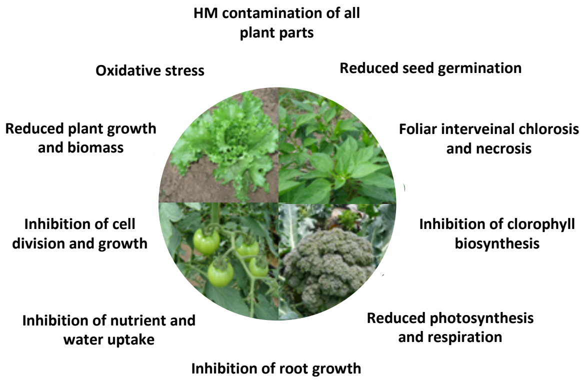
Doi: https://doi.org/10.17584/rcch.2023v17i2.16099

Heavy metal contamination of vegetables in urban and peri-urban areas. An overview

Contaminación por metales pesados sobre las hortalizas en zonas urbanas y periurbanas. Una perspectiva general

GERHARD FISCHER[1, 3]
FRANZ LEONARD FISCHER-GARCÍA[2]



Some effects of excessive accumulation of heavy metals (HM) in vegetable plants.

Source: The authors

ABSTRACT

The growth in urbanization and industrialization is causing an increase in environmental pollution in cities and their surrounding areas. Additionally, the growing urban population requires a greater volume of fresh vegetables. In nature, heavy metals (HM) are widely distributed; when they gradually enter the soil-plant-consumer continuum, they are difficult to remove from the system and accumulate at toxic levels. To gain an overview of this situation, the information in the ScienceDirect database was used in accordance with the PRISMA guide. For this, the keywords "vegetable", "contamination" and "urban" were used in a first step and, in a second step, the keywords "vegetable" and "heavy metal" were used. The most toxic HM for consumers are Cd, Pb, Hg, Cr and As, as well as essential MP for the plant (Zn, Cu, Ni, Fe, Mo). At excessive concentrations these cause neurological and kidney damage, cancer and other forms of damage to health. Crop contamination can come from the atmosphere, irrigation water, and/or the soil itself, proximity to busy roads, industry, polluted rivers, and excessive use of pesticides and fertilizers that contain HM. Plant poisoning by HM causes a decrease in root growth and biomass of the plant, foliar chlorosis, and other physiological alterations. Leafy vegetables (including aromatic herbs) and solanaceous vegetables accumulate the most HM, while cucurbits and legumes are the least affected. Plants that develop for a longer time accumulate a greater amount of HM. In general, to increase the food safety of urban horticulture, more studies are needed on HM contamination, soil aptitude, risk assessment for ingesting intoxicated vegetables, as well as appropriate instructions for the clean handling of these crops in cities and surrounding areas.

Additional key words: cadmium; lead; wastewater; toxicity; urban horticulture; food safety.

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[1] Universidad Nacional de Colombia, Facultad de Ciencia Agrarias, Departamento de Agronomía, Bogota (Colombia). ORCID Fischer, G.: https://orcid.org/0000-0001-8101-0507

[2] Universidad Nacional de Colombia, Facultad de Ingeniería, Departamento de Ingeniería Química y Ambiental, Bogota (Colombia). ORCID Fischer-García, F.L.: https://orcid.org/0000-0002-8840-1102

[3] Corresponding autor: gfischer@unal.edu.co

RESUMEN

La creciente urbanización e industrialización genera un aumento de la contaminación del ambiente en las ciudades y terrenos aledaños, en cambio, la crecida población urbana demanda un mayor volumen de hortalizas frescas. En la naturaleza, los metales pesados (MP) existen ampliamente distribuidos y cuando entran paulatinamente al continuo suelo-planta-consumidor se pueden retirar difícilmente del sistema, acumulándose a niveles tóxicos. La información de la base de datos ScienceDirect se utilizó de acuerdo con la guía PRISMA, utilizando en primera instancia las palabras clave “vegetable”, “contamination” y “urban”, y en una segunda búsqueda los términos “vegetable” y “heavy metal”. Los MP más tóxicos para los consumidores son el Cd, Pb, Hg, Cr y As, igualmente como concentraciones excesivas de los MP esenciales para la planta (Zn, Cu, Ni, Fe, Mo) que ocasionan, entre otros, daños neurológicos, renales y cáncer. La contaminación de los cultivos puede venir de la atmósfera, el agua de riego y/o del suelo, sobre todo por la cercanía a las carreteras muy transitadas, la industria, ríos contaminados y el uso excesivo de pesticidas y fertilizantes que contienen MP. La intoxicación vegetal por MP causa una disminución en el crecimiento de las raíces y en la biomasa de la planta, además por clorosis foliar, entre otras alteraciones fisiológicas. Las hortalizas de hoja (incluyendo las hierbas aromáticas) y las solanáceas son las que más acumulan MP, mientras las cucurbitáceas y leguminosas son las menos afectadas. Las plantas que se desarrollan durante más tiempo acumulan una mayor cantidad de MP. En general, para aumentar la seguridad alimentaria de la horticultura urbana, faltan estudios sobre la contaminación con MP, la aptitud de los suelos, la evaluación del riesgo por ingerir hortalizas intoxicadas y, además, de instrucciones apropiadas para el manejo limpio de estos cultivos en las ciudades y zonas aledañas.

Palabras clave adicionales: cadmio; plomo; aguas residuales; intoxicación; horticultura urbana; seguridad alimentaria.

Received: 07-06-2023 Accepted: 04-09-2023 Published: 15-09-2023

INTRODUCTION

Increased urbanization and industrialization have led to an increase in urban environmental pollution (Zwolak *et al*., 2019; Haider *et al*., 2021). Noonan and Barreau (2021) estimate that the world population will rise to 8.6 billion by 2030 and to 9 billion by 2050, with two thirds living in cities, requiring increased global food production on a large scale. In Latin America (including the Caribbean), 75% of the population lives in cities, and it is estimated that this number will increase to 83% by the year 2030 (Olivares *et al*., 2013). Increased urbanization means that the majority of the world’s population will live in cities and will require biological resource inputs and a healthy living environment (Yang and Yang, 2022). Meanwhile, the peri-urban zone represents the transition between urban and rural areas, playing an important role in the maintenance of urban ecosystems and safeguarding food security for the urban population (Jansma and Wertheim-Heck, 2022). Investigation results have found that urban systems provide many opportunities for the application of sustainable horticulture in urban areas through waste management and farming, that could together reinforce each other (Haitsma *et al*., 2002).

For these reasons, it is important to promote urban horticulture (the primary form of urban agriculture) (Crispo *et al*., 2021) and peri-urban horticulture, to supply the rapidly growing population of cities with fresh vegetables and fruits (Cohen and Wijsman, 2014); however, air, water and soil contamination are a barrier to achieving this goal (Miranda *et al*., 2008a). Heavy metal (HM) contamination of air, water, and soil strongly affect the food security of millions of people by causing reduced development of vegetables and, consequently, deficient crop yield (Elango *et al*., 2022).

Despite the positive perception of current urban horticulture and locally produced fresh vegetables, the possible food safety risks linked to these could be underestimated, inducing regulatory gaps (Buscaroli *et al*., 2021).

The United Nations (2020) classifies cities as one of the factors that most influences global warming, given that they use 78% of the world’s energy and emit 60% of greenhouse gases, while covering less than 2% of the earth’s surface. In addition, because of climate change, urban pollution increases with the increase in temperature (Santamouris *et al*., 2015), fostered by so-called "urban heat islands" (Ulpiani, 2021), as confirmed by Fischer and Beltrán (2021) by comparing three locations in Bogota (Colombia). In this context, urban horticulture is capable of mitigating the effects of climate change by growing the crops best adapted to local conditions, thus substituting a great part of the food produced from regular supply systems (Kulak *et al*., 2013), and sustaining various ecosystem services such as carbon storage (Dobson *et al*., 2021). The high temperatures in the urban area associated with the reduction of relative humidity also hinder agriculture because they can exceed the optimum ranges for plant growth in the city, e.g. in the case of the tomato, whose optimum temperature is 18-27°C and cannot withstand temperatures that exceed 35°C (Vallejo and Estrada, 2004). In addition, high temperatures can accelerate the phenology of the plant, especially in short-cycle vegetables (Chaves-Barrantes and Gutiérrez-Soto, 2017). On the other hand, in temperate zones of the northern hemisphere, the increase in temperature in cities due to heat islands and global warming offer possibilities for cultivating new horticultural species in urban gardens, with higher yields than in the past (Waffle *et al*., 2017).

Among urban agricultural plants, vegetables rank first because they are nutrient-rich foods and occupy suitable soils most efficiently because they are perishable and high-value (Weidner *et al*., 2019; Hume *et al*., 2021). Vegetables constitute an essential source for human nutrition, providing vitamins, minerals and fibers, as well as having important antioxidant effects (Begum *et al*., 2019). However, in food, both essential and non-essential elements can be harmful to human health if consumed in high concentrations, particularly heavy metals (HM) (Marschner, 2012), including the metalloid arsenic (As). The properties of metalloids are intermediate elements between metals and non-metals (Nag and Cummins, 2022). In the text of this article, As is included in the group of HM, despite being a metalloid.

In nature, HM are widely distributed, which makes their presence in living beings essential (Miranda *et al*., 2022). The processes that control the mobility and availability of HM are complex, these being factors of geochemical, biological, climatic and anthropogenic origin (Kabata-Pendias, 2004).

As they are biologically toxic, non-degradable and persistent, HM have received much consideration (Yu *et al*., 2022). The uptake of HM by plants generates several dangers for the environment that McLaughlin (2002) classifies mainly as (a) incorporation of HM into the food chain, (b) detriment of plant cover induced by phytotoxicity and (c) the cycling of metals to the superficial layers of the soil by tolerant plants, causing toxic effects on fauna and flora.

The rapid growth of industry and, in many cases, disorganized urbanization, have created a considerably higher risk of environmental contamination through HM (Zwolak *et al*., 2019). This situation, together with the application of large amounts of fertilizers and pesticides in agriculture, leads to the accumulation of toxic substances in the air, water, and soil (Kumar *et al*., 2015; Rodrigues *et al*., 2017).

Generally, HM have been classified according to their specific density, as elements with a density ≥5 g cm^{-3} (Covarrubias and Peña, 2017; Lambers and Oliveira, 2019) or ≥ 4 g cm^{-3} (Londoño-Franco *et al*., 2016). However, another term to refer to HM is toxic metals, due to their toxicity in ionic form (Epstein and Bloom, 2004), with resulting negative consequences (Alloway, 2013).

There are multiple reports on the presence of HM, such as cadmium (Cd), lead (Pb), chromium (Cr) and mercury (Hg) in higher plants, mainly due to environmental contamination, variations between genotypes in the critical levels of toxicity of these HM in plants and the appearance of HM in the food chain (Marschner, 2012).

Zwolak *et al*. (2019) mention that in addition to their wide distribution in the environment, heavy metals are notable chemical contaminants in food. Zwolak *et al*. (2019) group HM such as the so-called micronutrients Fe, Mn, Cu, Zn and Mo into essential elements for metabolic processes; in excessive amounts these are more harmful to plants than to animals, while elements such as Cd, Pb, Hg and As, even in low concentrations, are very harmful to animals and humans. Likewise, they affect, to a lesser degree, the growth and development of plants.

The Codex Alimentarius defines a contaminant as "Any substance unintentionally added to food as a result of the production (including operations carried out in crop husbandry, animal husbandry and veterinary medicine), manufacture, processing, preparation, treatment, packing, packaging, transport or holding of such food or as a result of environmental contamination" (FAO-OMS, 2009).

Due to its complexity, the topic "bioremediation", which involves the use of plants (phytoremediation) or microbes (microbial bioremediation) and is one of the most efficient procedures to eliminate HM from the soil (Elango *et al*., 2022), is not included. Bhat *et al*. (2022) described these eco-friendly and sustainable methods of phytoremediation of HM in water and soil as a multidisciplinary approach.

Studies on HM in urban and surrounding areas are scarce but, due to the risks posed by HM to the health of citizens, they are imperative (Antisari *et al*., 2015; Augustsson *et al*., 2023a). The objective of this document is to provide a description of the impact of HM contamination on vegetables cultivated in urban and peri-urban areas, reviewing results from various countries and regions affected by this problem that affects the health of consumers.

METHODOLOGY

The information in the ScienceDirect database was used in accordance with the PRISMA guide, applying the modified methodology of Page *et al*. (2021). In a first step the keywords "vegetable", "contamination" and "urban" were used for the last 10 years (2014-2023), which generated 361 articles, of which 25 (6.9%) were useful for this article. In a second step the keywords "vegetable" and "heavy metal" were used for the last 5 years (2019-2024), finding 1,640 articles of which 27 (1.6%) were included. Because of their importance, some studies from previous years and other databases, *e.g.* ResearchGate were also used.

