Engineered Biochar as Adsorbent for Removal of Heavy Metals from Soil Medium

M. L. Dotaniya, V. D. Meena, C. K. Dotaniya, M. D. Meena, R. K. Doutaniya, Rajhance Verma, R. C. Sanwal, H. P. Parewa, H. S. Jatav, Ramu Meena, Abhijit Sarkar, and J. K. Saha

Abstract Almost all of the world's fertile land is being used to its full capacity. Researchers and policymakers are paying close attention to the restoration and utilization of contaminated land for sustainable agricultural production. Different physical, chemical and biological treatment methods are used for remediation of pollutants. Chemical treatments take less time to remediate contaminated soil by adding organic and inorganic components. Biochar is a pyrolyzed material with a higher surface area, CEC, carbon and nutrient contents. It also helps in increasing the soil carbon-sequestration potential. Due to enhanced surface area, functional groups, mineral content and CEC, it increases the metal adsorption and reduces the labile fractions of heavy metal in soil solution. The impact of biochar in heavy metal dynamics in terms of soil health and plant yield potential is discussed in this chapter.

Keywords Biochar · Heavy metal adsorption · Plant nutrient · Phytoremedition process · Soil health

---

M. L. Dotaniya (✉) · V. D. Meena · M. D. Meena
ICAR-Directorate of Rapeseed-Mustard Research, Bharatpur 321303, India
e-mail: mohan30682@gmail.com

C. K. Dotaniya · R. C. Sanwal
Department of Soil Science & Agricultural Chemistry, SKRAU, Bikaner 334006, India

R. K. Doutaniya
Department of Agronomy, SKN College of Agriculture, Jobner 303329, India

R. Verma
Department of Soil Science & Agricultural Chemistry, SKN College of Agriculture, Jobner 303329, India

H. P. Parewa
College of Agriculture, Agriculture University, Jodhpur, Sumerpur, Pali 306902, India

H. S. Jatav · R. Meena
SKN Agriculture University, Jobner 303329, India

A. Sarkar · J. K. Saha
ICAR-Indian Institute of Soil Science, Bhopal 462038, India

S. Ramola et al. (eds.), *Engineered Biochar*,
https://doi.org/10.1007/978-981-19-2488-0_9

1 Introduction

Agriculture has faced numerous challenges in the twenty-first century. It needs to produce more food and fibre to feed a growing population with shrinking natural resources. The world's population has exploded in the recent century, reaching 8.6 billion in 2030 and 9.8 billion in 2050, with Africa playing a large role (Foresight 2011). The vast bulk of the world's population (60%) lives in Asia (4.4 billion people), followed by Africa (1.2 billion people), Europe (738 million people), Latin America and the Caribbean (634 million people) and the rest of the world (5%) (Table 1). China (1.4 billion) and India (1.3 billion) are the world's two largest countries, accounting for 19% and 18% of the global population, respectively (UNDESA 2015).

Food security is a relevant and important issue for many countries, with a particular focus on developing countries. There is growing concern about the world's future food consumption and supply. The global food system is under an unparalleled convergence of forces, which is expected to worsen by 2050 (Foresight 2011). Increased food production will necessitate more inputs, such as land, water or energy, or a combination of these. By 2050, demand for cereals for food and animal feed is expected to reach 3 billion tonnes, up from almost 2.1 billion tonnes currently. According to the forecasts, feeding a world population of 9.1 billion people in 2050 will necessitate a 70% increase in overall food production between 2005/07 and 2050. In poorer countries, production would have to nearly quadruple. This would result in considerable increase in the production of a number of important commodities. Annual cereal production, for example, would need to increase by about one billion tonnes, and meat production by more than 200 million tonnes, to a total of 470 million tonnes in 2050, with 72% of that in developing nations, up from 58% today. To sufficiently feed the world's population, it would be necessary to produce the types of foods that are currently unavailable in order to provide nutrition security (UNEP 2014).

India (24.3%) and China (16.7%) account for a major portion of world food demand (Dotaniya et al. 2022a). Because of rising incomes, emerging countries will seek more animal origin foods in the future. The rate of increase in global cereal

Table 1 Population of the world by region (UNDESA 2015)

Major region	Population (million)			
	2015	2030	2050	2100
World	7349	8501	9725	11,213
Africa	1186	1679	2478	4387
Asia	4393	4923	5267	4889
Europe	738	734	707	646
Latin America and the Caribbean	634	721	784	721
Northern America	358	396	433	500
Oceania	39	47	57	71

Table 2 The top 20 countries that influence global CE food demand (Emiko and Will 2017)

Country	Change (million tonne)	Share (%)	Cumulative (%)
India	1715.9	24.3	24.3
China	1176.6	16.7	41.0
Nigeria	357.6	5.1	46.1
Indonesia	301.0	4.3	50.4
United States	241.0	3.4	53.8
Pakistan	217.9	3.1	56.9
Brazil	178.5	2.5	59.4
Bangladesh	140.1	2.0	61.4
Egypt	139.8	2.0	63.4
Mexico	133.8	1.9	65.3
Philippines	128.8	1.8	67.1
Ethiopia	105.1	1.5	68.6
Turkey	91.8	1.3	69.9
Vietnam	91.2	1.3	71.2
Tanzania	81.1	1.2	72.4
Russia	76.0	1.1	73.4
Sudan	74.5	1.1	74.5
Iran	73.5	1.0	75.5
Uganda	73.4	1.0	76.6
Thailand	67.7	1.0	77.5

demand will slow until 2050. Cereals account for the majority of global food demand (49%) and will continue to do so until 2050. Global cereal demand grew at a constant rate of 1.3% per year from 1969 to 2007 and is expected to dip further to 1.2% in 2030 and 0.9% in 2050, despite a large increase in world cereal demand from 940 million tonnes in 2005/2007 to 3 billion metric tonnes by 2050. Developing countries will account for nearly all of the increase in cereal consumption. The top 20 nations account for about 77.5 of global CE food demand (Table 2).

2 Soil Fertility Status of Indian Soils

Increased soil erosion, declined soil fertility and reduced biodiversity at the local level, depletion and pollution of groundwater and eutrophication of surface waters at the regional level, and changes in atmospheric composition and climate at the global level are all known negative effects of agricultural intensification. Ramamurthy and Bajaj (1969) produced the first systematic soil fertility map of Indian soils in 1967. Around 4% of samples were rich in available P at the time. According to a soil fertility map released in 2002 (Motsara 2002), roughly 20% of soil samples have high levels of accessible P. Muralidharudu et al. (2011) used GIS to create district-level soil fertility maps in India, which revealed that 57% of districts had low available nitrogen, 36% had medium and 7% had high. In terms of available P, around 51% of districts had low soils, 40% had medium soils and 9% had high soils. The soils of roughly 9% of districts had low available K status, 42% had medium available K status and 49% had high available K status. Farmers' indiscriminate use of phosphatic fertilizers has resulted in excessive P levels in some soils. Because Indian soils have a low-to-medium organic matter level, the nitrogen deficit is likely to persist. The three estimations of soil fertility for K show that the percentage of samples that test high has risen over time (Ramamurthy and Bajaj 1969; Ghosh and Hasan 1980; Motsara 2002).

