



REVIEW

Biochar Amendments in Soil: A Sustainable Approach for Mitigating Heavy Metal Stress in Plants

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ABSTRACT: Heavy metal (HM) accumulation in soil poses a major hazard to both ecological health and plant growth progressions. Cadmium (Cd), lead (Pb), copper (Cu), chromium (Cr), arsenic (As), zinc (Zn), and nickel (Ni) are examples of HMs that negatively impact the growth and development of plants, resulting in lower agricultural output and food safety concerns. Biochar (BC), a substance rich in carbon that is formed by pyrolyzing natural biomass, has demonstrated remarkable promise in reducing HM stress in polluted soils. Research has shown that BC effectively lowers plant uptake of metals, and enhances soil qualities, and encourages microbial activity. Besides, BC improves the fertility of soil, retention of water, and nutrient absorption, while it interacts with soil microbes to help mitigate the negative effects. However, a number of variables affect how effective BC is as a soil supplement, including the kind of BC used, the soil's characteristics, and the metal's qualities. This review delves into the mechanisms of BC's interactions with HMs, its potential to mitigate stress caused by different metals, and the factors that influence its efficiency. Furthermore, it draws attention to the drawbacks and difficulties associated with using BC in heavy-metal-contaminated soils, offering suggestions for future studies focused on maximizing its utilization for long-term soil rehabilitation and sustainable agriculture.

KEYWORDS: Biochar; heavy metal; microbial activity; plant growth; sustainable agriculture

1 Introduction

Heavy metal (HM)-contaminated soil is now a major environmental concern that is negatively affecting agricultural systems across the globe. Among the most concerning HMs are cadmium (Cd), Lead (Pb), copper (Cu), chromium (Cr), arsenic (As), zinc (Zn), and nickel (Ni). Of these, trace levels of Cu, Zn, and Ni are thought to be necessary for plant metabolism, as they play a part in growth and enzymatic processes. However, even at low concentrations, Cd, Pb, Cr, and As are toxic and pose serious dangers to species at all levels of the trophic chain. They are also known to have no metabolic function in plants [1]. Numerous human



actions, like factory discharges, atmospheric mining, pollutants, production along with processing activities, excessive application of fertilizers and pesticides, and inappropriate trash management, are responsible for the introduction of these metals into the soil [2]. With far-reaching impacts on human health and ecosystems, HMs present serious obstacles to plant growth, food safety, and soil health, after they're in the ground [3]. Moreover, HMs accumulate in human tissues after passing through the food chain and into the body.

One of the most hazardous HMs is Pb, which accumulates in plants and lingers in the environment, where it caused growth retardation, decreased metabolic processes, and a marked decrease in photosynthetic activity, with a possible 42% drop in root growth [4]. Pb poses serious health concerns to both humans and animals due to its high mobility in the soil-plant system, which raises the possibility that it will enter the food chain. Cd is another very poisonous metal that is readily assimilated by plants, even in minimal concentrations. It is frequently linked to phosphate fertilizers and industrial processes. It inhibits development, oxidative stress, and metabolic processes [5]. Strong carcinogens, such as Cr in its hexavalent form Cr(VI), are present in soils, which has a detrimental effect on the molecular, biochemical, and physiological characteristics of crops [6]. Small amounts of micronutrients are necessary for the development and growth of plants, however, when doses get higher, they can become toxic and interfere with metabolic and physiological functions. Cu, an essential micronutrient, becomes harmful at elevated levels, inhibiting root elongation, reducing nutrient uptake, and causing oxidative damage caused by reactive oxygen species (ROS) production [7]. Another crucial mineral, Zn, can be hazardous in excess and cause stunted root growth, decreased nutrient uptake, and decreased photosynthetic efficiency [8]. Furthermore, tiny levels of Ni, which are necessary, turn poisonous at large doses. This results in oxidative stress, reduced growth, and inhibition of seed germination, all of which lower plant vigor [9]. As, a naturally occurring element that influences the growth of roots, decreases photosynthetic activity and causes health hazards since it accumulates in edible plant portions [10]. Plants exposed to As experience oxidative stress due to the production of ROS from phosphorylation metabolic disruption and redox-driven activities such as methylation and As(V) reduction to As(III) [11]. Humans who consume food containing As on a regular basis run a serious risk of developing cancer, skin sores, and developmental problems [12].

Crop productivity is being impacted by the strain that population increase and global warming are placing on agriculture. Researchers are using methods like applying biochar to improve output and lessen the negative impacts of plant stress [13]. Biochar (BC), a carbon-rich substance, is produced by pyrolyzing organic biomass—such as wood, animal dung, and crop residues—under low oxygen levels [14]. For the creation of biochar, the pyrolysis temperature normally falls between 300°C and 700°C. Depending on the required qualities of the biochar, the heating rate typically ranges from 5°C/min to 30°C/min. Biochar with a higher carbon content and porosity is typically produced at higher temperatures and at quicker heating rates [15]. Recently, soil amendments have gained popularity among researchers and practitioners as a sustainable way to counteract the negative impacts of various HMs [16,17]. The BC offers numerous binding sites due to its porous structure and large surface area, making it particularly promising for various applications [16]. The interactions of BC, for example, hydrogen bonding, electrostatic forces, and hydrophobicity play a complex function in the adsorption of HMs and aromatic substances, particularly influenced by the surface functional groups [18]. Long-term soil remediation is aided by its high cation exchange capacity (CEC), which further stabilizes HMs in the ground by decreasing their leaching and mobility [19]. The HMs can be effectively removed from environments by modifying BC. The removal efficiency can reach up to 99% for Pb and Cr, and >90% for Cd, As, and Hg with BC application [20]. Furthermore, BC enhances the pH, aeration, water retention, and soil structure, which are all more beneficial for the growth of plants. Additionally, it engages in interactions with soil microorganisms, boosting microbial activity and encouraging HMs' natural abatement [15]. However, the effectiveness of BC can differ based on

the variables such as types of BC, HMs characteristics, surrounding factors, and soil qualities. Moreover, the production method significantly influences its adsorption capacity and immobilization potential in plants as well as soil.

This review investigates BC's effects in alleviating HM stress in plants, emphasizing its potential as an environmentally friendly soil supplement for polluted soils. Although BC has the potential to be used as a soil amendment for contaminated soils, little is known about how it interacts with various HMs. What effects does it have on different metals? What factors influence its effectiveness? Therefore, this review examines the mechanisms by which BC interacts with different HMs and the specific effects on various metals. Additionally, the review addresses the limitations and difficulties in applying BC on soils contaminated with HMs, offering insights into future research directions to enhance its use for soil remediation and sustainable agriculture.

2 Negative Effect of HMs on Plant Development and Growth

HMs such as As, Ni, Zn, Cu, Pb, Cd, and Cr are poisonous to plants and interfere with a number of biochemical and physiological functions, which adversely impact the growth, development, and production of plants (Fig. 1). In this section, we briefly discussed the negative consequences of different HMs in the development and growth of plants.

