3 Biotech (2023) 13:155
https://doi.org/10.1007/s13205-023-03585-0

REVIEW ARTICLE

How heavy metal stress affects the growth and development of pulse crops: insights into germination and physiological processes

Sudipta Majhi[1] · **Mausumi Sikdar (née Bhakta)**[1]

Received: 30 December 2022 / Accepted: 23 April 2023 / Published online: 30 April 2023

Abstract

The current work is an extensive review addressing the effects of heavy metals in major pulse crops such as Chickpea (*Cicer arietinum* L.), Pea (*Pisum sativum* L.), Pigeonpea (*Cajanus cajan* L.), Mung bean (*Vigna radiata* L.), Black gram (*Vigna mungo* L.) and Lentil (*Lens culinaris* Medik.). Pulses are important contributors to the global food supply in the world, due to their vast beneficial properties in providing protein, nutritional value and health benefits to the human population. Several studies have reported that heavy metals are injurious to plants causing inhibition in plant germination, a decrease in the root and shoot length, reduction in respiration rate and photosynthesis. Properly disposing of heavy metal wastes has become an increasingly difficult task to solve in developed countries. Heavy metals pose one of the substantial constraints to pulse crops growth and productivity even at low concentrations. This article attempts to present the morphological, biochemical and various physiological changes induced on the pulse crops grown under various heavy metal stress such as As, Cd, Cr, Cu, Pb, and Ni.

Keywords Heavy metals · Pulse crops · Anthropogenic activities · Toxic effects · Plant response

Introduction

Heavy metal (HM) refers to a group of metals with a high atomic number, i.e. above 20 and having a higher density (5 g/cm^3), such as cadmium (Cd), mercury (Hg), lead (Pb), arsenic (As), nickel (Ni), chromium (Cr), copper (Cu) and zinc (Zn) (Mishra et al. 2019). These metals directly pollute the environment and cause biological toxicity when excess amounts of HMs are introduced into the environment. However, some of these metals including Zn, Cu and Ni are necessary micronutrients and only required in trace levels since they serve as cofactors for certain enzymes (Ghori et al. 2019). Organic pollutants are easily degradable, while the toxic HMs are unmodifiable by biochemical reactions and cause environmental pollution worldwide. Therefore, these metals are difficult to remediate from the water and soil by natural means (Ramesh kumar and Anbazhagan 2018). When these HMs enter agricultural lands they not only cause soil contamination, but also affect food quality, production and human health. Crops grown in HM polluted sites have been reported to display altered metabolism, biochemical and physiological processes leading to growth reduction, lower biomass production and HM accumulation (Edelstein and Ben-Hur 2018). One such important agricultural crops are pulses, which are globally very important and play a key role in dietary diversity to eliminate malnutrition and hunger.

Pulse crops belong to the Fabaceae family their importance ranks second to that of the Poaceae family in the agriculture system. Moreover, pulse crops can arrange as a substitute for animal protein and thus become an essential dietary protein required especially in developing countries (Farooq et al. 2018). Pulse crops are a source of rich protein in comparison to various other cultivated crops. In addition, pulses belong to a subgroup of legumes that harbors nitrogen-fixing bacteria in their root system which improves soil fertility (Schwember et al. 2019). Legume plants have an important role as health enhancers due to the fact these bioactive peptides possess various properties such as antioxidant activities, antimicrobial effects, immunomodulation, enhancing of mineral bioavailability/absorption, lowering of blood pressure and cholesterol (Çakir et al. 2019). Edible

---

✉ Mausumi Sikdar (née Bhakta)
mausumi.dbs@presiuniv.ac.in

[1] Microbiology, Nutrition and Dietetics Laboratory, Department of Life Sciences, Presidency University, 86/1 College Street, Kolkata, West Bengal 700073, India

seeds provided by the legume plants have shown anticarcinogenic properties. Many potential bioactive components provided by pulses are protease inhibitors, saponins, lectins, phytosterols and phytates which act as anticancer agents (Mathers 2002). Furthermore, the absence of gluten proteins in seeds of pulse crops is critical in meeting the need of gluten-free diets for the population suffering from celiac disease (Mlyneková et al. 2014).

Heavy metals

Chromium

Naturally, Cr is present on the Earth having an electronic configuration [Ar] $4d^5s^1$ and is the seventh most abundant element found in the Earth's crust having concentrations varying from 100 to 300 µg/g. Cr is found in nature in its compound states, and chromite (Fe, Mn) Cr_2O_4 is the most relevant Cr ore (Focardi et al. 2013). Table 1 summarises the sources of HMs/metalloids. Cr(III) is an important trace element for having a particular role in maintaining normal carbohydrate metabolism in yeast and mammals (Dębski et al. 2004). For normal insulin function Cr is required, insulin resistance have been reported at low levels of Cr. Extreme deficiency of Cr is followed by symptoms that mimic diabetes mellitus (Liu et al. 2015). In nature, Cr occurs in two distinct and stable oxidation states i.e. hexavalent Cr[Cr(VI)] and trivalent Cr[Cr(III)], in both Cr(VI) and Cr(III), there is a difference in toxicity, bioavailability and mobility (Panda and Choudhury 2005). Hexavalent Cr is more toxic than the trivalent form, which generally occurs in association with oxygen as dichromate ($Cr_2O_7^{2-}$) or chromate (CrO_4^{2-}) (Shanker et al. 2005). Cr(VI) is more mobile in comparison to Cr(III) and in aquatic and soil environments Cr(III) is mostly found confined to organic matter which is thought to take place due to the reduction of Cr(VI) to Cr(III) (Becquer et al. 2003). The International Agency for Research on Cancer (IARC) has classified Cr(III) compounds as Group 3 and Cr(VI) compounds as Group 1 (IARC 2012). In humans, Cr(VI) exposure can induce irritations in the skin and nose, nasal ulcer, contact dermatitis, nasal ulcer, lung cancer and respiratory tract disorders (Shrivastava et al. 2002). Exposure to Cr can cause serious phytotoxicity in plant cells, Cr causes a reduction in chlorophyll (Chl) content, breakdown of carotenoids and an increase in lipid peroxidation which hampers the growth of the plant (Panda and Patra 2000).

Table 1 Sources of HMs/metalloids

Metals/metalloids	Sources	References
Cr	Volcanic eruptions, weathering of parent rocks, fossil fuel combustion, waste incineration, industrial processes, pulp and paper mills, leather tanning, chromium plating, metal fabrication, wood preservatives, printing inks, paints and anti-corrosive materials	Bielicka et al. (2005), Biradar et al. (2012), Cheng et al. (2014) and Owlad et al. 2009)
As	Earth crusts as ores and minerals, industrial sites, mining, smelting, manufacturing alloys, burning fossil fuels, leather industry, wood preservatives, pesticides	Bissen and Frimmel (2003), Melamed (2005), Morin and Calas (2006) and Bencko and Slámová (2007)
Cd	Weathering of cadmium-rich rocks, volcanic activities, industrial processes, nickel–cadmium batteries, PVC products, electroplating, electrodes, phosphate fertilizer production, nuclear reactors, fossil fuel combustion and smoking	Genchi et al. (2020a) and Suhani et al. 2021)
Pb	Volcanic explosions, forest fire, mining, smelting, coal burning, batteries, painters, pigments, car radiators, cable wires, ammunitions, cement industry, automobile exhaust and oil combustion	Cheng and Hu (2010), Hou et al. (2015), Karrari et al. (2012) and Wang et al. (2000)
Cu	Volcanoes, windblown dust, forest fires, mining, milling, refining and smelting of ores, concentrating, electroplating industries, electrical wastes, fuel combustion, wood preservatives, copper biocides and pesticides	Alvarado et al. (2002), Freeman and McIntyre (2008), Kuehne et al. (2017), Lamichhane et al. (2018), Rehman et al. (2019) and Shrivastava (2009)
Ni	Wind-blown dust, weathering of rocks, forest fires, volcanic activities, mining, refining, nickel alloys, petroleum industries, smelting, paint, batteries, combustion of coal, diesel and fuel, incineration of waste and sludge	Ahn et al. (2019), Genchi et al. (2020b) and Iyaka 2011)

Cadmium

Cd is most commonly found as a divalent cation that is complexed with other elements (e.g., $CdCl_2$). Cd is found in the Earth's crust at roughly 0.1 parts per million, found as an impurity in Pb or Zn deposits; it is generally generated as a byproduct of Pb or Zn smelting (Bernhoft 2013). Cd is a soft, ductile, silvery-white metal belonging to the group 12 element, present in d block and period 5 with atomic number 48 and electronic configuration [Kr] $4d^{10}5s^2$ (Sharma et al. 2015). Normally + 2 oxidation state is present in most of its compounds although the + 1 oxidation state is found in rare instances (Morrow 2010). Cd is a widespread pollutant that persists in nature and pollutes soil and water. In addition, it is a non-essential metal for both plants and humans (Meysam Hoseini and Zargari 2013). Cd is considered to be a Group 1 human carcinogen (IARC 2012). Cd is a common HM contaminant that is extremely hazardous to living organisms. Exposure to Cd leads to shortness of breath, acute respiratory distress syndromes, lung edema, mucous membrane destruction due to pneumonitis, acute gastrointestinal disorder (vomiting and diarrhea), kidney damage and Cd induce deleterious effects in the reproductive system (Godt et al. 2006).

Arsenic

Arsenic, a metalloid, is the 20th most abundant element in the Earth's crust, 1.5–3 mg/kg As is present in the soil (Mandal and Suzuki 2002). Arsenic like nitrogen, phosphorus, antimony and bismuth, belong to group V element. It has the electronic configuration [Ar] $3d^{10}4s^24p^3$ with an atomic weight of 75 (Garelick et al. 2008). Only 3 compounds of 150 species of As containing minerals found in nature are regarded as As ore, due to their high amount of As, namely realgar or As sulfide (As_2S_2), orpiment or As tri-sulfide (As_2S_3) and arsenopyrite or ferrous As sulfide ($FeAsS_2$) (Hossain 2006). As can be found in both organic and inorganic forms in nature, while pentavalent arsenate As(V) and trivalent arsenite As(III) valence states of As are most commonly seen in environments contaminated with As (Dhankher et al. 2012). According to Environmental Protection Agency (EPA) and IARC, As is one of the most extremely toxic and carcinogenic element present on the planet. As and its compounds have been placed in Group 1 human carcinogen (IARC 2012). As is a potent carcinogenic metalloid pollutant with negative health effects in humans. Moreover, As can cause non-carcinogenic consequences, including weakness, edema, cardiovascular disease, hypertension, diabetes mellitus, respiratory problems, conjunctival congestion and neurological deficits (Bjørklund et al. 2018).

Lead

Pb is a notable hazardous HM, which has attracted a lot of interest due to its extensive distribution and potential environmental hazard (Zeng et al. 2007). Pb is slightly bluish to gray in color, easily molded and shaped, and has a melting point of 621.43 °F. Additionally, it can be combined with different metals to create alloys. Pb is placed in group 14 in the periodic table and has an atomic weight and an atomic number of 207.2 and 82, respectively, and having electronic configuration of [Xe] $6s^24f^{14}5d^{10}6p^2$ (Abd El-Hack et al. 2019). Pb is the most common HM pollutant in the environment according to EPA, IARC has classified Pb as a possible human carcinogen in Group 2B and its inorganic compounds in Group 2A (IARC 2012). In humans, Pb causes severe damage to the brain, kidneys, central nervous system, cardiovascular system, immune system. In addition, other notable effects caused by Pb exposure are depression, problems with sleep, fatigue, headaches, slurred speech, stupor, nausea, abdominal pain, lack of coordination, numbness, blood pressure increases, anaemia and miscarriage (Wani et al. 2015). Pb is not necessary for plant growth; a higher concentration of Pb causes a magnitude of negative effects causing inhibition of growth and germination, suppressing photosynthesis, altering membrane structure and permeability (Li et al. 2012). Pb toxicity destroys the chloroplast substructure and mitochondria, reduction in ascorbic acid and Chl contents, production of reactive oxygen species (ROS) and decline in the activity of antioxidative enzymes causing an overall reduction in plant growth and development (Xu et al. 2007).

Copper

Cu is present in group 11, period IV in the periodic table with the electronic configuration [Ar] $3d^{10}4s^1$, having atomic number 29 and an average molecular weight of 63.55 (Barber et al. 2021). All biological species, from bacteria to humans, require Cu as an essential trace element. Cu participates in redox reactions through cycling between Cu(I) and Cu(II) oxidation states, making it an important component of metalloenzymes and using coordination chemistry maintains higher order structure which serves as an essential component of macromolecules (Stern et al. 2007) Cu toxicity disturbs redox properties leading to a significant increase in ROS, damaging lipids, mitochondria, proteins and nucleic acids (Mehta et al. 2006). Excess Cu accumulation in humans causes Wilson disease, abdominal pain, headache, dizziness, nausea, vomiting, diarrhea, tachycardia, respiratory problems, hemolytic anemia, hematuria, substantial gastrointestinal bleeding, kidney and liver failure (Stern et al. 2007). In plants, Cu plays key roles in photosynthesis, respiration, cell wall metabolism and hormone perception. Multiple Cu transporters regulate the transport of Cu in a tightly controlled fashion, such as Copper transporter (COPT), Zrt/Irt-like protein (ZIP), HM ATPase (HMA), yellow stripe-like (YSL) transporters and natural resistance-associated macrophage protein (Nramp), directly maintaining Cu homeostasis (Liu et al. 2017).

Nickel

Ni is one of the major metal pollutants of concern due to its toxic effects at a higher concentration, which is increasing in the soil every year in various parts of the world. Ni is a long-term potential environmental hazard, ranking 22nd among the most common elements in the Earth's crust (Rizwan et al. 2019). Ni has a silvery-white color, hard and ductile, belonging to group VIII B of the transition metal series in the periodic table and having an atomic number 28 with the electronic configuration [Ar] $3d^{8}4s^{2}$. Although Ni can exist in numerous different oxidation states, Ni(II) i.e. in the + 2 valence state is the most prevalent oxidation state in the environment. Other valence states (− 1, + 1, + 3, and + 4) are also found in nature and are less frequent (Cempel and Nikel 2006). Many plant species require small amounts of Ni (0.01–5.0 mg/kg) to complete their life cycle, Ni also plays an important role in urease enzyme (Rizwan et al. 2017). Glyoxalases, hydrogenases, peptide deformylases, methyl-coenzyme reductase and superoxide dismutases, are among the enzymes that use Ni as a key component. Furthermore, Ni participates in various metabolic processes, including ureolysis, methane biogenesis, hydrogen metabolism and acetogenesis (Chen et al. 2009). Ni is carcinogenic to humans, Ni compounds belong to Group 1 and metallic Ni belong to Group 2B (IARC 2012). Ni is a known immunotoxic, haematotoxic, neurotoxic, pulmonary toxic, hepatotoxic, nephrotoxic, reproductive toxic, genotoxic and carcinogenic agent (Das et al. 2008). In humans, acute toxicity of Ni causes nausea, vomiting, irritation, vertigo, stiffness in chest, constant cough, cyanosis, dyspnea, tachycardia, palpitations, visual disturbances, sweating, weakness, cardiac arrest and death due to respiratory distress syndrome have been reported, whereas chronic toxicity leads to asthma and bronchitis (Das et al. 2018). Exposure to a high concentration of Ni disrupts many morphological and anatomical processes in plants causing growth reduction, chlorosis, wilting and necrosis (Jamil et al. 2014).