Different soils have their own set of difficulties that prevent them from obtaining long-term high production. Acidity in hill and laterite soils; nutrient leaching in sandy soils; nutrient fixation in red, laterite and clayey soils; obstructed drainage in swell-shrink soils; N volatilization losses from calcareous soils; Zn deficiency in low organic matter, sandy, high pH, high-water table soils; and B deficiency in highly calcareous leached acid soils. Zn deficiency was found in 49% of the soil samples tested, followed by S (41%), Fe (12%), Cu (3%), Mn (4%) and B (4%) (32% in some selected areas such as Bihar). In the case of P (15–20%), N (30–50%), S (8–12%), Zn (2–5%), Fe (1–2%) and Cu (1–2%), the current state of nutrient usage efficiency is fairly low (1–2%). In India's intensive cropping systems, fertilizer partial factor productivity is dropping.

Soil organic matter is essential for maintaining soil fertility. Organic matter status of soil in Alfisols of Ranchi deteriorated over time in the soybean-wheat system due to a lack of balanced fertilizer input. In the soybean-wheat system at Jabalpur, balanced fertilization with NPK and NPK + FYM increased the organic matter status in Vertisols. During the last three and a half decades, the partial factor productivity of fertilizers has decreased, from 15 kg food grains/kg NPK fertilizer in 1970 to 5 kg food grains/kg NPK fertilizer in 2005. In the rush to increase production, little thought was given to long-term soil quality and high productivity. As a result, main crop annual compound growth rates have decreased from 3.36% in 1981–85 to 0.11% in 2001–05. Deterioration in soil quality causes a drop in partial factor productivity and compound growth rates of key crops in intensive cropping systems as well as low nutrient use efficiency. Continuous cropping reduces organic C levels by 50–70%, bringing them closer to the climatic and precipitation-driven equilibrium values. The following are the primary causes of soil quality degradation: a large nutrient gap between demand and supply; high nutrient turnover in the soil–plant system combined with low and imbalanced fertilizer use; emerging deficiencies of secondary and micronutrients in soils; soil acidity; nutrient leaching in sandy soils; nutrient fixation in red, laterite and clayey soils; and obstructed drainage in Swedish soils.

3 Heavy metal

Metals are necessary for the survival of all living species on the planet. These are required for the plant, animal and human life cycles to be completed. Deficiency of these metals in a living body can cause a variety of symptoms or limit an organism's capacity to develop and operate (Minhas et al. 2021; Dotaniya et al. 2022b). Some metals are required for life, but if their concentration in the body exceeds their required concentration, they become poisonous (Dotaniya et al. 2014a). These metals are divided into groups depending on their toxicity, origin and concentration in the living body, among other factors. Several metals have been found harmful to human health, and their introduction into the human body via food chain pollution requires scientific supervision. Heavy metals have a geogenic origin and are distributed by anthropogenic activities such as industrial waste, geochemical structure, agriculture and mining (Table 3). These metals form compounds with other ambient elements, making them more harmful to living things (Singh et al. 2020). The toxicity of a metal is determined by the metal's type, chemical form, climatic variables and other factors. Heavy metals including As, Cd, Cu, Pb, Ni and Zn are prevalent contaminants that originate from both natural and anthropogenic sources (Dotaniya et al. 2018a).

3.1 Adverse effects of heavy metals on Plant

According to Arnon and Stout's (1939) essentiality criterion, a plant's heavy development necessitates 17 essential plant nutrients. Micronutrients such as zinc, copper,

Table 3 Sources of hazardous metals (CPCB 2009)

Metal	Industry
Chromium (Cr)	Leather tanning, mining, industrial coolants, chromium salts production
Lead (Pb)	Lead-acid batteries, paints, e-waste, smelting operations, coal-based thermal power plants, ceramics, bangle industry
Mercury (Hg)	Chlor-alkali plants, thermal power plants, fluorescent lamps, hospital waste (damaged thermometers, barometers, sphygmomanometers), electrical appliances
Arsenic (As)	Geogenic/natural processes, smelting operations, thermal power plants, fuel burning
Copper (Cu)	Mining, electroplating, smelting operations, vanadium (Va) spent catalyst, sulphuric acid plant
Nickel (Ni)	Smelting operations, thermal power plants, battery industry
Cadmium (Cd)	Zinc smelting, waste batteries, e-waste, paint sludge, incinerations and fuel combustion
Zinc (Zn)	Smelting, electroplating

Table 4 Adverse effects of heavy metals on plants (modified from Saha et al. 2017)

Pollutant	Its impact on plant
As	Red brown necrotic spots on old leaves, yellow browning of roots, growth reduction
Cd	Brown margin on leaves, chlorosis, necrosis, curved leaves, brown stunted roots, reddish veins and petioles, reduction in growth, purple colouration
Cr	Affect seed emergence, stunted plant growth and decrease dry matter production
Pb	Dark green leaves, stunted foliage, increased number of shoots
Ni	Chlorosis, necrosis, stunting, inhibition of root growth, decrease in leaf area
Hg	Severe stunting of seedlings and roots, chlorosis, browning of leaf tips, reduction in growth
Cu	Chlorosis, yellow colouration, purple colouration of the lower side of the midrib, less branched roots, inhibition of root growth
Se	Interveinal chlorosis, black spots, bleaching and yellowing of young leaves, pink spots on root

manganese, iron and nickel are regarded as important plant nutrients, yet larger concentrations of these metals are phytotoxic. Other heavy metals/toxic metals that are known to cause harm to humans and animals include Cd, Cr, Hg and Pb. These metals do not appear to play a defined role in plant physiology, and at high concentrations, they cause plant toxicity symptoms and reduce plant biomass (Dotaniya et al. 2018b, 2019a) (Table 4). Few plants in nature have the ability to modulate heavy metal uptake patterns from the soil–water system, as well as tolerance to a specific metal or combination of metals (Dotaniya et al. 2020b). However, these metals have a specific tolerance level, beyond which plants exhibit the same toxicity as common plants. Heavy metal toxicity resulted in the production of reactive oxygen, and the plant's enzyme cofactors are replaced (Sytar et al. 2013). Heavy metal toxicity, according to Saha et al. (2017), has a negative impact on transcription and antioxidative processes, cellular redox imbalance, ionic trafficking, DNA synthesis and damage, and amino acid synthesis. According to Haider et al. (2021), cadmium toxicity changed the uptake pattern of Ca, Mg, P and K from soil and cause water scarcity in plants, resulting in low growth and production. According to Panday and Sharma (2002), heavy metals (Co^{2+}, Ni^{2+}, Cd^{2+}) reduce chlorophyll content, Fe activities and associated enzymes (catalase, peroxidase), as well as chlorophyll heme biosynthesis in cabbage. Ni toxicity was more than Cd and Co toxicity in this experiment (Pandey and Sharma 2002).

