavy metals in soil and the food chain. Rapid and accurate mapping of soil pollution is needed to prevent the transfer of metallic contaminants into the food chain and to formulate suitable remediation strategies. Biological remediation, such as phytoremediation and PGPR, can be an environmentally friendly and cost-effective strategy for moderately contaminated soils. Eco-feasible technological innovations such as nano-tools and the awareness of farmers could boost local economies and livelihoods with certain financial guarantees.

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