Pulse crops

Chickpea

Chickpea is an annual grain legume, a self-pollinated diploid ($2n = 2x = 16$) plant with a genomic size of roughly 738 megabase pair (Mbp)/1C (Arumuganathan and Earle 1991). Chickpea plant in association with effective nitrogen-fixing symbiotic bacteria improves soil fertility by fixing atmospheric nitrogen. The amount of nitrogen fixed in the soil by different pulse crops are provided in Table 2. Chickpeas were first domesticated in Southeastern Turkey and have since adapted to a variety of environmental and climatic factors all over the globe from East Africa to South Asia in subtropical conditions to regions of North America in temperate conditions (Kozlov et al. 2019). Two distinct types of chickpeas are cultivated based on seed size, shape and color. Specifically, the *desi* form, which is characterized by pink or purple flowers, seeds are small, angular in shape, brown in color containing a high proportion of fiber primarily cultivated in East Africa and the Indian subcontinent and central Asia, while type *kabuli*, having white flowers, seeds are large, beige, containing a low proportion of fiber, cultivated in Central Asia and Mediterranean basin (Iruela et al. 2002). To increase chickpea productivity, *Mesorhizobium* is used for symbiotic nitrogen fixation where the beneficial microorganisms are traditionally applied either to the soils or to the seeds. To boost the nodulating capacity of the crop and the effectiveness of the symbiosis (Wani et al. 2007a), Chickpea is an essential source of protein for millions of people in India and other South Asian countries. Chickpeas have high fiber content, unsaturated fatty acids, β-carotene and are rich in minerals (calcium, phosphorus, magnesium, zinc and iron) (Gaur et al. 2010). Chickpea ranks third after beans in terms of production worldwide with a mean production of more than 10 million tons annually, with the majority of production concentrated in India. Chickpea plantation has begun to increase in land area in recent years. Reaching an estimated 13.5 million hectares, the rate of increase in per

Table 2 Amount of nitrogen fixed by different pulse crops in the soil

Pulse crops	Fixed nitrogen in the soil (kg/ha/year)	References
Cicer arietinum	31–186	Aslam et al. (2003) and López-Bellido et al. (2011)
Cajanus cajan	32–117	Adu-Gyamfi et al. (2007) and Wezi et al. (2017)
Lens culinaris	41–154	Schmidtke et al. (2004)
Pisum sativum	53–286	Gollner et al. (2019) and Kumar and Goh (2000)
Vigna radiata	25–112	Shah et al. (2003) and Delfin et al. (2008)
Vigna mungo	13–91	Hayat et al. (2008)

unit area production have been slow but steady. The global yield, production and area of major pulse crops data estimated from 2018 to 2020 based on Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) are provided in Table 3. Every year, more than 1.3 million tons of chickpea arrive in world markets where India, Pakistan, Iran, Turkey and Australia are the leading chickpea producing countries (Muehlbauer and Sarker 2017).

Pigeonpea

Pigeonpea (*Cajanus cajan* L.) is an important legume crop that is widely grown in tropical and subtropical regions for its nutritive seeds. Pigeonpea is extensively versatile, hardy, fast-growing and can withstand drought conditions (Bekele Tesemma 2007). These species are diploid in nature ($2n=2x=22$) having an estimated genome size of about 858 Mbp/1C (Greilhuber and Obermayer 1998). Due to its resistance to drought conditions, it is considered highly relevant for food security in areas where rainfall is uncertain and the prevalence of drought is common (Cox 2014). Cultivated varieties can be divided into two types, the cultivar *arhar* (*C. cajan* var. *bicolor*) is a large, bushy, late-maturing perennial plant whose dorsal side of the standard is either red or purple. Another variety is three seeded, shorter plant having a yellow standard and are earlier maturing known as *tur* cultivars *C. cajan* var. *flavus* (Sharma et al. 2008). Despite some postulation for African origin, it has been proved beyond a reasonable doubt that the most likely wild progenitor of pigeonpea was *Cajanus cajan ifolius* found in Eastern India today, comprising the present state of Odisha and neighboring states as an origin (Fuller et al. 2019). The most popular use of pigeonpea is to make *dhal* (hulled, soaked dried, and split seeds) (Shinde et al. 2017). In certain regions of Southeast Asia, the seeds are used to make *tempe* (Shurtleff and Aoyagi 2013). 20–22% of protein can be found in the seeds of pigeonpea along with a significant amount of minerals and essential amino acids. Pigeonpea is commonly consumed as whole grain, green peas or split peas (Saxena et al. 2002). India is the world's largest pigeonpea growing country. The primary pigeonpea producing countries are India, Myanmar, Tanzania, Malawi, Uganda, Mozambique and Southern Africa (Sharma et al. 2019). In terms of area and production in India, the following states comprise Maharashtra, Madhya Pradesh, Uttar Pradesh, Gujarat, Karnataka, Telangana, Andhra Pradesh and Bihar (Sameer Kumar et al. 2017).

Pea

The pea (*Pisum sativum* L.) plant was the first model organism utilized in Mendel's (1866) discovery of the laws of inheritance, laying the groundwork for modern plant genetics (Smýkal et al. 2012). Pea is grown all over the world having a temperate climate, it is a herbaceous, annual, self-pollinated diploid ($2n=2x=14$) plant with an enormous genome size estimated to be 4397 Mbp/1C (Arumuganathan and Earle 1991). Archaeological evidence indicates its cultivation in Greek settlements and the Near Eastern region in early 6000 BC, but there is no strong consensus on its actual

Table 3 Global yield, production and area of major pulse crops

Crop	Scientific name	Year	Yield (Mg/ha)	Production (Mt)	Area (Mha)
Chickpea	*Cicer arietinum*	2018	1.05	16.94	16.18
		2019	1.03	14.18	13.79
		2020	1.02	15.08	14.84
Pigeonpea	*Cajanus cajan*	2018	0.98	5.38	5.48
		2019	0.78	4.36	5.59
		2020	0.82	5.01	6.10
Lentils	*Lens culinaris*	2018	1.19	6.57	5.51
		2019	1.19	5.78	4.85
		2020	1.30	6.54	5.01
Pea (dry)	*Pisums ativum*	2018	1.80	13.41	7.45
		2019	1.96	14.00	7.14
		2020	2.40	14.64	7.19
Mung bean	*Vigna radiata*	2018	–	–	–
		2019	–	–	–
		2020	–	–	–
Black gram	*Vigna mungo*	2018	–	–	–
		2019	–	–	–
		2020	–	–	–

Data source: (FAOSTAT 2022)

origin. Primitive forms flourished throughout Central Asia, including Afghanistan, the Near East, the Mediterranean and Ethiopia, all of which are rich in genetic diversity (Wrigley et al. 2015). Pea is valuable due to their nutritional quality of protein having amino acids containing low levels of sulfur, methionine and cysteine, but lysine-rich and possessing other essential amino acids (Dahl et al. 2012). Furthermore, peas include substantial amounts of vital minerals such as calcium, iron and phosphorus, which are absent in cereals (Haque et al. 2015). Peas are frequently used as a break crop in continuous cropping systems and also used as forage for cattle (Borreani et al. 2007). Peas are grown extensively in India and the Indian subcontinent and are consumed as vegetables, *dhal* (pulses), *chhola* (whole grain), *chat* (spicy dish) and flour; thus making a major contribution to the business economy (Choudhury et al. 2007). The immature seeds of this crop are eaten as raw, frozen, or packaged vegetables in many countries around the world. Pea is a starchy plant with high protein, vitamins (A, B6, C, and K), elements (Cu, P, Mg, Fe, and Zn), fiber and lutein (El-Amier et al. 2019). Pea seeds, which contain 270–560 g/kg starch, 200 g/kg dietary fibers and 130–300 g/kg protein are an excellent source of plant protein for human and cattle feeds (Park et al. 2010). It is also consumed to avoid cardiovascular disorders due to its low fat, cholesterol and sodium contents (Shahid et al. 2018). Canada is the largest producer of pea, other prominent pea producing countries are France, Russia, China, India and Ukraine (Janzen et al. 2014).

Mung bean

The *Vigna* genus is pantropical consisting of about 170 species, Africa comprising 120 and 22 in Indo-Pak subcontinent and Southeast Asia, and few from other countries. Since ancient times, mung bean [*Vigna radiata* (L.) R. Wilczek] has been a major pulse crop in Asia (Ghafoor et al. 2002). Mung bean is an annual, self-pollinated diploid legume plant with 22 chromosomes ($2n = 2x = 22$) with approximately 579Mbp/1C genome size (Arumuganathan and Earle 1991). Mung beans are thought to be originated and domesticated in the Indian subcontinent around 2500 BC, data on the domestication of mung bean, morphological research, and archaeological findings suggest they might have originated from places like minor hill groups between the Krishna and Godavari rivers, near the upper Ganges in the Eastern Harappan zone and the Western Himalayan foothills (Fuller and Harvey 2006). *V. radiata var. sublobata* are the nearest wild relatives of the cultivated *V. radiata*, and are considered to be their wild progenitors (Singh and Jauhar 2006). Domestication and selection from *V. radiata* ssp. *radiata* resulted in the cultivation of mung bean which is widespread across Eastern and Southern Asia, Austronesia and Africa (Lambrides and Godwin 2007). Mung bean protein is easily digestible, dried grains can be eaten whole or split after cooking to make soup or *dhal*, deep-fried delicious cakes, noodles, and also flour for making biscuits and bread (Tomooka et al. 2005). On a dry weight (DW) basis, a mung bean seed contains 59–65% carbohydrate, 24–28% protein, 4.5–5.5% ash 3.5–4.5% fiber and 1.0–1.5% fat and provides energy in the range of 334–344 kcal (Mehandi et al. 2019). The majority of the mung bean production (90%) takes place in Asia where India is the world's largest producer, accounting for more than half of the global output. In India, mung beans are grown on approximately 4.2 million hectares, with an estimated annual production of 1.3 million tons in 2008 (Isemura et al. 2012).

Black gram

The *Vigna* genus is a leguminous plant consisting of a large taxon that is found in tropical and subtropical regions of America, Asia, Africa and Australia. Black gram is a self-pollinated diploid ($2n = 2x = 22$), short duration annual plant species with a genomic size estimated to be 574 Mbp/1C (Arumuganathan and Earle 1991). Cultivated black gram [*Vigna mungo* (L.) Hepper var. *mungo*] (known also as *urad*, *urd* or mash). It is believed in India that the domestication of black gram originated from *Vigna mungo* var. *silvestris* as its wild progenitor (Fuller et al. 2004). *Vigna mungo* seeds are a staple food in South Asia, and the split and de-hulled seeds (*dhal*) are a common dish (Joyner and Yadav 2015). Many traditional products are prepared from black gram like *papad, wari, idli, halwa, dosa* and *imrati* (Zia-Ul-Haq et al. 2014). Owing to its relatively short life cycle (75–90 days) and drought tolerance, the ability to fix nitrogen from the atmosphere with the help of soil bacteria *Bradyrhizobium* and *Rhizobium*, black gram is grown as part of a variety of cropping systems, although it is most commonly grown after wheat and rice (Kaewwongwal et al. 2015). Black gram is primarily grown in India, Afghanistan, Bangladesh, Pakistan, Myanmar, Nepal, Philippines, Thailand, Sri Lanka, South and Southeast Asian countries. India is the world's leading producer as well as consumer of black gram, owing to its major contribution to its production. In 5.44 million hectares, it is grown with an annual production of roughly 3.56 million tons in 2017–2018 and a productivity of 655 kg/ha (Raizada and Souframanien 2019).

Lentil

Lentil (*Lens culinaris* Medik.) is one of the oldest legume crops, dating back to 7000–6000 BC according to archeological evidence (Erskine et al. 2016). The lentil plant is present in the clade Hologalegina, tribe Vicieae, subfamily Faboideae as a member of the Fabaceae (Leguminosae) family (Chahota et al. 2018). Lentil plant is an annual diploid

($2n = 2x = 14$), a self-pollinated crop having genome size of 4063 Mbp/1C (Arumuganathan and Earle 1991). There are many wild lentils but *L. orientalis* is thought to be the progenitor of the cultivated lentil (Yadav et al. 2007). The lentils which are chiefly cultivated have been split into two commercial classes, acrosperma and microsperma, with seed diameters ranging from 6 to 9 mm and 2 to 6 mm, respectively (Koul et al. 2017). Lentil is a popular staple food crop in many parts of the world, having protein (20–30 g/100 g), healthy fats (< 2 g/100 g), dietary fiber, and a variety of micronutrients (selenium, zinc, beta-carotene and folates) (Sayğılı and Sayğılı 2019). In India, large-seeded macrosperma type of lentil varieties are chiefly grown in Madhya Pradesh and neighboring districts of Uttar Pradesh, covering about 35% of the total area, whereas small-seeded microsperma type varieties are cultivated mainly in Haryana, Punjab, Uttar Pradesh and Bihar covering 65% of the total area (Kishor et al. 2020). The lentils are usually grown with cereals in a rotation system to help break up the cycle of cereal disease and simultaneously fix atmospheric nitrogen. Lentil contains more than twice as much dietary protein as cereals due to their high protein content. Farmers in many developing countries prefer it because of its potential to survive in drought-prone environments and marginal lands where they can grow in very little rainfall of 250–300 mm (Solh and Van Ginkel 2014). In South Asia, lentils are commonly consumed as fried or boiled (*dhal*) which has a soupy texture and is traditionally served with unleavened bread (*roti*). Boiled rice is also popularly served as a staple along with lentil *dhal*. *Khichuri* is a dish made with split or de-hulled lentils and split rice or wheat. Lentils may also be eaten as a snack after being deep-fried or mixed with cereal flour to make foods like bread and cake (Sarker et al. 2004). After threshing, plant residues such as stalks, dried leaves, husk and podwall are used as an excellent source of animal feed (Maneepun 2003). Lentils are grown all over the world, from North and South America, Australia, Northern Africa, Middle East to the Indian subcontinent and Southern Europe (Rubeena et al. 2003). Global lentil production being led by Canada, India, Turkey and the United States (Johnson et al. 2020).