3.2 *Adverse effects of heavy metals on human*

Toxic metals are found to have a negative impact on the cell membrane as well as mitochondria, endoplasmic reticulum, nuclei and numerous enzymes associated with metabolism, detoxification and damage repair in biological systems (Table 5)

Table 5 Effects of heavy metals on human

Pollutant	Its impact on human
As	Bronchitis, dermatitis
Cd	Kidney damage, bronchitis, gastrointestinal disorder, bone marrow cancer
Cr	Hemolysis and ultimately, kidney and liver failure
Pb	Liver, kidney, gastrointestinal damage, mental retardation in children
Ni	Nausea, vomiting, diarrhoea, headache, cough, shortness of breath
Hg	Damage to nervous system, protoplasm poisoning
Cu	Harmful effect on brain, liver and lungs
Se	Nausea, vomiting, nail discoloration, brittleness, hair loss
Mn	Inhalation or contact causes damage to central nervous system
Zn	Zinc fumes have corrosive effect on skin, cause damage to nervous membrane

(Wang and Shi 2001; Dotaniya et al. 2014b, 2017). DNA damage and conformational changes caused by metal ions have been reported to affect cell cycle regulation, cancer or apoptosis when metal ions interact with cells (Kasprzak 2002; Beyersmann and Hartwig 2008). The production of reactive oxygen species (ROS) and oxidative stress have been implicated in the toxicity and carcinogenicity of metals like As (Tchounwou et al. 2004a, Yedjou and Tchounwou 2004b), Cd (Tchounwou et al. 2001), Cr (Patlolla et al. 2009; Dotaniya et al. 2019b) and Pb (Tchounwou et al. 2004b), among others (Sutton and Tchounwou 2007). Due to their extreme toxicity, these five elements are considered priority metals with substantial public health consequences. Toxins in the system have been proven to damage several organs at low levels. In addition, the United States Environmental Protection Agency (US EPA) and the International Agency for Research on Cancer (IARC) classify these metals as "known" or "probable" human carcinogens based on epidemiological and experimental studies that demonstrate a link between exposure and cancer incidence in humans and animals.

4 Heavy metal pathway in human being

Heavy metal concentrations in soil and their absorption by plants are increased when low-quality inputs are used, impacting the crop's yield and level of heavy metal in soil. Heavy metal concentrations have a negative influence on soil biota and other features (Muchuweti et al. 2006). Health risks are associated with elevated levels of heavy metals in soil and plant components, which can harm humans (Meena et al. 2020a). Toxic heavy metals can enter the human body from the soil through plants (Solanki et al. 2020). This means that identifying the numerous methods by which heavy metals are transported from soil to plants is vital. There are a variety of factors that influence how heavy metals accumulate in agricultural plants (Dotaniya

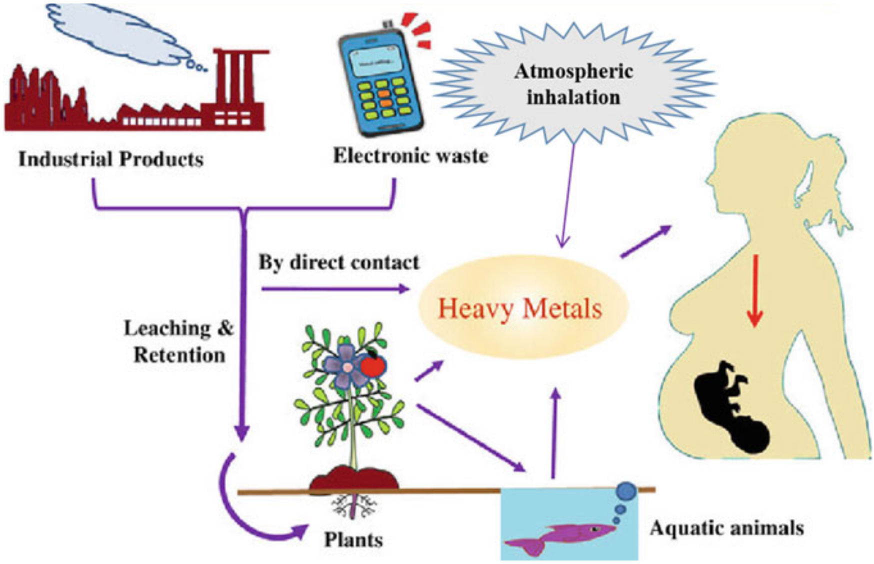

Fig. 1 Heavy metal pathway in human

et al. 2020b). Some plants are better at absorbing metal particles than others. For the transfer coefficient, the bio-concentration factor and accumulation factor are utilized (Rattan et al. 2005; Dotaniya et al. 2020c). It is more likely that heavy metal contamination will arise in peri-urban areas with sewage or polluted water (O' Connor et al. 2018a, b). Heavily contaminated vegetables provide a greater threat to human health than other crops (Dotaniya et al. 2020a; Meena et al. 2020b). Toxic metal ingestion inhibits the operation of other metal ions as well as the immune system, resulting in stunted growth, poor mental development as well as other human impairments (Fig. 1) (Iyengar and Nair 2000; Türkdogan et al. 2003).

5 Role of Biochar in Agriculture

Farmers in developing countries burn more than 10 billion tonnes of crop waste in their fields each year. This contributes to the release of 16.6 billion tonnes of CO_2, 11.2 billion tonnes of CO_{2e}, 1.1 billion tonnes of smog precursors and 65.7 million tonnes of $PM_{2.5}$ into the atmosphere. Crop waste burning produces enough CO_2 and CO_{2e} emissions to equal the annual emissions of 714 coal-fired power plants. Instead of burning the waste, converting it into biochar removes three tonnes of CO_2 from the atmosphere for every tonne produced; when added to fields as a soil amendment carbon is permanently sequestered. The use of biochar in soil remediation provides a number of environmental benefits that are consistent with GSR (Shen et al. 2019). For example, (1) biochar can be made from agricultural, household or industrial waste;

(2) co-products of biochar pyrolysis, such as syngas and bio-oil, can be used as green energy sources; (3) biochar can help increase soil fertility by adding nutrients or improving soil structure or pH and (4) biochar production converging.

Climate change is threatening global food security. Farmers who use biochar as a soil amendment will benefit in terms of higher yields, healthier soil, lower acidity, better water retention, stronger plants, richer soil life, less contamination, higher fertility and better seed germination (Novotny et al. 2015). Because of its high moisture adsorption capacity, it is extremely useful in reducing mildew in damp areas. Biochar adsorption properties make it an ideal solution for soil pollution remediation (Tripathi et al. 2016). The long-term benefits of producing biochar include a significant reduction in greenhouse gases, which contribute to global warming (Sullivan and Ball 2012). It is widely acknowledged as a powerful solution for reducing global warming.

