Review

Heavy metal uptake and stress in food crops: A Review

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Abstract. Heavy metal (HM) food contamination is detrimental to food safety and human health. Water scarcity, food shortage, illiteracy, failure to enforce environmental protection laws, and food quality regulations account for human HM contamination. Understanding their uptake pattern in food crops and how the crops behave under excessive concentration of these hazardous chemicals will guide farmers, researchers, and policymakers in devising appropriate control measures that will ensure the production and consumption of safer food crops. Relevant texts published by Science Direct, Springer Nature, and Wiley between January 2018 and December 2020 were cited in this article. The article discussed major factors affecting HM accumulation and the effects of HM stress on yield, physiology, and chemical properties of food crops. Wastewater irrigation, production in contaminated soil, and atmospheric deposit contributed to the contamination. Factors that influence HM uptake are those related to soil and irrigation water qualities and plant properties. The presence of other HMs and chemicals, growing season, crop age, planting method, and food crop type also affect HM uptake in food crops. HM stress affects anatomy, physiology including antioxidant defense mechanisms, nutrient availability and uptake, germination, seedlings development, growth, yield, leaf geometry, root and shoot length, plant genetics, pollination, and chemical composition including moisture content, soluble protein, and pigment content and characteristics.

Keywords: accumulation, contamination, food chain, irrigation water, soil, quality

Introduction

The menace of HM contamination is becoming a universal problem (Luo et al., 2021; Rizwan et al., 2021). HMs are found naturally in the environment, natural processes and human activities aid their movement in the ecosystem and account for soil, water, and food contamination (Rehman et al., 2020). Soil quality is fundamental to food safety and human health (Qin et al., 2021). Intense use of agrochemicals and wastewater irrigation have changed soil conditions and exposed consumers to many precarious chemicals (Kalkhajeh et al., 2021). There is a rising concern for human health and environmental safety due to the continuous release of these dangerous elements by many forms of anthropogenic activities (Samiee et al., 2019) in quantities much higher than those released by natural processes (Hu et al., 2018; Vareda et al., 2019; Yuan et al., 2019).

The jeopardy of HMs is detrimental to the environment, foods, and human life and the danger of HM contamination is becoming unbearable as it is affecting all categories of foods including organic foods (Anae et al., 2020). Ugulu et al. (2021) reported dangerous levels of Cd and Pb in organic pepper fertilized with farmyard manure and poultry waste. Vegetables produced in a greenhouse under controlled conditions were also reported to be contaminated by HMs (Kalkhajeh et al., 2021), higher levels of Hg and Cd were established by Fan et al. (2021) in vegetables produced in plastic greenhouse. When they have their way into the living tissue, HMs interfere with many physiological and biochemical processes in both plants and animals and at higher concentrations can lead to death (Rehman et al., 2020). The major route for food crops HM contamination is production in contaminated soil and irrigation with raw wastewater. Rapid population growth, hasty urbanization, and industrialization resulted in the production of a large volume of wastes and account for hiking-up soil HM content (Rai et al., 2019; Hanfi et al., 2020; Chia et al., 2020). These created ecosystem imbalances that are negatively affecting the environment (Hernandez-Ramirez et al., 2019) and the menace is intensifying soil and food HM contamination at a geometrical rate (Joseph et al., 2019; Magwaza et al., 2020; Sharma et al., 2020).

Understanding their uptake patterns in different food crops under different soil and farming conditions and factors determining their bioavailability, mobility and reactivity will assist researchers in devising means for controlling their activities in soil and water. When their mechanisms of action...
are understood, production conditions can be manipulated to ensure the production of food crops with safer levels of these metals. Humans and animal lives will be protected and food crops will be able to thrive without any stress.

The arguments presented motivated the writing of this review to clarify the factors and mechanisms leading to the accumulation of heavy metals in the crop plants and the consequences of this accumulation - stress, anatomical and morphological changes, reduced yields, changes in chemical composition, etc.

**HM uptake in food crops**

Soil temperature, pH, organic matter, texture, microorganisms, cation exchange capacity, presence of other metals, metals mobility, plant type, and transpiration rates determine HM uptake in food crops (Gupta et al., 2019). The uptake commonly occurs through roots when the growing soil is contaminated or when the irrigation water is contaminated, uptake through leaves is very occasional (Edelstein and Ben-Hur, 2018). Contamination of a crop simply means contamination of the entire food chain (Rai et al., 2019) and when the food chain is contaminated it will be very difficult to clean because the HMs will be rotating between the foods, humans, and environment (Kumar et al., 2019). HM contamination reaches all corners of the food chain to the level of breastmilk (Samiee et al., 2019; Zhou et al., 2019a) and food extracts such as oil (Zaanouni et al., 2018).