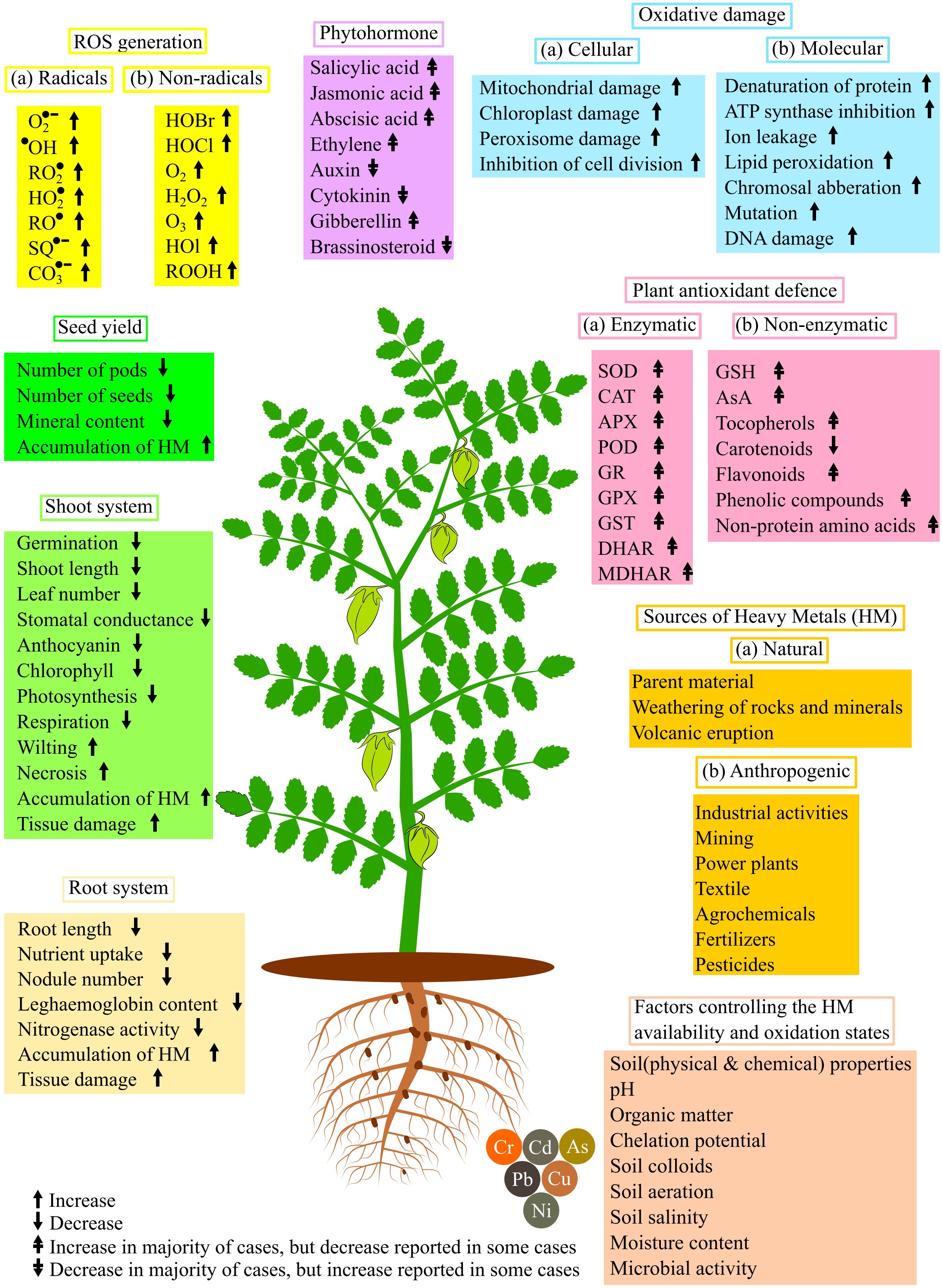
Mode of action of HMs in plant system

Contamination of the soil is the leading cause of the entry of HMs into the plant system. The root surface absorbs the bioavailable metal, which is then transported through the cellular membrane into the root cells. There are two primary pathways for the uptake of HMs by roots, the apoplastic pathway (passive diffusion) and the symplastic pathway (which involves concentration across the plasma membrane and active transport against electrochemical potential gradients) (Yan et al. 2020). The accumulation of HMs in plants involves a series of processes which include mobilization of the HMs, uptake by the roots, xylem loading, transportation from roots to shoots, compartmentalization within cells, sequestration and distribution to aerial parts (Dalvi and Bhalerao 2013). HMs are commonly absorbed through the symplastic pathway, which is an energy-dependent process facilitated by metal ion carriers or complexing agents (Okon et al. 2020). To enter the xylem, HMs are thought to use membrane pumps or channels, which also transport essential elements to the plant system (Peer et al. 2005). HMs activate distinct signaling cascades in plants, including but not limited to, calcium-dependent signaling, ROS signaling, mitogen-activated protein kinase (MAPK) signaling and hormone signaling pathways. These pathways subsequently augment the expression of transcription factors (TFs) and/or stress-responsive genes, thereby leading to a physiological response in the plant system (Dubey et al. 2014). Plants contain multiple Ca^{2+} sensors, e.g., calmodulins (CaMs), calcineurin B-like proteins (CBLs), CaM-like proteins and Ca^{2+}-dependent protein kinases (CDPKs) that detect, decode and transmit alteration in cytosolic Ca^{2+} levels to facilitate stress response (Steinhorst and Kudla 2014). HM stress has a significant impact on MAPK signaling pathways. The activation of MAPKs occurs in response to the recognition of particular metal ligands and ROS generated during metal stress (Jalmi et al. 2018).

Responses and effects of HM stress on pulse crops

Growth attributes

Medda and Mondal (2017) clearly showed that the structure of the xylem and phloem both in root and shoot were gradually distorted at a higher concentration of Cr ranging from 20 to 100 mg/L in *C. arietinum*. The root and shoot length significantly decreased at 33.3 mg As/kg dry weight (DW) contaminated soil after 12 days, while after 32 days, the root and shoot fresh weight (FW) and DW were significantly decreased at 73.3 mg As/kg DW in soil (Päivöke and Simola 2001). *P. sativum* grown at 30 mg/kg As soil had a higher As content in the tissue system of root than in shoot and least in grains (Alam et al. 2020). As (25 and 250 µM) caused mitotic aberrations, DNA fragmentation, degeneration of spindle and disrupted the microtubule architecture at different stages of cell cycle in the root apices (Dho et al. 2010). Mineral contents in seeds were found to decline under As stress, exhibiting decreased accumulation of Cu, Fe, Se, Zn, Mn, Ni and Co in different plant parts. Total amino acid contents also decreased by 46% in treated *C. arietinum* (Tripathi et al. 2015a, b). Hydroponically grown *P. sativum* exposed to Pb, accumulated the highest Pb content in the root system followed by stem and leaves. Moreover, Pb stress induced impairment in the meristematic


ROS generation
(a) Radicals
(b) Non-radicals
$O_2^{\bullet-}$ ↑
$^{\bullet}OH$ ↑
$RO_2^{\bullet}$ ↑
$HO_2^{\bullet}$ ↑
$RO^{\bullet}$ ↑
$SQ^{\bullet-}$ ↑
$CO_3^{\bullet-}$ ↑
HOBr ↑
HOCl ↑
O_2 ↑
H_2O_2 ↑
O_3 ↑
HOl ↑
ROOH ↑
Phytohormone
Salicylic acid ↟
Jasmonic acid ↟
Abscisic acid ↟
Ethylene ↟
Auxin ↡
Cytokinin ↡
Gibberellin ↟
Brassinosteroid ↡
Oxidative damage
(a) Cellular
(b) Molecular
Mitochondrial damage ↑
Chloroplast damage ↑
Peroxisome damage ↑
Inhibition of cell division ↑
Denaturation of protein ↑
ATP synthase inhibition ↑
Ion leakage ↑
Lipid peroxidation ↑
Chromosal abberation ↑
Mutation ↑
DNA damage ↑
Seed yield
Number of pods ↓
Number of seeds ↓
Mineral content ↓
Accumulation of HM ↑
Plant antioxidant defence
(a) Enzymatic
(b) Non-enzymatic
SOD ↟
CAT ↟
APX ↟
POD ↟
GR ↟
GPX ↟
GST ↟
DHAR ↟
MDHAR ↟
GSH ↟
AsA ↟
Tocopherols ↟
Carotenoids ↓
Flavonoids ↟
Phenolic compounds ↟
Non-protein amino acids ↟
Shoot system
Germination ↓
Shoot length ↓
Leaf number ↓
Stomatal conductance ↓
Anthocyanin ↓
Chlorophyll ↓
Photosynthesis ↓
Respiration ↓
Wilting ↑
Necrosis ↑
Accumulation of HM ↑
Tissue damage ↑
Sources of Heavy Metals (HM)
(a) Natural
Parent material
Weathering of rocks and minerals
Volcanic eruption
(b) Anthropogenic
Industrial activities
Mining
Power plants
Textile
Agrochemicals
Fertilizers
Pesticides
Root system
Root length ↓
Nutrient uptake ↓
Nodule number ↓
Leghaemoglobin content ↓
Nitrogenase activity ↓
Accumulation of HM ↑
Tissue damage ↑
Factors controlling the HM availability and oxidation states
Soil(physical & chemical) properties
pH
Organic matter
Chelation potential
Soil colloids
Soil aeration
Soil salinity
Moisture content
Microbial activity
Cr
Cd
As
Pb
Cu
Ni
↑ Increase
↓ Decrease
↟ Increase in majority of cases, but decrease reported in some cases
↡ Decrease in majority of cases, but increase reported in some cases

◀**Fig. 1** Schematic diagram showing responses and effects of HM on plant (aliphatic, aromatic or heterocyclic group R, alkoxy radical $RO^{\cdot}$, ascorbate AsA, ascorbate peroxidase APX, carbonate $CO_3^{\cdot-}$, catalase CAT, dehydroascorbate reductase DHAR, glutathione peroxidase GPX, glutathione reductase GR, glutathione S-transferase GST, heavy metal HM, hydrogen peroxide H_2O_2, hydroperoxides ROOH, hydroxyl radical $^{\cdot}OH$, hypobromous acid HOBr, hypochlorous acid HOCl, hypoiodous acid HOI, monodehydroascorbate reductase MDHAR, oxygen O_2, ozone O_3, perhydroxy radical $HO_2^{\cdot}$, peroxidase POD, peroxyl $RO_2^{\cdot}$, reduced glutathione GSH, semiquinone $SQ^{\cdot-}$, superoxide anion $O_2^{\cdot-}$, superoxide dismutase SOD)

zone, reduction of mitochondrial cristae, swelling of mitochondria, alterations in peroxisomal membrane, shrunken protoplasts and in severe cases degeneration was observed in the root system (Małecka et al. 2008). *P. sativum* seedlings showed a significant reduction in alkaline invertase and acid invertase activities under Pb stress. In Pb-treated seedlings, sucrose-6-phosphate synthase (SPS) and sucrose synthase (SS) enzyme production were inhibited in the root, whereas SS activity was upregulated in the cotyledons. Moreover, Pb increased glucose-6-phosphate dehydrogenase (G6PDH) and 6-phosphogluconate dehydrogenase (6PGDH) in cotyledons, while downregulation of G6PDH and upregulation of hexokinase in the root and shoot parts were reported in stressed seedlings (Devi et al. 2013). The growth attributes like leghemoglobin, carbohydrate and nitrogen content in the nodules, Chl content, photosynthetic rate, leaf water potential, transpiration rate, activities of carbonic anhydrase, nitrate reductase (NR) and nitrogenase decreased proportionately at higher concentrations of Ni at 45-day stage pot grown *V. radiata* (Yusuf et al. 2014). Similarly, enzyme activities like α-amylase, protease and H^+ ATPase decreased with increasing As exposure to cotyledons of germinating seeds (Ismail 2012). According to Garg and Kashyap (2017) As stress resulted in a significant decrease in seed yield, number of pods, seed development, seed weight, harvest index, nutrients uptake, plant biomass and productivity.

Photosynthetic performance

HM toxicity can remarkably damage the plant's photosynthetic machinery. HM in particular, can have a severe impact on the photosynthetic rate, Chl content, and intracellular CO_2 concentration of plants (Nikalje and Suprasanna 2018). 50 µM Cd stress greatly altered the physiological functions of leaves like net photosynthetic rate, internal CO_2 concentration, stomatal conductance, transpiration rate and maximum quantum yield of photosystem II (PSII) showed a significant decrease in their photosynthetic attributes (AS and Tahir 2019). Application of Pb interfered with the plant growth and metabolism leading to a significant reduction in the leaf area, harvest index and assimilation rate (Hussain et al. 2007). At 200 µM Cd, nicotinamide adenine dinucleotide (NADH) oxidase, nicotinamide adenine dinucleotide phosphate (NADPH) oxidase, 6-phosphogluconate dehydrogenase (6PGDH) and glucose-6-phosphate dehydrogenase (G6PDH) activities in root and shoot of *C. arietinum* seedlings increased considerably in treatment sets when compared to that of control (Sakouhi et al. 2016).

ROS and antioxidative system

One of the major outcomes of being exposed to HMs stress is the excessive generation of various reactive oxygen species (ROS) such as hydroxyl radicals (OH^-), superoxide (O_2^-), hydroperoxyl radicals (HOO), the peroxynitrite ($OONO^-$) ion, paramagnetic singlet oxygen ($^1O_2$), hydrogen peroxide (H_2O_2), nitrogen oxide radical (NO), ozone (O_3) and hypochlorous acid (HOCl) (Sharma et al. 2020a, b). The functioning of different antioxidative enzymes undergoes significant alterations in the plant system when they are exposed to HM stress. To counteract the harmful effects of ROS, plant tissues increase the expression and activity of enzymatic antioxidants, superoxide dismutase (SOD), guaiacol peroxidase (GPOX), catalase (CAT) and enzymes belonging to ascorbate–glutathione (AsA–GSH) cycle like ascorbate peroxidase (APX), dehydroascorbate reductase (DHAR), monodehydroascorbate reductase (MDHAR) and non-enzymatic glutathione reductase (GR), phytochelatins (PCs) along with total glutathione, oxidised glutathione (GSSG), glutathione-S-transferase (GST) (Saroy and Garg 2021; Garg and Aggarwal 2012; Hossain et al. 2020). Schematic diagram on the effects of HM stress on plant system is shown in Fig. 1. SOD, CAT and peroxidase (POD) increased under Cd stress during HM uptake, showing clear symptoms of Cd stress that were significantly higher than that of control (Garg and Aggarwal 2012). Similarly, Ni stress enhanced the activities of antioxidant enzymes such as NADH-oxidase, SOD, APX, CAT, GR and GST in comparison to control (Gajewska and Skłodowska 2005; El-Amier et al. 2019). Under As (50 µM) stress, NADP-dependent isocitrate dehydrogenase and NADP-dependent malic enzyme activities increased in roots, but in leaves remained unaffected. S-nitrosoglutathione reductase (GSNOR) activity, nitric oxide (NO) and peroxynitrite ($ONOO^-$) content decreased in roots, while in leaves, NO content increased, whereas no significant changes were registered for GSNOR activity and $ONOO^-$ content (Rodríguez-Ruiz et al. 2019). Polyamine contents (free polyamine, soluble-conjugated and insoluble-bound) such as spermine, spermidine and putrescine, along with activities of polyamine-biosynthetic enzymes such as arginine decarboxylase, S-adenosylmethionine decarboxylase and ornithine decarboxylase in *P. sativum* leaves increased under the influence of Ni stress (Shahid et al. 2014).