5.1 Properties of biochar

5.1.1 Larger surface area

Biochar is a porous carbonaceous material that can hold massive amounts of water. The porous structure of biochar also serves as an excellent habitat for soil microbes. Larger surface areas are helpful for regulating the nutrient concentration in soil solution (Cao et al. 2018; Sakhiya et al. 2020). The pore size of biochar varies greatly, with nanopores (0.9 nm), micropores (2 nm) and macropores (>50 nm). When pyrolysed at 800 °C, biochar made from malt wasted rootlets had a surface area of 340 m^2/g and a porosity of 0.21 cm^3/g (Manariotis et al. 2015). Manure and biosolid biochar have a substantially lesser surface area (5.4–94.2 m^2/g) than plant biochar (112–642 m^2/g) such as wheat, oak wood, maize stover and pine needles (Li et al. 2017).

5.1.2 pH value

Plants prefer soil with a pH of 6.5–7, but most soils in the developing world are acidic to very acidic (4–5.5). Even if nutrients are present in the soil, most plants cannot absorb them in acidic soils. The addition of biochar to such soils raises the pH by up to a whole point. More nutrients become available to crops as the pH rises.

5.1.3 Cation exchange capacity

Composting of biochar with calcium, iron, magnesium, phosphorous, potassium and sulphur may enhance the nutrient efficiency. Biochar provides long-lasting, slow-release nutrition effect on crop. Biochar in a heavy metal-contaminated field can make cadmium, lead or mercury chemically bound to it (adsorbed), where plants will no longer take them up and water will no longer wash them away. The cation exchange capacity (CEC) of biochar is an important property for improving soil nutrient retention and reducing fertilizer runoff. However, CEC estimations for biochar in the literature are highly diverse, ranging from 5 to 50 cmol (+)/kg and even reaching as high as 69–204 cmol (+)/kg (Munera-Echeverri et al. 2018).

5.1.4 Carbon substrates in soil

Plants cannot consume their elements in their natural state. They cannot just suck up nitrogen, no matter how much they need it; they need microbes to digest it first and release it out as nitrates or nitrites. Because of its high carbon content (60–90%) (McGlashan et al. 2012), the incorporation of biochar into soils is regarded as a significant and long-term approach to sinking atmospheric CO_2 in terrestrial ecosystems. Aside from the benefits of reduced emissions and GHG sequestration, biochar has a number of positive effects on soil quality (Lehmann and Joseph 2015). Adding biochar to soils boosts crop production by improving soil physico-chemical and biological properties such as water retention, pH and microbial activity (Ahmad et al. 2014). Furthermore, because of the lower fertilizer requirements, biochar can help to reduce agricultural emissions from fertilizer use (McGlashan et al. 2012).

6 Remediation methods of heavy metal from ecosystems

On the basis of practicality and resources, several types of remediation technologies are being used to remove heavy metals from the environment (Solanki et al. 2020). Metal concentration, shape and kind, as well as moisture in the soil, have a key role in the removal of heavy metals from ecosystems (Meena et al. 2020b). A brief description is given in Table 6.

6.1 Role of biochar in heavy metal remediation

Biochar comes under chemical remediation strategy for heavy metals removal. It is an environment-friendly method of removing heavy metals from the soil. In addition

Table 6 Heavy metal remediation methods

Method	Mode of action	Descriptions
Physical	Physical removal, filtration, scrapping	Heavy metal polluted soil is removed from the field, metal-contaminated waste is pre-filtered before being dumped, contaminated locations are segregated and pollutants are contained, preventing off-site dispersion and on-site bio-exposure to the contaminants
Chemical	Addition of organic and inorganic substances, chemical precipitation, adsorption, ion exchange, membrane filtration, coagulation-flocculation and floatation process	Metals are immobilized, and other than binding agents, stabilization, precipitation reagents/stabilizing chemicals are added into the contaminated soil to create physio-chemical interactions between the stabilizing reagents and heavy metals, reducing their mobility
Biological	Microbial bioremediation—use of microorganisms to break out pollutants by feeding them. Bioaugmentation is a technique that involves biostimulation.	Use of microorganisms to reduce the heavy metal concentration in soil
	Mycoremediation**—**breaks down of pollutants such as pesticide, hydrocarbon and heavy metals with the help of fungus' digestive enzymes	Use of the different fungal population to reduce heavy metal toxicity in soil–water systems
	Phytoremediation techniques—plant-based methods are used to bind, remove and clean up contaminants such as pesticides, petroleum hydrocarbons, metals and chlorinated solvents	*Phytodegradation* is breakdown of organic pollutants by internal and external metabolic processes triggered by the plant. *In Phytovolatilization,* plants absorb water-soluble pollutants and release them into the atmosphere as they transpire water. *Rhizofiltration* is similar to phytoextraction in concept, but it focuses on the treatment of contaminated groundwater rather than damaged soils. *Rhizodegradation* (also known as improved rhizosphere biodegradation, phytostimulation and plant-assisted bioremediation) is the process of soil-dwelling bacteria breaking down organic pollutants in the soil, which is aided by the presence of the rhizosphere. *Phytostabilization* is the use of plants (*Festuca rubra* L, *Agrostis tenuis*) to immobilize pollutants in soil and water.

to metal removal, it also adds nutrient-rich compounds to the soil that enhances crop output (Meena et al. 2021).

Recent biochar research basically explains two methods of adsorption by biochar: first, direct adsorption, and second, improving the physico-chemical properties of soil such as pH, CEC, mineral and organic matter (OM) content (He et al. 2019a, b; Wang et al. 2021). Physical sorption, ion exchange, electrostatic interaction, precipitation and complexation are some of the mechanisms involved in controlling the removal of heavy metals from polluted soils via direct adsorption by biochar (Dotaniya et al. 2016; Inyang et al. 2016). The surface of biochar possesses various functional groups, including hydroxyl, carbonyl and carboxyl (Tan et al. 2015), and their abundance is the most important factor for regulating the sorption-based heavy metal stabilization (Guo et al. 2020). Organic matter in the soil can assist reduction of trace metal availability in the soil solution, which can harm agricultural plant nutrition and growth (Zhang et al. 2017).

Researchers have suggested utilizing biochar as a binder to immobilize heavy metals from soil systems. It is used as a soil conditioner because it is high in organic carbon. Plants that have a higher capacity for water absorption have a better ability to transfer nutrients around. There is also an increase in cation exchange capacity as well as the ability to absorb heavy metals, resulting in a less contaminated soil solution. Biochar functions as a climate change mediator and enhances soil carbon sequestration, according to Hayyat et al. (2016).

For soil microbial populations, biochar application increases the amount of soil organic carbon and food sources that are available to them. By altering microbial community composition (Igalavithana et al. 2017), increasing variety (Cheng et al. 2018), and therefore stimulating particular microbial activities, soil biochemical cycles can be improved, increasing nutrient absorption and crop yield (Hayat et al. 2010). *Rhizobacteria* (bacteria belonging to the groups; *Azospirillum, Enterobacter, Klebsiella* and *Pseudomonas*) can be directly influenced by biochar-induced alterations in plant development (Tu et al. 2020). It has been observed that biochar reduces the accessible heavy metal concentration by 55.5% (Ahmad et al. 2014), while another study found that it reduces acid-soluble $Pb^{2,3+}$ and Cu^{2+} by 18.8–77.0 and 19.7–100.0%, respectively.