Health effects due to the consumption of contaminated vegetables

To comply with the WHO/FAO recommendations to consume a minimum of 400 g of fruit or vegetables (excluding potatoes, sweet potatoes, cassava and other starchy tubers) per day to prevent chronic diseases, the consumption of vegetables is very important (WHO, 2020) and its demand, especially in cities, is high.

Studies have shown that vegetables grown in contaminated urban and peri-urban soils may contain high concentrations of trace metals that may exceed acceptable limits for food safety (Nabulo *et al*., 2010; 2012). The human body needs very low concentrations of iron (Fe), copper (Cu), cobalt (Co), manganese (Mn), zinc (Zn), molybdenum (Mo), strontium (Sr) and vanadium (V) (Londoño-Franco *et al*., 2016).

Within the HM found in foods from urban and peri-urban areas that affect the health of living organisms (including humans) Zwolak *et al*. (2019) and Filipiak-Szok (2015) established the following descending order: Hg > Cu > Zn > Ni > Pb > Cd > Cr > Sn > Fe > Mn >Al, which, in small amounts, represents the danger they pose to health. The minimum that the consumer should do is wash the vegetables before consuming them. Augustsson *et al*. (2023b) verified in their study with Pb that the average daily consumption of this HM would augment by 130% if contaminated vegetables are not washed before eating them.

According to the WHO (2021), HM such as Cd, Pb and Hg cause neurological and kidney damage (Tab. 1), and are even more harmful if consumed over time throughout prenatal development and childhood, leading to irreversible alterations in the central nervous system (Zwolak *et al*., 2019). Through evaluating reports of Cd content in spinach, potatoes, rice, oats, barley and wheat in the United States, Pokharel and Wu (2023) found that the infant and child age groups (6-24 and 24-60 months old) are the most vulnerable to Cd in these foods that surpasses the maximum tolerable intake amount.

Li *et al*. (2023) modeled the health risks from anthropogenic activities on soil contamination and found that, in a large Chinese city, atmospheric deposition with HM contributes more to the carcinogenic risk in children than to adults, while the intensity of traffic and agricultural activities also has an effect on adults. In the assessment of the non-carcinogenic and carcinogenic risks of the population from HM, calculations such as (1) the daily consumption of vegetables and (2) the estimated daily intake of HM relative to weight of the consumers are used, also considering the exposure during the days of the year for a total lifetime (70 years). For more details on the health risk assessment of HM, see, among others, Liang *et al*. (2018) and Sharma *et al.* (2009).

Due to the threat to human health from the ingestion of toxic metals in food, permissible levels in food, with an emphasis on processed foods, have been adopted by institutions and countries including the European Union (EU Commission Regulation No. 1881/2006 of 19 December 2006 and amending

Table 1. Original sources and important effects on human health by HM.

Heavy metal	Sources	Health effects
Cadmium	Mining, plastic, refining, welding, fertilizers, pesticides	Kidney damage, gastroenteritis, bronchitis, bone marrow, cardiovascular disease, lung failure, cancer, itai-itai disease, hypertension, weight loss, nervous disorders
Lead	Mining, pigments, paint, battery manufacturing, electroplating, welding, coal burning, pesticides	Neurological damage, anemia, general malaise, anorexia, liver, kidney and gastrointestinal damage, hypertension, encephalopathy in children, immune and reproductive system disorders
Mercury	Mining, paint industry, paper industry, batteries, pesticides	Corrosive to skin, eyes and muscles, nervous system damage, protoplasm poisoning, pneumonia, kidney damage, dermatitis
Arsenic	Mining, smelting, rock sedimentation, paints, pesticides	Bone marrow depression, bronchitis, hemolysis, dermatitis, cancer, hepatomegaly, carcinogenic, neurotoxic, and genotoxic disorders
Zinc	Mining, refineries, plumbing, brass manufacturing, fertilizers	Gastrointestinal upset, short-term metal fume fever
Copper	Painting, plating, construction, copper polishing, printing operations, fungicides	Neurotoxicity and acute toxicity, neonatal ataxia, heart failure, diarrhea
Nickel	Non-ferrous metal, porcelain enameling, electroplating, paint formulation	Lung cancer, reduced lung function, chronic bronchitis

Source: according to Londoño-Franco *et al*. (2016); Sandeep *et al*. (2019) and Zwolak *et al*. (2019).

Regulation No. 420/2011 of 29 April 2011). The FAO/WHO publishes the Codex Alimentarius CXS 193-1995 (amendment 2019), which established the maximum levels for cadmium, lead, mercury, arsenic and tin in food, while Resolution Number 4506 of October 30, 2013 of the Ministry of Health and Social Protection of Colombia regulates maximum levels for cadmium and lead in vegetables.

For the different species and types of fresh vegetables, the maximum permissible concentrations with Pb and Cd have been established. Thus, EU Regulation 2021/1323 of August 10, 2021, for Cd, and EU Regulation 2021/1317 of August 9, 2021, for Pb, establish 0.02 and 0.05 mg kg^{-1} fresh weight for fruit vegetables, and 0.1 and 0.3 mg kg^{-1} fresh weight for leafy vegetables for Cd and Pb, respectively.

Origin of contamination in plants

The HM in the soil can be geogenic or anthropogenically originated; those of geogenic origin come from the parent material in the earth's crust, from the leaching of mineralization or from volcanic activity (Galán and Romero, 2008; Zwolak *et al*., 2019). And thus, this type of pollution evolved into a global problem that severely hampered sustainable agricultural production and put at risk environmental safety (Wang *et al*., 2022).

The WHO (2020) points out that the existence of HM in the food chain is caused especially by air, water and soil contamination. Aubry and Manouchehri (2019) characterize the factors of exposure of urban agriculture to pollution with respect to the type of crop, the location of the crops, and the characteristics of the pollutant and the soil.

Antisari *et al*. (2015) report that pollutants in urban areas are commonly from anthropogenic sources, such as road traffic, prior industrial use of the lots, incinerators, and atmospheric deposition caused by industrial activities. In their study on spatial distribution of Pb in peri-urban soils Wu *et al*. (2023) found that Pb concentration was elevated in sites near industrial firms (<4 km) and gasoline stations (<1.5 km).

HM sources that generate contamination during the production of horticultural crops are grouped by Li *et al*. (2018), Rai *et al*. (2019) and Thakali and MacRae (2021) as:

- Proximity to industrial areas, mining, and atmospheric deposition
- Automobile sources on highly trafficked roads that contaminate neighboring crops
- Industrial and road runoff

- Irrigation with wastewater from urbanized and/or industrial areas
- Excessive application of fertilizers, especially phosphoric types
- Livestock manure
- Sewage sludge-based amendments
- Application of metal-based pesticides

Marschner (2012) adds to these sources of HM high soil-plant transfer, especially to the harvest organ.

Air

Polluted air is one of the most important issues that affects the health and well-being of the urban population (Fischer and Beltrán, 2021). Urban areas have a substantial impact on air quality at all levels (Folberth *et al*., 2015). Airborne particles from anthropogenic sources usually transport trace elements (such as HM), salts (sulphates and nitrates) and organic compounds adsorbed on their surface (Izquierdo-Díaz *et al*., 2023). Due to their ability to associate with air masses, HM are recirculated by winds, depositing in areas far from their origin, either on the ground or on plants in urban and peri-urban areas (Imperato *et al*. 2003; Ferreira *et al*., 2018a). Cleaner air alone could provide up to 20% yield increase in important crops such as soybean and corn (Lobell and Burney, 2021). Augustsson *et al*. (2023a) found in a farm in southeast Sweden that leafy vegetables continue to hold 0.05-1.3 wt% of adhered particles after washing and, through ingesting 0.5% of these particles, considering a mean intake of vegetable food, an adult person could consume 100 mg of particles daily.

The level of pollutants decreases not only with distance from main roads but also with height, as Aubry and Manouchehri (2019) report for the city of Paris, in which pollution is markedly reduced at the fourth floor of buildings, making vegetables grown at these heights much more innocuous. Ercilla-Montserrat *et al.* (2018) proved the feasibility of growing leafy vegetables on the rooftops of Barcelona and its surroundings using soilless systems in high-traffic areas, resulting in low HM contents in edible parts of lettuce.

Most metals, such as Cd, Cu, Pb, Zn and Ni, are 75-90% bound to the PM_{10} fraction of particulate matter (Mohanraj *et al*., 2004).

In neighborhoods with a high population and few green areas in Bogota, such as Kennedy (960,797 inhabitants and 80 ha of tree cover), Fischer and Beltrán (2021) report a much higher concentration of PM_{10} (43.7 μg m^{-3}) than in the greener Usaquen (499,829 inhabitants and 120 ha of tree cover), with 24.7 μg m^{-3} PM_{10}, for the year 2019. Kumar *et al*. (2019) highlight the potential of urban trees to decontaminate the air due to the deposition of particulate matter on their leaves.

In a study in cities with high vehicular activity in the state of Zulia in Venezuela, concentrations of Pb and Ni were measured that exceeded the permissible levels of the WHO (Machado *et al*., 2008). Meanwhile, in the city of Manizales (Colombia), the concentrations of Hg, Ni, Cr, Pb and Cd did not exceed the limit values established by the WHO and the EPA (Velasco, 2005). In the highly industrialized area of Bogota, Puente Aranda, the main metals in the atmosphere were Fe and Pb ($\leq$4,000 ng m^{-3}), while intermediate concentrations were measured for Cr, Cu, Ni, Zn, and Mn (50-700 ng m^{-3}) and the lowest levels were found for Cd and Ag (Pachón and Sarmiento, 2008).

In Bologna (Italy), high HM concentrations (160 mg kg^{-1} dry weight [DW]) were measured near the road in lettuce, while 210 mg kg^{-1} DW was found in basil (Antisari *et al*., 2015). In this same study, comparing the accumulation of HM in tomato and zucchini fruits grown 10 or 60 m away from the main road, significantly higher concentrations of Cd, Cr, Ni and Zn were found in tomatoes and in zucchini of Ba, Ni, Sn and Zn at 10 m from the road, compared to plants of the same two species at a distance of 60 m.

Säumel *et al*. (2012) found in Berlin (Germany) that the aerial deposition of HM is high within the city, meaning that consumption of vegetables grown in the city, especially those grown near roads, would mean a high risk of exposure to toxic metals. Due to this situation, Säumel *et al*. (2012) highlight the importance of barriers, including buildings, between crop plots and roads, which reduce crop contamination. Likewise, ornamental trees in the city contribute to the reduction of air pollution due to the deposition of particulate matter (including HM) on their leaves, highlighting the importance of their proximity to urban vegetable crops (Antisari *et al*., 2015; Fischer and Beltrán, 2021). Sharma *et al*. (2009) point to the danger of contamination by atmospheric deposition during the production, transport and sale of products in urban areas. These authors found a higher concentration of Cd, Cu and Zn in vegetables in marketplaces in Varanasi (India) than in production farms, especially during the months of November to February.

Water

There are many differences in the susceptibility of different types of plants to air and soil contaminants, considering that irrigation water can contaminate both the soil and the plant (Miranda *et al*., 2008b; Aubry and Manouchehri, 2019). The United Nations (2019) stated that water and food security are of global interest and crucial to the achievement of sustainable development objectives. In urban areas and, particularly, in peri-urban areas, where rivers are used to irrigate vegetables, contamination can be high, as is the case of the Bogota River (Miranda *et al*., 2008a; Bello and Lesmes, 2011) or the Atoyac River (Puebla, Mexico) (Mora *et al*., 2021). Various studies found that the Bogota River contained toxic elements such as heavy metals and metalloids, for example, cadmium (Cd), arsenic (As), cobalt (Co), mercury (Hg), chromium (Cr), lead (Pb), tin (Sn), iron (Fe), copper (Cu), manganese (Mn), nickel (Ni) and zinc (Zn), the last five being essential elements for the development of plants, in very low concentrations (Miranda *et al*., 2008a).

Municipal and industrial wastewater are an important source of HM that contaminate rivers and thus irrigation water for neighboring crops. Zhao *et al.* (2022) classified municipal wastewater as the primary source of wastewater employed directly in vegetable crops. The use of treated or untreated wastewater for irrigation to relieve the deficit of freshwater resources has been very common in developing countries (Aftab *et al*., 2023; Ruan *et al*., 2023; Yahaya *et al.,* 2023). This situation is further aggravated if there are not enough wastewater treatment plants along the waterway, as is the case for the Bogota River (Díaz-Martínez and Granada-Torres, 2018).

Irrigation with wastewater that has contaminated rivers leads to significant contamination with toxic metals in soils and in vegetables grown in these sites (Zwolak *et al*., 2019) as well as with fecal coliforms (Ferreira *et al*., 2018a). Aubry and Manouchehri (2019) attribute the risks to food grown in the urban area mainly to bacteriological causes due to the use of wastewater by residents and, in addition, to crops located in low-lying areas prone to flooding.