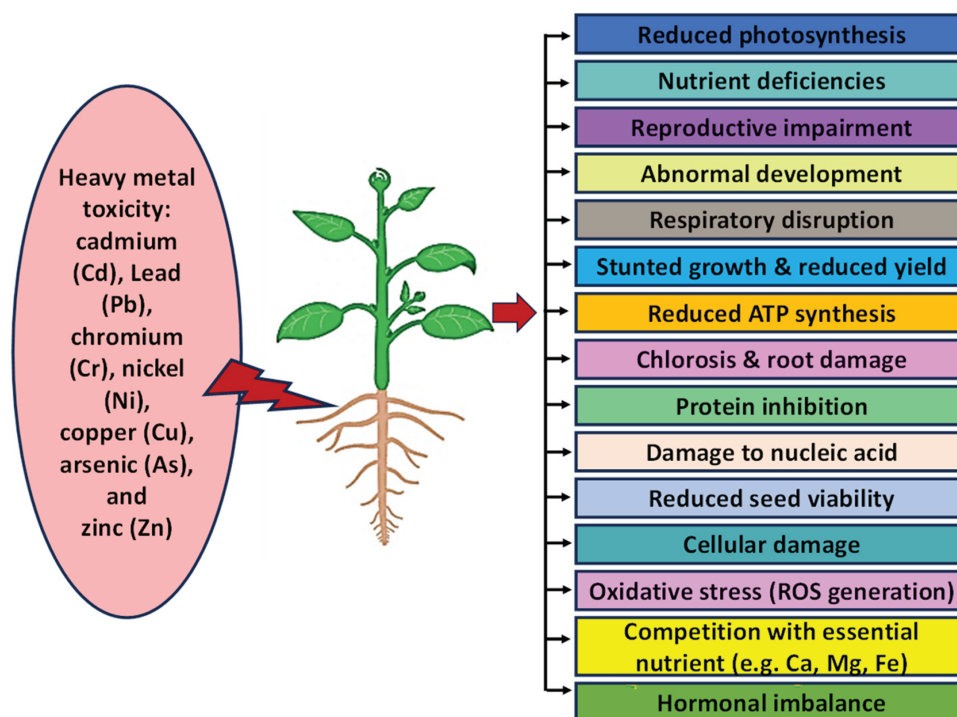


Figure 1: HMs' detrimental effects on plant development and progress of plant

The Pb is a toxic HM, which hampers nutrient uptake and causes oxidative stress and, consequently, hinders plant growth [4]. The Pb competes with vital elements such as iron and calcium, resulting in deficits that affect several physiological functions, including enzymatic activity, respiration, photosynthesis, and nutritional absorption [4,21]. It has been reported that decreased germination of seeds and unhealthy plants can also result from prolonged Pb pollution [22]. Leaves often display chlorosis due to decreased chlorophyll

synthesis, necrosis, and curling, which further diminishes photosynthetic efficiency [23]. Exposure to Pb prevents roots from growing longer, resulting in thicker, shorter roots with darker tips that are less able to absorb nutrients and water [24]. In shoots, Pb toxicity manifests as reduced plant height, smaller and malformed leaves, and overall stunted growth [25]. Visible symptoms such as leaf wilting, darkened root tips, and reduced canopy size are direct morphological indicators of Pb toxicity [26]. Pb exposure frequently causes aberrant development in flowers and fruits, such as decreased size and malformations, which further impairs the plants ability to reproduce [27].

The Pb also inhibits important mitochondrial enzymes, which lowers the synthesis of ATP and impacts cellular respiration in plant cells [28]. By causing oxidative stress and promoting ROS production, Pb damages lipids, proteins, and membranes, disrupting cellular structures and hormonal balance [29].

The Cd, even at extremely minute amounts (0.1–1 μM), can seriously hinder the growth and metabolism of plants [30]. It obstructs the intake and movement of vital nutrients and water, induces ROS production, and disrupts the photosynthetic system, which consequently kills tissues. According to reports, the production of chlorophyll is negatively impacted by Cd poisoning, which also decreases photosynthesis and tampers with water relations, hormonal balance, and nutritional homeostasis [30,31]. In addition, despite defense systems, Cd causes oxidative stress, interferes with nutrient transport, and lowers plant vitality and productivity [32,33].

The Cr is toxic to plants and affects various morpho-physiology in plants. This HM affects plants at different phases of their growth and development, causing serious abiotic stress. It hinders nutrient uptake and translocation, leading to reduced productivity [6]. It affects soil fertility, changes microbial activity, and inhibits plant growth [34]. According to reports, Cr disrupts chloroplast structures, impedes the growth of hypocotyls and epicotyls, and interferes with seed germination [35].

For plants, Cu is a necessary micronutrient. However, the elevated level of Cu may be hazardous and create abnormalities in the plant's physiology and biochemistry that hinder the growth [36]. It has been reported that Cu reduces the antioxidant enzymes, chlorophyll production, and mineral nutrition, which negatively impacts on photosynthesis, germination, and plant development [37]. According to reports, 25 μM Cu concentrations diminish phosphorus (P) input, hinder P absorption processes, and limit growth in the roots and shoots of plants. Furthermore, Cu poisoning may change the permeability of the root plasma membrane in these plants, further restricting the uptake of P [38].

One hazardous heavy element that seriously threatens plant health is As, adversely affecting physiological, biochemical, and structural processes. Plants exposed to As suffer from a number of negative consequences including disturbance in cell permeability and metabolic pathways, which leads to a reduction in plant biomass [10]. The As induced ROS and disrupted the mitochondria, peroxisomes, cell walls, plasma membranes, and chloroplasts [39].

A high concentration of Zn is considered as HM and its high concentrations in the soil can cause phytotoxicity, which damages plants by stunting growth, hampering photosynthesis and respiration, and lowering yield [40]. Zn is particularly toxic to plants because it is easily absorbed by them and is highly mobile and bioavailable. While less prevalent than Zn shortage, Zn poisoning in plants still carries serious dangers and can negatively impact ecosystem stability and agricultural productivity [8].

Plants suffer severe harm from Ni when it reaches lethal amounts because it disrupts several physiological functions. At poisonous concentrations, Ni damages plants by interfering with physiological processes. Reduced plant growth and production result from its effects on mineral absorption, photosynthesis, root growth, and enzyme activity [9]. The growth, biomass, and root characteristics of sweet potatoes are all

severely harmed by high Ni levels. Ni toxicity raises oxidative stress and decreases photosynthetic pigments, gas exchange, and relative water content (RWC) [41].

3 BC Amendments for HM Stress Mitigation

3.1 Lead (Pb) Stress Mitigation

BC amendments have been reported to mitigate Pb stress in different plants via different mechanisms (Table 1). The active functional groups, ion exchange capability, and microporous structure of BCs have all been shown to be significant factors in lowering HMs' bioavailability and mobility [42,43]. Application of varying BC rates in a Pb-polluted soil considerably decreases the extractability of Pb in ryegrass shoot (*Lolium multiflorum* Lam.) where the magnitude of the application directly influences the reduction of Pb [44]. According to Almaroai et al. [45], BC lowers maize shoot's Pb levels by attracting and retaining positively charged ions like Pb on its extremely negatively charged surface. Zheng et al. [46] examined how rice plants' metal mobility and iron plaque development changed as a result of amending BC in the Pb-contaminated soil and found that BC has the ability to decrease the translocation and accumulation of Pb in rice shoots. In addition, Ahmad et al. [47] found that applying BC was the most effective way to reduce Pb's phyto-availability and absorption which recommended it as a possible supplement to clean up Pb-contaminated soils [48,49]. Adejumo et al. [50] observed that higher rates of organic amendments, such as BC, and reduced light intensity led to a decrease in both post-cropping soil Pb content and the uptake of Pb by maize. As a result, compost and BC have been widely used to decrease soil metals and agricultural plants' absorption of Pb. Although BC shows superior efficiency in stabilizing Pb because of its alkaline pH and large surface area, some studies highlight the role of organic amendments like compost and BC in reducing Pb uptake [50,51]. Synergistic effects of BC with chelators like EDTA have also been reported for enhanced phytoextraction of Pb [52]. Hence, applying BC could help create a green layer over the trash to achieve long-term phyto-stabilization by the reduction of the bioavailability of HMs.

Table 1: Pb-induced stress mitigation by the application of BC on different plants

Plant species	HM concentration	BC rate and application methods	Effects & Outcomes	References
Ryegrass (<i>Lolium multiflorum</i> Lam.)	Pb 3110 mg kg ⁻¹ in Zn and Pb smelters)	BC 1%, 5%, and 10% (w/w)	Increased soil pH; Pb extractability reduced; decreased the concentration of Pb.	[44]
Wheat (<i>Triticum aestivum</i> L.)	Pb 717 mg kg ⁻¹ contaminated soil	BC 5% (w/w)	Decreased transfer coefficients of Pb; decreased initial shoot concentrations of Pb; reduced Pb accumulations.	[46]
Maize (<i>Zea mays</i> L.)	Pb 3970.65 mg kg ⁻¹	Application of BC in Pb-contaminated soils	Reduce Pb's phyto-availability and absorption.	[47]
	Pb 53,752 mg kg ⁻¹ industrially contaminated soil	BC 0, 2.5, 5, and 7.5 t ha ⁻¹ + mexican sunflower compost	Reduced oxidative stress; shortened post-cropping soil Pb concentration and uptake; enhanced maize growth.	[50]
	Pb 20 mg kg ⁻¹ spiked into 10 kg soil in pots	BC 0%, 0.5%, 1%, 2%, and 4% + compost	Efficiently stabilizes Pb in soil; reduces Pb toxicity.	[51]