Pyrolysis temperature of biochar and the chemical composition of the biomass have an impact on the adsorption capacity of biochar (Uchimiya et al. 2011; Xu et al. 2014). Biochar is commonly added to heavy metal-contaminated soil to raise its pH (Seneviratne et al. 2017; Soudek et al. 2017). This is largely due to variations in raw material that results in varying amounts of alkaline ash. Biochar made from mineral-rich raw materials that are pyrolyzed at high temperatures have a high ash content that results in soil alkalization (Cao and Harris 2010; Lehmann et al. 2011). In general, adding charcoal and raising the soil pH reduce the competition for sorption sites between H^+ and metal cations (Mn^+), lowering the mobility and availability of heavy metals in the soil (Gomez-Eyles et al. 2013).

The efficiency of bioavailability is affected by the biochar's source material, pyrolysis temperature, metal form and concentration and soil characteristics. Biochar incorporation creates various carbon–metal complexes in soil and aquatic systems, lowering metal bioavailability. The coordination of metal electrons to C=C (-electron) bonds in peat moss biochar decreases the mobility and bioavailability of copper, cadmium and lead (Park et al. 2016). Heavy metal bioavailability is reduced due to the presence of biochar functional groups and their affinity for heavy metals. Table 7 lists some of the biochar and their effects on availability of heavy metals in soil.

Table 7 Type of biochar and their effect on bioavailability of heavy metals in soil

Raw materials	Production temperature(°C)	Metal (s)	Effect/reaction	References
Rice straw	–	Cd, Cu, Pb	Lower down the bioavailability of Cu, Pb, Cd	Jianga et al. (2012)
Wheat straw	485	Cd, Pb	Reduced concentration of metal in dry soil conditions	Sui et al. (2018)
Cotton stacks	450	Cd	Enhance the adsorption and co-precipitation of Cd	Zhou et al. (2008)
Eucalyptus	550	As, Cd, Cu, Pb, Zn	Potential reduction of the Cd, Pb, Zn and Cd; enhance CEC and water retaining capacity	Namgay et al. (2010)
Sewage sludge	500	Cu, Ni, Zn, Cd, Pb	Reduction in bioavailability of metals	Méndez et al. (2013)
Pigeon pea straw		Cu	Reduce Cu toxicity	Coumar et al. (2016a,b)
Wood	450	As	Immobilization of As	Hartley et al. (2009)
Oakwood	400	Pb	Bioavailability reduced more than 75% whereas bio-accessibility reduced by 12.5%	Ahmad et al. (2012)
Chicken manure	550	Cr	Promote conversion rate of hexavalent Cr to trivalent Cr	Choppala et al. (2012)
Bamboo wood	750	Cd, Pb	Less plant uptake of Cd and Pb	Xu et al. (2016)
Coconut husk, sewage sludge	500	Cu	Reduce bioavailability of Cu	Li et al. (2019); Gonzaga et al. (2020)

Cheng et al. (2018) demonstrated that an increase in soil microbial richness and diversity, caused by a rise in pH from using biochar, results in favourable physico-chemical changes of the soil as well as an increase in the supply of accessible nutrients. Some of the positive and negative effects of biochar on soil properties are listed in Table 8.

Limitations of biochar applications:

1. High CEC may help in adsorption of heavy metal in biochar and release it during the high crop growth stages by release of root exudates.
2. The present experiments of use of biochar for heavy metals are limited to lab scale. It is critical to make biochar for practical field use. Future research should focus on improving the biochar pyrolysis process to fully exploit its potential for treating metal-contaminated environment.
3. Biochar aged in soil inhibits the growth of earthworms and/or fungi.
4. Use of biochar at high rates (15 t/ha) induces increased weed growth and immobilized plant nutrients.
5. Higher application of biochar may also disturb the soil organic matter decomposition rate by mediating the soil microbial population and diversity.

7 Conclusions and future prospects

A rise in industrial pollution has caused negative impact on soil health and food crop productivity. One of the biggest challenges is heavy metal toxicity, as these are very harmful for the health of environment. Biochar improves soil fertility for sustained crop production and it is an option worth considering to maintain the health of soil. Biochar has a high carbon-sequestration capacity and is climate robust. Larger surface area and CEC improve adsorption capacity, resulting in increased heavy metal immobilization. It also improves soil fertility and nutrient mineralization over time by regulating the variety and count of soil microbes. The stable C pool increased and CO_2 emissions from the soil are reduced under biochar application. More study should be done to know the effects of biochar immobilized heavy metals on the rhizospheric characteristics over time.

Table 8 Biochar effect on soil properties

Process	Positive changes	Negative changes
Abiotic: physico-chemical changes of the soil	• Reduction of heavy metal mobility, bioavailability and solubility to levels below the hazardous regulatory threshold • Increased soil pH, CEC and ECE • Increased soil organic matter, quantity of easily accessible C substrates, soil TOC and N status • Stabilization of soil aggregates • Increased soil WHC and decreased leaching of nutrients and heavy metals	• Some heavy metals are more mobile in biochar (indicating that albeit biochar application reduces heavy metal mobility, some biochar may also increase it) • Decreased availability of nutrients under conditions of increased biochar dose • Reduced soil N availability when biochar dose is increased
Biotic: microbiological and biological changes of the soil	• Improved microbial community composition and structure • Increased bacterial richness and diversity • Increased microbial respiration, microbial C utilization efficiency and microbial biomass C, N and P • Increased enzymatic activity	• Reduced relative concentrations of some bacteria (including the dominant species) at high biochar rates, with the prospect that biochar application would alter the indigenous microbial community • Increased earthworm mortality at high biochar rate • Reduced Arthropod reproductive stimulation at high biochar rate
Effects on plants, food chain and the environment	• Reduced abiotic stress that enhances soil fertility, seed germination, root characteristics, plant development and biomass output • Increased chlorophyll, protein and carbohydrates • Lower heavy metal root absorption and migration to above ground plant parts (i.e. shoots, leaves) and reduced heavy metal concentrations (phytotoxicity) in edible plant parts (i.e. fruits and grains) • Reduced heavy metal contamination in the food chain • Reduced leaching and danger of heavy metal migration to aquatic, biotic and abiotic environments	• No improvement in plant growth with increasing biochar application • Decreased heavy metal absorption in wet and flooded soil conditions than in dry and draught soil situations

References

Ahmad M, Lee SS, Yang JE, Ro HM, Lee YH, Ok YS (2012) Effects of soil dilution and amendments (mussel shell, cow bone, and biochar) on Pb availability and phytotoxicity in military shooting range soil. Ecotoxicol Environ Saf 79:225–231

Ahmad M, Rajapaksha AU, Lim JE, Zhang M, Bolan N, Mohan D et al (2014) Biochar as a sorbent for contaminant management in soil and water: a review. Chemosphere 99:1933

Beyersmann D, Hartwig A (2008) Carcinogenic metal compounds: recent insight into molecular and cellular mechanisms. Arch Toxicol 82(8):493–512