Soil HM concentrations vary globally (Afonne and Ifediba, 2020) and the concentration of HMs in food crops depends on the concentration of HMs in the growing location (Jafari et al., 2018). Variation in HM contents was reported in rice grown in different locations (Ebrahimi-Najafabadi et al., 2019). Human activities and geological setup account for the variation (Sharma et al., 2018). The following factors were reported to affect HM uptake in food crops.

**Soil and irrigation water factors**

HM uptake and transportation within a plant depends on the type of the plant, metal concentration in the soil, pH of the soil (Huang et al., 2020), age of the soil, texture, and organic matter content of the soil (Taghipour and Jalali, 2019; Zwolak et al., 2019), soil microorganisms, organic matter and redox potential (Hussain et al., 2021). Soil water levels affect root activities and metal bioavailability (Song et al., 2021). Soil pH affects the bioavailability of metals (Zhou et al., 2019b) and their accumulation is favored by low soil pH and higher organic matter content (Hu et al., 2017; Hou et al., 2019; Liu et al., 2020; Ouyang et al., 2020; Eid et al., 2020). Elevated pH lowers the solubility of HMs (Świątek et al., 2019), hence, alkaline soil retains HMs and prevents plants from accumulating them (Martínez-Cortijo and Ruiz-Canales, 2018; Hamid et al., 2019). Soil organic matter content dictates Cd uptake and translocation in the soil-rice system (Wu et al., 2021a). Irrigation with wastewater lowers soil pH (Li et al., 2019) and increases its electrical conductivity (Alghobar and Suresha, 2017). Effluent from the tannery industry is characterized by higher conductivity in addition to elevated Cr concentration (Alemu et al., 2019). High salinity in the irrigation water increases the uptake of Ni, Cu, Pb, Cr, and Cd by plants (Taghipour and Jalali, 2019).

**Plant factors**

Higher metal content in agricultural soil does not always correlate with plant metal content as many factors control the bioavailability and metal uptake by the plants (Weber et al., 2019). The distribution and concentrations of the HMs within the plant are also affected by the pH of the plant as reported by Ouyang et al. (2020) in rice. Huang et al. (2020) reported that plant Cd bioconcentration is negatively correlated with soil cation exchange capacity (CEC) and soil pH and positively correlates with soil Cd concentration and electrical conductivity (EC)/soil salinity. The findings of Bi et al. (2018) revealed that HM metal uptake by vegetables is affected by species and there is no correlation between soil HM concentration and that of the edible portion of vegetables. A similar finding was also reported by Elmi et al. (2020) in tomatoes grown in sewage sludge amended soil. Contrary findings were reported by Muhammad et al. (2019) in crop and fruit vegetables produced in Zhob valley, Baluchistan province, Pakistan, and Ai et al. (2018) in eggplants produced in Baiyin, China, linear positive correlation between soil and plant HM content was reported in both researches. Also, the results of a physiologically-based extraction test conducted by Liu et al. (2018) showed a significant correlation between total soil Cd, Cu, Ni, and Zn, and the fractions that are bio-accessible.

The concentration of HMs can vary within a crop, different organs can possess different concentrations as reported by Peng et al. (2020) in maize. Atamaleki et al. (2019) and Elmi et al. (2020) also reported higher concentrations in roots and stem than in the fruit of tomato. Similar results were also reported by Sagbara et al. (2020) in maize, Martínez-Cortijo and Ruiz-Canales (2018) and Ouyang et al. (2020) in rice, Huang et al. (2019) and Rezapour et al. (2019) in wheat and Li et al. (2019) in maize and wheat; with the grains having lower concentration than other parts in all the cases. Cell-wall carbohydrates such as pectin, hemicellulose, cellulose, and lignin determine the uptake of HMs in the plant cell wall, regulating the synthesis of these carbohydrates can alter the HM accumulation pattern in the plant (Jia et al., 2021).

