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REVIEW ARTICLE

Contamination of rice crop with potentially toxic elements and associated human health risks—a review

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Abstract
Production of rice, a major staple food crop, should be maintained both quantitatively and qualitatively to assure global food security. In recent decades, various natural (biogeochemical weathering of rocks) and anthropogenic (increased application of agrochemicals, solid and liquid waste discharges from domestic and industrial areas, vehicular pollution, etc.) activities have deteriorated soil and water resources by contributing potentially toxic elements (PTEs) to the environment. Shortage of land resources and requirements of the ever-increasing human population has led to increasing global trend of rice cultivation in contaminated soils, causing accumulation of various PTEs such as arsenic (As), mercury (Hg), cobalt (Co), cadmium (Cd), copper (Cu), lead (Pb), and nickel (Ni) in rice crop, especially in the grains. Rice plants uptake and accumulate PTEs leading to their entry into the food chain. Consumption of rice contaminated with PTEs disturbs the human metabolism as PTEs interfere with different physiological/molecular mechanisms causing various health problems such as weak bones; skin problems; respiratory, cardiovascular, endocrine, nervous, reproductive, and hepatic disorders; and cancer. Possible non-carcinogenic and carcinogenic health risks have been determined in some studies by following the guidelines provided by various governmental or non-governmental agencies. Considering these facts, the present study was conducted to give a broader perspective on rice contamination with various potentially toxic elements, their bioconcentration in rice, associated health risks in human beings, and strategies for bioremediation of soil and water resources to eliminate PTEs.

Keywords Bioaccumulation · Cancer · Metalloids · Metals · Phytoremediation · Soil pollution

Introduction

Food is a basic necessity for the existence of living beings. Uptake and accumulation of different potentially toxic elements (PTEs) such as metals and metalloids in edible plants, from both terrestrial and aquatic resources, have put all living beings in a food chain in a dangerous situation, where their food quality and health security have been jeopardised (Rafiq et al. 2014). The rapid increase in population in developing countries has led to food and land shortage over the years, which has been compensated by bringing the polluted or contaminated land (near industries, mining areas, and wastewater drains) under cultivation (Zhao et al. 2007; Hu and Ding 2009; Fan et al. 2017; Islam et al. 2019). The problem is further accentuated by the indiscriminate use of chemical-based pesticides and fertilisers to increase the yield of crop plants. The shortage of water resources has also encouraged the use of contaminated domestic and industrial wastewater for irrigation of fields (Chung et al. 2011; Tiwari et al. 2011). All these efforts to increase food production have ignored a major aspect of food safety and cumulatively led to the accumulation of various contaminants in food crops being cultivated in contaminated soils or being irrigated with polluted groundwater or subjected to the injudicious application of agrochemicals (Cao et al. 2010; Nagajyoti et al. 2010; Naser et al. 2012a, b).

Different potentially toxic elements such as aluminium (Al), gold (Au), thallium (Tl), antimony (Sb), tin (Sn), arsenic

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(As), lead (Pb), vanadium (V), barium (Ba), lithium (Li), bismuth (Bi), cadmium (Cd), mercury (Hg), nickel (Ni), and silver (Ag) may cause respiratory, endocrinal, and genetic disorders, cancer, seizures, hypotension, anaemia, osteomalacia, skin and hair problems, cardiac arrhythmias, and diseases related to stomach, kidneys, reproductive organs, nervous system, etc. (Järup 2003; Duruibe et al. 2007; Kar et al. 2008; Ali et al. 2013; Prashanth et al. 2015; NORD 2019). However, various trace elements such as copper (Cu), chromium (Cr), cobalt (Co), iron (Fe), manganese (Mn), selenium (Se), and zinc (Zn) are important components of biological molecules and play important role in various metabolic and physiological processes essential for normal functioning of the human body, but when present in excess amount, become harmful to human health (Tables 1 and 2) (Prashanth et al. 2015; Al-Fartusie and Mohssan 2017; NORD 2019). Table 1 gives **a** summary of the literature on some elements explaining their biological role in human beings which become potentially toxic at higher concentrations. Table 2 presents a summary of the literature on various human health hazards posed by different potentially toxic elements.

Food crops from contaminated sites are detrimental at every trophic level of the food chain because of microbial contamination of plants, higher bioaccumulation or bioconcentration of different elements, pesticides, and toxins in different parts of the plants (Khan et al. 2008; Ahmad et al. 2013; Wang et al. 2013). Rice (*Oryza sativa* L.) is an important staple food crop consumed worldwide (Fu et al. 2008). Among different continents, about 90% of land area under rice cultivation lies in Asia (Rafiq et al. 2014). The International Rice Research Institute (IRRI) compiled data on global production of paddy; production and consumption of milled rice (in Tonnes) from the year 2014 to 2018 (IRRI 2019), which are graphically presented in Fig. 1. Production of paddy and milled rice showed a slight

Table 1 Summary of literature on some elements explaining their biological role in human beings

Element	Biological role	References
Chromium (Cr)	Cr is required in carbohydrate metabolism, helps in biosynthesis of glucose tolerance factor (GTF), and reduces atherosclerosis.	Vincent (2004), Lewicki et al. (2014), Prashanth et al. (2015), Al-Fartusie and Mohssan (2017).
Cobalt (Co)	Co is part of vitamin B_{12}. It is required to induce erythropoietin and methionine metabolism. It also has role in synthesis of various amino acids and neurotransmitters.	Moore and Warren (2012), Li et al. (2015), Prashanth et al. (2015), Al-Fartusie and Mohssan (2017).
Copper (Cu)	Cu is core part of various enzymes such as catalase, superoxide dismutase, tyrosinase, and cytochrome oxidase. Cu is important for the neurologic and hematologic systems, development of bones, myelin sheaths, Fe absorption from gastrointestinal tract, and its incorporation in haemoglobin.	Angelova et al. (2011), Scheiber et al. (2014), Al-Fartusie and Mohssan (2017).
Iron (Fe)	It is part of myoglobin and haemoglobin. It is associated with various enzymes such as catalase, cytochrome C reductase, peroxidases, tryptophan pyrrolase, and tryptophan dioxygenase. It plays an important role in hormone synthesis and normal cellular functioning.	de Visser and Kumar (2011), Prashanth et al. (2015), Al-Fartusie and Mohssan (2017), Moll and Davis (2017)
Manganese (Mn)	Mn plays an important role in calcium absorption, carbohydrate and fat metabolism, oxidative phosphorylation, urea cycle, and mucopolysaccharide metabolism. It acts as an enzyme activator and exists as main component of various metalloenzymes. Mn helps in the formation of bones, sex hormones, and connective tissue. Mn is also responsible for normal functioning of the brain.	O'Neal and Zheng (2015), Prashanth et al. (2015), Al-Fartusie and Mohssan (2017).
Selenium (Se)	Se acts as a part of selenomethionine, selenocysteine (amino acids), and glutathione peroxidases (enzyme)	Hatfield et al. (2011), Al-Fartusie and Mohssan (2017).
Zinc (Zn)	Zn is part of many metallozymes and essential for cellular metabolism, cell growth, proper spermatogenesis, organogenesis, neurotransmitter functioning, wound healing, normal development of thymus, and pancreatic secretions.	Rout and Das (2009), Jacobsen et al. (2011), Prashanth et al. (2015), Al-Fartusie and Mohssan (2017).