(Continued)

Table 1 (continued)

Plant species	HM concentration	BC rate and application methods	Effects & Outcomes	References
	Pb 7.1–8.0 ppm contaminated irrigation water	BC 5- or 10-t ha ⁻¹	Adsorption, precipitation, and HM complexing; lessened concentrations of Pb.	[53]
	Pb 4626.39 mg kg ⁻¹ contaminated soil	Cow bone powder + BC + eggshell powder (5% w/w)	Negatively charged BC facilitates cation attraction; immobilizing substances reduce Pb bioavailability; decreased Pb concentration.	[45]
Tobacco (<i>Nicotiana tabacum</i> L.)	Pb 25.27 mg/kg (Yellow-brown soil), 76.53 mg/kg (Red soil)	BC 0.5% & 1% (HM-free BC + HM-rich BC) (w/w)	Increased soil pH; reduced phyto-availability of Pb; decreased the amount of Pb in soils; decreased of leaves, stem, and root's Pb content.	[54]
Orchard grass (<i>Dactylis glomerata</i> L.)	Pb 249, 220, 153, 198 mg kg ⁻¹ contaminated soil	BC 0%, 1%, 2.5%, and 5% (dry basis) (w/w)	Organic complexation and leaching of Pb; Reduces Pb toxicity; positive effects on plant growth.	[55]
Chinese mustard (<i>Brassica juncea</i> L.)	Pb 25 mg kg ⁻¹	BC 5% (w/w) + EDTA	Enhance Pb phyto-extraction; promote growth and survival; increase Pb uptake; maximize superoxide dismutase (SOD), POD, and catalase (CAT) activity.	[52]
Tomato (<i>Solanum lycopersicum</i> L.) and Spinach (<i>Spinacia oleracea</i> L.)	Pb 320 mg kg ⁻¹ , 2,250 mg Pb kg ⁻¹ contaminated soil	BCI 5- and 10-t ha ⁻¹ + PGPR + organic amendments	Immobilize Pb in soil; increase nutrient availability and uptake; minimize Pb toxicity.	[56]
Pea (<i>Pisum sativum</i> L.)	Pb 1000 ± 36.2 mg kg ⁻¹	BC (2%) + Bentonite (5%) + Iron Hydroxyl phosphate (2%) + Cement (0.5%) + Lignin (2%) (g/pot)	Reduced grain polyphenols and oxidative stress; greatest increase in plant height, shoot/root/grain DW, RWC, chl a/b, grain biochemistry, and micronutrients; lowest Pb in shoots, roots, and grain.	[57]
	Pb 3688 mg kg ⁻¹ mine soil	Sugar cane straw-derived BC 1.5%, 3.0% and 5.0% (w/w)	Phyto-stabilization reduces HM bioavailability; decreases Pb concentrations and uptake; reduces Pb in soil-water and mitigates leaching risks.	[49,58]

3.2 Chromium (Cr) Stress Mitigation

Among the HMs that represent the highest environmental and toxicological hazards, Cr is commonly recognized as one of the most severe and harmful pollutants that result from anthropogenic activity [45]. One kind of Cr that occurs naturally is trivalent chromium (Cr III). It is non-toxic, insoluble, and relatively less mobile [59]. Hexavalent chromium (Cr VI), on the other hand, is extremely soluble, mobile, and poisonous. It is created by human activity rather than occurring naturally. When hexavalent Cr is consumed

by contaminated food, the health risks are higher than those of Cr(III). Even at very low concentrations, it is also harmful to animals and plants [60–62]. When oxidizing agents (O_2 , CO_2 , NO_3 , SO_4^{2-} , and/or Mn(VI)) are present in the land environment, by removing electrons, Cr(III) is oxidized into its hazardous form, Cr(VI) [63].

BC lessens the harmful effect of Cr by lowering its levels in soil, plants, and water (Table 2). Its large porosity and surface area make it easier for processes including complexation, sorption, precipitation, and immobilization to occur, which lowers the bioavailability of Cr [64,65]. Applying BC to paddy rice reduced soil Cr accumulation and migration coefficients, with residual Cr rising as exchangeable Cr fell [66]. Likewise, BC reduced Cr bioaccumulation in tomato plants and alleviated poisoning symptoms by immobilizing Cr in soils contaminated by tannery waste and serpentine [67,68]. Additionally, research indicates that the combination of elemental sulfur (ES) and BC enhanced the physiological characteristics, stress tolerance, and plant development of maize. This included decreased oxidative stress and improved soil enzymatic activity, as well as increased biomass, chlorophyll content, photosynthesis, and nutrient uptake [63,69].

Table 2: Cr-induced stress mitigation by the application of BC on different plants

Plant species	HM concentration	BC rate and application methods	Effects & Outcomes	References
Rice (<i>Oryza sativa</i> L.)	Cr 0, 25, 50, 75 and 100 mg kg ⁻¹	Three levels of BC 20, 40 and 60-t ha ⁻¹	Increased the growth parameters; regulated migration coefficient and bioaccumulation coefficient; reduced the toxic effects of Cr.	[70]
	Cr 300 mg kg ⁻¹ (Cr(NO ₃) ₃ solution)	BC 1% (w/w)	Increased root biomass; reduced root Cr uptake; geobacter-enhanced Cr release via Fe dissolution; and limited Cr translocation.	[71]
Rye (<i>Secale cereale</i> L.)	Cr 109.83 mg kg ⁻¹	<i>Enteromorpha prolifera</i> -derived BC 5 to 30 g kg ⁻¹ of soil	Elevated soil residual Cr; decreased bioavailable Cr; reduced Cr transfer to rye; enhanced Cr detoxification in roots & Cr detoxification in stems.	[72]
Spinach (<i>Spinacia oleracea</i> L.)	Cr100 µM (29.40 mg using K ₂ Cr ₂ O ₇ of soil)	BC 5% (w/w) + selenium (Na ₂ SeO ₄) 1 mg L ⁻¹	Improved plant growth and antioxidant defenses; reduced Cr uptake and accumulation; decreased oxidative stress; reduced adverse effects of Cr.	[73]
Tomato (<i>Solanum lycopersicum</i> L.)	Cr 7.82 ± 0.91 mg kg ⁻¹ (Soil), 401.18 ± 5.23 mg kg ⁻¹ (Sewage sludge), 12.5 ± 0.03 mg kg ⁻¹ (Exchangeable Cr + 0.01 CaCl ₂), 12,285 ± 237 mg kg ⁻¹ (Tannery Waste Soil)	BC 2% (w/w) + sewage sludge; BC 1%, 2.5%, and 5% (w/w) + compost	Immobilized Cr in plant soil system; reduced bioaccumulation of Cr in plants; increased uptake of vital nutrients in tomato plants.	[67,68,74]

(Continued)

Table 2 (continued)