**Presence of other HMs and chemicals**

The bioavailability and uptake of HMs are affected by the presence of other HMs and other chemicals (Lizarazo et al., 2020). It is difficult to understand the actual behaviour of trace elements in their combined form because of the complexity involved in their inter-relationship which can easily be affected by natural and environmental factors (Gupta et al., 2019). Wang et al. (2019a) reported that increase in atmospheric nitrogen deposit facilitated Cd and Cu uptake in rice. Li et al. (2019) observed a positive correlation between soil fluoride and Cd, Cr, Cu, Mn, Ni, Pb, and Zn contents, and presence of water-soluble fluoride in the soil activated HMs and facilitated their
uptake by the plant roots. Wang et al. (2020a) also reported that the Ni concentration and its bioavailability in the soil was related to iron oxide content of the soil. Long-term optimal application of phosphorus fertilizer (50 kg ha\(^{-1}\)) reduces the uptake of Zn, Cu, Pb, and Ni in grain of wheat as well as decreased total noncancer and cancer risks by 15% and 21%, respectively, for both children and adults (Chen et al., 2020). The presence of cerium oxide lowers uptake and translocation of Cu, Mn, Zn, and Fe in sugar pea (Skiba and Wolf, 2019). The presence of Pb, As and Cd affects mobility and bioavailability of Cu, Cr, Zn, and Ni (Khan et al., 2019). The presence of H\(_2\)S reduces Cd uptake in Brassica rapa (Li et al., 2021a). Li et al. (2021b) reported that the presence of calcium hinders Cd uptake in ginseng. The uptake of As by leafy vegetables depends on the ratio of phosphorus to arsenic in the soil (Qin et al., 2021a). Uptake of HMs in rice increases with an increase in phosphorus fertilizer application (Song et al., 2021). Application of 1% silicon and fused calcium magnesium phosphate fertilizers lowers Cd uptake by more than 40% in Artemisia selengensis grown in Cd-rich soil (Wang et al., 2021). Presence of Ca(\text{OH})\(_2\) (lime) lowers Pb, Cd, Ni, Cu, and Zn extractability (Kaninga et al., 2020). A combined presence of diethyl phthalate and Cd\(^{2+}\) in the soil alters the sorption properties of biochar-treated soil (Chen et al., 2021). Nanomaterials demonstrate excellent absorption ability for Cd in contaminated soil (Zhang et al., 2021). Rezaeian et al. (2020) observed a positive correlation between soil As, Pb, and Cr contents and nitrogen-free extract in alfalfa.

Growing season, crop age, and planting method

The growing season significantly affects metal uptake by food plants, Weber et al. (2019) reported that onion accumulates more HMs and has a higher concentration factor for Pb and Cr during springtime than autumn. Likewise, higher concentrations of Mn, Pb, and Cd were found in tea leaves produced during summer than those produced during spring (Peng et al., 2018). This may be associated with the seasonal variation in the concentration of HMs in water (Utete and Fregene, 2020) and the effects of seasonal changes on the physicochemical properties of the irrigation water (Kayembe et al., 2018). Wang et al. (2019a) linked Cd seasonal variation in rice with seasonal change in the atmospheric nitrogen content. The age of the crop also affects bioaccumulation and translocation of HMs as reported by Adejumo et al. (2018) in maize and Peng et al. (2018) in tea leaves. Souri et al. (2019) associated higher concentrations of HMs in older crops with long-time exposure to atmospheric deposit.

Another factor that affects HM uptake and accumulation is the planting method as reported by Deng et al. (2020) in rice, the results of their findings revealed that planting by direct seeding facilitates Cd and Pb uptake than planting by manual transplanting and seedling throwing due to variations in the root features and properties. Intercropping significantly affects the HM accumulation pattern in food crops, Wang et al. (2020b) reported that intercropping wheat with blackberry increases the concentration of Cd in wheat tissue. Similarly, intercropping cauliflower with Sedum alfredii increases Cd content in the edible portion of the cauliflower (Ma et al., 2021). A modified rice-fish farming system devised by Luo et al. (2021) was reported to be an excellent way of remediating Cd contaminated paddy field, the system allows rice stubbles to absorb excess Cd after harvesting the grains.