Corrales *et al*. (2018) found that irrigation water taken from the middle basin of the Bogota River contained bacteria harmful to humans such as *Escherichia coli*, *Proteus vulgaris*, *Serratia marcenscens*, *Brevibacillus cereus* and *Enterobacter cloaceae*, as well as bacteria phytopathogenic for crops such as *Aspergillus fumigatus*, *A. flavus*, *Rhizopus* sp., *Mucor* sp., *Fusarium* sp. and *Penicillium* sp. A tomato crop irrigated with industrial wastewater produced the same yield as plants irrigated with clean groundwater, but with lower marketable fruit yields and with a fecal *E. coli* and *Enterococci* load that exceeded allowable limits (Gatta *et al*., 2015).

Rai *et al*. (2019) concluded that irrigation with insufficiently treated effluent or sludge represents the primary origin of contamination for vegetable crops in developing countries. In sewage sludge, the most commonly detected HM are Cr, Fe, Mn, Ni, Co, Cu, Hg, Zn, Pb, Cd, As and Se (Buta *et al.*, 2021). Irrigation with reclaimed water has a much lower pollution risk than untreated wastewater and, moreover, regenerated water contains organic matter and essential nutrients (N, P, K, among others) that can lead to optimal plant growth (Zhao *et al*., 2022). Panhwar *et al.* (2022), based on their experience using treated wastewater for growing healthy okra crops, suggest that reclaimed industrial wastewater could be an important and useful source for agricultural objectives, which would reduce the discharge of freshwater resources and contribute to protecting the environment.

Several studies in plantations near the Bogota River that measured the concentration of these elements in the river water and the soil, and vegetables irrigated with it found that the concentration of the pollutants in the water and soil were still within the level allowed by international standards (Miranda *et al*., 2008a). However, in the case of lettuce and celery plants, Cd concentrations exceeded the maximum limit allowed by the European Union (EU), and in the four vegetables in the study (lettuce, celery, cabbage and broccoli) the amount of Pb exceeded the maximum level permitted by the EU in foods for young children including infants (Miranda *et al*., 2008a). Similar results, exceeding the European norm, were recorded by Bello and Lesmes (2011) in chard and lettuce irrigated with water from the Bogota River, and chard exceeded the permissible limit for Cr, while in celery no contamination by Cd, Pb, Cr or As was found, as observed by the authors.

As well as industrial activities, technified agricultural production, especially in the vicinity of rivers, can produce high amounts of HM that will continue to accumulate in the river water, contaminating it (Yu *et al*., 2022). To avoid disasters due to flooding and waterlogging through rivers (with little pollution), the development of agricultural irrigation is one of the most sustainable solutions (Yu *et al*., 2022).

Soil

Previously, water and air pollution were considered more important than soil pollution. Recently, however, soil contamination has become severe, and now attracts global attention given the implications of this for the safety of agricultural products (Shukla and Jain, 2022).

In general, urban soils have been moved, leveled and/or compacted over the years (González *et al*., 2021), and therefore vary widely in their physical-chemical characteristics (Meftaul *et al*., 2020). They stand out for their low level of organic matter and, in addition, high pollutant content, normally due to air deposition (Pavao-Zuckerman, 2008). Ferreira *et al*. (2018a) mention that soil pollution is one of the greatest risks of urban agriculture, while Kabata-Pendias (2004) and Haider *et al.* (2021) attribute the soil as the main sink for pollutants, especially HM for plants. Contamination of soil by HM and pesticides leads to loss of fertile land and endangers vegetable production and quality (Naidu *et al*., 2021).

Contamination of urban soils results from vehicle emissions, industrial processes, application of herbicides and pesticides, and inappropriate waste treatment (Li *et al*., 2018). In many cases, urban soils contain toxic elements such as HM and polychlorinated biphenyls (PSBs) that can contaminate vegetable and fruit plants produced in urban horticulture, putting human health at risk (Ferreira *et al*., 2018b). Several studies showed the accumulation of toxic metals in vegetables grown in urban soils (Nabulo *et al*., 2012). In urban soils in Chengdu (China), the highest HM contamination measured originated from atmospheric deposition and traffic activities in areas of high and medium urban intensity. Cd was the highest pollutant in high intensity areas (Li *et al*., 2023).

Growing crops in peri-urban areas is an essential contribution to the provision of vegetables to urban residents (Hu *et al*., 2023). A recent worldwide study by Liu *et al*. (2023) shows that contamination of peri-urban soils with metal(loid)s, pesticides and microplastics is similar to that of soil in urban green areas, that is, natural peri-urban areas have the same contamination as green areas in the city. Likewise, Kumar *et al*. (2022) and Li *et al*. (2019) mentioned that pressures from industry, urban growth, transportation and agriculture led to a decrease in soil quality in peri-urban areas and thus to an accumulation of HM in these soils (Hu *et al*., 2023).

Lora and Bonilla (2010) warn of the need for remediation of soils adjacent to contaminated rivers due to the medium to high concentrations of Cd and Cr in soil samples between 0 and 20 cm deep in the route of the Bogota River between Villapinzon and Bosa (Cundinamarca).

The availability of HM for plants is largely conditioned by the cation exchange capacity, the clay content, humus and the pH of the soils (Umar *et al*., 2005). Kabata-Pendias (2004) generalized that in acidic, well-oxygenated (oxidizing) soils, several HM, especially Cd and Zn, are rapidly mobile and available to plants; while in neutral or alkaline soils with poor aeration (reducing), metals would be significantly less available. This implies that acid pH of the soil is the most important factor influencing the high absorption of HM by vegetables; Kabata-Pendias (2000) report that, in alkaline soils (pH 7.1-8.1), HM have a lower bioavailability for plants and the application of organic matter can reduce the absorption of HM from the soil solution.

In waterlogged or flooded soils, plants suffer from hypoxia stress due to the low level of oxygen (Habibi *et al*., 2023), an increasingly frequent situation due to extreme events of climate change in plantations near rivers or other bodies of water and their surrounding cities. Due to this adversity, the redox potentials decrease, generating an increase in the solubility of nutrients such as Fe^{2+} and Mn^{2+}, reaching phytotoxic concentrations in the rhizosphere (Marschner, 2012; Fischer *et al*., 2023); we assume that some non-essential HM can also reach these harmful levels under waterlogging and inundation conditions. For *Spartina alterniflora*, a species from estuarine wetlands, Xu *et al.* (2018) observed that the accumulation of Pb, Cr, Zn and Cu in the plant was proportional to the exchangeable fraction of these HM in the sediment, which increased with the time of flooding. In two tomato varieties placed under combined Cd and waterlogging stresses, Zhou *et al*. (2023) found that synergistic regulation between the antioxidant systems maintained the ROS at a normal level, but that damage from the two stresses to the structure and function of the chloroplasts generated a lower photosynthetic capacity, decreasing the biomass production of the plants.

In general, the use of interior urban spaces for agriculture reduces plant contamination by soil or air; however, contamination by soil increases if it has been used for industrial purposes (Aubry and Manouchehri, 2019). A study in Ohio (USA) confirmed that urban orchards managed for several years contained far fewer contaminants than soils not used for this purpose in the city, which contained higher levels of Pb, Zn, Cd, Cu and polyaromatic hydrocarbon; this was due to microbial activity and degradation as well as to the dilution of HM by mixing with clean soil (Kaiser *et al*., 2015). However, Säumel *et al*. (2012) found in the center of Berlin a significantly higher Pb content in vegetable species grown near busy roads than in vegetables sold in supermarkets, most likely coming from outside the city. For contaminated urban soils, Antisari *et al*. (2015) recommend hydroponic cultivation, for example, in the case of rosemary, as it is a HM accumulator plant. In urban horticulture, soilless cultivation systems can prevent the introduction of HM into vegetable plants because these processes can guarantee unpolluted substrates (Ercilla-Montserrat *et al.,* 2018).

Vega and Vega (2021) examined 49 organically managed urban orchards in the city of Bogota, near high vehicular traffic, finding that the concentration of Pb in soil, irrigation water and the plant did not exceed national and international standards. These authors also mentioned that the total level of Pb in the soil is not always fully available, since absorption, transport and bioaccumulation of this element by plant tissue are related to various variables.

Pesticides and fertilizers

The incidence of pests in crops has increased, for reasons including climate change, which has resulted in an increase in the use of pesticides (Wenning *et al*., 2010). One of the predominant environmental problems associated with pesticides is infiltration into aquifer complexes (Mora *et al*., 2021). In small scale crops in the urban environment, owners often inadvertently apply excessive doses of pesticides, leaving residues that constitute a threat to the area (Meftaul *et al*., 2020). Eijsackers and Maboeta (2023) reported that the heavy metal-containing fungicide copper oxychloride, applied under field conditions, can damage soil life.

Contamination of vegetables results from the excessive use of fertilizers because they can increase the accumulation of HM (Marschner, 2012; Zwolak *et al*., 2019). Near Bologna (Italy) an accumulation of 1.2 mg kg^{-1} dry weight of Cd was found in tomato fruits due to crop fertilization over many years, a higher concentration than in tomatoes from urban agriculture (Antisari *et al*., 2015). Also, in greenhouse tomato cultivation, Gil *et al*. (2004) report that, due to the specific use of substrates and fertilizers, in addition to the reuse of water and nutrients, the accumulation of Cd and Pb can increase. However, Wan *et al*. (2022) compared the soil of 60 greenhouse vegetable plots (5-20 years old) with those of 20 adjacent arable land plots of vegetable production, finding that the Pb and Cr soil concentrations were lower in greenhouses, possibly due to the protection provided by the greenhouse roof, which kept soils away from atmospheric depositions emitted by neighboring industries.

In peri-urban agriculture or in rural areas close to cities, the use of fertilizers and pesticides is generally higher due to the high demand of growing cities (Li *et al*., 2023). The excessive use of phosphate fertilizer is the primary source of high Cd concentrations in agricultural soils (Niu *et al*., 2023), which contain Cd concentrations between trace and 27.20 mg kg^{-1} (Li *et al*., 2020), while the application of diammonium phosphate (DAP) can increase the mobility of Cd, Ni, Cu and Zn (Jalali and Moharami, 2010). Liming soils can reduce Cd uptake by increasing pH and absorption competition between Ca and Cd, but, conversely, liming can also increase Cd uptake by reducing Zn levels and thus competition for Cd uptake (Marschner, 2012). Meanwhile, the foliar application of “InCa” which activates Ca transport in vegetable species containing among other substances $Ca(NO_3)$, decreased root Pb concentration in tomato and cucumber plants to 73% and 60%, respectively (Wierzbicka *et al*., 2023). In cauliflower genotypes Ma *et al*. (2022) observed that the application of nitric oxide relieved Cd-induced decrease of biomass and growth. They attributed this positive response mainly to the reduction of Cd uptake, sustaining essential minerals content, increasing the action of antioxidant enzymes and thereby inhibiting ROS content and protecting proteins and photosynthetic pigments.

In organic agriculture, the use of synthetic pesticides and fertilizers, emissions in general and nutrient runoff are reduced by using organic household debris and other available sources (Aubry and Manouchehri, 2019), but this can also decrease crop yields (Weidner *et al*., 2019). As mentioned before, biological management of plantations is very important around urban and suburban rivers (Yu *et al*., 2022). Also, in organic production, the natural phosphorous source in fertilization must not exceed 90 mg kg^{-1} of P_2O_5 according to the Codex Alimentarius.

Effect of heavy metals on plants

Heavy metal toxicity impairs the yield potential of many vegetable crops. It hampers physiological functions of plants, decreases seed germination, impedes the photosynthetic functionality, and generates oxidative stress (Elango *et al*., 2022).

In order for HM to accumulate in plant cells, they must be mobilized in the soil and taken up by the roots, where they are loaded into the xylem to be transported in the stem to the aerial parts of the plant, then distributed to the tissue of the leaves or fruits (DalCorso *et al*., 2014). For each of these steps, as reported by Clemens (2001), a complex interaction between chelating compounds and metal transporters is needed that affects the rate of accumulation of these metals.

Elango *et al*. (2022) described a non-linear response of increasing HM absorption, that depended on factors such as the availability and solubility of these elements in the soil, the leaf and the leaf type, fertilization, growing environment, redox potential, soil moisture, and others. Additionally, the latter authors mentioned that factors such as the form in which they are present in the soil, i.e. bound with soil particles or easily available in soil solution, determine the availability of these HM for plant uptake.

In most cases, the roots are damaged first and very severely, because the HM that are absorbed accumulate over time in this organ, which affects the general growth of the plant (Umar *et al*., 2005), hindering its supply of water and nutrients (Ernst, 2003). In the absorption of metals such as Cd, Xin *et al*. (2015) found that, in varieties of paprika (*Capsicum annuum*), the type of efflux of low molecular weight organic acids by the roots determined the difference in the volume of Cd accumulated between varieties with high and low Cd content. It is noteworthy that the translocation of the HM from the roots to the stem affects the senescent leaves more than the young leaves (Ernst, 2003).