Table 2 Summary of literature on human health hazards posed by different potentially toxic elements

Element	Health hazards	References
Aluminium (Al)	Encephalopathy, mouth and skin ulcers, dermatitis, diarrhoea, nausea, vomiting, loss of memory, Alzheimer's disease, haemodialysis, deterioration in kidney function, arthritic pain, osteomalacia, etc.	Srinivasan et al. (1999), Barabasz et al. (2002), Han et al. (2013), Jaishankar et al. (2014), NORD (2019).
Antimony (Sb)	Pneumoconiosis, cardiac disorders, stomach pain, diarrhoea, stomach ulcers, skin cancers, lung cancer, etc.	Cooper and Harrison (2009), ATSDR (2019), NORD (2019).
Arsenic (As)	Vomiting, abdominal pain, fever, diarrhoea, weakness, muscle aches, headaches, drowsiness, seizures, encephalopathy, polyneuritis, coma, seizures, oedema, hyperkeratosis, hyper pigmentation, exfoliative dermatitis, haemolysis, anaemia, hypertension, blood vessel damage, cardiomyopathy, ventricular arrhythmias, diabetes mellitus, pulmonary disorders, cancer, renal tubular acidosis, intestinal haemorrhage, etc.	Martin and Griswold (2009), Huy et al. (2014), Sun et al. (2014), Jaishankar et al. (2014), Engwa et al. (2019), NORD (2019).
Barium (Ba)	Pulmonary oedema, cardiac disorders, renal failure, gastric and intestinal haemorrhages, hypertension, cancer, etc.	Martin and Griswold (2009), Kravchenko et al. (2014).
Bismuth (Bi)	Somnolence, hallucinations, myoclonic jerks, seizures, ataxia, kidney damage, etc.	Nordberg et al. (2014), NORD (2019).
Cadmium (Cd)	Fatigue, nausea, vomiting, teeth yellowing, osteomalacia, osteoporosis, abdominal cramps, diarrhoea, emphysema, pulmonary oedema, dyspnoea, tachycardia, chronic anaemia, cyanosis, anosmia, proteinuria, hypercalciuria, renal tubular dysfunction, cancer, etc.	Hossen et al. (2014). Jaishankar et al. (2014), Burke et al. (2016), Engwa et al. (2019), NORD (2019)
Chromium (Cr)	Diarrhoea, vomiting, acidosis, skin diseases, cancer of lungs and respiratory tract, neural defects, foetal deaths, kidney diseases, and ulcers and lesions on the kidneys, liver, and myocardium	Suranjana and Ray (2009), Jaishankar et al. (2014), Prashanth et al. (2015), Shekhawat et al. (2015), Al-Fartusie and Mohssan (2017), Engwa et al. (2019), NORD (2019).
Cobalt (Co)	Nausea, tinnitus, vomiting, nerve damage, respiratory problems, anorexia, goiter, cancer, and cardiovascular and renal damages	Prashanth et al. (2015), Al-Fartusie and Mohssan (2017), Zadnipryany et al. (2017), NORD (2019).
Copper (Cu)	Diabetes; cardiac, renal, neurological, immunological, and hepatic problems; pregnancy-related complications; Wilson's disease; etc.	NRC (2000), Uriu-Adams and Keen (2005), Brewer (2009), Han et al. (2013), Prashanth et al. (2015), Al-Fartusie and Mohssan (2017), NORD (2019).
Gold (Au)	Skin rashes, myokymia, bone marrow depression, intestinal bleeding, jaundice, etc.	NORD (2019).
Iron (Fe)	Gastrointestinal ulceration and bleeding, diarrhoea, Alzheimer's disease, hypotension, tachycardia, hepatic necrosis, metabolic acidosis, atherosclerosis, cancer, etc.	Brewer (2009), Jaishankar et al. (2014), Prashanth et al. (2015), Al-Fartusie and Mohssan (2017), Engwa et al. (2019).
Lead (Pb)	Lethargy, allergies, mental retardation, depression, anxiety, dysarthria, pallor, abdominal pain, anorexia, anaemia, ataxia, paralysis, reproductive disorders, encephalopathy, hypertension, insomnia, peripheral, papilledema, neuropathy, renal disorders, hyperproteinemia, cancer, etc.	Martin and Griswold (2009); Jaishankar et al. (2014); Burke et al. (2016); Engwa et al. (2019), NORD (2019).
Lithium (Li)	Disorders related to parathyroid and thyroid glands; Disorders related to the stomach, central nervous system, kidneys, and intestinal tract	McKnight et al. (2012), NORD (2019).
Manganese (Mn)	Damage of central nervous system, liver damage, body stiffness, fatigue, hallucinations, dystonia, psychiatric abnormalities, bradykinesia, pneumonia, manganism, etc.	Genuis et al. (2011), Prashanth et al. (2015), Al-Fartusie and Mohssan (2017), Bjørklund et al. (2017), Engwa et al. (2019), NORD (2019).
Mercury (Hg)	Nausea, vomiting, depression, lethargy, gingivitis, dyspnoea, pulmonary oedema, lung damage, pneumonia, memory loss, cerebellar ataxia, choreoathetosis, polyneuropathy, seizures, dysarthria, mad hatter syndrome, hypertension, blindness, acrodynia, erythema, hyperesthesia, acute renal failure, cancer, etc.	Martin and Griswold (2009), Jaishankar et al. (2014), Genchi et al. (2017), Engwa et al. (2019), NORD (2019).
Nickel (Ni)	Lung cancer, pulmonary fibrosis, disorders related to cardiovascular, gastrointestinal, haematological, musculoskeletal, and hepatic systems; etc.	ATSDR (2004), Phillips et al. (2010), Al-Fartusie and Mohssan (2017), Engwa et al. (2019), NORD (2019).
Selenium (Se)	Diarrhoea; irritation of the respiratory tract, eyes, and gastrointestinal tract; liver inflammation, peripheral nerve damage; alopecia; skin depigmentation; cancer; etc.	Martin and Griswold (2009), Hatfield et al. (2011), Sun et al. (2014), Al-Fartusie and Mohssan (2017), NORD (2019).
Silver (Ag)	Nausea, diarrhoea, arygria, etc.	Martin and Griswold (2009), NORD (2019).

Table 2 (continued)

Element	Health hazards	References
Thallium (Tl)	Somnolence; nausea; hematemesis; alopecia; polyneuropathy; cranial nerve palsies; cerebellar ataxia; optic atrophy; retrobulbar neuritis; ophthalmoplegia; renal and cardiac failure; coma; etc.	Finkelman et al. (2002), Cvjetko et al. (2010), NORD (2019).
Tin (Sn)	Tremors, hallucinations, psychotic behaviour, convulsions, etc.	NORD (2019).
Vanadium (V)	Neurological, reproductive, gastrointestinal, immunological, and lymphoreticular disorders, cancer, etc.	ATSDR (2012), Crebelli and Leopardi (2012).
Zinc (Zn)	Liver, reproductive, neurological, and developmental dysfunctions, etc.	ATSDR (2005), Prashanth et al. (2015); Al-Fartusie and Mohssan (2017), NORD (2019).

increase from the year 2014 to 2018. However, the production of paddy rice was significantly higher than the milled rice every year. It was observed that in each year, there was very little difference between annual production and total consumption of milled rice, indicating high consumption of rice.

Consumption of milled rice (tonnes) in various countries in the year 2018 was recorded by IRRI (2019) (Fig. 2) and it was found that China is the major consumer of rice followed by India and Indonesia (Rafiq et al. 2014; IRRI 2019). It became evident from Fig. 2 that Asian countries are major consumers of milled rice, where rice is consumed in various forms such as steamed rice, fried rice, rice flour, rice cakes, congee, rice crackers, and puffed rice. According to Zeng et al. (2015a), in rice-consuming nations, contaminated rice is the main source of exposure to PTEs in the human population. The present work is an attempt to summarise recent literature on different sources of soil and water pollution and bioaccumulation of PTEs in rice crop followed by the discussion on possible human health risk posed due to consumption of rice grown in contaminated areas. Few studies regarding remediation strategies to control pollution of soils and irrigation water have also been discussed. During the preparation of this manuscript, the main focus was on literature from 2010 to 2019 and reports from Asia as rice is widely consumed in Asia. However, some reports earlier than 2010 and few from other continents are also included.