Cao X, Harris W (2010) Properties of dairy-manure-derived biochar pertinent to its potential use in remediation. Biores Technol 101:5222–5228

Cao Y, Gao Y, Qi Y, Li J (2018) Biochar-enhanced composts reduce the potential leaching of nutrients and heavy metals and suppress plant-parasitic nematodes in excessively fertilized cucumber soils. Environ Sci Pollu Res Intl 25(8):7589–7599

Cheng J, Li Y, Gao W, Chen Y, Pan W, Lee X, Tang Y (2018) Effects of biochar on Cd and Pb mobility and microbial community composition in a calcareous soil planted with tobacco. Biol Fert Soils 54:373–383

Choppala GK, Bolan NS, Mallavarapu M, Chen Z, Naidu R (2012) The influence of biochar and black carbon on reduction and bioavailability of chromate in soils. J Environ Qual 41:1–10

Coumar MV, Parihar RS, Dwivedi AK, Saha JK, Lakaria BL, Biswas AK, Rajendiran S, Dotaniya ML, Kundu S (2016a) Pigeon pea biochar as a soil amendment to repress copper mobility in soil and its uptake by spinach. BioRes 11(1):1585–1595

Coumar MV, Parihar RS, Dwivedi AK, Saha JK, Rajendiran S, Dotaniya ML, Kundu S (2016b) Impact of pigeon pea biochar on cadmium mobility in soil and transfer rate to leafy vegetable spinach. Environ Monit Assess 188:31

CPCB (2009) Sewage treatment in India. Central Pollution Control Board, New Delhi

Dotaniya ML, Aparna K, Choudhary J, Dotaniya CK, Solanki P, Narwal E, Kumar K, Doutaniya RK, Lal R, Meena BL, Lata M, Singh M, Singh U (2020a) Effect of soil pollution on soil microbial diversity. In: Nayak SK, Mishra SK (eds) Frontiers in soil and environmental microbiology. CRC Press, New York, pp 255–272

Dotaniya ML, Rajendiran S, Meena VD, Coumar MV, Saha JK, Bhogal NS, Patra AK (2020b) Comparative evaluation of phytoremediation potential of Indian mustard (Brassica juncea) varieties under sewage irrigated sites. J Indian Soc Soil Sci 68(4):450–457

Dotaniya ML, Das H, Meena VD (2014a) Assessment of chromium efficacy on germination, root elongation, and coleoptile growth of wheat (*Triticuma estivum* L.) at different growth periods. Environ Monit Assess 186:2957–2963

Dotaniya ML, Datta SC, Biswas DR, Dotaniya CK, Meena BL, Rajendiran S, Regar KL, Lata M (2016) Use of sugarcane industrial by products for improving sugarcane productivity and soil health-a review. Intl J Recyc Org Waste Agric 5(3):185–194

Dotaniya ML, Dotaniya CK, Kumar K, Doutaniya RK, Meena HM, Shirale AO, Meena MD, Meena VD, Kumar R, Meena BP, Kumawat N, Lal Roshan, Lata M, Singh M, Singh U, Meena AL, Kuri BR, Rai PK (2020b) Type of soil pollutant and their degradation: methods and challenges. Handbook of nanomaterials and nanocomposites for energy and environmental applications. Springer, pp 1–32

Dotaniya ML, Dotaniya CK, Solanki P, Meena VD, Doutaniya RK (2020c) Lead contamination and its dynamics in soil–plant system. In: Gupta D, Chatterjee S, Walther C (eds) Lead in plants and the environment. Radionuclides and heavy metals in the environment. Springer, pp 83–98

Dotaniya ML, Meena VD, Das H (2014b) Chromium toxicity on seed germination, root elongation and coleoptile growth of pigeon pea (*Cajanus cajan*). Legume Res 37(2):225–227

Dotaniya ML, Meena VD, Rajendiran S, Coumar MV, Saha JK, Kundu S, Patra AK (2017) Geo-accumulation indices of heavy metals in soil and groundwater of Kanpur, India under long term irrigation of tannery effluent. Bull Environ Conta Toxic 98(5):706–711

Dotaniya ML, Meena VD, Saha JK, Rajendiran S, Patra AK, Dotaniya CK, Meena HM, Kumar K, Meena BP (2018a) Environmental impact measurements: tool and techniques. In: Martínez L, Kharissova O, Kharisov B (eds) Handbook of ecomaterials. Springer, Cham. https://doi.org/10.1007/978-3-319-48281-1_60-1
Dotaniya ML, Panwar NR, Meena VD, Regar KL, Lata M, Saha JK (2018b) Bioremediation of metal contaminated soils for sustainable crop production. In: Meena VS (ed) Role of rhizospheric microbes in soil. Springer International, pp 143–173
Dotaniya ML, Saha JK, Rajendiran S, Coumar MV, Meena VD, Das H, Kumar A, Patra AK (2019a) Reducing chromium uptake through application of calcium and sodium in spinach. Environ Monit Assess 191:754
Dotaniya ML, Saha JK, Rajendiran S, Coumar MV, Meena VD, Kundu S, Patra AK (2019b) Chromium toxicity mediated by application of chloride and sulphate ions in Vertisol of Central India. Environ Monit Assess 191:429
Dotaniya ML, Meena VD, Saha JK, Dotaniya CK, Mahmoud AED, Meena BL, Meena MD, Sanwal RC, Meena Rs, Doutaniya RK, Solanki P, Lata M, Rai PK (2022a) Use of poor quality water for sustainable cropproduction in changing scenario of climate change. Environ Develop Sust. Article no. 2365:1–20
Dotaniya ML, Pipalde JS, Jain RC, Rajendiran S, Gupta SC, Vyas MD, Coumar MV, Sahoo S, Saha JK, Kumar A (2022b) Nickel-mediated lead dynamics and their interactive effect on lead partitioning and phytoremediation indices in spinach. Environ Monit Assess 194:334
Emiko F, Will M (2017) Economic growth, convergence, and world food demand and supply. Policy Research Working Paper 8257, World Bank
Foresight (2011) The future of food and farming. Executive summary. The Government Office for Science, London. https://www.gov.uk/government/publications/future-of-foodand-farming.
Ghosh AB, Hasan R (1980) Nitrogen fertility of soils of India. Fert News 15(11):19–24
Gomez-Eyles JL, Beesley L, Moreno-Jimenez E, Ghosh U, Sizmur T (2013) The potential of biochar amendments to remediate contaminated soils. In: Ladygina N, Rineau F (eds) Biochar and Soil Biota, Florida. CRC Press, Taylor & Francis Group, pp 100–133
Gonzaga MIS, Matias MI de AS, Andrade KR, Jesus AN de, Cunha G da C, Andrade RS de, Santos JC de J (2020) Aged biochar changed copper availability and distribution among soil fractions and influenced corn seed germination in a copper-contaminated soil. Chemosphere 240:124828
Guo M, Song W, Tian J (2020) Biochar-facilitated soil remediation: mechanisms and efficacy variations. Front Environ Sci 8. https://doi.org/10.3389/fenvs.2020.521512
Haider FU, Liqun C, Coulter JA, Cheema SA, Wu J, Zhang R, Wenjun M, Farooq M (2021) Cadmium toxicity in plants: impacts and remediation strategies. Ecotoxic Environ Saf 211:111887
Hartley W, Dickinson NM, Riby P, Lepp NW (2009) Arsenic mobility in brown field soils amended with green waste compost or biochar and planted with Miscanthus. Environ Pollut 157:2654–2662
Hayat R, Ali S, Amara U, Khalid R, Ahmed I (2010) Soil beneficial bacteria and their role in plant growth promotion: a review. Ann Microbiol 60:579–598
Hayyat A, Javed M, Rasheed I, Ali S, Shahid MJ, Rizwan M, Javed MT, Ali Q (2016) Role of biochar in remediating heavy metals in soil. In: Ansari et al (eds) Phytoremediation. Springer, pp 421–437
He E, Yang Y, Xu Z, Qiu H, Yang F, Peijnenburg WJGM, Zhang W, Qiu R, Wang S (2019a) Two years of aging influences the distribution and lability of metal(loid)s in a contaminated soil amended with different biochars. Sci Total Environ 673:245–253
He L, Zhong H, Liu G, Dai Z, Brookes PC, Xu J (2019b) Remediation of heavy metal contaminated soils by biochar: mechanisms, potential risks and applications in China. Environ Pollu 252:846–855
Igalavithana AD, Lee SE, Lee YH, Tsang DCW, Rinklebe J, Kwon EE, Ok YS (2017) Heavy metal immobilization and microbial community abundance by vegetable waste and pine cone biochar of agricultural soils. Chemosphere 174:593–603