According to Marschner (2012), there are still no convincing studies on the beneficial effects of HM such as Cd, Pb, Cr and Hg on higher plants and how they affect their growth and development. On the other hand, there are studies that show some effectiveness in reducing the level of toxic metals in plant species through the symbiosis between plants and fungi that form arbuscular mycorrhizae (AMF) (Aguirre *et al*., 2011).

In general, increased HM in vegetable crops has several effects on the physiological and biochemical functions of plants (Zulfiqar *et al*., 2019; Haider *et al*., 2021) (Tab. 2), which differ according to the phenological state of the plant, the concentration and the type of metal (Epstein and Bloom, 2004). Functional impairments from metal excess are associated with membrane damage, oxygen radical production, inhibition of key enzymes, and inactivation of photosynthesis and the respiration electron transport chain, as well as restriction in the absorption and assimilation of N, the last of which greatly affects growth (Larcher, 2003).

Elango *et al*. (2022) classified impacts of HM toxicity on plants into direct effects, such as reduced mineral uptake, photosynthesis, respiration, protein content, seed germination and plant biomass; and indirect effects, such as damage to lipids and DNA, generation of ROS, chromosomal abnormalities, cell injury or chlorosis, damage to cell membranes and disrupted enzyme activity.

In general, an overload of HM in the soil means a greater stress for crops than a deficiency of these elements, although that some plant species can establish a tool to protect themselves against this excess. The more the plant is tolerant of HM, the slower its growth (Epstein and Bloom, 2004). High Ni toxicity, as well as high Al content, can cause interveinal chlorosis due to induced Fe deficiency (Kabata-Pendias, 2000) while, according to Umar *et al*. (2005) foliar chlorosis due to Pb toxicity could be generated by the susceptibility of some enzymes to Pb ions, affecting chlorophyll biosynthesis.

Table 2. Symptoms of toxicity by important HM in plants.

Heavy metal	Critical foliar concentration in plants	Symptoms	Author
Nickel (Ni)	10-50 μg g^{-1} DW	Inhibition of root elongation, reduced stem growth, interveinal chlorosis	Marschner (2012); Kabata-Pendias (2000)
Copper (Cu)	20-30 μg g^{-1} DW	Inhibition of root growth before stem growth, oxidative stress	Marschner (2012); Epstein and Bloom (2004)
Zinc (Zn)	100-300 μg g^{-1} DW	Inhibition of root elongation, chlorosis in young leaves, decreased photosynthesis	Marschner (2012)
Manganese (Mn)	200-1,380 mg kg^{-1} DW	Brown spots on mature leaves, interveinal chlorosis and necrosis, deformation of young leaves, loss of apical dominance	Marschner (2012)
Iron (Fe)	$>$500 mg kg^{-1} DW	Bronzing, especially in waterlogged soils	Rengel *et al*. (2023)
Cobalt (Co)	0.4-few mg kg^{-1} DW	Foliar chlorosis, reduced biomass accumulation and nutrient uptake	Marschner (2012); DalCorso *et al*. (2014)
Aluminum (Al)		Inhibition of root elongation, nutrient and water uptake; inhibition of cell division and elongation	DalCorso *et al*. (2014); Casierra-Posada and Aguilar-Avendaño (2007)
Lead (Pb)		Physiological alterations in enzyme activities, water potential, mineral nutrition, hormonal status, electron transport and membrane structure; chlorosis, inhibition of root elongation	García (2006); Miranda *et al*. (2008b)
Mercury (Hg)	0.5-1 μg g^{-1} DW	Physiological changes such as aquaporin shutdown, leaf chlorosis, severe stunting of seedlings and roots	Miranda *et al.* (2008b); Kabata-Pendias (2000)
Arsenic (As)		Morphological changes in the plant, physiological alterations, decreased yields	Miranda *et al*. (2008b)
Cadmium (Cd)	5-10 μg g^{-1} DW	Morphological changes in the plant, atrophied roots, minor root elongation, leaf chlorosis, brown leaf margins, reddish veins, deterioration of xylem tissues, alterations of physiology and of enzymatic activities, reduced plant growth and biomass, alterations of photosynthetic pigments and gaseous exchange, mineral uptake and antioxidative defense machinery.	Miranda *et al*. (2008b); Kabata-Pendias (2000); Bautista *et al*. (2013); Ma *et al*. (2022)
Chromium (Cr)	1-2 μg g^{-1} DW	Foliar chlorosis, reductions in chlorophyll synthesis, CO_2 fixation and carbohydrate metabolism, root damage, decreased Ca, K, P, Fe and Mn incorporation caused by Cr^{6+}	Bello and Lesmes (2011); Lora and Bonilla (2010); Kabata-Pendias (2000)

DW: dry weight.

Kathpalia and Bhatla (2018) describe hyperaccumulators or metallophytes as plants that can absorb very high concentrations of HM from the soil and store them in their aerial tissues at levels between 100 to 1,000 times higher than a non-hyperaccumulator plant. An example of this is *Brassica*, which capable of accumulating up to 30,000 μg g^{-1} of Zn and 1,300 μg g^{-1} of Cd in its tissues. One of the reasons for this very high translocation of metals to the aerial part is the overexpression of HMA (heavy metal-transporting ATPase) proteins loading the HM to the xylem of these plants (Kathpalia and Bhatla, 2018). According to Lambers and Oliveira (2019), there is evidence that the hyperaccumulation of these metals increases defense against microbial and herbivorous pathogens.

The readiness with which the following HM are bioaccumulated by plants is in the order as follows (a) from an aquatic environment: Hg, Cd, Pb, Cu, Zn, Sr and (b) from soil: Cd, Zn, B, Ni, Sn, Cs, Rb (Kabata-Pendias, 2004). There is much variation in the concentrations of HM in the edible part of the vegetables; the ability to take up and accumulate HM was highest in leafy vegetables and lowest in cucurbitaceous vegetables (Zhou *et al*., 2016). For groups of plant species that accumulate Cd, Yang *et al*. (2009) established the following increasing order: legumes vegetables < melon vegetables < alliums vegetables < root vegetables < solanaceous vegetables < leafy vegetables (Fig. 1). The higher accumulation in HM concentrations by leafy vegetables is explained by their higher translocation and transpiration rates compared to fruit vegetables (Yadav, 2021).

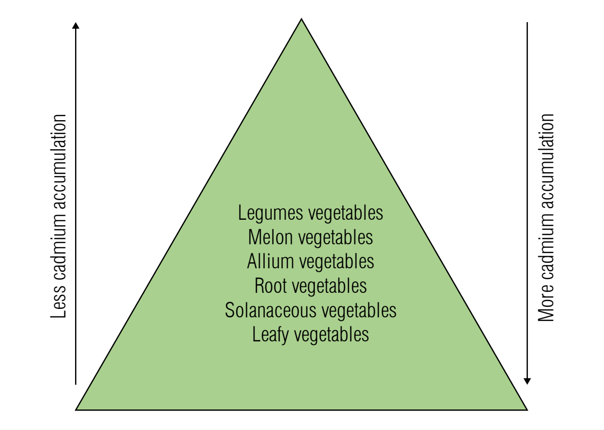

Figure 1. Cadmium accumulation according to the type of vegetables. Source: Yang *et al*. (2009).

Pb contamination does not greatly affect the eating quality of fruits but does harm it in some leafy vegetables such as lettuce, spinach, and cabbage due to the greater exposure of their leaf area to atmospheric particles. Root vegetables (radish, carrot, beetroot, etc.) are more susceptible to accumulating HM in large quantities compared to those that develop fruits (paprika, tomato, aubergine, etc.) and are not recommended for planting in contaminated soils (Aubry and Manouchehri, 2019; Zwolak *et al*., 2019).

Aromatic herbs, such as parsley, are highly exposed to contamination by air and soil alike (Aubry and Manouchehri, 2019) (Fig. 2). Urban and peri-urban growers should consider that a plant that develops for a long time absorbs more pollutants from the soil, water and air, as is the case with thyme, compared to basil (Aubry and Manouchehri, 2019).

There are physicochemical similarities between the different ions, which is why the transport proteins in the plasmatic membrane of root cells are not capable of efficiently differentiating between Ca^{2+} and Ba^{2+}, K^+ and Rb^+ or between phosphate and arsenate (Marschner, 2012). For this reason, many toxic ions cannot be excluded in the symplasm of the roots, allowing HM to enter plants and thus the food chain. A special case is Cr, which is essential for humans as Cr^{3+} as it promotes the action of insulin. Derivatives of Cr^{6+} (chromates and dichromates) are generally of anthropogenic origin, which at excessive levels produce toxicity in plants (Tab. 2) (Lora and Bonilla, 2010). Among the leafy vegetables, lettuce has been shown to be the most vulnerable to Cr^{6+} pollution (Yu *et al*., 2023).

Cd can be easily absorbed by roots and leaves (Kabata-Pendias, 2000; Bautista *et al*., 2013). In addition, these authors reported that root vegetables as a group are relatively highly susceptible to the accumulation of Cd. Lundgren *et al*. (2023) developed regression models to predict the uptake of the highly mobile Cd and the less mobile Pb in lettuce, which suggest that Cd uptake is predominantly via roots, in contrast to the physical contamination of Pb, which is primarily in the leaves.

Plants show specific mechanisms to take up, translocate and accumulate HM. Several metals and metalloids that are not essential for plants are absorbed, translocated and accumulated by electrochemical

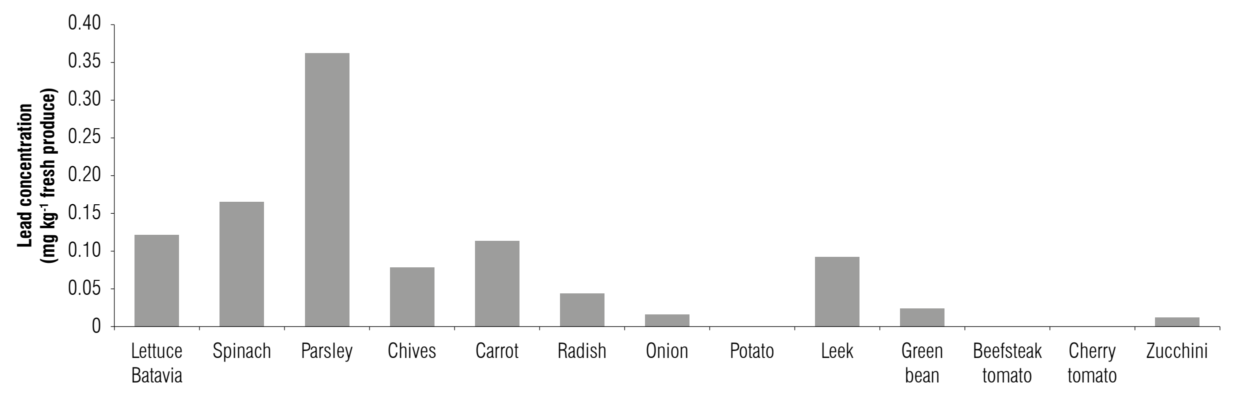

Figure 2. Example of results of lead (Pb) concentrations in vegetables growing in the city of Montreuil, near Paris. Taken from Aubry and Manouchehri (2019), with permission.

behavior similar to that of essential nutrients (Miranda *et al*., 2008a), competing, in many cases, with the essential elements of the active side of the enzyme (Umar *et al*., 2005). The toxicity of HM in plants, according to Tadeo and Gómez-Cadenas (2008), occurs mainly in acid soils, altering growth and the appearance of lateral and secondary roots.

Given that HM affects not only the physiology, development and quality, but also the safety and health risks of vegetables, the results of studies from countries of four continents on these contaminants and the permissible HM levels in the tissue of the vegetables are shown below (Tab. 3). The different levels in the same species can be explained mainly by the different sources of contamination, according to the study area, plant age and season of the year (Miranda *et al*., 2008a; Liang *et al*., 2018). As international and many national standards include, in most cases, only Cd and Pb in the different types of vegetables, these two toxic metals are largely referred to in table 3.

Some vegetables have mechanisms through which they accumulate more HM in the roots than in the aerial part, as is the case for tomato and eggplant with

Table 3. Results of some studies in different countries on heavy metals in harmful concentrations in the edible part of the plant, found in vegetables of urban and peri-urban production.