Sources of soil and water pollution

Soil is both sink and source of different PTEs (Wuana and Okieimen 2011; Brevik and Burgess 2012). Similarly, groundwater, an essential component of life, also contains different contaminant to varying degrees. All PTEs exist naturally in soil and water but due to anthropogenic activities, elements present in deeper layers of the earth get excavated and dispersed in the atmosphere at concentrations higher than the normal background concentrations (Singh et al. 2018). Different contaminants, i.e. metalloids and metals, e.g. As, Cd, Co, C, Cu, Pb, and Ni, in soil and water are toxic and may harm living beings by invading the food chain. Some of the sources of PTE in soil and water are discussed below:

Geogenic sources Metals and metalloids exist naturally and are released on the earth crust and introduced into groundwater via geothermal processes, volcanic activities, reductive dissolution of ores and minerals, weathering and erosion of soils, sediments and parent bed rock, etc. (Smith et al. 1998; IARC 2004; Ravenscroft et al. 2009; Patil et al. 2012; Owa 2014; Singh et al. 2018)

Anthropogenic sources Industrialisation and urbanisation on global scale have led to contamination of different environmental components with various PTEs over the last few

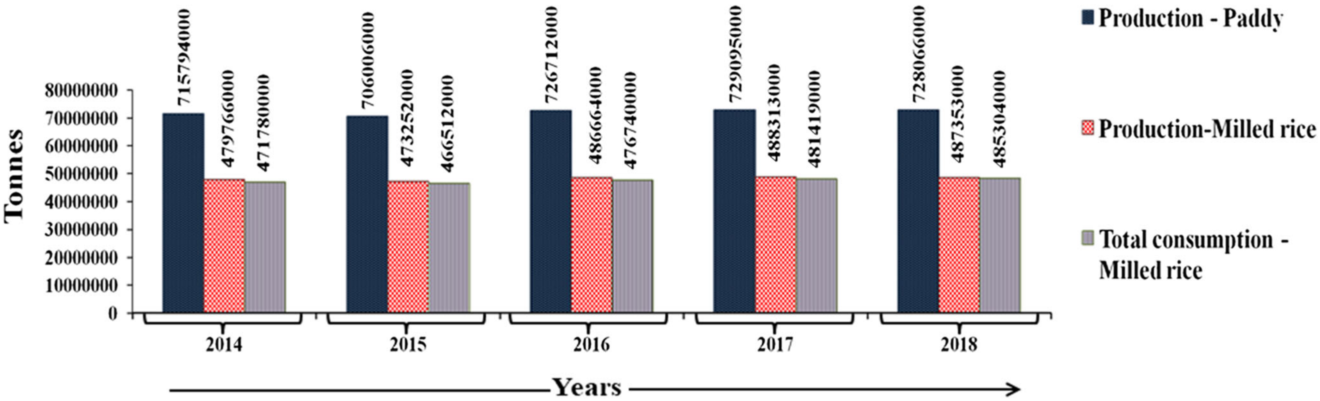

Fig. 1 Global scenario of production of paddy and milled rice; and consumption of milled rice from year 2014 to 2018 (IRRI 2019)

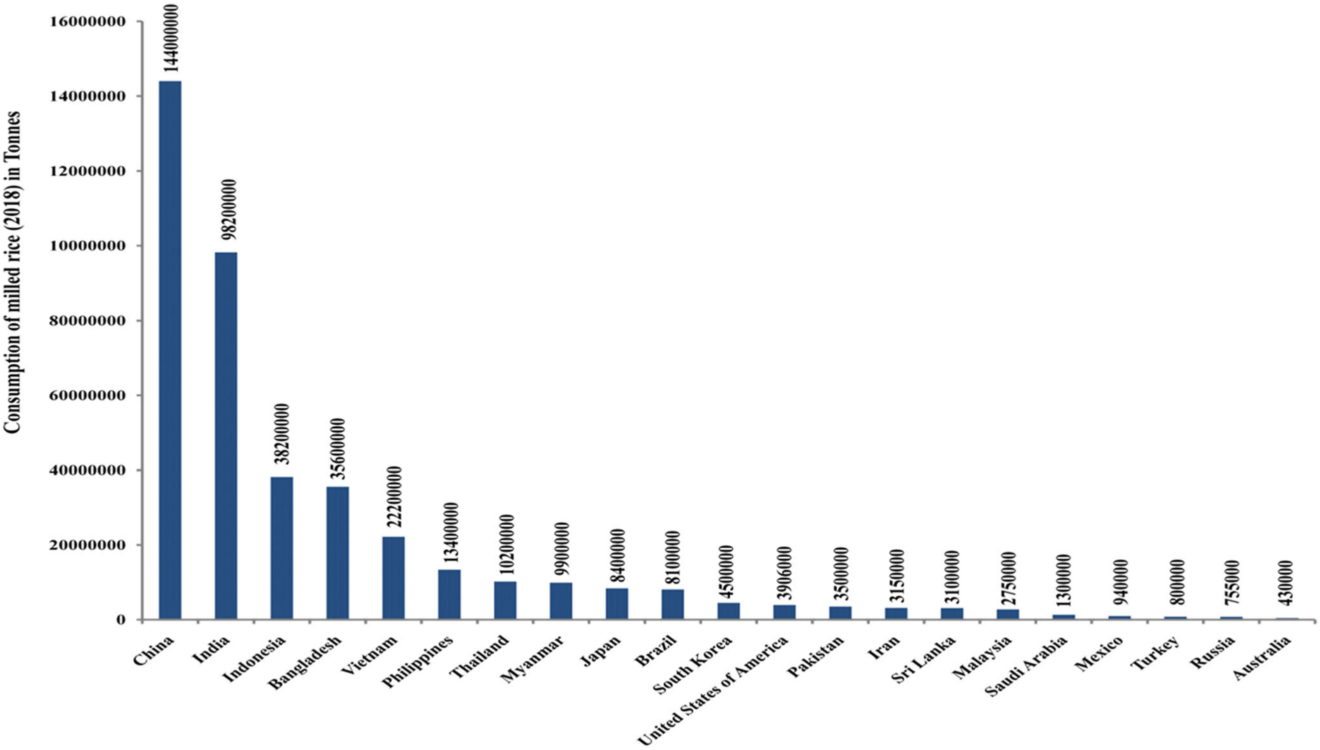

Fig. 2 Comparison of country wise consumption of milled rice (tonnes) in 2018 (IRRI 2019)

decades (Cai et al. 2015). The major anthropogenic sources of contamination in soils and groundwater are sewage discharge, untreated industrial wastewaters, nuclear power plants, mining activities, excessive application and leaching of agrochemicals (pesticides, fertilisers, and insecticides), urban storms, landfill leachates, oil seeping, deposition of atmospheric pollutants, such as coal fly ash released from industries and vehicular pollutants, on soil and surface water, etc. (Hutton 1983; Mehra et al. 1998; Smith et al. 1998; Gulz et al. 2005; Lee et al. 2008; Baba et al. 2010; Mulligan et al. 2001; Irfan et al. 2013; Lim and McBride 2015; Saleem et al. 2018; Chonokhuu et al. 2019; Yadav et al. 2019). As per the European Environment Agency (EEA 2009), the relative contribution of major anthropogenic sources to soil pollution is presented in Fig. 3. It was observed that industrial production and commercial services provided a maximum contribution to soil pollution (36%), followed by the oil industry (17%), municipal waste treatment, and disposal (15%), etc.

Accumulation of potentially toxic elements (PTEs) in rice

Plants, during their life cycle, act as miners of different elements from earth (Peralta-Videa et al. 2009). Transport and accumulation of various PTEs in edible parts of a plant from the soil are a major entry point for their incorporation into the food chain, posing a high health risk to human beings (Fu et al. 2008; Naser et al. 2012a, b; Liao et al. 2013). Accumulation of PTEs in plants from soil is dependent on physico-chemical properties of soil, contents of PTEs in soil, microbial activity in the soil, plant physiology, mechanism of PTE uptake and transport, plant's mineral requirements, etc. (Tangahu et al. 2011; Sahoo and Kim 2013; Chibuike and Obiora 2014). Plants growing in polluted soils uptake various environmental contaminants, such as metals/metalloids, and accumulate them in different tissues of the plants at varying degrees (Baker 1981). Bioconcentration factor (BCF) is an indicator of the fate of contaminants in the plants. It is a ratio of the concentration of a potentially toxic element (PTE) (metal/metalloid) in a plant (C_{P}) to the concentration of the same PTE in the soil (C_{S}). BCF can be determined as (Huang et al. 2008; Yang et al. 2009):

$$\mathrm{BCF} = C_{\mathrm{P}}/C_{\mathrm{S}}$$

According to Baker (1981) and Chibuike and Obiora (2014), if a plant is capable of accumulating high content of contaminant (element/metal/metalloid) from the soil, then the value of BCF will be greater than 1, it is called as an accumulator of that specific contaminant. BCF has been addressed as a bioaccumulation factor (BAF) or transfer factor (TF) in some studies (Cao et al. 2010; Šmuc et al. 2012; Kong et al. 2018).