Inyang MI, Gao B, Yao Y, Xue Y, Zimmerman A, Mosa A, Pullammanappallil P, Ok YS, Gao B (2016) A review of biochar as a low-cost adsorbent for aqueous heavy metal removal. Environ Sci Technol 46:406–433

Iyengar V, Nair P (2000) Global outlook on nutrition and the environment: meeting the challenges of the next millennium. Sci Total Environ 249:331–346

Jianga J, Xua R, Jianga T, Li Z (2012) Immobilization of Cu(II), Pb(II) and Cd(II) by the addition of rice straw derived biochar to a simulated polluted Ultisol. J Hazard Mater 229–230:145–150

Kasprzak KS (2002) Oxidative DNA and protein damage in metal-induced toxicity and carcinogenesis. Free Radical Biol Med 32(10):958–967

Lehmann J, Rillig MC, Thies J, Masiello CA, Hockaday WC, Crowley D (2011) Biochar effects on soil biota—a review. Soil Biol Biochem 43:1812–1836

Lehmann J, Joseph S (2015) Biochar for environmental management: science, technology and implementation. Routledge, New York

Li HB, Xiao L, Evandro B et al (2017) Mechanisms of metal sorption by biochars: biochar characteristics and modifications. Chemosphere 178:466–478

Li J, Wang SL, Zheng L, Chen D, Wu Z, Xie Y, Wu W, Niazi NK, Ok YS, Rinklebe J, Wang H (2019) Sorption of lead in soil amended with coconut fiber biochar: geochemical and spectroscopic investigations. Geoderma 350:52–60

Manariotis ID, Fotopoulou KN, Karapanagioti HK (2015) Preparation and characterization of biochar sorbents produced from malt spent rootlets. Ind Enginee Chem Res 54(39):9577–9584

McGlashan N, Shah N, Caldecott B, Workman M (2012) High-level techno-economic assessment of negative emissions technologies. Process Saf Environ Prot 90(6):501510

Meena MD, Dotaniya ML, Meena MK, Meena BL, Meena KN, Doutaniya RK, Meena HS, Moharana PC, Rai PK (2021) Maturity indices as an index to evaluate the quality of sulphur enriched municipal solid waste compost using variable byproduct of sulphur. Waste Manage 126:180–190

Meena MK, Singh AK, Prasad LK, Islam A, Meena MD, Dotaniya ML, Singh HV, Yadav BL (2020a) Impact of arsenic-polluted groundwater on soil and produce quality: a food chain study. Environ Monit Assess 192:785

Meena VD, Dotaniya ML, Saha JK, Das H, Patra AK (2020b) Impact of lead contamination on agroecosystem and human health. In: Gupta D, Chatterjee S, Walther C (eds) Lead in plants and the environment. Radionuclides and heavy metals in the environment. Springer, pp 67–82

Méndez A, Tarquis AM, Saa-Requejo A, Guerrero F, Gascó G (2013) Influence of pyrolysis temperature on composted sewage sludge biochar priming effect in a loamy soil. Chemosphere 93:668–676

Minhas PS, Saha JK, Dotaniya ML, Saha A, Saha M (2021) Wastewater irrigation in India: current status, impacts and response options. Sci Total Environ 808:1–17

Motsara MR (2002) Available nitrogen, phosphorus and potassium status of Indian soils as depicted by soil fertiliser maps. Fert News 47(8):15–21

Muchuweti M, Birkett JW, Chinyanga E, Zvauya R et al (2006) Heavy metal content of vegetables irrigated with mixture of wastewater and sewage sludge in Zimbabwe: implications for human health. Agric Ecosys Environ 112:41–48

Munera-Echeverri JL, Martinsen V, Strand LT, Zivanovic V, Cornelissen G, Mulder J (2018) Cation exchange capacity of biochar: an urgent method modification. Sci Total Environ 642:190–197

Muralidharudu Y, Reddy K, Mandal BN, Rao A, Singh KN, Sonekar S (2011) GIS based soil fertility maps of different states of India. All India Coordinated Project on Soil Test Crop Response Correlatio. Indian Institute of Soil Science, Bhopal. Pp 1–224

Namgay T, Singh B, Singh BP (2010) Infl uence of biochar application to soil on the availability of As, Cd, Cu, Pb, and Zn to maize (*Zea mays* L.). Soil Res 48:638–647

Novotny EH, Maia CMB de F, Carvalho MT de M, Madari BE (2015) Biochar: pyrogenic carbon for agricultural use—a critical review. Revista Brasileira de Ciência do Solo 39(2):321–344

O'Connor D, Peng T, Li G, Wang S, Duan L, Mulder J, Cornelissen G, Cheng Z, Yang S, Hou D (2018a) Sulfur-modified rice husk biochar: a green method for the remediation of mercury contaminated soil. Sci Total Environ 621:819–826

O'Connor D, Peng T, Zhang J, Tsang DCW, Alessi DS, Shen Z, Bolan NS, Hou D (2018b) Biochar application for the remediation of heavy metal polluted land: a review of in situ field trials. Sci Total Environ 619–620:815–826

Pandey N, Sharma C (2002) Effect of heavy metals Co^{2+}, Ni^{2+} and Cd^{2+} on growth and metabolism of cabbage. Plant Sci 163:753–758

Park JH, Lee SJ, Lee ME, Chung JW (2016) Comparison of heavy metal immobilization in contaminated soils amended with peat moss and peat moss-derived biochar. Environ Sci Proc Impac 18:514–520