Plant species	HM concentration	BC rate and application methods	Effects & Outcomes	References
Maize (<i>Zea mays</i> L.)	Cr (VI) 12.45 ± 1.02 mg kg ⁻¹ , 18.62 ± 1.29 mg kg ⁻¹ (in two different soils), Cr (III) 40.02 ± 2.03 mg kg ⁻¹ , 54.94 ± 2.30 mg kg ⁻¹ (in two different soils) Pb 20 mg kg ⁻¹	BC 3% (w/w) + elemental sulfur; BC + compost + tannery waste polluted soils BC 0, 0.5, 1%, 2%, and 4% + compost	Decreased lipid peroxidation, proline, sugars, leakage, and antioxidant enzymes; increased growth, chlorophyll, photosynthesis, water, starch, and protein; decreased soil Cr levels and root/shoot absorption. Decreased the soil's concentration of Cr over time and decreased plant phytotoxicity.	[63,75,76] [51]
Water spinach (<i>Ipomoea aquatica</i> Forssk.)	Cr 67.54 mg kg ⁻¹ soil contamination	BC 2% w/w + Se	Enhanced soil urease, phosphatase, CAT, and sucrase activities; increased soil organic matter content and accessible NPK nutrients; decreased levels of Cr in the roots and shoots; decreased toxicity and absorption of Cr.	[69]
Chinese cabbage (<i>Brassica pekinensis</i> Lour.)	Cr 237 mg kg ⁻¹ potting soil	Sewage sludge BC was applied with infertile soil and polluted soil	Improve soil fertility; enhance plant growth; decrease plant uptake of HMs.	[77]
Summer squash (<i>Cucurbita pepo</i> L.)	Cr 163.72 mg kg ⁻¹	Mango, Casuarina and Salix feedstocks BC 2% and 4% (w/w)	Enhanced electrical conductivity, organic matter, and pH of the soil, HM immobilization; reduced the availability and plant uptake of HMs.	[78]
Rapeseed (<i>Brassica napus</i> L.)	Cr 53.95 ± 8.65 (Cu-MT), 46.55 ± 13.48 (RCG) and 36.76 ± 9.72 (HTCG) mg kg ⁻¹	BC 30, 60 g + raw coal gangue, Cu tailing, and hydrothermally treated gangue	Reduction in HM leaching and bioavailability.	[79]
Wheat (<i>Triticum aestivum</i> L.)	Cr 0, 50, 100, and 200 mg kg ⁻¹	BC 10% (w/w)	Reduced proline contents, POD, MDA, CAT, SOD, and H ₂ O ₂ activities in both shoots and roots; enhances the resilience of wheat plants against Cr contamination; improved overall plant health.	[80]

3.3 Cadmium (Cd) Stress Mitigation

Cd is extremely toxic which is recognized as a carcinogenic element posing a severe health risk to humans even in a minute concentration [81] (Table 3). The Cd contaminations in agricultural lands are mostly caused by human activities like the use of fertilizer, mining, irrigation with wastewater, and sewage

sludge application. Given that Cd is comparatively more soluble and mobile in soil-plant systems, it resulted in crop growth retardation, reduced yield, lower grain quality, and increased Cd absorption in the edible parts of the plant [82]. In the human body, Cd mainly enters through the consumption of Cd-accumulated grains and vegetables [83]. There are many proposed methods to mitigate Cd contamination in soil and one of the most effective methods is the addition of organic amendments like BC [84]. The BC additions enhance the physical and biological characteristics of the soil, including its texture, electrical conductivity, structure, pH, bulk density, and cation exchange capacity, in addition to its fertility status [85]. BC has a higher surface area and organic functional groups that sorb HMs from soil that ultimately reducing the phyto-availability of HMs [86]. Once more, various research has shown that applying BC lessens the negative effects of Cd in plants by restricting Cd accumulation via plant roots. Reduced root and shoot Cd content were found in lettuce, barley, wheat, sunflower, etc. through BC application under Cd-contaminated soil [75,87,88]. In order to provide safer food production and environmental sustainability, BC application is a potential method for lowering Cd uptake in crops.

Table 3: Cd-induced stress mitigation by the application of BC on different plants

Plant species	HM concentration	BC rate and application methods	Effects & Outcomes	References
Fenugreek (<i>Trigonella corniculata</i> L.)	Cd 0, 25, 50, 75 and 100 mg kg ⁻¹	BC 0%, 3% and 5% (w/w)	Enhanced plant growth and fresh and dry biomass; higher levels of carotenoids, anthocyanins, and chlorophyll (a, b, and total); decreased root and shoot Cd concentration.	[89]
Barley (<i>Hordeum vulgare</i> L.)	Cd contaminated soil	BC 20 t ha ⁻¹ (w/w)	Reduced grain Cd content.	[90]
Rapeseed (<i>Brassica napus</i> L.)	Cd 1.66 mg kg ⁻¹	Soil incorporates BC 1% (w/w)	Increased SOD, CAT, and POD; improved Cd mitigation capacity; increased N content in roots; decreased root and shoot Cd contents.	[91]
Chinese cabbage (<i>Brassica chinensis</i> L.)	Cd 41 mg kg ⁻¹	Soil application of BC 1.5% and 3% (w/w)	Increased growth and biomass; reduced bioaccessibility and Cd uptake in shoot and root.	[92]
Chinese cabbage (<i>Brassica chinensis</i> L.) and maize (<i>Zea mays</i> L.)	Cd 0, 5 and 50 mg kg ⁻¹	BC 0%, 0.5%, 1% and 1.5% (w/w)	Enhanced the growth of cabbage; diminished shoots Cd concentrations.	[93]
Forage maize (<i>Zea mays</i> L.)	Cd 5 mg L ⁻¹	Soil incorporated BC 0%, 1%, and 3% (w/w)	Increased root and shoot dry weight; reduced shoot Cd concentration.	[94]
Foxtail millet (<i>Setaria italica</i> L.)	Cd 0.83 mg kg ⁻¹	BC 2% (w/w)	Increased plant growth; alleviated oxidative stress; reduced Cd bioaccumulation in shoots.	[95]

(Continued)

Table 3 (continued)

Plant species	HM concentration	BC rate and application methods	Effects & Outcomes	References
Eggplant (<i>Solanum melongena</i> L.) + Green pepper (<i>Capsicum annuum</i> L.) + Chinese cabbage (<i>Brassica chinensis</i> L.) Lettuce (<i>Lactuca sativa</i> L.)	Cd 20 mg kg ⁻¹	Soil application of BC 5% (w/w)	Increased yield; decreased Cd concentration in vegetables.	[96]
	Cd 4 mg kg ⁻¹	BC 0%, 1%, 2%, and 5% (w/w)	Enhanced growth performance of plant; decreased Cd accumulation.	[97]
	HM-contaminated upland soil	Soil incorporated BC 0%, 0.5%, 1%, 2%, 5%, and 10% (v/v)	Reduced Cd uptake by plants.	[98]
	Cd 0, 40, 80, and 120 mg kg ⁻¹	Soil incorporated with BC	Increased plant growth parameters; increased carotenoids, total chlorophyll, and total soluble sugar.	[88]
Maize (<i>Zea mays</i> L.)	Cd 18.2 mg kg ⁻¹	Soil incorporated BC 2%, 5%, and 10% (w/w)	Enhanced growth parameters and antioxidants activity; reduced root and shoot Cd concentration.	[99]
	Cd 0.61 mg kg ⁻¹	Soil incorporated BC 0%, 2.5% and 5% (w/w)	Improved the fresh biomass, shoot height, leaf area (LA), and photosynthesis rate; Reduced the root-shoot Cd concentrations.	[82]
	Cd 0.61 mg kg ⁻¹	BC 0%, 2.5% and 5% (w/w)	Increased the LA, fresh and dry root biomass, fresh and dry shoot biomass, and root-shoot length; increased photosynthesis rate; reduced oxidative stress; decreased root-shoot Cd concentration.	[31]
	Cd 0.40 mg kg ⁻¹	Compost mixed BC 0%, 0.50%, 0.75% and 1.00% (w/w)	Increased levels of carotenoids, chlorophyll a, b, which means photosynthetic rate, transpiration rate, and stomatal conductance, and plant height, number of leaves, fresh weight, and root length.	[43]
	Cd 2.62 mg kg ⁻¹	Soil application of BC 1% (w/w)	Increased biomass of the crop; increased available nutrients; decreased Cd content in stem and grain.	[100]

(Continued)

Table 3 (continued)