Kong et al. (2018) conducted a study to estimate the bioaccumulation of various heavy metals in rice from a high geological background (HGB) area in Guizhou Province, China. BAF values calculated for different PTEs such as As,

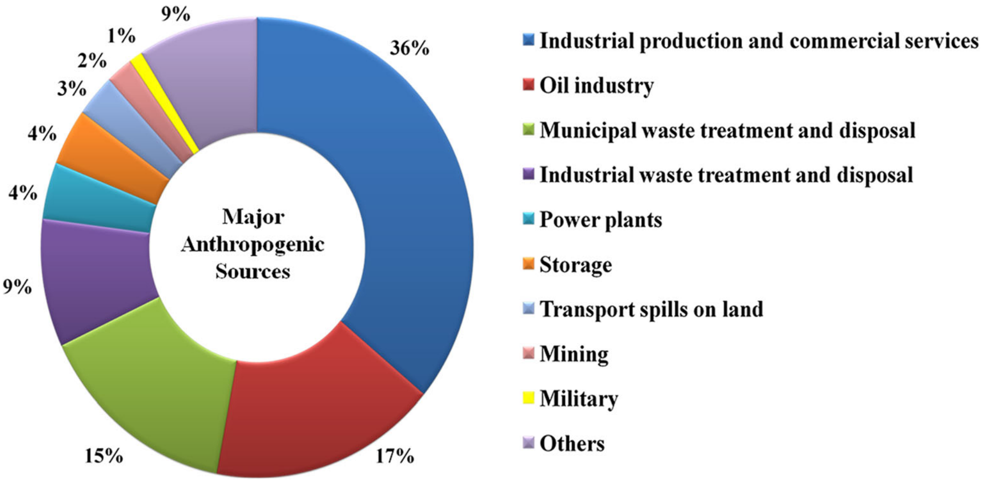

Fig. 3 Relative contribution of major anthropogenic sources to soil pollution (EEA 2009)

Cd, Cu, Pb, and Zn in rice were > 1. BAF values of all metals were higher in the HGB zone of alluvial plain type in comparison to metallogenic belt type except Cd. In another study conducted by Gaurav et al. (2018), BCF values for Cd, Cr, Ni, Cu, Pb, and Zn were > 1 in rice collected from industrial areas (Paper industry, distillery, and sugar mill) in uppermost Ganga-Yamuna Doab region of Saharanpur district. Another study was carried out by Juen et al. (2014) to determine the bioconcentration factor of metals in root, stem, and grains of paddy. Mean BCFs for As (38.40), Co (1.02), Pb (1.81), and Cd (7.10) in roots are > 1. In stems, BCF for only Cd (1.53) is > 1. In grains, none of the metals had BCF > 1. Results indicated that the highest amount of metals (especially As) was accumulated in roots than other plant parts. Transfer of various metals (Zn, Pb, Cd, and Cu) in different organs and tissues (roots, stalk, leaf, and husk) of rice was studied by Wang et al. (2013) in an area near a coal gangue pile in China. BAFs for Zn (1.32), Cd (4.22), and Cu (1.66) in roots were found to be > 1. In the case of stalk tissue, BAF for only Cd (1.02) was > 1. BAFs for none of the metals was > 1 in leaves and husk of rice plants. Liu et al. (2007) studied the accumulation of heavy metals in roots, straw, and grains of rice plants in agricultural soils near Zhengzhou City, People's Republic of China. It was observed that upper limits of BCFs for Cd (44.13), As (3.76), and Hg (3.90) in roots and for Cd (8.05) and Hg (1.53) in straw tissues of the rice plants were > 1, whereas in case of grains, BCFs for none of the heavy metals exceeded the value of 1. This suggested that aerial parts of the plant absorbed but did not accumulate heavy metals in comparison to roots.

Chen et al. (2018) also estimated BCFs for Cd, Zn, Cu, Ni, Pb, and Cr in rice and wheat grains collected from Lihe River Watershed of the Taihu Region, China. BCFs for different contaminants in rice varied as follows: Cd (0.577) > Zn (0.459) > Cu (0.259) > Ni (0.059) > Pb (0.015) > Cr (0.11), whereas for wheat grains, order of variation was as follows: Zn (0.651) > Cu (0.271) > Cd (0.254) > Ni (0.038) > Pb (0.014) > Cr (0.006). It was observed that BCFs for Cd, Cr, and Ni were relatively higher in rice in comparison to wheat, indicating a higher accumulation capacity of rice for these elements. Lee et al. (2017) estimated BCFs for different elements in rice from abandoned sites in Kyungpook Province, Korea. Mean BCFs were found to follow the order: Cr (0.688) > Hg (0.459) > Cu (0.287) > Mn (0.222) > Cd (0.171) > Zn (0.107) > As (0.042) > Pb (0.029) > Al (0.019). High BCF for Cr indicated a high affinity of rice for Cr (Mohanty et al. 2011; Sharma et al. 2018). Rahimi et al. (2017) determined BAF for Cd, Ni, Pb, and Zn in rice grains from four locations, i.e. Chamgordan, Varnamkhast, Zarrinshahr, and Sede, Iran. It was observed that BAFs for all heavy metals in all locations were < 1 except Cd, which had BCF > 1 in all locations except Sede, Iran. These results also suggested a relatively higher accumulation of Cd in rice in the study area in comparison to other heavy metals analysed. Yadav et al. (2016) estimated BCFs for metals such as Co, Cu, Zn, Ni, Cd, Ni, Cr, and Fe in rice grains from alluvial plain–type area in Fatehabad district, Haryana, India. The mean BCF for different metals in rice grains varied as: Zn (0.11) > Co (0.10) > Cu (0.08) > Cr (0.08) > Ni (0.02) > Pb (0.011) > Cd (0.009) > Fe (0.003). Zeng et al. (2015a) analysed the transfer and accumulation of heavy metals in brown rice from Shimen, Fenghuang, and Xiangtan counties of Hunan Province, China. It was observed that Cd (0.551) had the highest TF, followed by Hg (0.0853), suggesting that Cd had higher mobility than Hg from soil to rice plant.

Šmuc et al. (2012) determined TF in rice crop in Kočani field plant system in the Republic of Macedonia. Order of mean TFs for different elements in rice crop varied as follows: Mo (0.7) > Zn (0.03) > Cd (0.15) > Cu (0.10) > As (0.03) > Pb (0.01). Singh et al. (2011) investigated the accumulation of various heavy metals in paddy irrigated with water from Ramgarh Lake, Gorakhpur, UP, India (experimental site). It was found that contents of Cr, Pb, Cd, As, Mn, Zn, and Hg in roots, straw, and grains of plants from the experimental site were higher than the same in the control site (irrigated with bore well water). Contents of As, Hg, Cd, and Pb were higher in roots in comparison to the other plant parts. Order of BAFs of different contaminants in paddy plants from experimental site was observed as follows: Hg (0.308) > Mn (0.032) Pb (0.028) > Cd (0.017) > As (0.016) > Zn (0.008) > Cu (0.002) > Cr (0.001), whereas for control site, order was as follows: Hg (0.272) > Mn (0.038) > Pb (0.03) > Cd (0.016) > As (0.014) > Zn (0.007) > Cu (0.002) > Cr (0.002). It was evident from the results that BAFs were slightly higher for the experimental site. Order of different contaminants on the basis of TFs in rice grains from an area in the vicinity of an industrial zone in Jiangsu, China, has been reported in a study to be as follows: Zn (0.11) > Cu (0.081) ≥ Cd (0.080) > Hg (0.027) > Cr (0.0084) > Pb (0.0017) where mean contents (mg/kg) of Zn, Cu, Cd, Hg, Cr, and Pb in soils from the area under investigation were 102.70, 31.80, 0.169, 0.235, 97.40, and 29.60, respectively (Cao et al. 2010). The study concluded that Zn, Cu, and Cd were more easily transferred from soil to rice in comparison to other metals. It was revealed from a review of various studies that different PTEs were accumulated to different extents in rice grains depending on different factors such as the physiology of rice plant, its mineral requirements, physico-chemical properties of soil, and bioavailability of different PTEs in soil. Furthermore, it was observed that studies on rice contamination with PTEs were mainly from Asia, where rice is a staple crop and also it is mostly being cultivated either on contaminated soils or irrigated with waste water from industries or untreated/partially treated sewage to meet the needs of the ever-growing population there (Akinbile and Haque 2012; Satpathy et al. 2014; Chakraborti et al. 2018).