Table 4 Effects and response of different pulse crops under HM stress

Parameters studied	Alteration in plant parameters	HMs	References					
			C. arietinum	*C. cajan*	*L. culinaris*	*P. sativum*	*V. radiata*	*V. mungo*
Growth parameters and yield components of the respective plants were studied, like root and shoot length, root and shoot FW and DW, number of pods, seeds and grain yield	Root and Shoot length decreases Root and shoot FW and DW decreases No. of pods, seeds and grain yield decreases	Cr	Naz et al. (2015)	Dotaniya et al. (2014)	Fatima and Ahmed (2018) and Murtaza et al. (2017)	Pandey (2008)	Shanker et al. (2004)	Murugan et al. (2018)
		Cd	Mondal et al. (2013) and Ullah et al. (2020)	(Patnaik and Mohanty 2013)	Feizi et al. (2020)	Saleh (2007)	Ghani (2010)	Dutta et al. (2018)
		As	Bhattacharya et al. (2012), Gupta et al. (2004) and Malik et al. (2011)	(Dias et al. 2010), (Garg and Kashyap 2017)	Alam et al. (2019) and Ahmed et al. (2012)	Päivöke and Simola (2001) and Alam et al. (2020)	Swarnakar (2020)	Jha et al. (2021)
		Pb	Naz et al. (2015)	(Gandhi et al. 2020)	Cokkizgin and Cokkizgin (2010)	Borah and Devi (2012) and Anwar et al. (2020)	Sidhimol et al. (2011)	Mohaparta et al. (2018)
		Cu	Askari and Khurshid (2018)	(Gandhi et al. 2020)	Janas et al. (2010)	Nafisa et al. (2013)	Manivasagaperumal et al. (2011)	Akhtar et al. (2016)
		Ni	Khan and Khan (2010)	(Garg and Saroy 2020)	Saad et al. (2016)	Saleh (2007)	Ali et al. (2015)	–
Photosynthesis and related components, nodule development and number, leghemoglobin content and nitrogenase activity	Total carotenoid and Chl (*a,b*) content decreases Nodule number, nodule DW, NR and leghemoglobin content decreases	Cr	Oves et al. (2013)	–	Fatima and Ahmed (2018)	Pandey (2008)	Jabeen et al. (2016)	Hussain et al. (2006)
		Cd	Hasan et al. (2008)	(Garg and Singh 2018), (Sharma et al. 2020a, b)	–	Shamshad et al. (2018)	Sharma et al. (2021)	Dutta et al. (2018)
		As	AL-Huqail et al. (2017)	Garg and Kashyap (2017)	Mitra and Paul (2020)	Sharma (2013)	Upadhyaya et al. (2014)	Srivastava and Sharma (2013)
		Pb	Naz et al. (2018)	Nautiyal and Sinha (92012), Garg and Aggarwal (2011)	–	Chaturvedi et al. (2021)	Arif et al. (2019)	Hussain et al. (2006)
		Cu	Singh et al. (2010)	Sharma et al. (2017b)	Hossain et al. (2020)	Hattab et al. (2009)	(Wani et al. 2007b), (Ahmad et al. 2008)	Askari et al. (2017)
		Ni	Çanakci and Dursun (2011)	Garg and Saroy (2020)	Saad et al. (2016)	Srivastava et al. (2012)	(Yusuf et al. 2014)	Gurpreet et al. (2012)

Table 4 (continued)

Parameters studied	Alteration in plant parameters	HMs	References					
Antioxidant defense system (enzymatic and non-enzymatic)	SOD, CAT, POD, APX, GR, GPX, GSH, GSSG and GST activities mainly increases with the increase in HMs concentration	Cr	Saif and Khan (2018)	Battana and Ghanta (2014)	–	Tripathi et al. (2015a, b) and Gangwar and Singh (2011)	Gautam et al. (2020), Diwan et al. (2010) and Jabeen et al. (2016)	Karuppanapandian and Manoharan (2008)
		Cd	Ahmad et al. (2016)	Garg and Aggarwal (2012)	Talukdar (2012)	Dixit et al. (2001) and El-Amier et al. (2019)	Anjum et al. (2008) and Hassan and Mansoor (2017)	Dutta et al. (2018), Molina et al. (2008)
		As	Tripathi et al. (2017)	Garg and Kashyap (2019)	Mitra and Paul (2020)	Garg et al. (2015), Alsahli et al. (2020)	Pandey and Bhatt (2016)	Jha et al. (2021), Srivastava and Sharma (2013)
		Pb	Khwaza and Verma (2015)	Garg and Aggarwal (2012)	Haider and Azmat (2012)	Dias et al. (2019)	Singh et al. (2017), Arif et al. (2019) and Aly (2013)	Yasin et al. (2020)
		Cu	Sharama and Singh (2013)	Sharma et al. (2017a)	Chaoui and El Ferjani (2014) and Hossain et al. (2020)	Malecka et al. (2012) and Chaoui et al. (2004)	Fariduddin et al. (2014) and Mao et al. (2018)	Akhtar et al. (2016)
		Ni	Saif and Khan (2018)	Madhava Rao and Sresty (2000)	–	El-Amier et al. (2019) and Balal et al. (2016)	Srinivasan et al. (2015) and Yusuf et al. (2014)	Mahmood et al. (2016)
Stress response/indicators components and enzymes	EL, MDA, H_2O_2 and proline contents increases in response to HMs stress. Likewise, DHAR, MDHAR activities also increases in presence of HMs stress among different plant species	Cr	Singh et al. (2020)	Battana and Ghanta (2014)	–	Pandey et al. (2009)	Shanker et al. (2004) and Jabeen et al. (2016)	Karuppanapandian and Manoharan (2008)
		Cd	Kumari et al. (2010), Ahmad et al. (2016)	Garg and Singh (2018)	Talukdar (2012)	Rahman et al. (2017) and El-Amier et al. (2019)	Anjum et al. (2008) and Hassan and Mansoor (2017)	Dutta et al. (2018) and Molina et al. (2008)
		As	Chandrakar et al. (2020), Adhikary et al. (2019)	Garg et al. (2015) and Garg and Kashyap (2019)	Mitra and Paul (2020)	Alsahli et al. (2020)	Shabnam et al. (2019) and Singh et al. (2007)	Srivastava and Sharma (2013)
		Pb	Bhagyawant et al. (2019) and Reddy et al. (2005)	Garg and Aggarwal (2012)	Haider and Azmat (2012)	Chaturvedi et al. (2021) and Dias et al. (2019)	Aly (2013)	Gurpreet et al. (2012)
		Cu	Nair and Chung (2015)	Sharma et al. (2017b)	Islam et al. (2016)	Borah and Devi (2012) and Chaoui and El Ferjani (2005)	Gopalakrishnan Nair et al. (2014)	Akhtar et al. (2016)
		Ni	Saif and Khan (2018)	Saroy and Garg (2021)	–	El-Amier et al. (2019) and Balal et al. (2016)	Yusuf et al. (2014)	Gurpreet et al. (2012), Mahmood et al. (2016)

According to reports, when plants are exposed to HM toxicity, there is an increase in the production of ROS which can trigger an oxidative burst. This burst can damage various components of the plant such as lipids, proteins and pigments as well as stimulate the process of lipid peroxidation and electrolyte leakage (EL) (Kumari et al. 2010). The presence of Cd (0.3 mM)-induced oxidative stress and membrane injury which enhanced significant levels of total soluble protein and malondialdehyde (MDA) contents (Hassan and Mansoor 2014). EL increased significantly in both the root and shoot systems of pea upon As treatment (Rahman et al. 2017). At 100 µM Cr, along with an increase in activities of DHAR, MDHAR and H_2O_2 increased, respectively, in course of time (12–120 h) with respect to control in *V. mungo* (Karuppanapandian and Manoharan 2008). Under Cu stress, proline content and total phenolic content increased to variable levels in all treated sets (Akhtar et al. 2016). Table 4 represents HM induced phytotoxic effects and response on different plant species in their oxidative and biochemical traits.

Conclusion

In conclusion, HMs pose a great threat to pulse production. Most of the HMs get accumulated in the plant tissues and adversely affects plant growth and metabolism. This review article provides quick access to information about the effects of HM toxicity on important pulse crops in their development and physiological processes. To feed the ever increasing population, solving food demand and increasing crop production is a difficult task due to climate changes, biotic and abiotic stresses. The presence of HMs reduces plant yield and production, which negatively impacts the health and economy. Therefore, it is imperative to properly manage HM usage, release and distribution into the environment. Hence, environmental agencies and government bodies should take necessary steps to ensure keeping HM pollution to a minimum. Plants have developed mechanisms to prevent the toxic effects of HMs, but in excess concentration, even the plant defense mechanisms fail to recover from the toxic effects of HMs. Additionally, attempts should be undertaken to decipher the precise biochemical pathways and molecular mechanisms of HM toxicity in plants. Moreover, further research in genomics, transcriptomics, proteomics, metabolomics and signaling pathways are required to explore the intricate crosstalk of HM tolerance and modulation in the plant system. So that in the future, HMs do not cause any significant constraints limiting crop productivity worldwide.

Conflict of interest

The authors declare that they have no conflict of interest.

Ethical statements

Not applicable.

Consent to participate

Not applicable.

Consent to publish

Not applicable.

Acknowledgements The authors acknowledge Prerona Biswas, Sima Sikdar and Aparna Shil for critically reading the manuscript and for their valuable inputs. We also acknowledge the infrastructural support received from Presidency University, Kolkata for the preparation of the manuscript. We also gratefully acknowledge funding from the FRPDF (Faculty Research & Professional Development Fund) Grant of Presidency University, Kolkata, to the corresponding author, the DST-FIST (Department of Science & Technology-Fund for Improvement of S&T Infrastructure) Programme of Department of Life Sciences, Presidency University, Kolkata [Grant no. SR/FST/LSI-560/2013(c); dated 23-06-2015] and also the DBT-BUILDER (Department of Biotechnology-Boost to University Interdisciplinary Life Science Departments for Education and Research) Grant of Department of Life Sciences, Presidency University, Kolkata [Grant No. BT/INF/22/SP45088/2022; dated 17.02.2022]. University Grants Commission National Eligibility Test Fellowship Grant [F.16-6(DEC. 2016)/2017(NET), UGC-Ref. No.: 764/(ST)(CSIR-UGC NET DEC. 2016)] to Mr. Sudipta Majhi.

Author contributions The first draft including figure and tables in the manuscript was prepared by SM. The final manuscript was supervised, reviewed and edited by MS (née Bhakta). The authors have read and approved the final manuscript.

Funding The authors acknowledge the financial assistance received from the FRPDF (Faculty Research & Professional Development Fund) Grant of Presidency University, Kolkata, to the corresponding author, the DST-FIST Programme of Department of Life Sciences, Presidency University, Kolkata [Grant no. SR/FST/LSI-560/2013(c); dated 23-06-2015] and also the DBT-BUILDER Grant of Department of Life Sciences, Presidency University, Kolkata [Grant no. BT/INF/22/SP45088/2022; dated 17.02.2022]. University Grants Commission National Eligibility Test Fellowship Grant [F.16-6(DEC. 2016)/2017(NET), UGC-Ref. No.: 764/(ST)(CSIR-UGC NET DEC. 2016)] to Mr. Sudipta Majhi.

Data availability The data presented in Table 3 were collected from FAOSTAT and are available in https://www.fao.org/faostat/en/#home. The schematic diagram, i.e., Fig. 1 is a tiff file which was generated electronically in.emf format via Inkscape software (https://inkscape.org/release/inkscape-1.2.1/) and later converted to .tiff file.

References

Abd El-Hack ME, Abdelnour SA, Abd El-Moneim AEME et al (2019) Putative impacts of phytogenic additives to ameliorate lead toxicity in animal feed. Environ Sci Pollut Res 26:23209–23218. https://doi.org/10.1007/s11356-019-05805-8

Adhikary A, Kumar R, Pandir R et al (2019) *Pseudomonas citronellolis*; a multi-metal resistant and potential plant growth promoter against arsenic (V) stress in chickpea. Plant Physiol Biochem 142:179–192. https://doi.org/10.1016/j.plaphy.2019.07.006

Adu-Gyamfi JJ, Myaka FA, Sakala WD et al (2007) Biological nitrogen fixation and nitrogen and phosphorus budgets in farmer-managed intercrops of maize-pigeonpea in semi-arid southern and eastern Africa. Plant Soil 295:127–136. https://doi.org/10.1007/s11104-007-9270-0

Ahmad MSA, Hussain M, Ijaz S, Alvi AK (2008) Photosynthetic performance of two mung bean (*Vigna radiata*) cultivars under lead and copper stress. Int J Agric Biol 10:167–172

Ahmad P, Abdel Latef AA, Abd-Allah EF et al (2016) Calcium and potassium supplementation enhanced growth, osmolyte secondary metabolite production, and enzymatic antioxidant machinery in cadmium-exposed chickpea (*Cicer arietinum* L.). Front Plant Sci 7:513. https://doi.org/10.3389/fpls.2016.00513

Ahmed FRS, Alexander IJ, Mwinyihija M, Killham K (2012) Effect of arsenic contaminated irrigation water on *Lens culinaris* L. and toxicity assessment using lux marked biosensor. J Environ Sci 24:1106–1116. https://doi.org/10.1016/S1001-0742(11)60898-X

Ahn BM, Ahn CW, Hahn BD et al (2019) Easy approach to realize low cost and high cell capacity in sodium nickel-iron chloride battery. Compos Part B Eng 168:442–447. https://doi.org/10.1016/j.compositesb.2019.03.064

Akhtar S, Shoaib A, Akhtar N, Mehmood R (2016) Separate and combined effects of Macrophomina phaseolina and copper on growth, physiology and antioxidative enzymes in *Vigna mungo* L. J Anim Plant Sci 26:1339–1345

Alam MZ, Hoque MA, Ahammed GJ et al (2019) Arsenic accumulation in lentil (*Lens culinaris*) genotypes and risk associated with the consumption of grains. Sci Rep 9:1–9. https://doi.org/10.1038/s41598-019-45855-z

Alam MZ, Hoque MA, Ahammed GJ, Carpenter-Boggs L (2020) Effects of arbuscular mycorrhizal fungi, biochar, selenium, silica gel, and sulfur on arsenic uptake and biomass growth in *Pisum sativum* L. Emerg Contam 6:312–322. https://doi.org/10.1016/j.emcon.2020.08.001

AL-Huqail AA, AL-Rashed SA, Ibrahim MM et al (2017) Arsenic induced eco-physiological changes in Chickpea (*Cicer arietinum*) and protection by gypsum, a source of sulphur and calcium. Sci Hortic (amsterdam) 217:226–233. https://doi.org/10.1016/j.scienta.2017.02.007

Ali MA, Asghar HN, Khan MY et al (2015) Alleviation of nickel-induced stress in mungbean through application of gibberellic acid. Int J Agric Biol 17:990–994. https://doi.org/10.17957/IJAB/15.0001