Plant species	HM concentration	BC rate and application methods	Effects & Outcomes	References
Peanut (<i>Arachis hypogaea</i> L.)	Cd 1 mg kg ⁻¹	Soil application of BC 5%, crop straw 5%	Enhanced the biomass and physiological quality of seed; increased chlorophyll content, proline, and soluble sugar; decreased Cd concentration in plant.	[101]
Red amaranth (<i>Amaranthus tricolor</i> L.)	Cd 6.1 mg kg ⁻¹	BC 3% (w/w)	Increased plant biomass; reduced Cd concentration in root, shoot, and leaves.	[102]
Rice (<i>Oryza sativa</i> L.)	Cd 26.22 mg kg ⁻¹	BC 5% (w/w)	Decreased levels of Cd in rice tissues.	[103]
	Cd contaminated soil	BC 1.5% (w/w)	Decreased levels of Cd in rice shoots and roots.	[104]
	DTPA-Cd extracts in the 0–17 and 17–29 cm soil layer	BC 10, 20, 30, and 40 t ha ⁻¹	Limit rice's uptake of Cd, increase the amount of Cd enrichment in micro-aggregates, and decrease the amount of Cd available in the soil profile.	[105]
Soybean (<i>Glycine max</i> L.)	Cd 10, or 30 ppm	Soil incorporated BC 5% (w/w)	Increased plant biomass; higher levels of intercellular CO ₂ , stomatal conductance, photosynthetic rate, transpiration rate, chlorophyll content, and water usage efficiency; increased nutrient contents, and antioxidant enzyme activities; reduced ROS production; reduced plant root and shoot Cd concentration.	[31]
Fenugreek (<i>Trigonella corniculata</i> L.) and spinach (<i>Spinacia oleracea</i> L.)	Ammonium bicarbonate-diethylenetriaminepen taacetic acid 17/mg kg ⁻¹	BC 3%, 5% (w/w)	Enhanced plant development; higher levels of carotenoids and chlorophyll (a, b, and total); higher levels of soluble proteins and amino acids; lower levels of Cd in the roots and stems; and decreased Cd uptake.	[89]
Summer squash (<i>Cucurbita pepo</i> L.)	Cd 2.56 mg kg ⁻¹	Soil incorporated BC 2% and 4% (w/w)	Increased root and shoot dry weight; reduced root and shoot Cd concentrations.	[78]
Sunflower (<i>Helianthus annuus</i> L.)	Cd > 5 mg kg ⁻¹	BC 2% (w/w) mixed with soil	Enhanced plant development, increased biomass from fresh and dried shoot roots, increased chlorophyll levels, decreased physiological and toxicological stress, and decreased build-up of Cd in roots and shoots.	[106]

(Continued)

Table 3 (continued)

Plant species	HM concentration	BC rate and application methods	Effects & Outcomes	References
Tomato (<i>Solanum lycopersicum</i> L.)	Cd (2 mg L ⁻¹ + Cd 0.13 mg L ⁻¹ (sewage water))	Cotton stalks BC 1% (w/w)	Increased growth of plants, dry weight of roots and shoots; enhanced chl. <i>a</i> and <i>b</i> , anthocyanin, carotenoids, and lycopene; decreased shoot Cd concentration.	[107]
Wheat (<i>Triticum aestivum</i> L.)	Cd 15 mg kg ⁻¹	Soil incorporated BC 0, 50 g kg ⁻¹ (w/w)	Improved morphological and yield attributes; increased photosynthetic pigments (chlorophyll <i>a</i> , <i>b</i> , <i>a+b</i> , and <i>a/b</i>) carotenoid, enzymatic activities, lipid peroxidation, and osmo-protectants.	[108]
	Cd 2.86 mg kg ⁻¹	Soil application of BC 1.5%, 3.0%, and 5% (w/w)	Increased growth and yield; reduced the Cd concentration.	[87]
Mint plants (<i>Mentha crispa</i> L.)	Cd 60 mg kg ⁻¹ + fluoride	BC 25 g kg ⁻¹	Reduced fluoride and Cd toxicities; improved soil CEC, pH, LA, chlorophyll content, photosystem II efficiency, biomass, and essential oil production; decreased oxidative stress.	[109]

3.4 Copper (Cu) Stress Mitigation

Because of its detrimental effect on ecosystem food and health security, HM contamination in soil has drawn attention from all around the world. In contaminated soils, soil amendments such as BC can lower the bioavailability of HMs and lower the likelihood that they will reach the food chain. The impact of BC use on the buildup of HMs of Cu in several plants showed in Table 4. It has been suggested that incorporating BC into soil could be a significant way to lower emissions of greenhouse gases worldwide [110]. In contaminated soils, BC can reduce the bioavailability of metals, which could result in micronutrient shortages and decreased crop yields in agricultural contexts. The decrease in metal solubility caused by a higher soil pH or the direct binding of metals to BC surfaces could be the cause of this drop in bioavailability [111].

By lowering Cu bioavailability and promoting development, BC efficiently reduces Cu stress in a variety of plants. Citrus wood BC at doses of 1%–4% decreased Cu in sunflower [112], however BC at 1% enhanced enzyme activity and decreased Cu bioavailability and oxidative stress in lettuce [113]. 3% BC improved the development and physiological characteristics of maize cultivated in soils contaminated by tanneries [106,114]. P-loaded BC decreased HM forms in soils and enhanced phosphorus availability [64]. Applications of BC decreased Cu uptake and enhanced biomass and soil conditions in barley, quinoa, black beans, stonecrops, and soybeans [102,115–117]. However, by altering the degree of BC contact with the soil, the BC application techniques—such as integration vs. surface application—had an impact on Cu uptake and plant growth. Because incorporation allowed for better distribution and binding of Cu in the soil, it generally increased Cu immobilization and plant development more efficiently than surface application. Finally, BC

provides a sustainable remedy for HM contamination by reducing Cu toxicity, increasing plant growth, and improving soil health.

Table 4: Cu-induced stress mitigation by the application of BC on different plants

Plant species	HM concentration	BC rate and application methods	Effects & Outcomes	References
Sunflower (<i>Helianthus annuus</i> L.)	Cu fertilizer 50 and 200 mg/kg	Citrus wood BC 1%, 2% and 4% (w/w)	Significantly reduced available Cu in soil; lowered Cu concentration in aerial parts; and decreased overall Cu uptake by the plants.	[112]
Lettuce (<i>Lactuca sativa</i> L.)	Cu 100 mg kg ⁻¹	BC 1% (w/w)	Decreased the bioavailability of Cu; reduced H ₂ O ₂ formation; lowered cell membrane peroxidation; restored ascorbate levels and enzyme activity to control levels; and alleviated Cu-induced oxidative stress in lettuce.	[113]
Maize (<i>Zea mays</i> L.)	Soils in Kasur and Sialkot were contaminated by two separate tanneries that contained Cu	BC 3% (w/w)	Increased plant height, biomass, LA, pigments, RWC, and photosynthesis; decreased electrolyte leakage, antioxidant enzyme activity, proline content, lipid peroxidation, soluble sugars, and Cr concentrations in maize tissues.	[76]
	Cu @ 0 and 100 ppm	BC 1% and 2% (w/w)	Increased water holding capacity, macronutrient content, shoot growth, optimum growth of the plant and photosynthetic efficiency of Photosystem II; improved CO ₂ /H ₂ O gas exchange; reduced tissue Cu ²⁺ levels, ETR/Pg ratio, environmental risk, and phytotoxicity in soils.	[114]
	HMs contaminated soil containing Cu @ 3474 mg kg ⁻¹	P-loaded BC 5, 10, 20 and 30 g kg ⁻¹	Enhanced soil phosphorus availability; reduced labile HMs; stabilized HMs in soil; improved plant growth; mitigated wind and water erosion.	[118]

(Continued)

Table 4 (continued)

Plant species	HM concentration	BC rate and application methods	Effects & Outcomes	References
Barley (<i>Hordeum vulgare</i> L.)	HMs contaminated soil containing Cu 1430 mg kg ⁻¹	Soil application of BC 1%, 3%, and 5% w/w	Increased shoot biomass (dry) and soil moisture; soil bulk density reduced, extractable HMs (indicating effective immobilization); reduced shoot HM concentrations, phytotoxicity, and metal accessibility in contaminated soils.	[119]
	Cu 200 and 400 mg kg ⁻¹	Three BC types (coconut husks, orange bagasse, sewage sludge) 30 and 60 t ha ⁻¹	Reduced Cu availability; increased soil pH, organic matter, Cu distribution, and crop growth; long-term effectiveness.	[120]
	Cu 200 and 400 mg kg ⁻¹	Soil application of BC 2% w/w	Reduced Cu extractability and plant uptake; mitigated HM availability with minimal pH changes; greater metal reduction in rhizosphere soil than bulk soil; linked reduced plant uptake to ammonium nitrate extractability.	[121]
Stonecrops (<i>Sedum plumbizincicola</i>)	HMs contaminated soil containing Cu	Bamboo and rice straw BC 1% and 5% (w/w)	Increased the above-ground biomass and soil pH; significantly lowered the solubility of Cu and other HMs in soil; decreased HMs accumulation in plant biomass and in shoots.	[122]
Black beans (<i>Phaseolus vulgaris</i> L.)	Cu 1000 mg kg ⁻¹ of dry soil	BC 0.5%, 1.0%, 1.5%, and 2.0% mm ⁻¹ of dry soil	Lower the amount of Cu present in polluted soil and lower the amount of Cu in black bean roots, aerial parts, and grains.	[116]
Quinoa (<i>Chenopodium quinoa</i> Willd.)	Cu 50 and 200 µg g ⁻¹	Soil applicatuion of BC 2%, and 4% (w/w)	Improved plant performance; reduced Cu in tissues; enhanced CO ₂ exchange; increased biomass; Cu adsorption to BC; better water supply.	[115]
Sweet Corn (<i>Zea mays</i> L.) and Soybean (<i>Glycine max</i> L.)	Cu 200 and 400 mg kg ⁻¹	BC 2% and 5% (w/w)	Reduced Cu concentrations; decreased soil acid-soluble Cu and increased oxidizable Cu; improved Cu speciation and reduced toxicity in contaminated soil.	[117]