Health risks

Contamination of soil and irrigation water with different organic and inorganic pollutants may lead to uptake and accumulation of pollutants in rice (Satpathy et al. 2014). Long-term consumption of contaminated rice may cause various human health problems (Jiang et al. 2017). PTEs such as metals and metalloids are persistent environmental contaminants, which are toxic at varied concentrations (Kar et al. 2008; Reza and Singh 2010; Assubaie 2015; Faisal et al. 2014). Elements such as As, Cd, and Pb have no known biological role and are toxic even at low concentrations (Duruibe et al. 2007; Haloi and Sarma 2012). On the other hand, few elements such as Cr, Co, Cu, Fe, Mn, and Zn are essential for the normal functioning of living beings having a biological role in different metabolic processes and required in minute quantities. However, these essential elements when consumed over long durations or even in small quantities may accumulate in different tissues of the body causing various irregularities such as skeletomuscular, respiratory, gastrointestinal, reproductive, renal, endocrinal, cardiovascular, neurological, hepatic, and genetic disorders, and cancer (Järup 2003; Duruibe et al. 2007; Kar et al. 2008; Ali et al. 2013). The summary of some studies indicating human health hazards posed by exposure to different potentially toxic elements has been presented in Table 2.

Estimation of the potential health risk posed to consumers eating contaminated rice over long durations has been reported in various reports from all over the globe signifying the impact of rice contamination with different PTEs on human health (Table 3). During the literature survey, various reports from different counties such as China, India, Bangladesh, Iran, South Korea, Nigeria, and Thailand were noticed. It was observed that in most of the studies, contents of different PTEs in rice were compared with food safety standards given by different government agencies such as the Joint FAO/WHO Expert Committee on Food Additives (JECFA 2005, 2014), the Ministry of Health of the People's Republic of China (MHPRC 2005, 2012, 2017), and the Food and Agriculture Organization and World Health Organization (FAO/WHO 2001). In these studies, health risks posed to the human population due to daily intake of rice grains contaminated with PTEs such as Cd, As, Pb, Cr, Fe, Zn, Hg, Cu, Mn, Co, and Ni were calculated and risks were categorised into two categories: non-carcinogenic and carcinogenic. In the case of non-carcinogenic risk, hazard quotient (HQ) and hazard index (HI) were analysed. HQ is an index used to estimate non-carcinogenic health risk whereas HI is the sum of HQs estimated for different PTEs and used for assessment of overall non-carcinogenic health risk posed to consumers. Similarly, to analyse the possibility of cancer occurrence in the population, another index, i.e. cancer risk (CR), is being used. If CR was estimated for more than one PTE, then CR posed by individual PTEs were added to estimate total cancer risk (TCR). Results were compared with the safe limits given by USEPA (2010). HQ or HI > 1.00 and CR or TCR > 1.00E−06 indicated a high possibility of occurrence of non-cancerous health problems and cancer, respectively. In many reports, abbreviations used for risk assessment were different as some used abbreviations, NHQ (non-carcinogenic hazard quotient), THQ (target hazard quotient), and HRI (health risk index) instead of HQ. In some reports, HI was replaced with the following abbreviations: THI (total hazard index), THQ (total hazard quotient), TTHQ (total target hazard quotient), and AR (accumulative risk). In place of CR, other abbreviations such as TCR (target carcinogenic risk) and "Risk" have been used. Similarly, in some reports, TCR has been replaced with $\mathrm{Risk}_{\mathrm{total}}$. It was observed that in most of the studies given in Table 3, PTEs such as As, Pb, Cd, Co, and Cr exceeded the corresponding food safety limits prescribed by different agencies as mentioned earlier and were reported to pose health risks to the human population such as paralysis, depression, encephalopathy, seizures, oedema, dermatitis, anaemia,

Table 3 Summary of some recent studies on contamination of rice grains with potentially toxic elements and associated health risk assessment

S. no.	Nature of samples and study area	Potentially toxic elements in rice (mean)	Health risks (mean)	Inference (reference)
1.	Rice fields in Abakaliki, Nigeria.	Farm A (*N* = 20, µg/g): Pb (1.731), Cd (0.024), Zn (5.252), Cr (0.704), and Fe (101.446). Farm B (*N* = 20, µg/g): Pb (2.415), Cd (0.098), Zn (5.551), Cr (0.936), and Fe (28.244).	Farm A: hazard quotient (HQ): Pb (0.484), Cd (0.027), Zn (0.020), Cr (0.000525), and Fe (0.162). Total hazard index (THI): 0.693 Farm B: hazard quotient (HQ): Pb (0.675), Cd (0.110), Zn (0.021), Cr (0.000698), and Fe (0.045). Total hazard index (THI): 0.852	Pb content was found to exceed the WHO (1996) limit of 0.2 µg/g. No possible health risks were posed to rice consumers as HQ or THI < 1. (Ihedioha et al. 2019).
2.	A secondary lead smelter, Khulna city, Bangladesh.	*N* = 29 (mg/kg, fresh weight): Pb (7.48), As (1.40), and Zn (25.00).	Target hazard quotient (THQ): Adults: Pb (6.30), As (28.55) and Zn (0.52). Children: Pb (3.51), As (15.93) and Zn (0.29). Target carcinogenic risk (TCR): Adults: Pb (0.00021) and As (0.1284). Children: Pb (0.00011) and As (0.00717).	Pb and As contents were higher than maximum allowable concentrations of 0.2 for both given by JECFA (2005). THQ values > 1 and TCR > 1.00E−06 (USEPA 2010) for Pb and As indicated high health risk of non-carcinogenic and carcinogenic health problems (Islam et al. 2019).
3.	Crop fields situated in Jiangsu Province, Zhejiang and Shanghai in Yangtze River Delta, China.	*N* = 137 (mg/kg): As (0.132), Cd (0.064), Cu (5.241), Cr (0.193), Hg (0.007), Pb (0.098), and Zn (22.792).	Adults: hazard quotient (HQ): As (2.332), Cd (0.339), Cu (0.696), Cr (0.001), Hg (0.222), Pb (0.145), and Zn (0.403). Total hazard quotient (THQ): 4.138 Cancer risk (Risk): As (1.05E0−3), Cd (5.10E−03), Cr (5.13E-04), and Pb (4.44E−06). Total cancer risk ($\text{Risk}_{\text{total}}$): 6.70E−03 Children: hazard quotient (HQ): As (2.661), Cd (0.387), Cu (0.794), Cr (0.001), Hg (0.253), Pb (0.165), and Zn (0.460). Total hazard quotient (THQ): 4.721 Cancer risk (Risk): As (1.19E−03), Cd (5.80E−03), Cr (5.8E−04), and Pb (5.06E−06). Total cancer risk ($\text{Risk}_{\text{total}}$): 7.60E−03	As was found to be mainly responsible for posing non-carcinogenic health risk, whereas, cancer risk was primarily caused by Cd and As (Mao et al. 2019).
4.	Agricultural area around the Xiazhuang uranium mine, China.	*N* = 27 (mg/kg): U (< 0.005), Th (0.006), As (0.154), Cd (0.071), Cr (1.975), Co (3.791), Cu (2.308), Mn (83.375), Ni (3.094), Pb (0.079), and Zn (18.113).	Hazard quotient (HQ): Th (< 0.01), As (0.15), Cd (0.71), Cu (1.14), and Pb (0.11).	Rice grains were found to be highly contaminated with Cr, Co, and Ni as contents of these metals were higher than National food safety standards (MHPRC 2017) of 1, 2.5, and 1, respectively. HQ for Cu > 1, indicating potential health risks to rice consumers (Wang et al. 2019).
5.	Lihe river watershed, Taihu region, East China.	*N* = 32 (mg/kg): contents of different heavy metals such as Cd, Cr, Cu, Pb, Ni, and Zn, in rice samples, varied as: Zn > Cu > Ni > Pb > Cr > Cd.	Adults: hazard quotient (HQ): Cd (6.36E−01), Cr (1.23E−03), Cu (5.33E−01), Ni (2.59E−01), Pb (4.70E−01), and Zn (5.40E−01). Accumulative risk (AR): 2.44 Children: hazard quotient (HQ): Cd (6.93E−01), Cr (1.34E−03), Cu (5.31E−01), Ni (2.83E−01), Pb (5.12E−01), and Zn (5.88E−01). Accumulative risk (AR): 2.66	Pb in all rice samples and Cd in 26.5% samples were higher than tolerance limits of Pb (0.20 mg/kg) and Cd (0.20 mg/kg), respectively (MHPRC 2005). HQ and AR > 1, indicated high non-carcinogenic risk posed to rice consumers (Chen et al. 2018).
6.	Market area, Iranshahr city, Iran.	*N* = 36 (mg/kg): As (0.369), Cd (0.0337), Pb (0.123), Cu (3.095), Al (39.6), and Mo (1.106).	Hazard quotient (HQ): As (5.23), Cd (0.15), Pb (0.14), Cu (0.32), Al (0.18), and Mo (0.85). Hazard index (HI): 6.67 Cancer risk (CR): As (2.37E−03).	Rice grains were found to be highly contaminated with Al. HI > 1.00 and CR > 1.00E−06 indicated high risk of health problems in human beings consuming contaminated