Alsahli AA, Bhat JA, Alyemeni MN et al (2020) Hydrogen sulfide (H_2S) mitigates arsenic (As)-induced toxicity in pea (*Pisum sativum* L.) plants by regulating osmoregulation, antioxidant defense system, ascorbate glutathione cycle and glyoxalase system. J Plant Growth Regul 40:2515–2531. https://doi.org/10.1007/s00344-020-10254-6

Alvarado S, Maldonado P, Barrios A, Jaques I (2002) Long term energy-related enviromental issues of copper production. Energy 27:183–196. https://doi.org/10.1016/S0360-5442(01)00067-6

Aly H (2013) Ameliorating role of nitric oxide in germinating mung bean seeds (*Vigna Radiata*) under lead stress. Catrina Int J Environ Sci 8:75–85. https://doi.org/10.12816/0010677

Anjum NA, Umar S, Ahmad A, Iqbal M (2008) Responses of components of antioxidant system in moongbean genotypes to cadmium stress. Commun Soil Sci Plant Anal 39:2469–2483. https://doi.org/10.1080/00103620802292871

Anwar T, Qureshi H, Fatimah H, Waseem M (2020) Effects of lead on vegetative, propagative and physiochemical parameters of *Pisum sativum*. Proc Int Acad Ecol Environ Sci 10:32–37

Arif MS, Yasmeen T, Shahzad SM et al (2019) Lead toxicity induced phytotoxic effects on mung bean can be relegated by lead tolerant *Bacillus subtilis* (PbRB3). Chemosphere 234:70–80. https://doi.org/10.1016/j.chemosphere.2019.06.024

Arumuganathan K, Earle ED (1991) Nuclear DNA content of some important plant species. Plant Mol Biol Report 9:208–218

As W, Tahir I (2019) Screening of different chickpea varieties for their sensitiveness and tolerance to cadmium and/or salt stress. J Adv Plant Sci 2:1–7

Askari S, Khurshid H (2018) *Conocarpus* mediated improvement in photosynthetic pigments of *Cicer arietinum* growing under copper stress. RADS J Biol Res Appl Sci 9:41–49. https://doi.org/10.37962/jbas.v9i1.115

Askari S, Siddiqui A, Kaleem M (2017) Potato peel mediated improvement in organic substances of *Vigna mungo* growing under copper stress. J Pharmacogn Phytochem 6:1373–1378

Aslam M, Mahmood IA, Peoples MB et al (2003) Contribution of chickpea nitrogen fixation to increased wheat production and soil organic fertility in rain-fed cropping. Biol Fertil Soils 38:59–64. https://doi.org/10.1007/s00374-003-0630-5

Balal RM, Shahid MA, Javaid MM et al (2016) Foliar treatment with *Lolium perenne* (Poaceae) leaf extract alleviates salinity and nickel-induced growth inhibition in pea. Brazilian J Bot 39:453–463. https://doi.org/10.1007/s40415-016-0253-3

Barber RG, Grenier ZA, Burkhead JL (2021) Copper toxicity is not just oxidative damage: zinc systems and insight from wilson disease. Biomedicines 9:316. https://doi.org/10.3390/biomedicines9030316

Battana S, Ghanta RG (2014) Antioxidative enzyme responses under single and combined effect of water and heavy metal stress in two Pigeon pea cultivars. J Sci Innov Res 3:72–80

Becquer T, Quantin C, Sicot M, Boudot JP (2003) Chromium availability in ultramafic soils from New Caledonia. Sci Total Environ 301:251–261. https://doi.org/10.1016/S0048-9697(02)00298-X

Bekele Tesemma A (2007) Profitable Agroforestry Innovations for Eastern Africa: Experience from 10 agroclimatic zones of Ethiopia, India, Kenya, Tanzania and Uganda. In: World Agroforestry Centre (ICRAF), Eastern Africa Region.

Bernhoft RA (2013) Cadmium toxicity and treatment. Sci World J 2013:1–7. https://doi.org/10.1155/2013/394652

Bhagyawant SS, Narvekar DT, Gupta N et al (2019) Variations in the antioxidant and free radical scavenging under induced heavy metal stress expressed as proline content in chickpea. Physiol Mol Biol Plants 25:683–696. https://doi.org/10.1007/s12298-019-00667-3

Bhattacharya S, Sarkar ND, Banerjee P et al (2012) Effects of Arsenic toxicity on germination, Seedling growth and Peroxidase activity in Cicer arietinum. Int J Agric Food Sci 2:131–137

Bielicka A, Bojanowska I, Wiśniewski A (2005) Two faces of chromium—Pollutant and bioelement. Polish J Environ Stud 14:5–10

Biradar NV, Sindagi AS, Reddy J, Ingalhalli SS (2012) Bioremediation of Chromium in Pulp and Paper Processing Industrial

Effluents by Indigenous Microbes. J Bioremediation Biodegrad. https://doi.org/10.4172/2155-6199.1000171

Bissen M, Frimmel FH (2003) Arsenic—a review. Part I: occurrence, toxicity, speciation. Mobility Acta Hydrochim Hydrobiol 31:9–18. https://doi.org/10.1002/aheh.200390025

Bjørklund G, Aaseth J, Chirumbolo S et al (2018) Effects of arsenic toxicity beyond epigenetic modifications. Environ Geochem Health 40:955–965. https://doi.org/10.1007/s10653-017-9967-9

Borah M, Devi A (2012) Effect of Heavy metals on *Pisum sativum* Linn. Int J Adv Biol Res 2:314–321

Borreani G, Peiretti PG, Tabacco E (2007) Effect of harvest time on yield and pre-harvest quality of semi-leafless grain peas (*Pisum sativum* L.) as whole-crop forage. F Crop Res 100:1–9. https://doi.org/10.1016/j.fcr.2006.04.007

Çakir Ö, Uçarli C, Tarhan Ç et al (2019) Nutritional and health benefits of legumes and their distinctive genomic properties. Food Sci Technol 39:1–12. https://doi.org/10.1590/fst.42117

Çanakci S, Dursun B (2011) Some physiological and biochemical responses to nickel in salicylic acid applied chickpea (*Cicer arietinum* L.) seedlings. Acta Biol Hung 62:279–289. https://doi.org/10.1556/ABiol.62.2011.3.7

Cempel M, Nikel G (2006) Nickel: a review of its sources and environmental toxicology. Polish J Environ Stud 15:375–382

Chahota RK, Sharma TR, Sharma SK (2018) Conventional genetic manipulations. Elsevier Inc, Amsterdam

Chandrakar V, Yadu B, Korram J et al (2020) Carbon dot induces tolerance to arsenic by regulating arsenic uptake, reactive oxygen species detoxification and defense-related gene expression in *Cicer arietinum* L. Plant Physiol Biochem 156:78–86. https://doi.org/10.1016/j.plaphy.2020.09.003

Chaoui A, El Ferjani E (2005) Effects of cadmium and copper on antioxidant capacities, lignification and auxin degradation in leaves of pea (*Pisum sativum* L.) seedlings. Comptes Rendus Biol 328:23–31. https://doi.org/10.1016/j.crvi.2004.10.001

Chaoui A, El Ferjani E (2014) Heavy metal-induced oxidative damage is reduced by β-estradiol application in lentil seedlings. Plant Growth Regul 74:1–9. https://doi.org/10.1007/s10725-014-9891-2

Chaoui A, Jarrar B, El Ferjani E (2004) Effects of cadmium and copper on peroxidase, NADH oxidase and IAA oxidase activities in cell wall, soluble and microsomal membrane fractions of pea roots. J Plant Physiol 161:1225–1234. https://doi.org/10.1016/j.jplph.2004.02.002

Chaturvedi R, Favas PJC, Pratas J et al (2021) Harnessing *Pisum sativum*–*Glomus mosseae* symbiosis for phytoremediation of soil contaminated with lead, cadmium, and arsenic. Int J Phytoremediation 23:279–290. https://doi.org/10.1080/15226514.2020.1812507

Chen C, Huang D, Liu J (2009) Functions and toxicity of nickel in plants: Recent advances and future prospects. Clean - Soil, Air, Water 37:304–313. https://doi.org/10.1002/clen.200800199

Cheng H, Hu Y (2010) Lead (Pb) isotopic fingerprinting and its applications in lead pollution studies in China: a review. Environ Pollut 158:1134–1146. https://doi.org/10.1016/j.envpol.2009.12.028

Cheng H, Zhou T, Li Q et al (2014) Anthropogenic chromium emissions in China from 1990 to 2009. PLoS ONE 9:e87753. https://doi.org/10.1371/journal.pone.0087753

Choudhury PR, Tanveer H, Dixit GP (2007) Identification and detection of genetic relatedness among important varieties of pea (*Pisum sativum* L.) grown in India. Genetica 130:183–191. https://doi.org/10.1007/s10709-006-9005-9

Cokkizgin A, Cokkizgin H (2010) Effects of lead ($PbCl_2$) stress on germination of lentil (*Lens culinaris* Medic.) lines. African J Biotechnol 9:8608–8612. https://doi.org/10.4314/ajb.v9i50

Cox P (2014) Food for drought. Appropr Technol 41:23–24

Dahl WJ, Foster LM, Tyler RT (2012) Review of the health benefits of peas (*Pisum sativum* L.). Br J Nutr 108:S3–S10. https://doi.org/10.1017/S0007114512000852

Dalvi AA, Bhalerao SA (2013) Response of plants towards heavy metal toxicity: an overview of avoidance, tolerance and uptake mechanism. Ann Plant Sci 2:362–368

Das KK, Das SN, Dhundasi SA (2008) Nickel, its adverse health effects & oxidative stress. Indian J Med Res 128:412–425

Das KK, Reddy RC, Bagoji IB et al (2018) Primary concept of nickel toxicity—an overview. J Basic Clin Physiol Pharmacol 30:141–152

Dębski B, Zalewski W, Gralak MA, Kosla T (2004) Chromium-yeast supplementation of chicken broilers in an industrial farming system. J Trace Elem Med Biol 18:47–51. https://doi.org/10.1016/j.jtemb.2004.02.003

Delfin EF, Paterno ES, Torres FG, Santos PJA (2008) Biomass, nitrogen uptake and fixed nitrogen partitioning in field grown mungbean (*Vigna radiata* L. Wilczek) inoculated with *Bradyrhizobium* sp. Philipp J Crop Sci 33:24–33

Devi R, Munjral N, Gupta AK, Kaur N (2013) Effect of exogenous lead on growth and carbon metabolism of pea (*Pisum sativum* L) seedlings. Physiol Mol Biol Plants 19:81–89. https://doi.org/10.1007/s12298-012-0143-5

Dhankher OP, Pilon-Smits EAH, Meagher RB, Doty S (2012) Biotechnological approaches for phytoremediation

Dho S, Camusso W, Mucciarelli M, Fusconi A (2010) Arsenate toxicity on the apices of *Pisum sativum* L. seedling roots: effects on mitotic activity, chromatin integrity and microtubules. Environ Exp Bot 69:17–23. https://doi.org/10.1016/j.envexpbot.2010.02.010

Dias LE, Melo RF, de Mello JWV et al (2010) Growth of seedlings of pigeon pea (*Cajanus cajan* (l.) millsp), wand riverhemp (*Sesbania virgata* (Cav.) Pers.), and lead tree (*Leucaena leucocephala* (Lam.) de Wit) in an arsenic-contaminated soil. Rev Bras Cienc Do Solo 34:975–983. https://doi.org/10.1590/s0100-06832010000300039

Dias MC, Mariz-Ponte N, Santos C (2019) Lead induces oxidative stress in *Pisum sativum* plants and changes the levels of phytohormones with antioxidant role. Plant Physiol Biochem 137:121–129. https://doi.org/10.1016/j.plaphy.2019.02.005

Diwan H, Khan I, Ahmad A, Iqbal M (2010) Induction of phytochelatins and antioxidant defence system in Brassica juncea and *Vigna radiata* in response to chromium treatments. Plant Growth Regul 61:97–107. https://doi.org/10.1007/s10725-010-9454-0

Dixit V, Pandey V, Shyam R (2001) Differential antioxidative responses to cadmium in roots and leaves of pea (*Pisum sativum* L. cv. Azad). J Exp Bot 52:1101–1109. https://doi.org/10.1093/jexbot/52.358.1101

Dotaniya ML, Meena VD, Das H (2014) Chromium toxicity on seed germination, root elongation and coleoptile growth of pigeon pea (*Cajanus cajan*). Legum Res 37:227–229. https://doi.org/10.5958/j.0976-0571.37.2.034

Dubey S, Shri M, Misra P et al (2014) Heavy metals induce oxidative stress and genome-wide modulation in transcriptome of rice root. Funct Integr Genomics 14:401–417. https://doi.org/10.1007/s10142-014-0361-8

Dutta P, Karmakar A, Majumdar S, Roy S (2018) *Klebsiella pneumoniae* (HR1) assisted alleviation of Cd(II) toxicity in *Vigna mungo*: a case study of biosorption of heavy metal by an endophytic bacterium coupled with plant growth promotion. Euro-Mediterranean J Environ Integr 3:1–10. https://doi.org/10.1007/s41207-018-0069-6

Edelstein M, Ben-Hur M (2018) Heavy metals and metalloids: Sources, risks and strategies to reduce their accumulation in horticultural crops. Sci Hortic (amsterdam) 234:431–444. https://doi.org/10.1016/j.scienta.2017.12.039

El-Amier Y, Elhindi K, El-Hendawy S et al (2019) Antioxidant system and biomolecules alteration in *Pisum sativum* under heavy metal stress and possible alleviation by 5-aminolevulinic acid. Molecules 24:4194. https://doi.org/10.3390/molecules24224194

Erskine W, Sarker A, Kumar S (2016) Lentil: breeding, 2nd edn. Elsevier Ltd, Amsterdam

FAOSTAT (2022). https://www.fao.org/faostat/en/#data/QCL. Accessed 11 Jun 2022

Fariduddin Q, Khan TA, Yusuf M (2014) Hydrogen peroxide mediated tolerance to copper stress in the presence of 28-homobrassinolide in *Vigna radiata*. Acta Physiol Plant 36:2767–2778. https://doi.org/10.1007/s11738-014-1647-0

Farooq M, Hussain M, Usman M et al (2018) Impact of abiotic stresses on grain composition and quality in food legumes. J Agric Food Chem 66:8887–8897. https://doi.org/10.1021/acs.jafc.8b02924

Fatima H, Ahmed A (2018) Micro-remediation of chromium contaminated soils. PeerJ 6:e6076. https://doi.org/10.7717/peerj.6076

Feizi H, Agheli N, Sahabi H (2020) Titanium dioxide nanoparticles alleviate cadmium toxicity in lentil (*Lens culinari*s Medic) seeds. Acta Agric Slov 116:59–68. https://doi.org/10.14720/AAS.2020.116.1.1116

Focardi S, Pepi M, Focardi ES (2013) Microbial reduction of hexavalent chromium as a mechanism of detoxification and possible bioremediation applications. Biodegradation—life of Science. InTech, New York, pp 321–347

Freeman MH, McIntyre CR (2008) A comprehensive review of copper-based wood preservatives with a focus on new micronized or dispersed copper systems. For Prod J 58:6–27