(Continued)

Table 4 (continued)

Plant species	HM concentration	BC rate and application methods	Effects & Outcomes	References
Tomato (<i>Solanum lycopersicum</i> L.)	Cu 150 mg kg ⁻¹	Glycine/alanine enriched BC 0.5% and 1% (w/w)	Enhanced root and shoot dry weight; decreased malondialdehyde and hydrogen peroxide levels; increased tomato fruit dry weight and juice content.	[123]
Ramie (<i>Boehmeria nivea</i> L.)	Soil from mining area available Cu 145.41 mg kg ⁻¹ and total Cu 2221.15 mg kg ⁻¹	Rice straw BC 2.5%, 5% and 10% (w/w)	Reduced oxidative stress; improved plant growth; increased chlorophyll and gas exchange; decreased Cu in roots, leaves, and stems; reduced soil bioavailable Cu.	[124]
Brown mustard (<i>Brassica juncea</i> L.)	Smelter and mine contaminated soils 0–20 cm depth in a 50 × 50 m ² area	Bamboo BC 1%, 2.5% and 5% (w/w)	Immobilized Cu in soil leads to increased pH and electrical conductivity (EC); decreased bioavailability and uptake of Cu; enhanced amounts of carotenoid and chlorophyll, increased shoot/root development and dry plant matter, and accelerated enzymatic activity (urease, alkaline phosphatase, and β -glucosidase), as well as improved antioxidant activities (PPO, POD, SOD, CAT).	[125]

3.5 Zinc (Zn) Stress Mitigation

In contaminated soils, BC can lower metal bioavailability [126]. This might possibly lock up metals in an agricultural setting, leading to micronutrient shortages and ultimately lowering output. This could be due to the metals adhering directly to the BC surfaces or the higher pH of the soil decreasing metal solubility [127]. Table 5 displays the reaction to organic amendments and how they affect the level of HMs (Zn) in plant tissues. The consequences of lower metal concentrations in plant tissues were noted for treatments using BC and the combination of BC. Several studies demonstrate that applying BC (1%–10% w/w) can immobilize Zn by increasing organic matter, altering the pH of the soil, and changing the form of Zn that is bioavailable into one that is less toxic. For example, BC dramatically boosted plant height, leaf number, water content, and photosynthesis in rubber plants (*Ficus elastica* Roxb.) under Zn stress, while decreasing lipid peroxidation and Zn bioavailability [128]. Similarly, BC applications in maize (*Z. mays*) significantly mitigated Zn toxicity, reducing metal concentrations in plant tissues and improving overall plant health [119]. In foxtail millet (*Setaria italica* L.), BC promoted plant growth and decreased oxidative stress by stabilizing Zn and reducing its bioavailability in the soil [95]. BC's ability to reduce Zn uptake in crops like tomatoes (*S. lycopersicum*) led to improved fruit yield and quality, enhancing key parameters like total acidity, vitamin C, and lycopene content [56]. Similarly, in ryegrass (*Lolium perenne* L.), BC reduced Zn accumulation in shoots, increased soil pH, and bolstered the soil's acid-neutralizing

capacity [44]. In vegetables like radish, lettuce, spinach, and parsley, BC application, either alone or in combination with compost, effectively regulated Zn mobility and decreased HM uptake, promoting healthier crop production [129]. BC from sources like bamboo, rice straw, or sewage sludge shows varying success in stabilizing Zn and improving soil fertility. For example, bamboo and rice straw BC increased plant biomass and reduced Zn solubility in stone crops, while sewage sludge BC decreased Zn availability and promoted healthier soil microbial activity in tomatoes [122,130]. In general, BC consistently improves soil properties, fertility, and mitigates HM toxicity, particularly Zn, making it a valuable tool for rehabilitating contaminated soils and promoting sustainable agriculture.

Table 5: Zn-induced stress mitigation by the application of BC on different plants

Plant species	HM concentration	BC rate and application methods	Effects & Outcomes	References
Rubber plant (<i>Ficus elastica</i> Roxb.)	Zn 880 mg kg ⁻¹	BC 1%, 3% and 5% (w/w)	Increased plant height, RWC, number of leaves, net photosynthesis rates, leaf transpiration; higher stomatal conductance; reduced lower lipid peroxidation, Zn bioavailability, Zn concentration in leaf tissue, and oxidative stress.	[128]
Foxtail millet (<i>Setaria italica</i> L.)	Total Zn 470 mg kg ⁻¹ ; DTPA-Zn 90.32 mg kg ⁻¹	BC 2% (w/w)	Alleviated Zn phytotoxicity; reduced DTPA-Zn content by stabilizing HMs; promoted growth; reduced oxidative stress; decreased HM bioaccumulation and transport; enhanced soil macrobiotic diversity and richness.	[95]
Maize (<i>Zea mays</i> L.)	Zn 5453 mg kg ⁻¹	BC 1%, 3%, and 5% (w/w)	Effectively mitigated Zn stress in maize plants by significantly decreasing Zn concentrations in plant tissues.	[119]
	Zn 981 mg kg ⁻¹	Sheep bone-derived BC 2%, 5%, and 10% (w/w)	Increased organic matter of soil, phosphorus, and total nitrogen; converted bioavailable Zn to less bioavailable and residual fractions; reduced Zn uptake in roots and shoots and improved soil enzyme activities (phosphatase and urease); promoting healthier plant growth and microbial activity.	[99]
Ryegrass (<i>Lolium perenne</i> L.)	Zn 12,980 mg kg ⁻¹	BC 1%, 5% and 10% (w/w)	Significantly reduced the extractability of Zn; reduced metal availability in shoots; and enhanced pH of soil and acid-neutralizing capacity.	[44]

(Continued)

Table 5 (continued)

Plant species	HM concentration	BC rate and application methods	Effects & Outcomes	References
<i>Bentgrass (Agrostis capillaris L.)</i> and white lupin (<i>Lupinus albus L.</i>)	Total Zn 3080 mg kg ⁻¹	BC 5% (w/w)	Lowered the metal's exchangeable pool in soil; reduced metal uptake.	[131]
Tomato (<i>Solanum lycopersicum L.</i>)	Total Zn 600 mg kg ⁻¹ ; DTPA-extractable Zn @ 8.8 mg kg ⁻¹	BC 5- and 10-t ha ⁻¹	Reduced metal concentrations in fruit, increased fruit yield; enhanced juice quality by improving total acidity, TSS, vitamin C, and lycopene content.	[56]
	Zn 421 mg kg ⁻¹	Sewage sludge BC 2%, 5%, and 10% (w/w)	Reduced the availability and uptake of Zn in tomatoes, mitigating both organic and inorganic contaminants in soils.	[130]
Barley (<i>Hordeum sativum</i>)	Zn approximately 220 mg kg ⁻¹	BC 2.5% and 5% (w/w) + Granular activated carbon	Diminished the availability of loosely bound Zn; decreased mobile metal forms; lowered metal absorption; improved soil fertility.	[132]
Mustard (<i>Brassica juncea L.</i>)	Total Zn 1018.61 mg kg ⁻¹ ; DTPA-extractable Zn @ 150.01 mg kg ⁻¹	BC 2%, 4%, and 6% (w/w)	Increased soil organic matter; enhanced EC; improved soil pH; promoted plant growth; reduced HM availability; elevated N and P in plant shoots.	[133]
Oat (<i>Avena sativa L.</i>)	Former sewage-field soil contaminated with Zn	Poplar-derived hydrochar and maize-derived pyrochar 1%, 2.5% and 5% g 100g ⁻¹	Increased biomass production; reduced Zn uptake by plants; potential for soil remediation; positive effect on plant growth.	[134]
Rice (<i>Oryza Sativa L.</i>)	Zn contaminated soil (near a mining area)	Straw, husk and bran-char 5% (w/w)	decreased the concentrations of Zn in shoots; reducing water concentrations of Zn and enhancing iron plaque formation on root surfaces.	[46]
	Zn 1578.67 mg kg ⁻¹	Wine lees-derived BC 0.5% and 1% (w/w)	Increased soil pH; decreased interchangeable HMs; promoted transformation to less bioavailable residual fractions; reduced HM accumulation in plants; decreased migration to aboveground parts; and lowered contents in leaves, stems, roots, rice, and rice husk.	[66]