Food crop type

Crop type determines the type of HMs and their uptake capability by the food crop (Margenat et al., 2019). Different crops have different affinity to HMs (Sharma et al., 2018). Vegetables, cereals, and legumes are the common food crops prone to HM contamination. Leafy vegetables were reported most among vegetables, wheat was reported more than any other cereals, and onion more than any crops with underground storage. Wang et al. (2019b) reported that wheat accumulates more HMs than corn. Arsenic contaminates rice more than any other cereal (Mawia et al., 2020). Leafy vegetables accumulate more HMs than other food crops (Qureshi et al., 2016; Hu et al., 2017; Gupta et al., 2019; Mahmood et al., 2020) due to their fleshy tissues (Sharma and Nagpal, 2020). The larger surface area in leafy vegetables provides abundant space for HM uptake from the atmospheric deposit (Kalkhajeh et al., 2021). Growing leafy vegetables in contaminated soil can be very dangerous due to their higher HM transfer factor and accumulation capacity (Hu et al., 2017; Kumar et al., 2019a), and they tend to accumulate more HMs in the leaf than in the shoot and root (Nzediegwu et al., 2020). The health hazard quotient index is higher in leafy vegetables than root and fruit vegetables because of their higher HM affinity (Hu et al., 2017). Higher concentrations of Pb, Zn, Cr, Cd (Obiora et al., 2019) Ca, Fe, K, Mg, and Na (Mahmood et al., 2020) were found in leafy vegetables than other vegetables with edible underground storage organs. Gupta et al. (2021) also reported higher concentrations of Zn, Pb, Mn, Ni, Cu, Co, and Cd in spinach than in eggplant and chilli. Fan et al. (2017) also reported higher transfer factors for As, Cr, Ni, and Pb in leafy and fruit vegetables than in tuber vegetables grown in a greenhouse. Gebeylehu and Bayissa (2020) observed higher concentrations of Cr, Cd, Zn, Fe, Pb, As, Mn, Cu, Hg, Ni, and Co in cabbage than in tomatoes. Nzediegwu et al. (2020) established that spinach leaves accumulated more heavy metals (Cd, Cu, Cr, Fe and Pb) than the roots and stems.

Moreover, foliage density affects metal accumulation in vegetables, hence, some leafy vegetables accumulate more HMs than others. Sayo et al. (2020) reported higher concentrations of HMs in spinach than in kale grown under the same soil conditions. Water spinach and sweet potato leaves possessed higher bioaccumulation factors for As than lettuce and amaranth (Qin et al., 2021b). Likewise, Lizarrazo et al. (2020) reported higher concentrations of HMs in parsley than in artichoke. Rehman et al. (2019) also reported higher concentrations in amaranth and mustard leaves than in cabbage and cauliflower. On the other hand, florescence vegetables tend to accumulate more HMs in the root than in the leaf and flower as reported by Kumar et al. (2019b) in cauliflower.

Mwesigye et al. (2019) associated the high concentrations
of HMs in leafy vegetables with atmospheric deposits from contaminated soil dust which cannot be removed even after thorough washing. This was supported by the findings of Pariyar and Noga (2018) which revealed that successive rainfall over a long time does not affect the ionic mass accumulation from an aerosol deposit on barley leaves. Contrary to these, Noh et al. (2019) found that thorough washing of leafy vegetables with clean tap water reduces Pb content from the atmospheric deposit. Liao et al. (2016) and Dala-Paula et al. (2018) also associated leafy vegetables Pb contamination with atmospheric deposit. Leaf uptake of HMs can occur through aqueous pores, cuticular cracks, stomata, or ectodermis (Edelstein and Ben-Hur, 2018). The uptake through atmospheric deposit is affected by the leaf stomata size as reported by Gao et al. (2020) in Chinese cabbage. HM uptake from the atmospheric deposit is quite very insignificant as reported by Ercilla-Montserrat et al. (2018) in hydroponic lettuce produce around Barcelona busy roads. It could be deduced from the above discussion that the concentration of HMs in leafy crops depends on both soil contamination and air pollution.

Tuber crops absorb HMs more easily than leafy and fruit crops due to their proximity to the soil (Byers et al., 2020). Unlike in leafy vegetables where the absorbed HMs are evenly distributed, in tubers HMs concentrate more in the peel than in the tuber flesh as reported by Nzediegwu et al. (2019) and Dhiman et al. (2020) in potato tubers. Unlike other crops with underground storage, onion accumulates more HMs in the bulb than in the leaves (Atamaleki et al., 2019).

**HM stress in food crops**

The nutritional qualities and safety of food depend on the availability of good quality water, clean soil, optimum temperature, availability of sunlight, and CO2 (Ruszkiewicz et al., 2019). Most food crops are subtle to HM contamination and at higher concentrations, their physiology is affected (Poustie et al., 2020). Ahsan et al. (2018) reported that the effects of HM stress can affect the anatomy of the plant as well. Food crops that are capable of withstanding HM stress are characterized by low metal uptake (Rai et al., 2019). HM stress can interfere with the antioxidant production within the cell (AbdElgawad et al., 2020). An excessive amount of HMs in the soil can cause oxidative stress that can lead to growth retardation, can reduce the activities of antioxidant defense mechanisms, and can trigger H2O2 accumulation through lipid peroxidation (Colak et al., 2019). The antioxidant activities of enzymes such as catalases, superoxide dismutases, ascorbate, and glutathione can be modified in rice under Cd stress (Hussain et al., 2021). Excess Cu in the soil causes protein oxidation and lipid peroxidation in plants (Kumar et al., 2021).