Patlolla A, Barnes C, Yedjou C, Velma V, Tchounwou PB (2009) Oxidative stress, DNA damage and antioxidant enzyme activity induced by hexavalent chromium in Sprague Dawley rats. Environ Toxicol 24(1):66–73

Ramamurthy B, Bajaj JC (1969) Available N, P and K status of Indian soils. Fert News 14(8):24–26

Rattan RK, Datta SP, Chhonkar PK, Suribabu K, Singh AK (2005) Long-term impact of irrigation with sewage effluents on heavy metal content in soils, crops and groundwater—a case study. Agric Ecosyst Environ 109:310–322

Saha JK, Rajendiran S, Coumar MV, Dotaniya ML, Kundu S, Patra AK (2017) Agriculture, soil and environment. Soil pollution—an emerging threat to agriculture. Springer, Singapore, pp 1–320

Sakhiya AK, Anand A, Kaushal P (2020) Production, activation, and applications of biochar in recent times. Springer, Singapore

Seneviratne M, Weerasundara L, Ok YS, Rinklebe JJ, Vithanage M (2017) Phytotoxicity attenuation in Vigna radiata under heavy metal stress at the presence of biochar and N fixing bacteria. J Environ Manage 186:293–300

Shen Z, Zhang Y, McMillan O, O'Connor D, Hou D (2019b) The use of biochar for sustainable treatment of contaminated soils. In: Hou D (ed) Sustainable remediation of contaminated soil and groundwater: materials, processes, and assessment. Elsevier

Singh D, Sharma NL, Singh CK, Sarkar SK, Singh I, Dotaniya ML (2020) Effect of chromium (VI) toxicity on morpho-physiological characteristics, yield, and yield components of two chickpea (*Cicer arietinum* L.) varieties. PLoS ONE 15(12):e0243032

Solanki P, Dotaniya ML, Khanna N, Meena SS, Rabha AK, Rawat S, Dotaniya CK, Srivastava RK (2020) Recent advances in bioremediation for clean-up of inorganic pollutant-contaminated soils. In: Nayak SK, Mishra SK (eds) Frontiers in soil and environmental microbiology. CRC Press, New York, pp 299–310

Soudek P, Rodriguez Valseca IM, Petrová Š, Song J, Vaněk T (2017) Characteristics of different types of biochar and effects on the toxicity of heavy metals to germinating sorghum seeds. J Geochem Explor 182:157–165

Sui F, Zuo J, Chen D, Li L, Pan G, Crowley DE (2018) Biochar effects on uptake of cadmium and lead by wheat in relation to annual precipitation: a 3-year field study. Environ Sci Pollu Res 25:3368–3377

Sullivan AL, Ball R (2012) Thermal decomposition and combustion chemistry of cellulosic biomass. Atmos Environ 47:133–141

Sutton DJ, Tchounwou PB (2007) Mercury induces the externalization of phosphatidylserine in human proximal tubule (HK-2) cells. Int J Environ Res Public Health 4(2):138–144

Sytar O, Kumar A, Latowski D et al (2013) Heavy metal-induced oxidative damage, defense reactions, and detoxification mechanisms in plants. Acta Physiol Plant 35:985–999

Tan X, Liu Y, Zeng G, Wang X, Hu X, Gu Y, Yang Z (2015) Application of biochar for the removal of pollutants from aqueous solutions. Chemosphere 125:70–85

Tchounwou PB, Centeno JA, Patlolla AK (2004a) Arsenic toxicity, mutagenesis and carcinogenesis—a health risk assessment and management approach. Mol Cell Biochem 255(1–2):47–55

Tchounwou PB, Yedjou CG, Foxx D, Ishaque A, Shen E (2004b) Lead-induced cytotoxicity and transcriptional activation of stress genes in human liver carcinoma cells (HepG2). Mol Cell Biochem 255(1–2):161–170

Tripathi M, Sahu JN, Ganesan P (2016) Effect of process parameters on production of biochar from biomass waste through pyrolysis: a review. Renew Sust Energ Rev 55:467–481

Tchounwou PB, Ishaque AB, Schneider J (2001) Cytotoxicity and transcriptional activation of stress genes in human liver carcinoma cells (HepG2) exposed to cadmium chloride. Mol Cellular Biochem 222(1–2):21–28

Tu C, Wei J, Guan F, Liu Y, Sun Y, Luo Y (2020) Biochar and bacteria inoculated biochar enhanced Cd and Cu immobilization and enzymatic activity in a polluted soil. Environ Int 137:105576

Türkdogan MK, Kilicel F, Kara K, Tuncer I, Uygan I (2003) Heavy metals in soil, vegetables and fruits in the endemic upper gastrointestinal cancer region of Turkey. Environ Toxicol Pharmacol 13:175–179

Uchimiya M, Wartelle LH, Klasson KT, Fortier CA, Lima IM (2011) Influence of pyrolysis temperature on biochar property and function as a heavy metal sorbent in soil. J Agric Food Chem 59:2501–2510

UNDESA (United Nations, Department of Economic and Social Affairs), Population Division (2015) World population prospects: the 2015 revision. United Nations, New York. https://en.wikipedia.org/wiki/Projections_of_population_growth#cite_note-UN-WPP-2015-4

UNEP (2014) Assessing global land use: balancing consumption with sustainable supply. In: Bringezu S, Schütz H, Pengue W, O'Brien M, Garcia F, Sims R et al (eds) A report of the working group on land and soils of the international resource panel. United Nations Environment Programme, Nairobi

Wang S, Shi X (2001) Molecular mechanisms of metal toxicity and carcinogenesis. Mol Cell Biochem 222(1–2):3–9

Wang J, Shi L, Zhai L, Zhang H, Wang S, Zou J, Shen Z, Lian C, Chen Y (2021) Analysis of the long-term effectiveness of biochar immobilization remediation on heavy metal contaminated soil and the potential environmental factors weakening the remediation effect: a review. Ecotoxicol Environ Saf 207:111261

Xu D, Zhao Y, Sun K, Gao B, Wang Z, Jin J, Zhang Z, Wang S, YanY LX, Wu F (2014) Cadmium adsorption on plant- and manure-derived biochar and biochar-amended sandy soils: Impact of bulk and surface properties. Chemosphere 11:320–326

Xu P, Sun CX, Ye XZ, Xiao WD, Zhang Q, Wang Q (2016) The effect of biochar and crop straws on heavy metal bioavailability and plant accumulation in a Cd and Pb polluted soil. Ecotoxicol Environ Saf 132:94–100

Zhang R, Zhang Y, Song L, Song X, Hanninen H, Wu J (2017) Biochar enhances nut quality of Torreya grandis and soil fertility under simulated nitrogen deposition. Forest Ecol Manage 391:321–329

Zhou JB, Deng CJ, Chen JL, Zhang QS (2008) Remediation effects of cotton stalk carbon on cadmium (Cd) contaminated soil. Ecol Environ 17:1857–1860