(Continued)

Table 5 (continued)

Plant species	HM concentration	BC rate and application methods	Effects & Outcomes	References
Orchard grass (<i>Dactylis glomerata</i> L.)	Zn 368, 553, 697, 780 mg kg ⁻¹	BC 1%, 2.5% and 5% (w/w)	Increased production of biomass; Zn conc. in soil solution and plants reduced; decreased Zn uptake in plants; improved soil pH stability; reduced HM availability to plants.	[55]
Velvet bean (<i>Mucuna aterrima</i> Merr.)	Zn 698 mg kg ⁻¹	Sugarcane-straw-derived BC 1.5%, 3.0%, and 5.0% (w/w)	Reduced the conc. of Zn in contaminated mine soil; decreased Zn solubility in pore water; lowered plant uptake of HMs; prevented symptoms of HM toxicity in plants.	[58]
Radish (<i>Raphanus sativus</i> L.), Lettuce (<i>Lactuca sativa</i> L.), Dill (<i>Anethum graveolens</i> L.), Spinach (<i>Spinacia oleracea</i> L.), Parsley (<i>Petroselinum crispum</i> Mill.)	Zn 32.4 ± 1.4 mg kg ⁻¹	BC 5% and 10% (v/w) + compost	BC reduced HM uptake by leafy vegetables; effectively regulated metal mobility; and improved results when applied alone or in combination with compost at higher doses.	[129]
Stonecrops (<i>Sedum plumbizincicola</i> F.-Z.Li & X.-H.Guo)	Zn 1471 mg kg ⁻¹	Bamboo and rice straw BC @ 1% and 5% (w/w)	Increased biomass of plant, raised soil pH, reduced metal solubility, and decreased HM accumulation in plants.	[122]
Lettuce (<i>Lactuca sativa</i> L.)	Zn 300 mg kg ⁻¹	BC 1%, 2%, and 5% (w/w)	Increased soil pH; reduced photo available Zn; decreased HM uptake and improved yield.	[135]
Summer squash (<i>Cucurbita pepo</i> L.)	Zn 120 mg kg ⁻¹	BC 2% and 4% (w/w)	Reduced HM conc. in roots and shoots; organic matter, electrical conductivity increased, and increased soil pH; enhanced the plant growth.	[78]

3.6 Arsenic (As) Stress Mitigation

In addition to having negative effects on plant development, As is a non-essential element that causes cancer [136]. It also has significant deleterious impacts on human health. Arsenite (AsIII) and arsenate (AsV), two forms of As that are commonly found, are generally considered to be quite poisonous to both plants and humans [137]. Both natural and human-caused processes discharge them into the land and water. Furthermore, As pollution causes a variety of physiological, morphological, and biochemical alterations in plants [138]. However, due to these unfavorable effects, numerous scientists have looked at how well BC (BC) works to lower As toxicity in soil and lower its uptake by plants [139] (Table 6).

According to Yu et al. [140] and Irshad et al. [104], applying BC to rice plants improved their biomass production, growth, photosynthetic pigments, and gas exchange properties while lowering the accumulation

of As in their edible plant sections [104,140]. In an experiment using mountain brome plants, Strawn et al. [141] discovered decreased root-shoot As concentration, increased plant root biomass, and root growth. According to Beesley et al. [142], tomato plants that had their soil supplemented with BC had increased fruit bulk and decreased fruit As content. Furthermore, when the soil was treated with BC, ryegrass showed considerably higher root-shoot biomass and plant tillering [143]. According to Hakeem et al. [139], BC's application decreased the amount of As in the leaves and stem as well as the inhibitory effects of As on plant growth. When BC was applied to vegetable plant's edible portion, the bio-accessibility of As was decreased [144]. When rice plants were grown in soil that had been contaminated with As, it was discovered that certain nutrients, such as P, N, S, and K, and activities of antioxidant enzymes, like as APX and CAT, were significantly elevated [145] (Table 6). However, compared to generic BC, poultry manure-based BC improves nutritional availability (P, S, K, N), increases antioxidant enzyme activities (CAT, APX), and lessens As buildup. Other BC sources, including wood or BC generated from crop residues, may not provide as many nutrient benefits but primarily enhance biomass, root development, and As bioavailability.

Table 6: As-induced stress mitigation by the application of BC on different plants

Plant species	HM concentration	BC rate and application methods	Effects & Outcomes	References
Rice (<i>Oryza sativa</i> L.)	As contaminated soil	BC 0.5, 1.0, 1.5% (w/w)	Increased growth of the plant, biomass production, gas exchange, photosynthetic pigments of the plant.	[104]
	Heavily contaminate 73.0 mg kg ⁻¹ As and Moderately 47.2 mg kg ⁻¹ As	BC 0.5%, 1%, and 2% (w/w)	Increased grain and root weight, and the biomass of the plant; reduced as accumulation in edible plant parts.	[140]
	As 60 mg kg ⁻¹	Poultry manure BC 20 g kg ⁻¹	Reduced plant's H ₂ O ₂ concentrations; increased CAT and APX activities and P, S, K, and N conc. of plants; reduced As concentration.	[145]
Mountain brome (<i>Bromus marginatus</i> Nees ex Steud.)	As 3541 mg kg ⁻¹	BC10% (w/w)	Increased plant root biomass, and root development; reduced root and shoot As concentration.	[141]
Ryegrass (<i>Iolium perenne</i> L. cv Nui)	As 200 to 2000 mg kg ⁻¹	BC 10 and 20 g kg ⁻¹	Enhanced root-shoot biomass and tillering of plant.	[143]
Tomato (<i>Solanum lycopersicum</i> L.)	As ~6000 mg kg ⁻¹	BC 30% vol.	Increased fruit mass; Reduced shoot, root, and fruit As concentrations.	[142]
Maize (<i>Zea mays</i> L.)	As 10, and 50 mg/kg	BC 0, 5, and 15 g kg ⁻¹	Reduced the availability of trace elements to plants; Decreased shoots As concentration.	[146]
	As 100 mg kg ⁻¹ soil	BC 2.5% and 5.0% (w/w)	Reduced As in roots/leaves, improved growth, photosynthesis, chlorophyll, and antioxidant activity; less oxidative stress.	[147]

(Continued)

Table 6 (continued)

Plant species	HM concentration	BC rate and application methods	Effects & Outcomes	References
	As 12 mg kg ⁻¹	BC 50 g kg ⁻¹ + Si	Improved maize yield (12.12%), reduced As in shoots (69%) and grains (142%), enhanced antioxidant activity, and mitigated negative effects of As contamination on chlorophyll, primary metabolites, and yield-related attributes.	[148]
	As 0, 300, 600 mg As/kg soil	0.5% composted BC	Increased maize plant height, shoot & root length, biomass, chlorophyll, and nutrient conc.; alleviation of As-induced stress.	[149]
Creeping Gynura (<i>Gynura cusimbua</i> D.)	As 68.3 mg kg ⁻¹	Soil incorporation with BC	Decreased the bio-accessibility of As in the vegetable's edible portion and prevented the plant from absorbing As.	[144]
Soybean (<i>Glycine max</i> L.)	As contaminated soil	Soil incorporation with BC	Increased osmolytes comprising sugar, proline, and protein; lowered the detrimental effects of As on the plant growth; reduced the As uptake by stem.	[139]
Quinoa (<i>Chenopodium quinoa</i> Willd.)	As 20 mg kg ⁻¹	BC 1% (w/w)	Improved growth, yield, and antioxidant defense, and reduced As accumulation in grains.	[150]