Growth and yield could be affected by HM stress as reported by Ai et al. (2018) in eggplant grown in wastewater contaminated soil. Higher concentrations of HMs in the soil can affect the bioavailability of essential nutrients and subsequently affects plant growth (Khan et al., 2019; Świątek et al., 2019). Waheed et al. (2021) reported that Cd stress in spinach can lower total biomass, leaf length and area, and root and shoot length. Reduction in mineral uptake, leaf relative moisture content, growth rate, soluble protein content, photosynthetic pigments, and antioxidant activities were observed in *Brassica rapa* exposed to artificially induced Cd stress (Li et al., 2021a). Cu is highly toxic for tomato, wheat, and pea seeds and can affect their germination and seedling growth (Baruah et al., 2019). It also interferes with the activities of soil microorganisms and affects their population, diversity, and evolution (Wang et al., 2019c). Certain species of fungus withstand higher HM concentrations due to their metal stress adaptation ability in natural and contaminated soil (Torres-Cruz et al., 2018).

Sabeen et al. (2020) reported that HM stress can affect the genetic setup of a plant by causing serious chromosomal abnormalities that can influence their normal growth, and these effects can be passed to the plant offspring and to the human after consumption, and this may cause genetic complications in humans. On the other hand, genetic modification of food crops may not affect their HM uptake pattern, a comparable accumulation pattern of As, Cd, Cr, Ni, and Pb was reported by Wei et al. (2020) in *polyphosphate kinase* (ppk)-expressing transgenic rice and in wild-type species. Higher concentrations of HMs in maize male inflorescence can impede pollen grain development and subsequently affects yield (Li et al., 2019). Soil amendment can change the metal chemical form and enhance translocation pattern within plant tissue (Wu et al., 2021b)

**Conclusion**

Understanding HM uptake patterns in food crops and how the crops behave under excessive concentration will guide farmers, researchers, and policymakers in devising appropriate control measures that will ensure the production and consumption of safer food crops. The main causes of HM food crops contamination are wastewater irrigation, production in contaminated soil, and atmospheric deposit in areas with contaminated air. Factors that influence HM uptake are those related to soil and irrigation water qualities and plant properties. The presence of other HMs and chemicals, growing season, crop age, planting method, and food crop type also affect HM uptake in food crops. HM stress affects anatomy, physiology including antioxidant defense mechanisms, nutrients availability and uptake, germination and seedlings growth, growth and yield, leaf geometry, root and shoot length, plant genetics, pollination, and chemical composition including moisture contents, soluble protein, and pigment content and characteristics. Leafy vegetables are reported to have higher metal accumulation capacity than any other food crop, therefore their production in contaminated fields or fields under remediation is seriously discouraged. Food with underground storage organs that are consumed without their outer parts and grains were reported to accumulate fewer metals in their edible parts, hence, can be produced in contaminated soil.

Soil amendment using immobilization techniques is recommended in a contaminated active agricultural field, this
will prevent HM uptake by the plant and subsequently passing them to humans. The crops will also not be exposed to metals, therefore, germination, soil microorganism, essential nutrient uptake, growth, and yield will not be affected. More importantly, the chemical composition of the food crops, their safety, and their food value will be protected. Food crops that are known to accumulate fewer HMs in their edible portions and those that are not used as staples should be used for phytoremediation; when the method is the only alternative, this will minimize HM consumption through food crops.

There are serious debates regarding the actual source of HMs in leafy vegetables, some researchers opined that their contamination is largely by uptake from contaminated soil with a very insignificant amount taken through atmospheric deposit, while others opined that larger amounts of the metal contaminants are coming from the atmospheric deposit. More researches are needed in this area to eliminate the existing confusion.

Another very hazy research area is on the nature of the heavy metals contaminants in leafy foods, some findings reported that the HMs taken through atmospheric deposit are chemically bound to the leaves and cannot be removed by series of washing, while other researchers reported that the contamination is physical and just a merely surface deposit that can be removed by washing using clean water. Further researches need to be conducted to understand the effects of leaf microstructure (such as stomata size, aqueous pores), chemical composition (such as carbohydrates, pectin, hemicellulose, cellulose, and lignin), and physical cracks on the uptake of HMs through an atmospheric deposit.

Conflict of interest

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