Table 3 (continued)

S. no.	Nature of samples and study area	Potentially toxic elements in rice (mean)	Health risks (mean)	Inference (reference)
				rice primarily (Djahed et al. 2018).
7.	Agricultural areas in Ropar wetland and its environs.	*N* = 13 (mg/kg): Cd (0.99), Co (15.21), Cr (19.98), Cu (69.89), Pb (17.13), and Zn (35.71).	Hazard quotient (HQ): Cd (0.32), Co (16.67), Cr (2.19), Cu (0.57), Pb (not calculated), and Zn (0.04). Hazard index (HI): 19.79 Cancer risk (CR): Cr (3.28E−03).	All rice samples had Co and Pb contents above the safe limit (mg/kg) of 0.48 and 2.50 given by Bowen (1966) and Awasthi (2000), respectively. HI > 1.00 indicated high potential health risk in residents, primarily due to Co and Cr, whereas, CR > 1.00E−06 suggested high cancer risk posed to residents due to Cr in rice (Sharma et al. 2018).
8.	Mining area, Hunan Province, Central China.	*N* = 54 (mg/kg): Cd (0.103), Pb (0.131), Sb (5.175), Mn (6.007), and As (0.524).	Combined hazard index (HI): 22.5917, which was > 1.00. Total cancer risk (CR): 0.1773, which was > 1.00E−06.	Mean As content in rice was slightly higher than maximum allowable concentration (MAC) of 0.524 mg/kg given by Zhao et al. (2015). High potential non-carcinogenic and carcinogenic health problems were posed to residents (Fan et al. 2017).
9.	Abandoned metal mines in South Korea.	Dalsung mine (*N* = 10, mg/kg): As (0.314), Cd (0.052), Cu (3.02), Pb (1.14) and Zn (13.3). Yeongdae mine (*N* = 10, mg/kg): As (0.218), Cd (0.344), Cu (4.32), Pb (0.748), and Zn (15.6). Munmyung mine (*N* = 10, mg/kg): As (0.217), Cd (0.180), Cu (7.80), Pb (0.655), and Zn (19.8). Sambo mine (*N* = 10, mg/kg): As (0.238), Cd (0.114), Cu (3.63), Pb (0.676), and Zn (18.4).	Daily intake (mg/day): Dalsung mine: As (0.063), Cd (0.010), Cu (0.601), Pb (0.226), and Zn (2.650). Yeongdae mine: As (0.043), Cd (0.069), Cu (0.858), Pb (0.148), and Zn (3.100). Munmyung mine: As (0.043), Cd (0.036), Cu (0.982), Pb (0.130), and Zn (3.936). Sambo mine: As (0.047), Cd (0.023), Cu (0.723), Pb (0.135), and Zn (3.667).	Estimated daily intake values of As and Cd through rice consumption were found to be approximately 50 and 80%, respectively of corresponding acceptable daily intake (ADI) guidelines prescribed by FAO/WHO Joint Food Additive and ContaminantsCommittee (Kwon et al. 2017).
10.	Villages around Xinqiao mine, Tongling, Anhui province, China.	*N* = 60 (mg/kg): Cr (2.41), Ni (2.86), Cu (17.71), Zn (35.59), Pb (0.17), and Cd (0.78).	Adults: hazard quotient (HQ): Cr (0.01), Ni (0.89), Cu (2.75), Zn (0.74), Pb (0.30), and Cd (4.85). Cancer risk (CR): Cr (7.59E−03), Ni (1.49E−02), and Cd (2.96E−02). Children: hazard quotient (HQ): Cr (0.02), Ni (1.81), Cu (5.62), Zn (1.50), Pb (0.62), and Cd (9.88). Cancer risk (CR): Cr (1.31E−03), Ni (2.61E−03), and Cd (5.16E−03).	Contents of Cr, Cu, and Cd exceeded maximum levels of contaminants allowed in food (MLC) (mg/kg) (MHPRC 2005), i.e. 1, 10, and 0.2, respectively. Cu and Cd posed non-carcinogenic health risk, whereas, cancer risk was posed by Cr, Ni, and Cd present in rice grains (Li et al. 2017).
11.	E-waste dumping areas, Khong Chai, Kalasin Province, Thailand.	*N* = 15 (mg/kg): Cr (1.09), Pb (1.06), Mn (65.21), and Ni (0.67).	Health risk index (HRI): Cr (0.30), Pb (1.50), Mn (2.60), and Ni (0.002).	Pb content in rice exceeded the maximum level of contaminants and toxins in food (0.2 mg/kg) (FAO/WHO 1972). HRI > 1 for Pb and Mn > 1, indicated high potential risk of health problem in residents (Neeratanaphan et al. 2017).
12.	Villages in around the Ropar wetland, Punjab, India.	*N* = 12 (mg/kg): total arsenic (As = 0.18) and inorganic arsenic (i-As = 0.13).	Hazard quotient (HQ): i-As (0.14). Cancer risk (CR): i-As (62.73E−06).	Total arsenic and inorganic arsenic contents in rice grains were well below the corresponding safe standards (mg/kg) 1.00 (Abedin et al. 2002) and 0.30 (JECFA 2014). HQ > 1 and CR > 1.00E−06, indicated high risk of health problems in residents of the study area due to rice consumption (Sharma

Table 3 (continued)