Analyzed elements	Study and country	HM exceeding international standards	Authors
Cd, Pb, Cr, Cu, Zn, Ni	Analysis on tomato, bean, carrot, potato, kohlrabi, white cabbage, parsley, chard, basil, mint, thyme within the inner-city neighborhoods of Berlin, Germany	Pb in 52% of all samples (EU standard). >50% of the carrot, potato, chard, mint, thyme and parsley samples exceeded EU standards. <33% of the tomato, bean, kohlrabi, and white cabbage samples, but no basil sample, exceeded these values	Säumel *et al*. (2012)
Cd, Pb, Cr, Co, Ni, Mn	Irrigation of pumpkin, spinach, cauliflower, luffa and coriander with water from the Chenab River, Pakistan	Cd in all species; Cr in coriander, luffa and cauliflower; Pb in cauliflower (FAO standard)	Aftab *et al.* (2023)
Cd, Pb, Ni	Analysis of leek, cress, parsley, basil, mint, chives and radish in three supermarket brands in Tehran, Iran	Cd and Pb in all vegetables and herbs (FAO/WHO and Codex Alim. standards)	Mostafidi *et al.* (2021)
Cd, Pb, Cu, Zn	Analysis of spinach, okra and cauliflower in production and markets in Varanasi, India	Cd and Pb in the three vegetables in production and in the market (EU standard). Cd, Zn and Cu in the three vegetables on markets (PFA[1] standard)	Sharma *et al*. (2009)
Cd, Pb, Hg, As, Cr	Analysis of the groups of bulb, stalk, stem, cabbage and brassica vegetables, leafy vegetables, fruiting solanaceous vegetables, legumes, root and tuber vegetables, fruiting cucurbits and aquatic vegetables in 21 cities in Guangdong province, China	Cd (2.14%), Pb (1.61%), Hg (0.55%) and Cr (0.48%) of all samples (MACs[2] standard)	Liang *et al*. (2018)
Cd, Pb, Cr, Cu, Zn, Ni, Fe, Mn	Analysis of lettuce, eggplant, cucumber, tomato, pepper, pumpkin, mint, and dill near effluent from a wastewater treatment plant in Egypt	Cd in tomato and eggplant (FAO standard)	Hamad *et al*. (2021)
Cd, Pb, Cr, Cu	Irrigation of potato, tomato, onion, cabbage, carrot, beetroot and lettuce with lake and river water, near Bahir Dar town, northwestern Ethiopia	Pb in carrot, potato and beetroot and Cd in carrot (FAO/WHO standard)	Asrade and Ketema (2023)
Cd, Pb, Cr, Cu, Zn	Irrigation of spinach and kale with water from two rivers near Machakos, Kenya	Pb, Cr and Zn in spinach; Cr and Zn in kale (WHO standard)	Tomno *et al*. (2020)
Cd, Pb, Hg, As	Irrigation of lettuce, broccoli, cabbage and celery with water from the Bogotá River, Colombia	Cd in lettuce and celery, 74 days after transplanting (EU standard)	Miranda *et al*. (2008a)
Cd, Pb, As, Cr, Co, Zn, Ni	Analysis of carrot, artichoke and parsley in crops near the middle basin of the Bogotá River, in Sibate, Colombia	Cd and Pb in the three vegetables (EU and Colombian standards). High concentrations in the other HM as well	Herrera and Lizarazo (2018)

[1]PFA, prevention of Food Adulteration Act (New Delhi) with 30, 50, 1.5 and 2.5 $\mu g\ g^{-1}$ for Cu, Zn, Cd and Pb, respectively; [2]MACs, maximum allowable concentrations established by the Chinese government.

Cd (and several other HM). Thus, a study in Egypt of soils contaminated with HM (Tab. 3) showed that tomatoes accumulated 3.27 and 2.62 mg kg^{-1} Cd in dry weight of root and stem+leaves, respectively, whereas eggplant accumulated 2.56 and 0.67 mg kg^{-1} in root and stem, respectively (Hamad *et al*., 2021), significantly exceeding the level allowed by the EU and the FAO (0.2 mg kg^{-1} dry weight).

The toxic concentration depends greatly on the species and variety (Marschner, 2012). Margenat *et al*. (2019), comparing trace elements (TE) in tomato, lettuce, cauliflower and broad beans growing in peri-urban areas of Barcelona with vegetables from more widely distanced rural vegetable fields, found that the occurrence of chemical contaminants in vegetables depended more on the commodity rather than whether the location was peri-urban or rural. Tomato fruits contained the highest concentration of TE.

Hamad *et al*. (2021) found that the transfer factor (the relationship between the concentration of HM in the aerial part and in the roots that coincides with the percentage translocated from the roots to the aerial part) was, in the case of paprika, greater than 1 (because of its high accumulation) for Cu, Fe and Zn; interestingly, this species did not absorb Cd and Pb. In the other species analyzed by Hamad *et al*. (2021) (Tab. 3), the transfer factor for the HM was less than 1. In the case of Pb, Kabata-Pendias (2000) reported that only 3% of the Pb is translocated from the roots to the stem.

Begum *et al*. (2019) studied spinach in contaminated soil near the Buriganga river in Dhaka (Bangladesh), evaluating the transfer factors from the soil to the roots and from the roots to the leaves (Tab. 4). They found that the transfer from the soil to the root was highest for Cr and from the root to the leaves highest for Cd.

Higher transfer factors for Cd from the soil to the harvestable part of spinach and kale, 2.23 and 4.10, respectively, were found by Tomno *et al*. (2020) in crops irrigated from two rivers near the town of Machakos in Kenya (Tab. 4). In comparison, Herrera and Lizarazo (2018) found, in parsley grown near the Bogota River, transfer factors from the soil to the plant of 0.23 for Cd, 0.11 for Pb, 0.14 for Cr and 0.11 for As; and for carrot in the same location, transfer factors of 0.23 for Cd, 0.08 for Pb, 0.05 for Cr and 0.08 for As.

Since grafting could alleviate the toxicity of HM to the aboveground parts to some degree (Savvas *et al*., 2013) the grafting of melon on more HM resistant pumpkin (*Cucurbita moschata*) rootstock can reduce contamination of melon fruits. Guo *et al*. (2023) observed that the ZF1 pumpkin hybrid rootstock had a Cd accumulation ability of roots higher than that of MB3 and FB1 parents and the transfer coefficient of the shoot was lower, which decreased the Cd concentration in leaves, increased the photosynthetic assimilation of leaves and Cd tolerance of these seedlings, and augmented the antioxidant enzyme activities (POD, SOD, CAT).

Added to the factors mentioned above that affect contamination of the soil and the plant by HM, is the influence of climatic factors, such as wind that transports atmospheric pollutants (Fischer and Beltrán, 2021), and rain that drops these toxic substances to the surface and leaches them to deeper depths or causes their runoff to other lands and crops. In extreme cases, heavy rains and storms can cause chemical contamination in surrounding water bodies and watersheds (Noyes *et al*., 2009) from flooding that distribute HM over wider terrain. In addition, atmospheric humidity conditions contribute to the absorption and translocation of HM (as with any other essential nutrient) within the plant, due to the upward flow of transpiration, especially for plants with larger leaf area (Marschner, 2012). In general, drier conditions and higher temperatures generate greater contamination by air pollution (Emekwuru and Ejohwomu, 2023).

Table 4. Transfer factors (TF) of HM from soil to roots and from roots to leaves of spinach.

TF	Cd	Pb	Cr	Cu	Ni	Fe	Zn
Soil-roots	0.19	0.17	0.35	0.04	0.02	0.04	0.63
Roots-leaves	0.82	0.87	0.34	0.96	0.79	0.36	0.37

Source: data taken from Begum *et al*. (2019).

CONCLUSIONS

For the rapidly growing population of cities, urban and peri-urban horticulture is an important opportunity for the supply of fresh vegetables. This type of horticulture is capable of mitigating the effects of climate change by growing crops most adapted to urban and peri-urban conditions. However, on the other hand, growing urbanization and industrialization increase environmental pollution in the cities and surrounding lands.

In nature, HM are widely distributed; when they progressively enter the soil-plant-consumer continuum, they can no longer be easily removed from the system, accumulating at toxic levels.

Apart from an excessive accumulation of the essential HM for the plant (Fe, Zn, Cu, Ni), the most toxic for consumers are Cd, Pb, Hg, Cr and As. HM such as Cd, Pb and Hg cause, neurological and kidney damage as well as cancer and other adverse effects on health, generating even more damage when ingested throughout prenatal development and childhood, leading to irreversible alterations in the central nervous system.

HM can come from air, water and soil. Air is most highly polluted near busy roads and industry, while polluted irrigation water comes from industry and wastewater. Polluted soil arises from contaminated irrigation water, vehicle emissions, industrial processes, application of pesticides and fertilizers containing HM.

High contamination of plants occurs in particular from the accumulation of HM in their tissues, with differences between the absorption and retention of HM in the roots, depending on species and variety.

Plant poisoning, most significantly, decreased root growth and plant biomass and chlorosis, among other physiological alterations. Leafy vegetables (including aromatic herbs) and Solanaceae accumulate the most HM, while cucurbits and legumes are the vegetables that least accumulate HM.

Examples from four different continents show high contamination with HM, especially Cd and Pb, of vegetables grown in urban and peri-urban areas. There are still no international standards from the EU, FAO and WHO for the other HM (Hg, Cr, As) in fresh vegetables, only in other foods or in processed form.

In many studies, irrigation water and soils do not exceed the permissible HM concentration but, due to the accumulation in crops with a longer duration, HM content in the plant can exceed these permissible standards. It is suggested that reclaimed industrial wastewater could be a significant and useful source for irrigation of vegetable crops, which will reduce discharge of freshwater resources and contribute to protecting the environment.

In general, to increase the food safety of urban and peri-urban horticulture, more studies are needed on HM contamination, soil aptitude, risk assessment for ingesting intoxicated vegetables, as well as appropriate instructions for the clean handling of these crops in cities and surrounding areas. Not washing vegetables before consumption alone increases the average daily intake of Pb by 130%.

Conflict of interests: The manuscript was prepared and reviewed with the participation of the authors, who declare that there exists no conflict of interest that puts at risk the validity of the presented results.

BIBLIOGRAPHIC REFERENCES

Aftab, K., S. Iqbal, M.R. Khan, R. Busquets, R. Noreen, N. Ahmad, S.G. T. Kazimi, A.M. Karami, N.M.S. Al Suliman, and M. Ouladsmane. 2023. Wastewater-irrigated vegetables are a significant source of heavy metal contaminants: toxicity and health risks. Molecules 28(3), 1371. Doi: https://doi.org/10.3390/molecules28031371

Aguirre, W., G. Fischer, and D. Miranda. 2011. Tolerancia a metales pesados a través del uso de micorrizas arbusculares en plantas cultivadas. Rev. Colomb. Cienc. Hortíc. 5(1), 141-153. Doi: https://doi.org/10.17584/rcch.2011v5i1.1260

Alloway, B.J. 2013. Heavy metals in soils: trace metals and metalloids in soils and their bioavailability. 3rd ed. Springer, Reading, UK. Doi: https://doi.org/10.1007/978-94-007-4470-7

Antisari, L.V., F. Orsini, L. Marchetti, G. Vianello, and G. Gianquinto. 2015. Heavy metal accumulation in vegetables grown in urban gardens. Agron. Sustain. Dev. 35, 1139-1147. Doi: https://doi.org/10.1007/s13593-015-0308-z

Asrade, B. and G. Ketema. 2023. Determination of the selected heavy metal content and its associated health risks in selected vegetables marketed in Bahir Dar Town, Northwest Ethiopia. J. Food Qual. 2023, 7370171. Doi: https://doi.org/10.1155/2023/7370171

Aubry, C. and N. Manouchehri. 2019. Urban agriculture and health: assessing risks and overseeing practices. Field Actions Sci. Rep. (Special Issue 20), 108-111.

Augustsson, A., M. Lundgren, A. Qvarforth, R. Hough, E. Engström, C. Paulukat, and I. Rodushkin. E. Moreno-Jiménez, L. Beesley, L. Trakal, and R.L. Hough. 2023a. Urban vegetable contamination - The role of adhering particles and their significance for human exposure. Sci. Total Environ. 900, 165633. Doi: https://doi.org/10.1016/j.scitotenv.2023.165633

Augustsson, A., M. Lundgren, A. Qvarforth, R. Hough, E. Engström, C. Paulukat, and I. Rodushkin. 2023b. Managing health risks in urban agriculture: The effect of vegetable washing for reducing exposure to metal contaminants. Sci. Total Environ. 863, 160996. Doi: https://doi.org/10.1016/j.scitotenv.2022.160996

Bautista, O.V., G. Fischer, and J.F. Cárdenas. 2013. Cadmium and chromium effects on seed germination and root elongation of lettuce, spinach and Swiss chard. Agron. Colomb. 31(1), 48-57.

Bhat, S.A., O. Bashir, S.A. Ul Haq, T. Amin, A. Rafiq, M. Ali, J.H.P. Américo-Pinheiro, and F. Sher. 2022. Phytoremediation of heavy metals in soil and water: An eco-friendly, sustainable and multidisciplinary approach. Chemosphere 303(Part 1), 134788. Doi: https://doi.org/10.1016/j.chemosphere.2022.134788

Begum, M.L., U.H.B. Naher, M.R. Hosen, and A. Rahaman. 2019. Levels of heavy metals in soil and vegetables and health risk assessment. Int. J. Sci. Technol. Res. 8(7), 770-775.

Bello, P. and L. Lesmes. 2011. Determinación de metales pesados en apio (*Apium graveolens* L.), lechuga (*Lactuca sativa* L. var. Batavia) y acelga (*Beta vulgaris* L.) mediante ICP-AES en dos zonas de producción de hortalizas de la Sabana de Bogotá. Undergraduate thesis. Facultad de Ciencias Agrarias, Universidad Nacional de Colombia, Bogota.