Fuller DQ, Harvey EL (2006) The archaeobotany of Indian pulses: identification, processing and evidence for cultivation. Environ Archaeol 11:219–246. https://doi.org/10.1179/174963106x123232

Fuller D, Korisettar R, Venkatasubbaiah PC, Jones MK (2004) Early plant domestications in southern India: some preliminary archaeobotanical results. Veg Hist Archaeobot 13:115–129. https://doi.org/10.1007/s00334-004-0036-9

Fuller DQ, Murphy C, Kingwell-Banham E et al (2019) *Cajanus cajan* (L.) Millsp. origins and domestication: the South and Southeast Asian archaeobotanical evidence. Genet Resour Crop Evol 66:1175–1188. https://doi.org/10.1007/s10722-019-00774-w

Gajewska E, Skłodowska M (2005) Antioxidative responses and proline level in leaves and roots of pea plants subjected to nickel stress. Acta Physiol Plant 27:329–340. https://doi.org/10.1007/s11738-005-0009-3

Gandhi N, Sridhar J, Pallavi A et al (2020) Germination, growth, physiological and biochemical response of pigeon pea (*Cajanus cajan*) under varying concentrations of copper (Cu), lead (Pb), manganese (Mn) and barium (Ba). Int J Res Rev 7:321–347

Gangwar S, Singh VP (2011) Indole acetic acid differently changes growth and nitrogen metabolism in *Pisum sativum* L. seedlings under chromium (VI) phytotoxicity: implication of oxidative stress. Sci Hortic (amsterdam) 129:321–328. https://doi.org/10.1016/j.scienta.2011.03.026

Garelick H, Jones H, Dybowska A, Valsami-jones E (2008) Arsenic pollution sources. Rev Environ Contam 197:17–60. https://doi.org/10.1007/978-0-387-79284-2

Garg N, Aggarwal N (2011) Effects of interactions between cadmium and lead on growth, nitrogen fixation, phytochelatin, and glutathione production in mycorrhizal *Cajanus cajan* (L.) Millsp. J Plant Growth Regul 30:286–300. https://doi.org/10.1007/s00344-010-9191-7

Garg N, Aggarwal N (2012) Effect of mycorrhizal inoculations on heavy metal uptake and stress alleviation of *Cajanus cajan* (L.) Millsp. genotypes grown in cadmium and lead contaminated soils. Plant Growth Regul 66:9–26. https://doi.org/10.1007/s10725-011-9624-8

Garg N, Kashyap L (2017) Silicon and Rhizophagus irregularis: potential candidates for ameliorating negative impacts of arsenate and arsenite stress on growth, nutrient acquisition and productivity in *Cajanus cajan* (L.) Millsp. genotypes. Environ Sci Pollut Res 24:18520–18535. https://doi.org/10.1007/s11356-017-9463-x

Garg N, Kashyap L (2019) Joint effects of Si and mycorrhiza on the antioxidant metabolism of two pigeonpea genotypes under As (III) and (V) stress. Environ Sci Pollut Res 26:7821–7839. https://doi.org/10.1007/s11356-019-04256-5

Garg N, Saroy K (2020) Interactive effects of polyamines and arbuscular mycorrhiza in modulating plant biomass, N_2 fixation, ureide, and trehalose metabolism in *Cajanus cajan* (L.) Millsp. genotypes under nickel stress. Environ Sci Pollut Res 27:3043–3064. https://doi.org/10.1007/s11356-019-07300-6

Garg N, Singh S (2018) Mycorrhizal inoculations and silicon fortifications improve rhizobial symbiosis, antioxidant defense, trehalose turnover in pigeon pea genotypes under cadmium and zinc stress. Plant Growth Regul 86:105–119. https://doi.org/10.1007/s10725-018-0414-4

Garg N, Singla P, Bhandari P (2015) Metal uptake, oxidative metabolism, and mycorrhization in pigeonpea and pea under arsenic and cadmium stress. Turkish J Agric for 39:234–250. https://doi.org/10.3906/tar-1406-121

Gaur P, Tripathi S, Gowda C, et al (2010) Chickpea Seed Production Manual

Gautam V, Sharma P, Bakshi P et al (2020) Effect of *Rhododendron arboreum* leaf extract on the antioxidant defense system against chromium (VI) stress in *Vigna radiata* Plants. Plants 9:164

Genchi G, Carocci A, Lauria G, Sinicropi MS (2020a) Nickel: human health and environmental toxicology. Int J Environ Res Public Health 17:679

Genchi G, Sinicropi MS, Lauria G et al (2020b) The effects of cadmium toxicity. Int J Environ Res Public Health 17:3728. https://doi.org/10.3390/ijerph17113782

Ghafoor A, Ahmad Z, Qureshi AS, Bashir M (2002) Genetic relationship in *Vigna mungo* (L.) Hepper and *V. radiata* (L.) R. Wilczek based on morphological traits and SDS-PAGE. Euphytica 123:367–378. https://doi.org/10.1023/A:1015092502466

Ghani A (2010) Effect of cadmium toxicity on the growth and yield components of mungbean [V*igna radiata* (L.) Wilczek]. Appl Sci 8:26–29

Ghori NH, Ghori T, Hayat MQ et al (2019) Heavy metal stress and responses in plants. Int J Environ Sci Technol 16:1807–1828. https://doi.org/10.1007/s13762-019-02215-8

Godt J, Scheidig F, Grosse-Siestrup C et al (2006) The toxicity of cadmium and resulting hazards for human health. J Occup Med Toxicol 1:22. https://doi.org/10.1186/1745-6673-1-22

Gollner G, Starz W, Friedel JK (2019) Crop performance, biological N fixation and pre-crop effect of pea ideotypes in an organic farming system. Nutr Cycl Agroecosystems 115:391–405. https://doi.org/10.1007/s10705-019-10021-4

Gopalakrishnan Nair PM, Kim SH, Chung IM (2014) Copper oxide nanoparticle toxicity in mung bean (*Vigna radiata* L.) seedlings: physiological and molecular level responses of in vitro grown plants. Acta Physiol Plant 36:2947–2958. https://doi.org/10.1007/s11738-014-1667-9

Greilhuber J, Obermayer R (1998) Genome size variation in *Cajanus cajan* (Fabaceae): a reconsideration. Plant Syst Evol 212:135–141. https://doi.org/10.1007/BF00985225

Gupta DK, Tohoyama H, Joho M, Inouhe M (2004) Changes in the levels of phytochelatins and related metal-binding peptides in chickpea seedlings exposed to arsenic and different heavy metal ions. J Plant Res 117:253–256. https://doi.org/10.1007/s10265-004-0152-8

Gurpreet S, Rajneesh KA, Rajendra SR, Mushtaq A (2012) Effect of lead and nickel toxicity on chlorophyll and proline content of

Urd (*Vigna mungo* L.) seedlings. Int J Plant Physiol Biochem 4:136–141. https://doi.org/10.5897/ijppb12.005

Haider S, Azmat R (2012) Failure of survival strategies in adaption of heavy metal environment in *Lens culinaris* and *Phaseolus mungo*. Pakistan J Bot 44:1959–1964

Haque S, Akter N, Khan M et al (2015) Yield potential of garden pea varieties at varied harvesting dates. Bangladesh Agron J 17:21–28. https://doi.org/10.3329/baj.v17i2.24648

Hasan SA, Hayat S, Ali B, Ahmad A (2008) 28-Homobrassinolide protects chickpea (*Cicer arietinum*) from cadmium toxicity by stimulating antioxidants. Environ Pollut 151:60–66. https://doi.org/10.1016/j.envpol.2007.03.006

Hassan M, Mansoor S (2014) Oxidative stress and antioxidant defense mechanism in mung bean seedlings after lead and cadmium treatments. Turkish J Agric for 38:55–61. https://doi.org/10.3906/tar-1212-4

Hassan M, Mansoor S (2017) Priming seeds with phytohormones alleviates cadmium toxicity in mung bean (*Vigna radiata* L. wilczek) seedlings. Pakistan J Bot 49:2071–2078

Hattab S, Dridi B, Chouba L et al (2009) Photosynthesis and growth responses of pea *Pisum sativum* L. under heavy metals stress. J Environ Sci 21:1552–1556. https://doi.org/10.1016/S1001-0742(08)62454-7

Hayat R, Ali S, Siddique MT, Chatha TH (2008) Biological nitrogen fixation of summer legumes and their residual effects on subsequent rainfed wheat yield. Pakistan J Bot 40:711–722

Hossain MF (2006) Arsenic contamination in Bangladesh—an overview. Agric Ecosyst Environ 113:1–16. https://doi.org/10.1016/j.agee.2005.08.034

Hossain MS, Abdelrahman M, Tran CD et al (2020) Insights into acetate-mediated copper homeostasis and antioxidant defense in lentil under excessive copper stress. Environ Pollut 258:113544. https://doi.org/10.1016/j.envpol.2019.113544

Hou A, Zhang R, Wilson VL, Meng G (2015) Source of lead pollution, its influence on public health and the countermeasures. Anim Sci Food Saf 2:18–31

Hussain M, Aqeel Ahmad MS, Kausar A (2006) Effect of lead and chromium on growth, photosynthetic pigments and yield components in mash bean [*Vigna mungo* (L.) Hepper]. Pakistan J Bot 38:1389–1396

Hussain M, Yasin G, Ali A, Ahmed R (2007) Amelioration of toxic effects of lead (Pb) and chromium (Cr) in four black gram (*Vigna mungo* L.) Hepper cultivars with the application of kinetin. Pakistan J Agric Sci 44:251–258

IARC (International Agency for Research on Cancer) (2012) Agents classified by the IARC monographs. Igarss 2014 1–105:1–5

Iruela M, Rubio J, Cubero JI et al (2002) Phylogenetic analysis in the genus *Cicer* and cultivated chickpea using RAPD and ISSR markers. Theor Appl Genet 104:643–651. https://doi.org/10.1007/s001220100751

Isemura T, Kaga A, Tabata S et al (2012) Construction of a genetic linkage map and genetic analysis of domestication related traits in Mungbean (*Vigna radiata*). PLoS ONE 7:e41304. https://doi.org/10.1371/journal.pone.0041304

Islam F, Yasmeen T, Ali Q et al (2016) Copper-resistant bacteria reduces oxidative stress and uptake of copper in lentil plants: potential for bacterial bioremediation. Environ Sci Pollut Res 23:220–233. https://doi.org/10.1007/s11356-015-5354-1

Ismail GSM (2012) Protective role of nitric oxide against arsenic-induced damages in germinating mung bean seeds. Acta Physiol Plant 34:1303–1311. https://doi.org/10.1007/s11738-012-0927-9

Iyaka YA (2011) Nickel in soils: a review of its distribution and impacts. Sci Res Essays 6:6774–6777. https://doi.org/10.5897/SREX11.035

Jabeen N, Abbas Z, Iqbal M et al (2016) Glycinebetaine mediates chromium tolerance in mung bean through lowering of Cr uptake and improved antioxidant system. Arch Agron Soil Sci 62:648–662. https://doi.org/10.1080/03650340.2015.1082032

Jalmi SK, Bhagat PK, Verma D et al (2018) Traversing the links between heavy metal stress and plant signaling. Front Plant Sci 9:1–21. https://doi.org/10.3389/fpls.2018.00012

Jamil M, Zeb S, Anees M et al (2014) Role of *Bacillus licheniformis* in phytoremediation of nickel contaminated soil cultivated with rice. Int J Phytoremediation 16:554–571. https://doi.org/10.1080/15226514.2013.798621

Janas KM, Zielińska-Tomaszewska J, Rybaczek D et al (2010) The impact of copper ions on growth, lipid peroxidation, and phenolic compound accumulation and localization in lentil (*Lens culinaris* Medic.) seedlings. J Plant Physiol 167:270–276. https://doi.org/10.1016/j.jplph.2009.09.016

Janzen JP, Brester GW, Smith VH, et al (2014) Dry peas: trends in production, trade, and price. Agric Mark Policy Cent

Jha R, Patel I, Panigrahi J (2021) Morphological and biochemical facets of arsenic toxicity on *Vigna mungo* L morphological *Vigna mungo* L and biochemical of arsenic. Indian J Nat Sci 12:31997–32008

Johnson N, Johnson CR, Thavarajah P et al (2020) The roles and potential of lentil prebiotic carbohydrates in human and plant health. Plants People Planet 2:310–319. https://doi.org/10.1002/ppp3.10103

Joyner JJ, Yadav BK (2015) Microwave assisted dehulling of black gram (*Vigna mungo* L). J Food Sci Technol 52:2003–2012. https://doi.org/10.1007/s13197-013-1182-9

Kaewwongwal A, Kongjaimun A, Somta P et al (2015) Genetic diversity of the black gram [*Vigna mungo* (L.) Hepper] gene pool as revealed by SSR markers. Breed Sci 65:127–137. https://doi.org/10.1270/jsbbs.65.127

Karrari P, Mehrpour O, Abdollahi M (2012) A systematic review on status of lead pollution and toxicity in Iran; guidance for preventive measures. DARU J Pharm Sci 20:1–17. https://doi.org/10.1186/1560-8115-20-2

Karuppanapandian T, Manoharan K (2008) Uptake and translocation of tri- and hexa-valent chromium and their effects on black gram (*Vigna mungo* L. Hepper cv. Co4) roots. J Plant Biol 51:192–201. https://doi.org/10.1007/BF03030698

Khan MR, Khan MM (2010) Effect of varying concentration of Nickel and Cobalt on the plant growth and yield of Chickpea. Aust J Basic Appl Sci 4:1036–1046

Khwaza G, Verma Y (2015) Effect of lead and cadmium stress on biochemical parameters and antioxidant activity in germinated seedlings of *Cicer arietinum* L. Plant Arch 15:717–721

Kishor R, Sharma V, Saini HK (2020) Variability studies for yield and its component traits in Lentil (Lens culinaris *Medikus* spp. Culinaris) under Bundelkhand region. J Pharmacogn Phytochem 9:1436–1441

Koul PM, Sharma V, Rana M et al (2017) Analysis of genetic structure and interrelationships in lentil species using morphological and SSR markers. 3 Biotech 7:83. https://doi.org/10.1007/s13205-017-0683-z

Kozlov K, Singh A, Berger J et al (2019) Non-linear regression models for time to flowering in wild chickpea combine genetic and climatic factors. BMC Plant Biol 19:1–14. https://doi.org/10.1186/s12870-019-1685-2

Kuehne S, Roßberg D, Röhrig P et al (2017) The use of copper pesticides in Germany and the search for minimization and replacement strategies. Org Farming 3:66–75. https://doi.org/10.12924/of2017.03010066

Kumar K, Goh KM (2000) Biological nitrogen fixation, accumulation of soil nitrogen and nitrogen balance for white clover (*Trifolium repens* L.) and field pea (*Pisum sativum* L.) grown for seed. F Crop Res 68:49–59. https://doi.org/10.1016/S0378-4290(00)00109-X

Kumari A, Sheokand S, Swaraj K (2010) Nitric oxide induced alleviation of toxic effects of short term and long term Cd stress on growth, oxidative metabolism and Cd accumulation in chickpea. Brazilian J Plant Physiol 22:271–284. https://doi.org/10.1590/S1677-04202010000400007