S. no.	Nature of samples and study area	Potentially toxic elements in rice (mean)	Health risks (mean)	Inference (reference)
				et al. 2017).
13.	Supermarkets, Henyang, China.	Hunan (13 polished rice brands) (*N* = 39, mg/kg): Cd (0.215), Pb (0.313), Cr (0.348), Cu (1.923), Zn (14.713), and Mn (8.531). Jiangxi (2 polished rice brands) (*N* = 4, mg/kg): Cd (0.153), Pb (0.150), Cr (0.232), Cu (2.472), Zn (14.787), and Mn (8.828). Jilin (2 polished rice brands) (*N* = 4, mg/kg): Cd (0.137), Pb (0.333), Cr (0.330), Cu (2.128), Zn (13.103), and Mn (9.326). Thailand (3 polished rice brands) (*N* = 9, mg/kg): Cd (0.100), Pb (0.537), Cr (0.224), Cu (1.338), Zn (17.259), and Mn (7.809).	Hunan: hazard quotient (HQ): Cd (0.710) and Cr (0.319). Cancer risk (CR): Cd (8.87E−03) and Cr (4.80E−04). Jiangxi: hazard quotient (HQ): Cd (0.507) and Cr (0.213). Cancer risk (CR) Cd (6.33E−03) and Cr (3.20E−04). Jilin: hazard quotient (HQ): Cd (0.451) and Cr (0.303). Cancer risk (CR) Cd (5.64E−03) and Cr (4.60E−04). Thailand: hazard quotient (HQ): Cd (0.330) and Cr (0.206). Cancer risk (CR) Cd (4.13E−03) and Cr (3.210E−04).	Cd and Pb contents exceeded the allowable limits of 0.2 for both Cd and Pb (MHPRC 2012) in 5 and 11 brands, respectively. High cancer risk was posed to rice consumers due to Cd and Cr contamination in rice (Dai et al. 2016).
14.	Area irrigated with acid mine drainage contaminated with thallium around the Yunfu pyrite mine, Guangdong Province, China.	*N* = 144 (mg/kg): Tl = 1.42	Hazard quotient (HQ): range of mean HQ for different age groups were 4.08 to 24.50 (males) and 3.84 to 22.38 (females).	Tl content in rice exceeded the maximum permissible level of Tl (0.5 mg/kg) in foods and feedstuffs (LaCoste et al. 2001). High risk of non-carcinogenic risk was observed for consumers, especially for age group of 21 to < 70 years (Huang et al. 2016b).
15.	Industrial regions, Isfahan Province, Iran.	*N* = 9 (mg/kg): Zarrinshahar: Cd (0.28), Fe (63.23), Ni (1.25), and Pb (2.10). Mobarakeh: Cd (0.15), Fe (50.53), Ni (1.70), and Pb (1.21).	Combined target hazard quotient (THQ) for rice grains consumption was > 1.	Contents of Ni and Pb were found to be higher than maximum permitted concentration (mg/kg) of 0.6 and 0.3 (FAO/WHO 2001), respectively. High non-carcinogenic health risk indicated for resident of the study area (Moradi et al. 2016).
16.	Agricultural fields, Ilorin, Nigeria.	*N* = 40 (mg/kg): Cu (3.57), Cd (1.57), Zn (100.5), and Pb (3.97).	Adults: hazard quotient (HQ): Cu (0.07), Cd (1.31), Zn (0.28), and Pb (0.94). Hazard index (HI): 2.60 Children: hazard quotient (HQ): Cu (0.35), Cd (6.00), Zn (1.30), and Pb (4.28). Hazard index (HI): 11.93	Rice were highly contaminated as contents of Cd, Zn, and Pb exceeded the limits (mg/kg) 0.1, 50 (CODEX 2006), and 0.2 (WHO 2011), respectively. High potential health risk observed, primarily due to Cd and Pb. Children were found to be more prone to health risk in comparison to adults (Ogunkunle et al. 2016).
17.	Croplands, Fatehabad district, Haryana, India.	*N* = 8 (mg/kg): Fe (17.2), Cu (1.9), Cd (0.05), Pb (0.62), Ni (0.40), Zn (11.6), Co (0.68), and Cr (0.57).	Non carcinogenic hazard quotient (NHQ): Fe (5.84E−02), Cu (1.22E−01), Cd (1.34E−01), Pb (4.45E−01), Ni (5.85E−02), Zn (5.85E−02), and Cr (1.09E−03).	NHQ < 1.00 for all heavy metals, therefore rice grains were found to be safe for consumption (Yadav et al. 2016).
18.	Agroecological zones, Bangladesh.	*N* = 30 (mg/kg): Cd (0.88), As (0.321), Pb (0.713), Cr (0.183), Ni (0.213), Zn (13.178), Se (0.0256), Cu (1.985), Mo (0.102), Mn (4.654), Sb (0.0033), Ba (0.144), V (0.081), and Ag (0.007).	Target hazard quotient (THQ): Cd (0.610), As (7.419), Pb (1.236), Cr (0.001), Ni (0.074), Zn (0.305), Se (0.035), Cu (0.344), Mo (0.141), Mn (0.230), Sb (0. 57), Ba (0.005), V (0.080), and Ag (0.010). Total target hazard quotient (TTHQ): 10.548 Carcinogenic risk (CR): As (3.3E−03) and Pb (4.2E−05).	THQ > 1.00 and CR > 1.00E−06 for As and Pb indicated health risks posed to residents (Ahmed et al. 2015).
19.				

Table 3 (continued)

S. no.	Nature of samples and study area	Potentially toxic elements in rice (mean)	Health risks (mean)	Inference (reference)
	Agricultural fields in vicinity of mines, Hunan Province, China.	*N* = 66 (mg/kg): Pb (0.18–0.72), Cd (0.10–1.32), Cu (3.83–5.95), and Zn (8.64–15.18).	Hazard quotient (HQ): Pb (1.19E−01–4.71E−01), Cd (2.51E−01–2.85E+00), Cu (2.50E−01–3.88E−01), and Zn (7.51E−02–1.32E−01). Hazard index (HI): 1.19E+00–4.13E+00.	Upper limit of range of mean contents of Pb and Cd exceeded maximum level of contaminants (mg/kg) ≤ 0.4 and ≤ 0.2 in foods, respectively (MCLF) (MH 2005). Cd emerged as main culprit to pose high potential health risk in rice consumers (Lei et al. 2015).
20.	Riverine communities, China.	Tangjun (*N* = 15, mg/kg): As (0.14), Pb (0.05), Cd (0.64), Cr (0.04), and Hg (0.02). Sanhe (*N* = 13, mg/kg): As (0.14), Pb (0.05), Cd (0.39), Cr (0.04), and Hg (0.008). Lasha (*N* = 11, mg/kg): As (0.17), Pb (0.06), Cd (0.12), Cr (0.19), and Hg (0.005).	Adults: Tangjun: hazard quotient (HQ): As (2.55), Pb (0.08), Cd (3.50), Cr (0.07), and Hg (1.09). Hazard index (HI): 7.29 Cancer risk (CR): As (6.1E+03), Pb (1.2E+01), Cd (2.8E+05), and Cr (5.8E+02). Total cancer risk ($\text{Risk}_{\text{Total}}$): 2.9E+05 Sanhe: hazard quotient (HQ): As (2.55), Pb (0.08), Cd (2.13), Cr (0.16), and Hg (0.44). Hazard index (HI): 5.36 Cancer risk (CR): As (6.1E+03), Pb (.2E+01), Cd (1.7E+05), and Cr (1.3E+03). Total cancer risk ($\text{Risk}_{\text{Total}}$): 1.8E+05 Lasha: hazard quotient (HQ): As (3.10), Pb (0.09), Cd (0.66), Cr (0.27), and Hg (0.27). Hazard index (HI): 4.39 Cancer risk (CR): As (7.4E+03), Pb (1.5E+01), Cd (5.2E+04), and Cr (2.2E+03). Total cancer risk ($\text{Risk}_{\text{Total}}$): 6.2E+04 Children: Tangjun: hazard quotient (HQ): As (2.65), Pb (0.08), Cd (3.63), Cr (0.08), and Hg (1.14). Hazard index (HI): 7.58 Cancer risk (CR): As (3.0E+03), Pb (6.0E+01), Cd (3.5E+01), and Cr (not calculated). Total cancer risk ($\text{Risk}_{\text{Total}}$): 6.0E+01 Sanhe: hazard quotient (HQ): As (2.65), Pb (0.08), Cd (2.21), Cr (0.17), and Hg (0.45). Hazard index (HI): 5.56 Cancer risk (CR): As (7.6E+02), Pb (1.5E+00), Cd (2.1E+04), and Cr (1.6E+02). Total cancer risk ($\text{Risk}_{\text{Total}}$): 2.2E+04 Lasha: hazard quotient (HQ): As (3.22), Pb (0.10), Cd (0.68), Cr (0.28), and Hg (0.28). Hazard index (HI): 4.56 Cancer risk (CR): As (9.3E+02), Pb (1.9E+00), Cd (6.5E+03), and Cr (2.7E+02). Total cancer risk ($\text{Risk}_{\text{Total}}$): 7.7E+03.	100%, 92.30%, and 9.10% samples from Tangjun, Sanhe, and Lasha exceeded the Cd content than the Chinese food safety standard (0.20 mg/kg) (MHPRC 2012). High potential non-carcinogenic (primarily due to As, Cd, and Hg) and cancer risk (due to all contaminants) were posed to rice consumers (Zhang et al. 2015).