Buscaroli, E., I. Braschi, C. Cirillo, A. Fargue-Lelièvre, G.C. Modarelli, G. Pennisi, I. Righini, K. Specht, and F. Orsini. 2021. Reviewing chemical and biological risks in urban agriculture: a comprehensive framework for a food safety assessment of city region food systems. Food Contr. 126, 108085. Doi: https://doi.org/10.1016/j.foodcont.2021.108085

Buta, M., J. Hubeny, W. Zieliński, M. Harnisz, and E. Korzeniewska. 2021. Sewage sludge in agriculture – the effects of selected chemical pollutants and emerging genetic resistance determinants on the quality of soil and crops – a review. Ecotoxicol. Environ. Saf. 214, 112070. Doi: https://doi.org/10.1016/j.ecoenv.2021.112070

Casierra-Posada, F. and O.E. Aguilar-Avendaño. 2007. Estrés por aluminio en plantas: reacciones en el suelo, síntomas en vegetales y posibilidades de corrección. Una revisión. Rev. Colomb. Cienc. Hortic. 1(2), 246-257. Doi: https://doi.org/10.17584/rcch.2007v1i2.8701

Chaves-Barrantes, N.F. and M.V. Gutiérrez-Soto. 2017. Respuestas al estrés por calor en los cultivos. I. Aspectos moleculares, bioquímicos y fisiológicos. Agron. Mesoamer. 28(1), 237-253. Doi: https://doi.org/10.15517/am.v28i1.21903

Clemens, S. 2001. Molecular mechanisms of plant metal tolerance and homeostasis. Planta 212, 475-486. Doi: https://doi.org/10.1007/s004250000458

Cohen, N. and K. Wijsman. 2014. Urban agriculture as green infrastructure: the case of New York city. Urban Agric. Magaz. (27), 16-19.

Corrales, L.C., L.C. Sánchez, and M.E. Quimbayo. 2018. Microorganismos potencialmente fitopatógenos en aguas de riego proveniente de la cuenca media del rio Bogotá. NOVA 16(29), 71-89. Doi: https://doi.org/10.22490/24629448.2691

Covarrubias, S.A. and J.J. Peña. 2017. Contaminación ambiental por metales pesados en México: Problemática y estrategias de fitorremediación. Rev. Int. Contam. Ambie. 33, 7-21. Doi: https://doi.org/10.20937/RICA.2017.33.esp01.01

Crispo, M., M.C. Dobson, R.S. Blevins, W. Meredith, J.A. Lake, and J.L. Edmondson. 2021. Heavy metals and metalloids concentrations across UK urban horticultural soils and the factors influencing their bioavailability to food crops. Environ. Pollut. 288, 117960. Doi: https://doi.org/10.1016/j.envpol.2021.117960

DalCorso, G., A. Manara, S. Piasentin, and A. Furini. 2014. Nutrient metal elements in plants. Metallomics 6(10), 1770-1788. Doi: https://doi.org/10.1039/C4MT00173G

Díaz-Martínez, J.A. and C.A. Granada-Torres. 2018. Efecto de las actividades antrópicas sobre las características fisicoquímicas y microbiológicas del río Bogotá a lo largo del municipio de Villapinzón, Colombia. Rev. Fac. Med. 66(1), 45-52. Doi: http://doi.org/10.15446/revfacmed.v66n1.59728

Dobson, M.C., M. Crispo, R.S. Blevins, P.H. Warren, and J.L. Edmondson. 2021. An assessment of urban horticultural soil quality in the United Kingdom and its contribution to carbon storage. Sci. Total Environ. 777, 146199. Doi: https://doi.org/10.1016/j.scitotenv.2021.146199

Eijsackers, H. and M. Maboeta. 2023. Pesticide impacts on soil life in southern Africa: Consequences for soil quality and food security. Environ. Adv. 13, 100397. Doi: https://doi.org/10.1016/j.envadv.2023.100397

Elango, D., K.D. Devi, H.K. Jeyabalakrishnan, K. Rajendran, V.K.T. Haridass, D. Dharmaraj, C.V. Charuchandran, W. Wang, M. Fakude, R. Mishra, K. Vembu, and X. Wang. 2022. Agronomic, breeding, and biotechnological interventions to mitigate heavy metal toxicity problems in agriculture. J. Agric. Food Res. 10, 100374. Doi: https://doi.org/10.1016/j.jafr.2022.100374

Emekwuru, N. and O. Ejohwomu. 2023. Temperature, humidity and air pollution relationships during a period of rainy and dry seasons in Lagos, West Africa. Climate 11(5), 113. Doi: https://doi.org/10.3390/cli11050113

Epstein, E. and A.J. Bloom. 2004. Mineral nutrition of plants: principles and perspectives. 2nd ed. Sinauer Associates, Sunderland, MA.

Ercilla-Montserrat, M., P. Muñoz, J.I. Montero, X. Gabarrell, and J. Rieradevall. 2018. A study on air quality and heavy metals content of urban food produced in a Mediterranean city (Barcelona). J. Cleaner Prod. 195, 385-395. Doi: https://doi.org/10.1016/j.jclepro.2018.05.183

Ernst, W.H.O. 2003. Evolution of adaptation mechanism of plants on metal-enriched soils. pp. 433-436. In: Larcher, W. (ed.). Physiological plant ecology. 4th ed. Springer, Berlin.

FAO-OMS. 2009. Codex alimentarius. Norma general para los contaminantes y las toxinas presentes en los alimentos y piensos. CXS 193-1995. Ginebra.

Ferreira, A.J.D., R.I.M.M. Guilherme, C.S.S. Ferreira, and M.F.M.L. Oliveira. 2018a. Urban agriculture, a tool towards more resilient urban communities? Curr. Opin. Environ. Sci. Health 5, 93-97. Doi: https://doi.org/10.1016/j.coesh.2018.06.004

Ferreira, C.S.S., R.P.D Walsh, and A.J.D. Ferreira. 2018b. Degradation in urban areas. Curr. Opin. Environ. Sci. Health 5, 19-25. Doi: https://doi.org/10.1016/j.coesh.2018.04.001

Filipiak-Szok, A., M. Kurzawa, and E. Szłyk. 2015. Determination of toxic metals by ICP-MS in Asiatic and European medicinal plants and dietary supplements. J. Trace Elem. Med. Biol. 30, 54-58. Doi: https://doi.org/10.1016/j.jtemb.2014.10.008

Fischer, F.L. and D.F. Beltrán. 2021. Análisis del material particulado en relación con la percepción de la calidad de vida en tres localidades de Bogotá - Colombia. Gestión Ambiente 24(2), 98601. Doi: https://doi.org/10.15446/ga.v24n2.98601

Fischer, G., F. Casierra-Posada, and M. Blanke. 2023. Impact of waterlogging on fruit crops in the era of climate change, with emphasis in tropical and subtropical species. Agron. Colomb. 41(2).

Folberth, G.A., T.M Butler, W.J. Collins, and S.T. Rumbold. 2015. Megacities and climate change - A brief overview. Environ. Pollut. 203, 235-242. Doi: https://doi.org/10.1016/j.envpol.2014.09.004

Galán, E. and A. Romero. 2008. Contaminación de suelos por metales pesados. Macla: Rev. Soc. Esp. Mineral. (10), 48-59.

García, D. 2006. Efectos fisiológicos y compartimentación radicular en plantas de *Zea mays* L. expuestas a la toxicidad por plomo. PhD thesis. Facultad de Ciencias, Universidad Autónoma de Barcelona, Barcelona, Spain.

Gatta, G., A. Libutti, A. Gagliardi, L. Beneduce, L. Brusetti, L. Borruso, G. Disciglio, and E. Tarantino. 2015. Treated agro-industrial wastewater irrigation of tomato crop: effects on qualitative/quantitative characteristics of production and microbiological properties of the soil. Agric. Water Manage. 149, 33-43. Doi: https://doi.org/10.1016/j.agwat.2014.10.016

Gil, C., R. Boluda, and J. Ramos. 2004. Determination and evaluation of cadmium, lead and nickel in greenhouse soils of Almería (Spain). Chemosphere 55(7), 1027-1034. Doi: https://doi.org/10.1016/j.chemosphere.2004.01.013

González, J.E., P. Ramamurthy, R.D. Bornstein, F. Chen, E.R. Bou-Zeid, M. Ghandehari, J. Luvall, C. Mitra, and D. Niyogi. 2021. Urban climate and resiliency: a synthesis report of state of the art and future research directions. Urban Clim. 38, 100858. Doi: https://doi.org/10.1016/j.uclim.2021.100858

Guo, H., H. Yang, W. Guo, X. Li, and B. Chen. 2023. Defense response of pumpkin rootstock to cadmium. Sci. Hortic. 308, 111548. Doi: https://doi.org/10.1016/j.scienta.2022.111548

Habibi, F., T. Liu, M.A. Shahid, B. Schaffer, and A. Sarkhosh. 2023. Physiological, biochemical, and molecular responses of fruit trees to root zone hypoxia. Environ. Exp. Bot. 206, 105179. Doi: https://doi.org/10.1016/j.envexpbot.2022.105179

Haider, F.U., C. Liqun, J.A. Coulter, S.A. Cheema, J. Wu, R. Zhang, M. Wenjun, and M. Farooq. 2021. Cadmium toxicity in plants: Impacts and remediation strategies. Ecotoxicol. Environ. Saf. 211, 111887. Doi: https://doi.org/10.1016/j.ecoenv.2020.111887

Haitsma, M.C.G., F.H.M. van de Ven, and P. Kirshen. 2022. Circularity in the urban water-energy-nutrients-food nexus. Energy Nexus 7, 100081. Doi: https://doi.org/10.1016/j.nexus.2022.100081

Hamad, A.A., K.H. Alamer, and H.S. Alrabie. 2021. The accumulation risk of heavy metals in vegetables which grown in contaminated soil. Baghdad Sci. J. 18(3), 471-479. Doi: http://doi.org/10.21123/bsj.2021.18.3.0471

Herrera, C.D. and M.F. Lizarazo. 2018. Cuantificación de metales pesados en hortalizas producidas en la cuenca media del río Bogotá, Sibaté. Undergraduate thesis. Facultad de Ingeniería, Universidad El Bosque, Bogota. https://repositorio.unbosque.edu.co/handle/20.500.12495/3310

Hu, N.-W., H.-W. Yu, B.-L. Deng, B. Hu, G.-P. Zhu, X.-T. Yang, T.-Y. Wang, Y. Zeng, and Q.-Y. Wang. 2023. Levels of heavy metal in soil and vegetable and associated health risk in peri-urban areas across China. Ecotoxicol. Environ. Saf. 259, 115037. Doi: https://doi.org/10.1016/j.ecoenv.2023.115037

Hume, I.V., D.M. Summers, and T.R Cavagnaro. 2021. Self-sufficiency through urban agriculture: nice idea or plausible reality¿ Sustain. Cities Soc. 68, 102770. Doi: https://doi.org/10.1016/j.scs.2021.102770

Imperato, M., P. Adamo, D. Naimo, M. Arienzo, D. Stanzione, and P. Violante. 2003. Spatial distribution of heavy metals in urban soils of Naples city (Italy). Environ. Pollut. 124(2), 247-256. Doi: https://doi.org/10.1016/S0269-7491(02)00478-5

Izquierdo-Díaz, M., V. Hansen, F. Barrio-Parra, E. De Miguel, Y. You, and J. Magid. 2023. Assessment of lettuces grown in urban areas for human consumption and as bioindicators of atmospheric pollution. Ecotoxicol. Environ. Saf. 256, 114883. Doi: https://doi.org/10.1016/j.ecoenv.2023.114883

Jalali, M. and S. Moharami. 2010. Effects of the addition of phosphorus on the redistribution of cadmium, copper, lead, nickel, and zinc among soil fractions in contaminated calcareous soil. Soil Sediment Contam.: Int. J. 19(1), 88-102. Doi: https://doi.org/10.1080/15320380903390521

Jansma, J.E. and S.C.O. Wertheim-Heck. 2022. Feeding the city: a social practice perspective on planning for agriculture in peri-urban Oosterwold, Almere, the Netherlands. Land Use Policy 117, 106104. Doi: https://doi.org/10.1016/j.landusepol.2022.106104

Kabata-Pendias, A. 2000. Trace elements in soils and plants. 3rd ed. CRC Press, Boca Raton, FL. Doi: https://doi.org/10.1201/9781420039900

Kabata-Pendias, A. 2004. Soil-plant transfer of trace elements - an environmental issue. Geoderma 122(2-4), 143-149. Doi: https://doi.org/10.1016/j.geoderma.2004.01.004

Kathpalia, R. and S.C. Bhatla. 2018. Plant mineral nutrition. pp. 37-82. In: Bhatla, S.C. and M.A. Lal (eds.). Plant physiology, development and metabolism. Springer Nature Singapore. Doi: https://doi.org/10.1007/978-981-13-2023-1_2