Lambrides CJ, Godwin ID (2007) Mungbean. In pulses, sugar and tuber crops. Genome Mapp Mol Breed Plants 3:69–90

Lamichhane JR, Osdaghi E, Behlau F et al (2018) Thirteen decades of antimicrobial copper compounds applied in agriculture. A review. Agron Sustain Dev 38:1–18. https://doi.org/10.1007/s13593-018-0503-9

Li X, Bu N, Li Y et al (2012) Growth, photosynthesis and antioxidant responses of endophyte infected and non-infected rice under lead stress conditions. J Hazard Mater 213–214:55–61. https://doi.org/10.1016/j.jhazmat.2012.01.052

Liu L, Cui WM, Zhang SW et al (2015) Effect of glucose tolerance factor (GTF) from high chromium yeast on glucose metabolism in insulin-resistant 3T3-L1 adipocytes. RSC Adv 5:3482–3490. https://doi.org/10.1039/c4ra10343b

Liu Q, Luo L, Wang X et al (2017) Comprehensive analysis of rice laccase gene (*OsLAC*) family and ectopic expression of *OsLAC10* enhances tolerance to copper stress in *Arabidopsis*. Int J Mol Sci 18:209. https://doi.org/10.3390/ijms18020209

López-Bellido RJ, López-Bellido L, Benítez-Vega J et al (2011) Chickpea and faba bean nitrogen fixation in a Mediterranean rainfed Vertisol: effect of the tillage system. Eur J Agron 34:222–230. https://doi.org/10.1016/j.eja.2011.01.005

Madhava Rao KV, Sresty TVS (2000) Antioxidative parameters in the seedlings of pigeonpea (*Cajanus cajan* (L.) Millspaugh) in response to Zn and Ni stresses. Plant Sci 157:113–128. https://doi.org/10.1016/S0168-9452(00)00273-9

Mahmood S, Ishtiaq S, Yasin G, Irshad A (2016) Dose dependent rhizospheric Ni toxicity evaluation: membrane stability and antioxidant potential of *Vigna* species. Chil J Agric Res 76:378–384. https://doi.org/10.4067/S0718-58392016000300017

Małecka A, Piechalak A, Morkunas I, Tomaszewska B (2008) Accumulation of lead in root cells of *Pisum sativum*. Acta Physiol Plant 30:629–637. https://doi.org/10.1007/s11738-008-0159-1

Malecka A, Piechalak A, Mensinger A et al (2012) Antioxidative defense system in *Pisum sativum* roots exposed to heavy metals (Pb, Cu, Cd, Zn). Polish J Environ Stud 21:1721–1730

Malik JA, Goel S, Sandhir R, Nayyar H (2011) Uptake and distribution of arsenic in chickpea: effects on seed yield and seed composition. Commun Soil Sci Plant Anal 42:1728–1738. https://doi.org/10.1080/00103624.2011.584593

Mandal BK, Suzuki KT (2002) Arsenic round the world: a review. Talanta 58:201–235. https://doi.org/10.1016/S0065-2113(08)70013-0

Maneepun S (2003) Traditional processing and utilization of legumes

Manivasagaperumal R, Vijayarengan P, Balamurugan S, Thiyagarajan G (2011) Effect of copper on growth, dry matter yield and nutrient content of *Vigna radiata* (L.) Wilczek. J Phytol 3:53–62

Mao F, Nan G, Cao M et al (2018) The metal distribution and the change of physiological and biochemical process in soybean and mung bean plants under heavy metal stress. Int J Phytoremediation 20:1113–1120. https://doi.org/10.1080/15226514.2017.1365346

Mathers JC (2002) Pulses and carcinogenesis: potential for the prevention of colon, breast and other cancers. Br J Nutr 88:273–279. https://doi.org/10.1079/bjn2002717

Medda S, Mondal NK (2017) Chromium toxicity and ultrastructural deformation of *Cicer arietinum* with special reference of root elongation and coleoptile growth. Ann Agrar Sci 15:396–401. https://doi.org/10.1016/j.aasci.2017.05.022

Mehandi S, MohdQuatadah S, Prasad Mishra S et al (2019) Mungbean (*Vigna radiata* L. Wilczek): retrospect and Prospects. Legum Crop Charact Breed Improv Food Secur. https://doi.org/10.5772/intechopen.85657

Mehta R, Templeton DM, O'Brien PJ (2006) Mitochondrial involvement in genetically determined transition metal toxicity. II Copper Toxicity Chem Biol Interact 163:77–85. https://doi.org/10.1016/j.cbi.2006.05.011

Melamed D (2005) Monitoring arsenic in the environment: a review of science and technologies with the potential for field measurements. Anal Chim Acta 532:1–13. https://doi.org/10.1016/j.aca.2004.10.047

MeysamHoseini S, Zargari F (2013) Cadmium in plants: a review. Int J Farming Allied Sci 2:579–581

Mishra S, Bharagava RN, More N et al (2019) Heavy metal contamination: an alarming threat to environment and human health. Environ Biotechnol Sustain Futur. https://doi.org/10.1007/978-981-10-7284-0_5

Mitra S, Paul D (2020) Iron plaque formation on roots and phosphate mediated alleviation of toxic effects in *Lens culinaris* Medik. induced by arsenic. South African J Bot 131:267–276. https://doi.org/10.1016/j.sajb.2020.02.024

Mlyneková Z, Chrenková M, Formelová Z (2014) Cereals and legumes in nutrition of people with celiac disease. Int J Celiac Dis 2:105–109. https://doi.org/10.12691/ijcd-2-3-3

Mohaparta M, Mohanta D, Behera SS et al (2018) Ecophysiological studies of lead stress on *Vigna mungo* L. Seedlings. Int J Appl Sci Biotechnol 6:227–231. https://doi.org/10.3126/ijasbt.v6i3.20595

Molina AS, Nievas C, Chaca MVP et al (2008) Cadmium-induced oxidative damage and antioxidative defense mechanisms in *Vigna mungo* L. Plant Growth Regul 56:285–295. https://doi.org/10.1007/s10725-008-9308-1

Mondal NK, Das C, Roy S, Datta JK (2013) Effect of varying cadmium stress on chickpea (*Cicer arietinum* L) seedlings: an ultrastructural study. Ann Environ Sci 7:59–70

Morin G, Calas G (2006) Arsenic in soils, mine tailings, and former industrial sites. Elements 2:97–101. https://doi.org/10.2113/gselements.2.2.97

Morrow H (2010) Cadmium and cadmium alloys. Kirk-Othmer Encycl Chem Technol. https://doi.org/10.1002/0471238961.0301041303011818.a01.pub3

Muehlbauer FJ, Sarker A (2017) Economic importance of chickpea: production, value, and world trade. In: Cogent Food & Agriculture. pp 5–12

Murtaza S, Parveen N, Murtaza S et al (2017) Effects of chromium on seed germination, growth and yield of pink lentil. Biosci Res 14:1246–1252

Murugan AK, Sundaramoorthy P, Ganesh KS (2018) Effect of chromium on growth and yield of *Vigna mungo* (L.). J Plant Stress Physiol 4:17–21. https://doi.org/10.25081/jpsp.2018.v4.3484

Nafisa SA, Javaid A (2013) Growth of *Pisum sativum* under single or combined action of *Sclerotium rolfsii* and copper [Cu(II)]. Int J Agric Biol 15:1363–1366

Nair PMG, Chung IM (2015) Changes in the growth, redox status and expression of oxidative stress related genes in chickpea (*Cicer arietinum* L.) in response to copper oxide nanoparticle exposure. J Plant Growth Regul 34:350–361. https://doi.org/10.1007/s00344-014-9468-3

Nautiyal N, Sinha P (2012) Lead induced antioxidant defense system in pigeon pea and its impact on yield and quality of seeds. Acta Physiol Plant 34:977–983. https://doi.org/10.1007/s11738-011-0894-6

Naz H, Naz A, Ashraf S (2015) Impact of heavy metal toxicity to plant growth and nodulation in chickpea grown under heavy metal stress. Int J Res Emerg Sci Technol 2:248–260

Naz H, Naz A, Ashraf S, Khan HH (2018) Effect of heavy metals (Ni, Cr, Cd, Pb and Zn) on nitrogen content, chlorophyll, leghaemoglobin and seed yield in chickpea plants in Aligarh City, U.P., India. Int J Curr Microbiol Appl Sci 2018:4387–4399

Nikalje GC, Suprasanna P (2018) Coping with metal toxicity—cues from halophytes. Front Plant Sci 9:777. https://doi.org/10.3389/fpls.2018.00777

Okon E, Udo OO, Archibong IA, Victor IA (2020) Phytomechanistic processes in environmental clean-up: a biochemical perspective. Int J Res Innov Appl Sci V:213–222

Oves M, Khan MS, Zaidi A (2013) Chromium reducing and plant growth promoting novel strain *Pseudomonas aeruginosa OSG41* enhance chickpea growth in chromium amended soils. Eur J Soil Biol 56:72–83. https://doi.org/10.1016/j.ejsobi.2013.02.002

Owlad M, Aroua MK, Daud WAW, Baroutian S (2009) Removal of hexavalent chromium-contaminated water and wastewater: a review. Water Air Soil Pollut 200:59–77. https://doi.org/10.1007/s11270-008-9893-7

Päivöke AEA, Simola LK (2001) Arsenate toxicity to *Pisum sativum*: Mineral nutrients, chlorophyll content, and phytase activity. Ecotoxicol Environ Saf 49:111–121. https://doi.org/10.1006/eesa.2001.2044

Panda SK, Choudhury S (2005) Chromium stress in plants. Brazilian J Plant Physiol 17:95–102. https://doi.org/10.1590/s1677-04202005000100008

Panda SK, Patra HK (2000) Does chromium(III) produce oxidative damage in excised wheat leaves? J Plant Biol 27:105–110

Pandey S (2008) Germination and seedling growth of field pea *Pisum sativum* Malviya Matar-15 (HUDP-15) and Pusa Prabhat (DDR-23) under varying level of copper and chromium. J Am Sci 4:33–47

Pandey N, Bhatt R (2016) Role of soil associated Exiguobacterium in reducing arsenic toxicity and promoting plant growth in *Vigna radiata*. Eur J Soil Biol 75:142–150. https://doi.org/10.1016/j.ejsobi.2016.05.007

Pandey V, Dixit V, Shyam R (2009) Chromium effect on ROS generation and detoxification in pea (*Pisum sativum*) leaf chloroplasts. Protoplasma 236:85–95. https://doi.org/10.1007/s00709-009-0061-8

Park SJ, Kim T, Baik BK (2010) Relationship between proportion and composition of albumins, and in vitro protein digestibility of raw and cooked pea seeds (*Pisum sativum* L.). J Sci Food Agric 90:1719–1725. https://doi.org/10.1002/jsfa.4007

Patnaik A, Mohanty BK (2013) Toxic effect of mercury and cadmium on germination and seedling growth of *Cajanus cajan* L (Pigeon Pea). Ann Biol Res 4:123–126

Peer WA, Baxter IR, Richards EL et al (2005) Phytoremediation and hyperaccumulator plants. In: Tamas MJ, Martinoia E (eds) Molecular biology of metal homeostasis and detoxification. Springer, Berlin, pp 299–340. https://doi.org/10.1007/4735_100

Rahman MF, Ghosal A, Alam MF, Kabir AH (2017) Remediation of cadmium toxicity in field peas (*Pisum sativum* L.) through exogenous silicon. Ecotoxicol Environ Saf 135:165–172. https://doi.org/10.1016/j.ecoenv.2016.09.019

Raizada A, Souframanien J (2019) Transcriptome sequencing, de novo assembly, characterisation of wild accession of blackgram (*Vigna mungo* var. *silvestris*) as a rich resource for development of molecular markers and validation of SNPs by high resolution melting (HRM) analysis. BMC Plant Biol 19:1–16. https://doi.org/10.1186/s12870-019-1954-0

Ramesh Kumar K, Anbazhagan V (2018) Analysis and assessment of heavy metals in soils around the industrial areas in Mettur, Tamilnadu, India. Environ Monit Assess. https://doi.org/10.1007/s10661-018-6899-5

Reddy AM, Kumar SG, Jyothsnakumari G et al (2005) Lead induced changes in antioxidant metabolism of horsegram (*Macrotyloma uniflorum* (Lam.) Verdc.) and bengalgram (*Cicer arietinum* L.). Chemosphere 60:97–104. https://doi.org/10.1016/j.chemosphere.2004.11.092

Rehman M, Liu L, Wang Q et al (2019) Copper environmental toxicology, recent advances, and future outlook: a review. Environ Sci Pollut Res 26:18003–18016. https://doi.org/10.1007/s11356-019-05073-6

Rizwan M, Imtiaz M, Dai Z et al (2017) Nickel stressed responses of rice in Ni subcellular distribution, antioxidant production, and osmolyte accumulation. Environ Sci Pollut Res 24:20587–20598. https://doi.org/10.1007/s11356-017-9665-2

Rizwan M, Mostofa MG, Ahmad MZ et al (2019) Hydrogen sulfide enhances rice tolerance to nickel through the prevention of chloroplast damage and the improvement of nitrogen metabolism under excessive nickel. Plant Physiol Biochem 138:100–111. https://doi.org/10.1016/j.plaphy.2019.02.023

Rodríguez-Ruiz M, Aparicio-Chacón MV, Palma JM, Corpas FJ (2019) Arsenate disrupts ion balance, sulfur and nitric oxide metabolisms in roots and leaves of pea (*Pisum sativum* L.) plants. Environ Exp Bot 161:143–156. https://doi.org/10.1016/j.envexpbot.2018.06.028

Rubeena FR, Taylor PWJ (2003) Construction of an intraspecific linkage map of lentil (*Lens culinaris* ssp. culinaris). Theor Appl Genet 107:910–916. https://doi.org/10.1007/s00122-003-1326-9

Saad R, Kobaissi A, Robin C et al (2016) Nitrogen fixation and growth of *Lens culinaris* as affected by nickel availability: a pre-requisite for optimization of agromining. Environ Exp Bot 131:1–9. https://doi.org/10.1016/j.envexpbot.2016.06.010

Saif S, Khan MS (2018) Assessment of toxic impact of metals on proline, antioxidant enzymes, and biological characteristics of *Pseudomonas aeruginosa* inoculated *Cicer arietinum* grown in chromium and nickel-stressed sandy clay loam soils. Environ Monit Assess 190:1–18. https://doi.org/10.1007/s10661-018-6652-0

Sakouhi L, Rahoui S, Ben Massoud M et al (2016) Calcium and EGTA alleviate cadmium toxicity in germinating chickpea seeds. J Plant Growth Regul 35:1064–1073. https://doi.org/10.1007/s00344-016-9605-2

Saleh AAH (2007) Influence of UV_{A+B} radiation and heavy metals on growth, some metabolic activities and antioxidant system in pea (*Pisum sativum*) plant. Am J Plant Physiol 2:139–154. https://doi.org/10.3923/ajpp.2007.139.154