Table 4 Summary of some studies showing different remediation techniques used for reduction of PTE contents in soil using hyperaccumulator plants and reduction of PTE uptake by plants by stabilisation of PTEs in soil

S. no.	Technique used	Heavy metals/ metalloids removed or stabilised in soil	Methodology	Results	Inferences	Reference
1	Vermicomposting	Cd, Cu, Ni, Mn, Pb, and Zn.	Vermicompost treatments (V) (t ha^{-1}, dry weight): 0 (V0), 25 (V25), 50 (V50), 100 (V100), 150 (V150), and 250 (V250). Sewage sludge amendment (SSA) (t ha^{-1}, dry weight): 140 (SSA140). pH (5:1) for amendments V0, V25, V50, V100, V150, V250 and SS140 were 9.34, 9.32, 9.26, 9.03, 8.93, 8.97, and 8.73, respectively.	In comparison to sewage sludge treatment, vermicompost treatments showed higher decrease in available contents of Cd, Cu, Mn, Ni, Pb and Zn i.e., 11.7%, 48.8%, 38.7%, 37.3%, 15.8%, and 41.5%, respectively.	Vermicompost amendments increased accumulation of heavy metal, in the top 20-cm layer of mudflat soil, in a more stable binding form. This reduced their bioavailability to maize plant in comparison to sewage sludge amendment.	Zuo et al. (2019)
2	Amendments with Biochar and compost	Cd, Cu, Zn, and Pb.	Amendments: Compost (C), Biochar (B), mixture of compost and biochar (B + C), cComposted biochar (Bced) and biochar-composting (BCing). Soil moisture: 60%. Relative humidity: 28% Temperature: 25 °C Duration: 60 days.	All the amendments reduced the available contents of Cd, Cu, Zn, and Pb. Compost increased the available Cu content in soil. Bced and BCing showed maximum reduction in availability and mobility of metals.	Amendments with biochar and compost were successful in reducing available heavy metal contents in soil.	Zeng et al. (2015b)
3	Biosorption using freshwater alga *Spirogyra hyaline.*	Cd, Hg, Pb, As, and Co.	Initial concentrations of the heavy metals (mg/L): 20, 40, 60, and 80. Exposure period (min.): 30, 60, 90, and 120.	Maximum absorption Cd, Hg and As occurred at initial concentration of 40 mg/L. Highest Co and Pb removal occurred at 80 mg/L. The Freundlich model constant varied from 0.342 to 0.693 for different heavy metals. Langmuir separation factor values ranged from 0.114 to 0.719.	Dried biomass of *Spirogyra hyaline* showed high biosorption capacity.	Kumar and Oommen (2012).
4	Phytoremediation using *Brassica napus*	Cd, Cu, Pb, Zn, and As	Soil digestion procedure: Aqua regia method. Sequential extraction method used for speciation of heavy metals and As.	Heavy metal uptake in *Brassica napus* increased with phytoavailable concentration of heavy metals in soil. High accumulation of Pb and As in comparison to other contaminants.	*Brassica napus* exhibited high phytoremediation capacity.	Park et al. (2012)
5	Bioremediation using hyperaccumulator endophytic bacterium *Bacillus* sp. L14 (EB L 14).	Cd (II), Pb (II), Cu (II) and Cr (VI).	*Bacillus* sp. L14 was isolated from *Solanum nigrum* L. (a Cd hyperaccumulator). Initial treatment concentration: 10 mg/L Treatment (h): 0, 2, 4, 6, 8, 12, and 24. pH: 7.0. Treatment temperature: 30°C. Rotations per minute: 150.	EB L14 at 24 h incubation period and initial concentration of 10 mg/L, exhibited 75.78% uptake of Cd (II), 80.48% of Pb (II), and 21.25% of Cu (II). However, almost no Cr uptake was shown.	EB L 14 was revealed to be a promising bacterium for heavy metal remediation even at low concentrations.	Guo et al. (2010)
6	Phytoremediation using *Jatropha curcas* L. and	As, Cr and Zn.	Treatments: a) T1 = Experimental soil + heavy metal	Bioaccumulation potential of *Jatropha curcas* L. increased with	*Jatropha curcas* L. *showed high* bioaccumulation capacity.	Yadav et al. (2009)

Table 4 (continued)

S. no.	Technique used	Heavy metals/ metalloids removed or stabilised in soil	Methodology	Results	Inferences	Reference
	amendments with dairy sludge and biofertiliser.		b) T2 = Experimental soil + heavy metal + dairy sludge c) T3 = Experimental soil + heavy metal + biofertilizer d) T4 = Experimental soil + heavy metal + dairy sludge + biofertilizer Biofertilizer: *Azotobacter chroococcum* Concentrations of heavy metal added to experimental soil: ≫ For As and Cr (mg/kg): 0, 25, 50, 100, 250 and 500. ≫ For Zn (mg/kg): 0, 500, 1000, 2000, 3000 and 4000. Soil moisture content: 40 to 50% of the maximum limit of field water holding capacity.	increase in soil metal/ metalloid content. DTPA-extractable concentrations of As, Cr, and Zn in soil reduced with usage of dairy sludge. Organic amendments and biofertiliser significantly stabilised As, Cr and Zn in soil.	Dairy sludge and biofertiliser are helpful amendments to reduce phytoavailable concentrations of heavy metals.	

cardiomyopathy, osteoporosis, proteinuria, renal tubular dysfunction, emphysema, reproductive disorders, and cancer as described in Table 2.

Remediation strategies

Removal of PTEs from soil and water is necessary to alleviate the problem of uptake and accumulation of these contaminants by plants from soil and irrigation water. Bioremediation is a method which utilises living organisms, i.e. microorganisms or plants or both for the removal of PTEs from the environment, i.e. soil and water (Chibuike and Obiora 2014). Phytoremediation, an eco-friendly method, is a bioremediation technique which uses hyperaccumulating plants, such as *Jatropha curcas* L., *Lactuca sativa* L., and *Brassica juncea* L., for removal of PTEs from the environment (Cioica et al. 2019). There are different mechanisms of phytoremediation: phytoextraction (extraction of contaminants from soil/water and transport to other plant parts), rhizofiltration (uptake of contaminants from wetlands or wastewater streams), phytostabilisation (immobilisation of contaminants in plant tissue and conversion in less toxic form by complexation or metal precipitation or reduction of contaminants), and phytovolatisation (uptake of contaminants by plants and release in the environment in form of less toxic volatile forms via transpiration) (Mahajan and Kaushal 2018). Bioremediation, using microorganisms, is a highly efficient and low-cost technique for degrading different contaminants into less harmless forms for decontaminating soils, waste water, and sediments (Mejáre and Bülow 2001). Microbes such as *Pseudomonas putida*, *Bacillus subtilis*, *Ralstonia eutropha*, and *Enterobacter cloacae have been used* to sequester or reduce heavy metals in harmless forms (Chibuike and Obiora 2014).

Addition of soil amendments in the form of organic wastes after composting or vermicomposting add organic matter to the soil which retains heavy metals in soil decreasing their mobility and also increases soil fertility (Huang et al. 2016a). The addition of inorganic amendments such as lime to soils for reduction of metal uptake by plants is applied globally (Khan and Jones 2009). Treatment of waste waters before irrigation, rainwater harvesting to collect rain water for irrigation, and treatment of solid and liquid wastes before dumping them in land resources are some other techniques that can be used for avoiding the problem of soil contamination (McLaughlin et al. 1999). Few studies using different remediation techniques for reduction of contents of different PTEs in soil by using hyperaccumulator plants or reduction of uptake of PTEs by plants via their stabilisation in soil have been summarised in Table 4.

Conclusion

The quality of rice crop has deteriorated globally due to both geogenic and anthropogenic contamination of soil and irrigation water with PTEs after the advent of the industrialisation era. Rice being a staple food in majority of countries in the world has led to transfer of contaminants to human bodies through food chain. Consequently, the occurrence of various health problems (both carcinogenic and non-carcinogenic) in rice consumers has increased over the years. It was evident from the literature survey that in most of the studies, contents of As, Cd, and Pb in rice plants exceeded the safe limits provided by different agencies. These contaminants also posed health risks to rice consumers. Therefore, it is important to avoid accumulation of PTEs in rice crop by different remediation techniques such as phytoremediation and bioremediation of soil, and irrigation of water by using plants and/or microorganisms. Moreover, treatments of solid and liquid wastes from domestic sectors and industries before their disposal, rain water harvesting, and soil amendments are also few strategies to control rice contamination.

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