Kaiser, M.L., M.L. Williams, N. Basta, M. Hand, and S. Huber. 2015. When vacant lots become urban gardens: characterizing the perceived and actual food safety concerns of urban agriculture in Ohio. J. Food Prot. 78(11), 2070-2080. Doi: https://doi.org/10.4315/0362-028X.JFP-15-181

Kulak, M., A. Graves, and J. Chatterton. 2013. Reducing greenhouse gas emissions with urban agriculture: a life cycle assessment perspective. Landsc. Urban Plann. 111, 68-78. Doi: https://doi.org/10.1016/j.landurbplan.2012.11.007

Kumar, N., S. Kumar, K. Bauddh, N. Dwivedi, P. Shukla, D.P., Singh, and S.C Barman. 2015. Toxicity assessment and accumulation of metals in radish irrigated with battery manufacturing industry effluent. Int. J. Veg. Sci. 21(4), 373-385. Doi: https://doi.org/10.1080/19315260.2014.880771

Kumar, P., A. Druckman, J. Gallagher, B. Gatersleben, S. Allison, T.S. Eisenman, U. Hoang, S. Hama, A. Tiwari, S. Sharma, K.V. Abhijith, D. Adlakha, A. McNabola, T. Astell-Burt, X. Feng, A.C. Skeldon, S. de Lusignan, and L. Morawska. 2019. The nexus between air pollution, green infrastructure and human health. Environ. Int. 133(Part A), 105181. Doi: https://doi.org/10.1016/j.envint.2019.105181

Kumar, S., S. Prasad, M. Shrivastava, A. Bhatia, S. Islam, K.K. Yadav, S.K. Kharia, A. Dass, N. Gupta, S. Yadav, and M.M.S. Cabral-Pinto. 2022. Appraisal of probabilistic levels of toxic metals and health risk in cultivated and marketed vegetables in urban and peri-urban areas of Delhi, India. Environ. Toxicol. Pharm. 92, 103863. Doi: https://doi.org/10.1016/j.etap.2022.103863

Lambers, H. and R.S. Oliveira. 2019. Plant physiological ecology. 3rd ed. Springer Nature Switzerland, Cham, Switzerland. Doi: https://doi.org/10.1007/978-3-030-29639-1

Larcher, W. 2003. Physiological plant ecology. 4th ed. Springer, Berlin. Doi: https://doi.org/10.1007/978-3-662-05214-3

Li, G., G.X. Sun, Y. Ren, X.-S. Luo, and Y.-G. Zhu. 2018. Urban soil and human health: a review. Eur. J. Soil Sci. 69(1), 196-215. Doi: https://doi.org/10.1111/ejss.12518

Li, S., L. Yang, L. Chen, F. Zhao, and L. Sun. 2019. Spatial distribution of heavy metal concentrations in peri-urban soils in eastern China. Environ. Sci. Pollut. Res. 26, 1615-1627. Doi: https://doi.org/10.1007/s11356-018-3691-6

Li, X., Z. Zhou, T. Li, J. An, S. Zhang, X. Xu, Y. Pu, G. Wang, Y. Jia, X. Liu, and Y. Li. 2023. Soil potentially toxic element pollution at different urbanization intensities: quantitative source apportionment and source-oriented health risk assessment. Ecotoxicol. Environ. Saf. 251, 114550. Doi: https://doi.org/10.1016/j.ecoenv.2023.114550

Liang, H., W.-L. Wu, Y.-H. Zhang, S.-J. Zhou, C.-Y. Long, J. Wen, B.-Y. Wang, Z.-T. Liu, C.-Z. Zhang, P.-P. Huang, N. Liu, X.-L. Deng, and F. Zou. 2018. Levels, temporal trend and health risk assessment of five heavy metals in fresh vegetables marketed in Guangdong Province of China during 2014-2017. Food Contr. 92, 107-120. Doi: https://doi.org/10.1016/j.foodcont.2018.04.051

Liu, Y.-R., M.G.A. van der Heijden, J. Riedo, C. Sanz-Lazaro, D.J. Eldridge, F. Bastida, E. Moreno-Jiménez, X.-Q. Zhou, H.-W. Hu, J.-Z. He, J.L. Moreno, S. Abades, F. Alfaro, A.R. Bamigboye, M. Berdugo, J.L. Blanco-Pastor, A. de los Ríos, J. Duran, T. Grebenc, J.G. Illán, T.P. Makhalanyane, M.A. Molina-Montenegro, T.U. Nahberger, G.F. Peñaloza-Bojacá, C. Plaza, A. Rey, A. Rodríguez, C. Siebe, A.L. Teixido, N. Casado-Coy, P. Trivedi, C. Torres-Díaz, J.P. Verma, A. Mukherjee, X.-M. Zeng, L. Wang, J. Wang, E. Zaady, X. Zhou, Q. Huang, W.

Tan, Y.-G. Zhu, M.C. Rillig, and M. Delgado-Baquerizo. 2023. Soil contamination in nearby natural areas mirrors that in urban greenspaces worldwide. Nature Comm. 14, 1706. Doi: https://doi.org/10.1038/s41467-023-37428-6

Lobell, D.B. and J.A. Burney. 2021. Cleaner air has contributed one-fifth of US maize and soybean yield gains since 1999. Environ. Res. Lett. 16, 074049. Doi: https://doi.org/10.1088/1748-9326/ac0fa4

Londoño-Franco, L.F., P.T. Londoño-Muñoz, and F.G. Muñoz-García. 2016. Los riesgos de los metales pesados en la salud humana y animal. Rev. Bio Agro 14(2), 145-153. Doi: https://doi.org/10.18684/BSAA(14)145-153

Lora, R. and H. Bonilla. 2010. Remediación de un suelo de la cuenca alta del río Bogotá contaminado con los metales pesados cadmio y cromo. Rev. UDCA Act. Div. Cient. 13(2), 61-70. Doi: https://doi.org/10.31910/rudca.v13.n2.2010.730

Lundgren, M., M. Troldborg, J. Stubberfield, A. Augustsson, and R.L. Hough. 2023. Predictive modeling of plant uptake of Pb and Cd: implications of aerial deposition and the origin of parameterisation data. Environ. Challenges 12, 100734. Doi: https://doi.org/10.1016/j.envc.2023.100734

Ma, J., M.H. Saleem, M. Alsafran, H.A. Jabri, Mehwish, M. Rizwan, M. Nawaz, S. Ali, and K. Usman. 2022. Response of cauliflower (*Brassica oleracea* L.) to nitric oxide application under cadmium stress. Ecotoxicol. Environ. Saf. 243, 113969. Doi: https://doi.org/10.1016/j.ecoenv.2022.113969

Machado, A., N. García, C. García, L. Acosta, A. Córdova, M. Linares, D. Giraldoth, and H. Velásquez. 2008. Contaminación por metales (Pb, Zn, Ni y Cr) en aire, sedimentos viales y suelo en una zona de alto tráfico vehicular. Rev. Int. Contam. Ambient. 24(4), 171-182.

Margenat, A., V. Matamoros, S. Díez, N. Cañameras, J. Comas, and J.M. Bayona. 2019. Occurrence and human health implications of chemical contaminants in vegetables grown in peri-urban agriculture. Environ. Int. 124, 49-57. Doi: https://doi.org/10.1016/j.envint.2018.12.013

Marschner, P. (ed.). 2012. Marschner's mineral nutrition of higher plants. 3th ed. Elsevier, Amsterdam.

McLaughlin, M.J. 2002. Bioavailability of metals to terrestrial plants. pp. 39-68. In: Allen, H.E. (ed.). Bioavailability of metals in terrestrial ecosystems. Importance of partitioning for bioavailability to invertebrates, microbes and plants. SETAC Press, Pensacola, FL.

Meftaul, I.M., K. Venkateswarlu, R. Dharmarajan, P. Annamalai, and M. Megharaj. 2020. Pesticides in the urban environment: a potential threat that knocks at the door. Sci. Total Environ. 711, 134612. Doi: https://doi.org/10.1016/j.scitotenv.2019.134612

Miranda, A.I., N.P. Brito-Manzano, P.M. Vargas-Falcón, and J. Bernat-Rodríguez. 2022. Evaluación de la contaminación por metales pesados en la laguna Machona, Tabasco, México. Braz. J. Animal Environ. Res. 5(1), 1062-1078. Doi:https://doi.org/10.34188/bjaerv5n1-080

Miranda, D., C. Carranza, and G. Fischer. 2008b. Calidad de agua de riego en la Sabana de Bogotá. Facultad de Agronomía, Universidad Nacional de Colombia, Bogota.

Miranda, D., C. Carranza, C.A. Rojas, C.M. Jerez, G. Fischer, and J. Zurita. 2008a. Acumulación de metales pesados en suelo y planta de cuatro cultivos hortícolas, regados con agua del río Bogotá. Rev. Colomb. Cienc. Hortic. 2(2), 180-191. Doi: https://doi.org/10.17584/rcch.2008v2i2.1186

Mohanraj, R., A. Azeez, and T. Priscilla. 2004. Heavy metals in airborne particulate matter of urban Coimbatore. Arch. Environ. Contam. Toxicol. 47, 162-167. Doi: https://doi.org/10.1007/s00244-004-3054-9

Mora, A., M. García-Gamboa, M.S. Sánchez-Luna, L. Gloria-García, P. Cervantes-Avilés, and J. Mahlknecht. 2021. A review of the current environmental status and human health implications of one of the most polluted rivers of Mexico: The Atoyac River, Puebla. Sci. Tot. Environ. 782, 146788. Doi: https://doi.org/10.1016/j.scitotenv.2021.146788

Mostafidi, M., F. Shirkhan, M.T. Zahedi, P. Ziarati, B. Hochwimmer, and L. Cruz-Rodriguez. 2021. Bioaccumulation of the heavy metals contents in green leafy vegetables. J. Nutr. Food Sci Tech. 2(1), 1-7.

Nabulo, G., C.R. Black, J. Craigon, and S.D. Young. 2012. Does consumption of leafy vegetables grown in peri-urban agriculture pose a risk to human health¿ Environ. Pollut. 162, 389-398. Doi: https://doi.org/10.1016/j.envpol.2011.11.040

Nabulo, G., S.D. Young, and C.R. Black. 2010. Assessing risk to human health from tropical leafy vegetables grown on contaminated urban soils. Sci. Total Environ. 408(22), 5338-5351. Doi: https://doi.org/10.1016/j.scitotenv.2010.06.034

Nag, R. and E. Cummins. 2022. Human health risk assessment of lead (Pb) through the environmental-food pathway. Sci. Total Environ. 810, 151168. Doi: https://doi.org/10.1016/j.scitotenv.2021.151168

Naidu, R., B. Biswas, I.R. Willett, J. Cribb, B.K. Singh, C.P. Nathanail, F. Coulon, K.T. Semple, K.C. Jones, A. Barclay, and R.J. Aitken. 2021. Chemical pollution: a growing peril and potential catastrophic risk to humanity. Environ. Int. 156, 106616. Doi: https://doi.org/10.1016/j.envint.2021.106616

Niu, L., C. Li, W. Wang, J. Zhang, M. Scali, W. Li, H. Liu, F. Tai, X. Hu, and X. Wu. 2023. Cadmium tolerance and hyperaccumulation in plants – A proteomic perspective of phytoremediation. Ecotoxicol. Environ. Saf. 256, 114882. Doi: https://doi.org/10.1016/j.ecoenv.2023.114882

Noonan, E. and M.-S. A. Barreau. 2021. Urban farming: A gateway to greater food security¿ Strategic Foresight and Capabilities Unit. PE 679.091. European Parliamentary Research Service (EPRS), Brussels.

Noyes, P.D., M.K. McElwee, H.D. Miller, B.W. Clark, L.A. van Tiem, K.C. Walcott, K.N. Erwin, and E.D. Levin. 2009. The toxicology of climate change: environmental contaminants in a warming world. Environ. Int. 35(6), 971-986. Doi: https://doi.org/10.1016/j.envint.2009.02.006

Olivares, S., D. García, L. Lima, I. Saborit, A. Llizo, and P. Pérez. 2013. Niveles de cadmio, plomo, cobre y zinc en hortalizas cultivadas en una zona altamente urbanizada de la ciudad de La Habana, Cuba. Rev. Int. Contam. Ambient. 29(4), 285-294.

Pachón, J.E. and H. Sarmiento. 2008. Análisis espacio-temporal de la concentración de metales pesados en la localidad de Puente Aranda de Bogotá-Colombia. Rev. Fac. Ing. Univ. Antioquia (43), 120-133.