Sameer Kumar CV, Satheesh Naik SJ, Mohan N et al (2017) Botanical Description of Pigeonpea [*Cajanus Cajan* (L) Millsp.]. The Pigeonpea Genome Springer, C. https://doi.org/10.1007/978-3-319-63797-6_3

Sarker A, Erskine W, Bakr MA et al (2004) Lentil improvement in Bangladesh. Asia-Pacific Assoc Agric Res Instit 1:1–38

Saroy K, Garg N (2021) Relative effectiveness of arbuscular mycorrhiza and polyamines in modulating ROS generation and ascorbate-glutathione cycle in *Cajanus cajan* under nickel stress. Environ Sci Pollut Res 28:48872–48889. https://doi.org/10.1007/s11356-021-13878-7

Saxena KB, Kumar RV, Rao PV (2002) Pigeonpea nutrition and its improvement. J Crop Prod 5:227–260. https://doi.org/10.1300/J144v05n01_10

Sayğılı H, Sayğılı GA (2019) Optimized preparation for bimodal porous carbon from lentil processing waste by microwave-assisted K_2CO_3 activation: Spectroscopic characterization and dye decolorization activity. J Clean Prod 226:968–976. https://doi.org/10.1016/j.jclepro.2019.04.121

Schmidtke K, Neumann A, Hof C, Rauber R (2004) Soil and atmospheric nitrogen uptake by lentil (*Lens culinaris* Medik.) and barley (*Hordeum vulgare* ssp. *nudum* L.) as monocrops and intercrops. F Crop Res 87:245–256. https://doi.org/10.1016/j.fcr.2003.11.006

Schwember AR, Schulze J, del Pozo A, Cabeza RA (2019) Regulation of symbiotic nitrogen fixation in legume root nodules. Plants 8:333. https://doi.org/10.3390/plants8090333

Shabnam N, Kim M, Kim H (2019) Iron (III) oxide nanoparticles alleviate arsenic induced stunting in *Vigna radiata*. Ecotoxicol Environ Saf 183:109496. https://doi.org/10.1016/j.ecoenv.2019.109496

Shah Z, Shah SH, Peoples MB et al (2003) Crop residue and fertiliser N effects on nitrogen fixation and yields of legume-cereal rotations and soil organic fertility. F Crop Res 83:1–11. https://doi.org/10.1016/S0378-4290(03)00005-4

Shahid MA, Balal RM, Pervez MA et al (2014) Exogenous proline and proline-enriched *Lolium perenne* leaf extract protects against phytotoxic effects of nickel and salinity in *Pisum sativum* by altering polyamine metabolism in leaves. Turk J Botany 38:914–926. https://doi.org/10.3906/bot-1312-13

Shahid M, Ahmed B, Zaidi A, Khan MS (2018) Toxicity of fungicides to: *Pisum sativum*: a study of oxidative damage, growth suppression, cellular death and morpho-anatomical changes. RSC Adv 8:38483–38498. https://doi.org/10.1039/c8ra03923b

Shamshad S, Shahid M, Rafiq M et al (2018) Effect of organic amendments on cadmium stress to pea: a multivariate comparison of germinating vs young seedlings and younger vs older leaves. Ecotoxicol Environ Saf 151:91–97. https://doi.org/10.1016/j.ecoenv.2018.01.002

Shanker A, Djanaguiraman M, Sudhagar R et al (2004) Differential antioxidative response of ascorbate glutathione pathway enzymes and metabolites to chromium speciation stress in green gram ((L.) R.Wilczek. cv CO 4) roots. Plant Sci 166:1035–1043. https://doi.org/10.1016/j.plantsci.2003.12.015

Shanker A, Cervantes C, Lozatavera H, Avudainayagam S (2005) Chromium toxicity in plants. Environ Int 31:739–753. https://doi.org/10.1016/j.envint.2005.02.003

Sharama A, Singh G (2013) Studies on the effect of Cu (II) ions on the antioxidant enzymes in chickpea (*Cicer arietinum* L.) cultivars. J Stress Physiol Biochem 9:5–13

Sharma I (2013) Arsenic-induced oxidative stress and antioxidant defense system of *Pisum sativum* and *Pennisetum typhoides*: a comparative study. Res J Biotechnol 8:48–56

Sharma KK, Sreelatha G, Saxena KB, Rao DM (2008) Pigeonpea. Compendium of transgenic crop plants: transgenic legume grains and forages. Blackwell Publishing, Oxfordshire, pp 133–162

Sharma H, Rawal N, Mathew BB (2015) The characteristics, toxicity and effects of cadmium. Int J Nanotechnol Nanosci 3:1–9

Sharma P, Sirhindi G, Kaur H, Singh AK (2017a) Methyl jasmonate regulated antioxidants and oxidative stress management in *Cajanus Cajan* (L.) Millsp. under copper stress condition. Int J Adv Res Sci Eng 6:184–192

Sharma P, Sirhindi G, Singh AK et al (2017b) Consequences of copper treatment on pigeon pea photosynthesis, osmolytes and antioxidants defense. Physiol Mol Biol Plants 23:809–816. https://doi.org/10.1007/s12298-017-0461-8

Sharma S, Paul PJ, Kumar CVS et al (2019) Evaluation and identification of promising introgression lines derived from wild cajanus species for broadening the genetic base of cultivated pigeonpea [*Cajanus cajan* (L.) Millsp.]. Front Plant Sci 10:1269. https://doi.org/10.3389/fpls.2019.01269

Sharma A, Kapoor D, Wang J et al (2020a) Chromium bioaccumulation and its impacts on plants: an overview. Plants 9:1–17. https://doi.org/10.3390/plants9010100

Sharma RK, Barot K, Archana G (2020b) Root colonization by heavy metal resistant Enterobacter and its influence on metal induced oxidative stress on *Cajanus cajan*. J Sci Food Agric 100:1532–1540. https://doi.org/10.1002/jsfa.10161

Sharma P, Gautam A, Kumar V et al (2021) Naringenin reduces Cd-induced toxicity in *Vigna radiata* (mungbean). Plant Stress 1:100005. https://doi.org/10.1016/j.stress.2021.100005

Shinde YH, Amogha V, Pandit AB, Joshi JB (2017) Kinetics of cooking of unsoaked and presoaked split peas (*Cajanus cajan*). J Food Process Eng 40:1–7. https://doi.org/10.1111/jfpe.12527

Shrivastava AK (2009) A review on copper pollution.pdf. Indian J Environ Prot 29:552–560

Shrivastava R, Upreti RK, Seth PK, Chaturvedi UC (2002) Effects of chromium on the immune system. FEMS Immunol Med Microbiol 34:1–7. https://doi.org/10.1016/S0928-8244(02)00345-0

Shurtleff W, Aoyagi A (2013) History of tofu and tofu products (965 CE to 2013): extensively annotated bibliography and sourcebook

Sidhimol PD, Anitha CT, Sabeena PM (2011) Amelioration of toxic effects of lead in *Vigna radiata* (L.) Wilczek with the application of *Pseudomonas fluorescens*. Nat Environ Pollut Technol 10:505–510

Singh RJ, Jauhar PP (2006) Genetic resources, chromosome engineering, and crop improvement. CRC Press, New York

Singh HP, Batish DR, Kohli RK, Arora K (2007) Arsenic-induced root growth inhibition in mung bean (*Phaseolus aureus* Roxb.) is due to oxidative stress resulting from enhanced lipid peroxidation. Plant Growth Regul 53:65–73. https://doi.org/10.1007/s10725-007-9205-z

Singh V, Bhatt I, Aggarwal A et al (2010) Proline improves copper tolerance in chickpea (*Cicer arietinum*). Protoplasma 245:173–181. https://doi.org/10.1007/s00709-010-0178-9

Singh H, Singh NB, Singh A et al (2017) Oxidative stress induced by lead in *Vigna radiata* L. seedling attenuated by exogenous nitric oxide. Trop Plant Res 4:225–234. https://doi.org/10.22271/tpr.2017.v4.i2.031

Singh D, Sharma NL, Singh CK et al (2020) Effect of chromium (VI) toxicity on morpho-physiological characteristics, yield, and yield components of two chickpea (*Cicer arietinum* L.) varieties. PLoS ONE 15:1–27. https://doi.org/10.1371/journal.pone.0243032

Smýkal P, Aubert G, Burstin J et al (2012) Pea (*Pisum sativum* L.) in the Genomic Era. Agronomy 2:74–115. https://doi.org/10.3390/agronomy2020074

Solh M, Van Ginkel M (2014) Drought preparedness and drought mitigation in the developing world's drylands. Weather Clim Extrem 3:62–66. https://doi.org/10.1016/j.wace.2014.03.003

Srinivasan P, Rathika R, Sengottaiyan A et al (2015) The Effects of Nickel sulphate ($NiSO_4$) on growth and antioxidant enzyme activities in green gram plant (*Vigna radiata* L.). Int J Adv Interdiscip Res 2:1–9

Srivastava S, Sharma YK (2013) Impact of arsenic toxicity on black gram and its amelioration using phosphate. ISRN Toxicol 2013:1–8. https://doi.org/10.1155/2013/340925

Srivastava G, Kumar S, Dubey G et al (2012) Nickel and ultraviolet-B stresses induce differential growth and photosynthetic responses in *Pisum sativum* L. seedlings. Biol Trace Elem Res 149:86–96. https://doi.org/10.1007/s12011-012-9406-9

Steinhorst L, Kudla J (2014) Signaling in cells and organisms—calcium holds the line. Curr Opin Plant Biol 22:14–21. https://doi.org/10.1016/j.pbi.2014.08.003

Stern BR, Solioz M, Krewski D et al (2007) Copper and human health: Biochemistry, genetics, and strategies for modeling dose-response relationships. J Toxicol Environ Heal—Part B Crit Rev 10:157–222. https://doi.org/10.1080/10937400600755911

Suhani I, Sahab S, Srivastava V, Singh RP (2021) Impact of cadmium pollution on food safety and human health. Curr Opin Toxicol 27:1–7. https://doi.org/10.1016/j.cotox.2021.04.004

Swarnakar A (2020) Phytotoxicity of arsenite on early seedling growth of mung bean: a threat to potential pulse cultivation. Adv Zool Bot 8:69–73. https://doi.org/10.13189/azb.2020.080206

Talukdar D (2012) Exogenous calcium alleviates the impact of cadmium-induced oxidative stress in *Lens culinaris* medic. Seedlings through modulation of antioxidant enzyme activities. J Crop Sci Biotechnol 15:325–334. https://doi.org/10.1007/s12892-012-0065-3

Tomooka N, Vaughan DA, Kaga A (2005) Mungbean [*Vigna radiata* (L.) Wilczek]. Genet Resour Chromosom Eng Crop Improv Grain Legum 325–345

Tripathi DK, Singh VP, Prasad SM et al (2015a) Silicon nanoparticles (SiNp) alleviate chromium (VI) phytotoxicity in *Pisum sativum* (L.) seedlings. Plant Physiol Biochem 96:189–198. https://doi.org/10.1016/j.plaphy.2015.07.026

Tripathi P, Singh PC, Mishra A et al (2015b) *Trichoderma* inoculation augments grain amino acids and mineral nutrients by modulating arsenic speciation and accumulation in chickpea (*Cicer arietinum* L.). Ecotoxicol Environ Saf 117:72–80. https://doi.org/10.1016/j.ecoenv.2014.10.027

Tripathi P, Singh PC, Mishra A et al (2017) Arsenic tolerant *Trichoderma* sp. reduces arsenic induced stress in chickpea (*Cicer arietinum*). Environ Pollut 223:137–145. https://doi.org/10.1016/j.envpol.2016.12.073

Ullah S, Khan J, Hayat K et al (2020) Comparative study of growth, cadmium accumulation and tolerance of three chickpea (*Cicer arietinum* L.) cultivars. Plants 9:310. https://doi.org/10.3390/plants9030310

Upadhyaya H, Shome S, Roy D, Bhattacharya MK (2014) Arsenic induced changes in growth and physiological responses in *Vigna radiata* seedling: effect of curcumin interaction. Am J Plant Sci 05:3609–3618. https://doi.org/10.4236/ajps.2014.524377

Wang J, Guo P, Li X et al (2000) Source identification of lead pollution in the atmosphere of Shanghai City by analyzing single aerosol particles (SAP). Environ Sci Technol 34:1900–1905. https://doi.org/10.1021/es9907818

Wani PA, Khan MS, Zaidi A (2007a) Impact of heavy metal toxicity on plant growth, symbiosis, seed yield and nitrogen and metal uptake in chickpea. Aust J Exp Agric 47:712–720

Wani PA, Khan MS, Zaidi A (2007b) Cadmium, chromium and copper in greengram plants. Agron Sustain Dev 27:145–153. https://doi.org/10.1051/agro:2007036

Wani AL, Ara A, Usmani JA (2015) Lead toxicity: a review. Interdiscip Toxicol 8:55–64. https://doi.org/10.1515/intox-2015-0009

Wezi GM, Sieglinde S, George YKP (2017) Biological nitrogen fixation and yield of pigeonpea and groundnut: quantifying response on smallholder farms in northern Malawi. African J Agric Res 12:1385–1394. https://doi.org/10.5897/ajar2017.12232

Wrigley CW, Corke H, Seetharaman K, Faubion J (2015) Encyclopedia of Food Grains, 2nd edn.

Xu Y, Zhou G, Zhou L et al (2007) Expression patterns of the rice class I metallothionein gene family in response to lead stress in rice seedlings and functional complementation of its members in lead-sensitive yeast cells. Chin Sci Bull 52:2203–2209. https://doi.org/10.1007/s11434-007-0335-5

Yadav SS, McNeil D, Stevenson PC (2007) Lentil. Springer Netherlands, Dordrecht

Yan A, Wang Y, Tan SN et al (2020) Phytoremediation: a promising approach for revegetation of heavy metal-polluted land. Front Plant Sci 11:359. https://doi.org/10.3389/fpls.2020.00359

Yasin G, Fatima S, Saher A et al (2020) Indices for antioxidant enzymes activity and yield attributes of mash bean [*Vigna mungo* L. Hepper] genotypes under rhizospheric intensified lead (Pb) concentrations. J Pure Appl Agric 5:70–78

Yusuf M, Fariduddin Q, Ahmad I, Ahmad A (2014) Brassinosteroid-mediated evaluation of antioxidant system and nitrogen metabolism in two contrasting cultivars of *Vigna radiata* under different levels of nickel. Physiol Mol Biol Plants 20:449–460. https://doi.org/10.1007/s12298-014-0259-x

Zeng LS, Liao M, Chen CL, Huang CY (2007) Effects of lead contamination on soil enzymatic activities, microbial biomass, and rice physiological indices in soil-lead-rice (*Oryza sativa* L.) system. Ecotoxicol Environ Saf 67:67–74. https://doi.org/10.1016/j.ecoenv.2006.05.001

Zia-Ul-Haq M, Ahmad S, Bukhari SA et al (2014) Compositional studies and biological activities of some mash bean (*Vigna mungo* (L.) Hepper) cultivars commonly consumed in Pakistan. Biol Res 47:1–14. https://doi.org/10.1186/0717-6287-47-23