Page, M.J., J.E. McKenzie, P.M. Bossuyt, I. Boutron, T.C. Hoffmann, C.D. Mulrow, L. Shamseer, J.M. Tetzlaff, E.A. Akl, S.E. Brennan, R. Chou, J.M. Glanville, J.M. Grimshaw, A. Hróbjartsson, M.M. Lalu, T. Li, E.W. Loder, E. Mayo-Wilson, S. McDonald, L.A. McGuinness, L.A. Stewart, J. Thomas, A.C. Tricco, V.A. Welch, P. Whiting, and D. Moher. 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 372, n71. Doi: https://doi.org/10.1136/bmj.n71

Panhwar, A., K. Faryal, A. Kandhro, S. Bhutto, U. Rashid, N. Jalbani, R. Sultana, A. Solangi, M. Ahmed, S. Qaisar, Z. Solangi, M. Gorar, and E. Sargani. 2022. Utilization of treated industrial wastewater and accumulation of heavy metals in soil and okra vegetable. Environ. Chall. 6, 100447. Doi: https://doi.org/10.1016/j.envc.2022.100447

Pavao-Zuckerman, P.M.A. 2008. The nature of urban soils and their role in ecological restoration in cities. Restor. Ecol. 16(4), 642-649. Doi: https://doi.org/10.1111/j.1526-100X.2008.00486.x

Pokharel, A. and F. Wu. 2023. Dietary exposure to cadmium from six common foods in the United States. Food Chem. Toxicol. 178, 113873. Doi: https://doi.org/10.1016/j.fct.2023.113873

Rai, P.K., S.S. Lee, M. Zhang, Y.F. Tsang, and K.-H. Kim. 2019. Heavy metals in food crops: health risks, fate, mechanisms, and management. Environ. Int. 125, 365-385. Doi: https://doi.org/10.1016/j.envint.2019.01.067

Rengel, Z., I. Cakmak, and P. White (eds.). 2022. Marschner's mineral nutrition of plants. 4th ed. Elsevier, Amsterdam.

Rodrigues, A.A.Z., M.E.L.R. Queiroz, A.F. Oliveira, A.A. Neves, F.F. Heleno, L. Zambolim, J.F. Freitasa, and E.H.C. Morais. 2017. Pesticide residue removal in classic domestic processing of tomato and its effects on product quality. J. Environ. Sci. Health. Part. B, 52(12), 850-857. Doi: https://doi.org/10.1080/03601234.2017.1359049

Ruan, X., S. Ge, Z. Jiao, W. Zhan, and Y. Wang. 2023. Bioaccumulation and risk assessment of potential toxic elements in the soil-vegetable system as influenced by historical wastewater irrigation. Agric. Water Manag. 279, 108197. Doi: https://doi.org/10.1016/j.agwat.2023.108197

Sandeep, G., K.R. Vijayalatha, and T. Anitha. 2019. Heavy metals and its impact in vegetable crops. Int. J. Chem. Stud. 7(1), 1612-1621.

Santamouris, M. 2015. Analyzing the heat island magnitude and characteristics in one hundred Asian and Australian cities and regions. Sci. Total Environ. 512-513, 582-598. Doi: https://doi.org/10.1016/j.scitotenv.2015.01.060

Säumel, I., I. Kotsyuk, M. Hölscher, C. Lenkereit, F. Weber, and I. Kowarik. 2012. How healthy is urban horticulture in high traffic areas¿ Trace metal concentrations in vegetable crops from plantings within inner city neighbourhoods in Berlin, Germany. Environ. Pollut. 165, 124-132. Doi: https://doi.org/10.1016/j.envpol.2012.02.019

Savvas, D., G. Ntatsi, and P. Barouchas. 2013. Impact of grafting and rootstock genotype on cation uptake by cucumber (*Cucumis sativus* L.) exposed to Cd or Ni stress. Sci. Hortic. 149, 86-96. Doi: https://doi.org/10.1016/j.scienta.2012.06.030

Sharma, R.K., M. Agrawal, and F.M. Marshall. 2009. Heavy metals in vegetables collected from production and market sites of a tropical urban area in India. Food Chem. Toxicol. 47(3), 583-591. Doi: https://doi.org/10.1016/j.fct.2008.12.016

Shukla, L. and N. Jain. 2022. A review on soil heavy metals contamination: effects, sources and remedies. Appl. Ecol. Environ. Sci. 10(1), 15-18.

Tadeo, F.R. and A. Gómez-Cadenas. 2008. Fisiología de las plantas y el estrés. pp. 577-597. In: Azcón-Bieto, J. and M. Talón (eds.). Fundamentos de fisiología vegetal. 2nd ed. McGraw-Hill Interamericana, Madrid.

Thakali, A. and J.D. MacRae. 2021. A review of chemical and microbial contamination in food: what are the threats to a circular food system¿ Environ. Res. 194, 110635. Doi: https://doi.org/10.1016/j.envres.2020.110635

Tomno, R.M., J.K. Nzeve, S.N. Mailu, D. Shitanda, and F. Waswa. 2020. Heavy metal contamination of water, soil and vegetables in urban streams in Machakos municipality, Kenya. Sci. Afr. 9, e00539. Doi: https://doi.org/10.1016/j.sciaf.2020.e00539

Ulpiani, G. 2021. On the linkage between urban heat island and urban pollution island: three-decade literature review towards a conceptual framework. Sci. Total Environ. 751, 141727. Doi: https://doi.org/10.1016/j.scitotenv.2020.141727

Umar, S., Moinuddin, and M. Iqbal. 2005. Heavy metals: availability, accumulation and toxicity to plants. pp. 325-343. In: Dwivedi, P. and R.S. Dwivedi (eds.). Physiology of abiotic stress in plants. Agrobios, Jodhpur, India.

United Nations. 2019. The sustainable development goals report. New York, NY.

United Nations. 2020. Las ciudades y la contaminación contribuyen al cambio climático. In: https://www.un.org/es/climatechange/climate-solutions/cities-pollution; consulted: September, 2020.

Vallejo, F.A. and E.I. Estrada. 2004. Producción de hortalizas de clima cálido. Universidad Nacional de Colombia, Palmira, Colombia.

Vega, L.T. and D.A. Vega. 2021. Contenidos de plomo en hortalizas cultivadas en huertos urbanos de la ciudad de Bogotá, Colombia. Idesia 39(4), 129-137. Doi: http://doi.org/10.4067/S0718-34292021000400129

Velasco, M. 2005. La calidad del aire asociado con metales pesados en la ciudad de Manizales. Undergraduate thesis. Especialización en Ingeniería Ambiental, Universidad Nacional de Colombia, Manizales, Colombia.

Waffle, A.D., R.C. Corry, T.J. Gillespie, and R.D. Brown. 2017. Urban heat islands as agricultural opportunities: an innovative approach. Landsc. Urban Plann. 161, 103-114. Doi: http://doi.org/10.1016/j.landurbplan.2017.01.010

Wan, K., H. Lv, W. Qasim, L. Xia, Z. Yao, J. Hu, Y. Zhao, X. Ding, X. Zheng, G. Li, S. Lin, and K. Butterbach-Bahl. 2022. Heavy metal and nutrient concentrations in top- and sub-soils of greenhouses and arable fields in East China – Effects of cultivation years, management, and shelter. Environ. Pollut. 307, 119494. Doi: https://doi.org/10.1016/j.envpol.2022.119494

Wang, Q., Q. Zhou, L. Huang, S. Xu, Y. Fu, D. Hou, Y. Feng, and X. Yang. 2022. Cadmium phytoextraction through *Brassica juncea* L. under different consortia of plant growth-promoting bacteria from different ecological niches. Ecotoxicol. Environ. Saf. 237, 113541. Doi: https://doi.org/10.1016/j.ecoenv.2022.113541

Weidner, T., A. Yangand, and M.W. Hamm. 2019. Consolidating the current knowledge on urban agriculture in productive urban food systems: learnings, gaps and outlook. J. Clean. Prod. 209, 1637-1655. Doi: https://doi.org/10.1016/j.jclepro.2018.11.004

Wenning, R.J., S.E. Finger, L. Guilhermino, R.C. Helm, M.J. Hooper, W.G. Landis, C.A. Menzie, W.R. Munns Jr., J. Römbke, and R.G. Stahl Jr. 2010. Global climate change and environmental contaminants: a SETAC call for research. Integr. Environ. Assess. Manage. 6(2), 197-198. Doi: https://doi.org/10.1002/ieam.49

Wierzbicka, M., K. Bodzon, A. Naziębło, Z. Tarnawska, M. Wróbel, K. Brzost, and D. Panufnik-Mędrzycka. 2023. Reducing lead uptake by plants as a way to lead-free food. Ecotoxicol. Environ. Saf. 256, 114875. Doi: https://doi.org/10.1016/j.ecoenv.2023.114875

WHO, World Health Organization. 2020. Food safety. In: https://www.who.int/news-room/fact-sheets/detail/food-safety; consulted: May, 2023.

WHO, World Health Organization. 2021. Nutrition – Data and statistics. In: https://www.who.int/europe/news-room/photo-stories/item/data-and-statistics; consulted: April, 2023.

Wu, Z., Y. Chen, Z. Yang, Y. Liu, Y. Zhu, Z. Tong, and R. An. 2023. Spatial distribution of lead concentration in peri-urban soil: threshold and interaction effects of environmental variables. Geoderma 429, 116193. Doi: https://doi.org/10.1016/j.geoderma.2022.116193

Xin, J., B. Huang, H. Dai, W. Zhou, Y. Yi, and L. Peng. 2015. Roles of rhizosphere and root-derived organic acids in Cd accumulation by two hot pepper cultivars. Environ. Sci. Pollut. Res. 22, 6254-6261. Doi: https://doi.org/10.1007/s11356-014-3854-z

Xu, Y., X. Sun, Q. Zhang, X. Li, and Z. Yan. 2018. Iron plaque formation and heavy metal uptake in *Spartina alterniflora* at different tidal levels and waterlogging conditions. Ecotoxicol. Environ. Saf. 153, 91-100. Doi: https://doi.org/10.1016/j.ecoenv.2018.02.008

Yadav, R.S. 2021. Health risk due to heavy metals-vegetables. Int. J. Res. Analyt. Rev. 8(4), 374-377.

Yahaya, S.M., A.A. Mahmud, and N. Abdu. 2023. The use of wastewater for irrigation: pros and cons for human health in developing countries. Total Environ. Res. Themes 6, 100044. Doi: https://doi.org/10.1016/j.totert.2023.100044

Yang, N.-H.N. and A. Yang. 2022. Urban bioeconomy: uncovering its components, impacts and the urban bio-symbiosis. Clean. Prod. Lett. 3, 100015. Doi: https://doi.org/10.1016/j.clpl.2022.100015

Yang, Y., F.S. Zhang, H.F. Li, and R.F. Jiang. 2009. Accumulation of cadmium in the edible parts of six vegetable species grown in Cd-contaminated soils. J. Environ. Manag. 90(2), 1117-1122. Doi: https://doi.org/10.1016/j.jenvman.2008.05.004

Yu, X., H. Li, Q. Yang, Z. Sun, and Y. Ma. 2023. Accumulation of Cr in different vegetables and derivation of soil Cr threshold using the species sensitivity distribution method. Ecotoxicol. Environ. Saf. 258, 114993. Doi: https://doi.org/10.1016/j.ecoenv.2023.114993

Yu, H., M. Lin, W. Peng, and C. He. 2022. Seasonal changes of heavy metals and health risk assessment based on Monte Carlo simulation in alternate water sources of the Xinbian River in Suzhou City, Huaibei Plain, China. Ecotoxicol. Environ. Saf. 236, 113445. Doi: https://doi.org/10.1016/j.ecoenv.2022.113445

Zhao, P., M. Ma, Y. Hu, W. Wu, and J. Xiao. 2022. Comparison of international standards for irrigation with reclaimed water. Agric. Water Manag. 274, 107974. Doi: https://doi.org/10.1016/j.agwat.2022.107974

Zhou, R., L. Niu, J. Yin, F. Jiang, Y. Wang, T. Zhao, Z. Wu, and W. Zhu. 2023. Differences in physiological responses of two tomato genotypes to combined waterlogging and cadmium stresses. Antioxidants 12(6), 1205. Doi: https://doi.org/10.3390/antiox12061205

Zhou, H., W.T. Yang, X. Zhou, L. Liu, J.-F., Gu, W.-L. Wang, J.-L. Zou, T. Tian, P.-Q. Peng, and B.-H. Liao. 2016. Accumulation of heavy metals in vegetable species planted in contaminated soils and the health risk assessment. Int. J. Environ. Res. Pub. Health 13(3), 289. Doi: https://doi.org/10.3390/ijerph13030289

Zulfiqar, U., M. Farooq, S. Hussain, M. Maqsood, M. Hussain, M. Ishfaq, M. Ahmad, and M.Z. Anjum. 2019. Lead toxicity in plants: impacts and remediation. J. Environ. Manage. 250, 109557. Doi: https://doi.org/10.1016/j.jenvman.2019.109557

Zwolak, A., M. Sarzyńska, E. Szpyrka, and K. Stawarczyk. 2019. Sources of soil pollution by heavy metals and their accumulation in vegetables: a review. Water Air Soil Pollut. 230, 164. Doi: https://doi.org/10.1007/s11270-019-4221-y