3.7 Nickel (Ni) Stress Mitigation

Numerous investigations have shown that BC's use improves a variety of physio-biochemical and morphological processes in plants, such as germination, enzymatic activity, photosynthesis, and minimizes the detrimental effects of Ni stress on plants (Table 1). Ni is the 24th abundant element in the crust of the planet [151]. For enzymes like glutathione regeneration, urease, SOD, and ROS detoxification in plants, Ni in minute amounts is necessary [152]. However, if the level of Ni exceeds the threshold (20 mmol m⁻³), it is very phytotoxic [153]. Ni is extremely mobile in soil and water, and excess amounts could quickly be absorbed by edible plant sections, leading to major biochemical and physiological problems in exposed plants [154,155]. Ni is one of the high-risk HM contaminants that poses a harm to the ecosystem, the environment, and food security [156]. Ni toxicity slows plant growth and results in leaf margin black patches, decreased chlorophyll production, Fe mobilization to leaves, decreased rate of transpiration, and decreased water potential of the leaf [157]. Furthermore, Ni buildup in exposed plants impairs the absorption and subsequent essential macro and micronutrients translocation, as well as causing oxidative stress from an excess of ROS [158,159]. Compared to other organic amendments, BC, a cheap porous pyrogenous material made by pyrolyzing organic feedstock under oxygen-deficient conditions, has a higher cation exchange capacity (CEC), a bigger surface area, and a higher porosity [160]. Currently, BC is being used both economically and scientifically for HM cleanup, crop productivity enhancement, and soil amendment in agriculture [158] (Table 7). Application

of BC increased stem diameter, plant height, flag LA, number of leaves plant⁻¹, root and shoot dry weight, root and shoot fresh weight, and RWC of maize, rapeseed and summer squash plant under Ni stress condition [53,78,161,162]. In general, BC efficiently reduces Ni stress in plants, fostering development and enhancing physiological processes.

Table 7: Ni-induced stress mitigation by the application of BC on different plants

Plant species	HM concentration	BC rate and application methods	Effects & Outcomes	References
Wheat (<i>Triticum aestivum</i> L.)	Ni 100 and 200 mM	BC 2% (w/w), surface applied	Increased chlorophylls, gas exchange, carotenoids, transpiration, stomatal conductance, total soluble proteins, sugars, and net photosynthesis; decreased electrolyte leakage, MDA, H ₂ O ₂ , anthocyanins, flavonoids, phenolics, and proline; overall reduced oxidative stress, improved growth, and mitigated Ni stress.	[153]
Spinach (<i>Spinacia oleracea</i> L.)	Ni 25, 50 and 100 mg kg ⁻¹	BC 3, and 5 % (w/w), filled with each pot	Enhanced fresh and dry biomass, transpiration and photosynthetic rate, chlorophylls, carotenoids, sub-stomatal CO ₂ concentrations, amino acids, and protein contents; decreased: MDA content, Ni concentrations in roots and shoots; overall improved growth, and alleviated Ni toxicity and availability.	[89]
Corn (<i>Zea mays</i> L.)	Ni 0.0007 mg kg ⁻¹	BC 22.5 t ha ⁻¹ , mixed with soil	Increased plant height and dry shoot biomass; decreased HM concentrations and their bioavailability for plants.	[163]
	Ni 5.4–5.8 ppm	BC 5 and 10 t ha ⁻¹ , mixed with soil	Plant height, leaf count, flag LA, stem diameter, fresh and dry weight of the shoots, RWC, stomatal conductance (gs), chlorophyll content, leaf P, N, Ca ⁺ , and K ²⁺ , biomass yield, shelling ratio, 1000-grain weight, grain yield, and irrigation use efficiency (IUE) all increased; however, the concentration of Na ⁺ in the leaves and the ratio of Na ⁺ to K ⁺ decreased.	[53]
Spinach (<i>Spinacia oleracea</i> L.) and Fenugreek (<i>Trigonella corniculata</i> L.)	Ni 13.8 mg kg ⁻¹ and 15.45 mg kg ⁻¹	BC 3%, and 5% (w/w), mixed with soil	Enhanced shoot fresh and dry mass, root dry mass; increased chlorophylls, carotenoids, transpiration and photosynthetic rate, soluble proteins, sub-stomatal CO ₂ concentrations, and amino acids; reduced MDA contents; overall improved plant growth and production, alleviated HM stress.	[164,165]

(Continued)

Table 7 (continued)

Plant species	HM concentration	BC rate and application methods	Effects & Outcomes	References
Rapeseed (<i>Brassica napus</i> L.)	Ni 1.38 mg kg ⁻¹	BC 1% and 2% w/w (15.6 t ha ⁻¹ and 31.2 t ha ⁻¹), mixed with soil	Enhanced shoot and root fresh as well as dry biomass, chlorophylls, total pigments, carotenoids, and lycopene concentration; Decreased anthocyanin concentrations; increased POD, CAT, APX, and PPO activity.	[162]
	Ni 100 mg kg ⁻¹	BC 3% (w/w), mixed with soil	Increased dry biomass, chlorophyll <i>a</i> and <i>b</i> , RWC, stomatal conductance, net photosynthesis, intracellular CO ₂ concentration, and transpiration rate; decreased H ₂ O ₂ , O ₂ ⁺ , and malondialdehyde (MDA) contents; improved APX, SOD, GR, CAT, MDHA, and DHAR activities, as well as carotenoid, amino acid, protein, and ascorbic acid contents.	[161]
Summer squash (<i>Cucurbita pepo</i> L.)	Ni 45 mg kg ⁻¹	BC 2% and 4% (w/w), mixed with soil	Increased shoot and root dry weight; enhanced the growth of plants.	[78]
Fenugreek (<i>Trigonella corniculata</i> L.)	Ni 25, 50, and 100 mg kg ⁻¹	BC 3%, and 5% (w/w), mixed with soil	Increased chlorophyll <i>a</i> , <i>b</i> , <i>a</i> + <i>b</i> , carotenoids, transpiration, and photosynthetic rate, sub-stomatal CO ₂ concentration; enhanced fresh and dry biomass, protein, amino acids, sugar contents, and carbon flux rate; decreased MDA content; reduced the adverse effect of Ni stress.	[166]
Sunflower (<i>Helianthus annuus</i> L.)	Ni 2.1 mg kg ⁻¹	BC 1% + chitosan	Enhanced Zn bioavailability and reduced Ni toxicity in sunflower seeds, improving seed weight, Fe and Zn content, and antioxidant defense; decreasing oxidative stress and Ni concentration.	[167]
Sunflower (<i>Helianthus annuus</i> L.) and maize (<i>Zea mays</i> L.)	Ni 77 mg kg ⁻¹	BC 2% and BC in combinations with cationic zeolite were BC @ 25%, 50% and 75%	Immobilized Ni in soil, reducing Ni concentrations in tissues; reduced Ni bioavailability, improved grain yield, plant biomass, biochemical and physiological parameters, and antioxidant defense; minimizing Ni-induced oxidative stress.	[168]

4 Mechanism of BC-Mediated HMs Stress Mitigation

From the above sections, we summarized that BC amendments have many positive effects on HMs stress mitigation. By increasing pH, porosity, CEC, and water retention and decreasing HM stress and availability, BC improves soil health [15,109,169]. BC is rich in nutrients, functional groups, and porosity. It improves the growth and efficacy of microbial inoculants. This promotes development in contaminated

soils and increases plant resilience to metal stress [122,170]. Besides, BC is an effective alternative to non-renewable substrates for microbial inoculants. It supports soil biochemical processes, nitrogen cycling, and HM removal [171]. Additionally, BC enhances microbial activity and diversity in the rhizosphere, especially in metal-contaminated soils. Microorganisms help detoxify metals through adsorption, adhesion, electron transport, and ion exchange [109] (Fig. 2).

BC can lessen the solubility of some HMs and decrease their accessibility to plants by controlling the pH of the soil [78]. Again, the effect of BC enhances the number of soil particle's negatively charged sites, particularly in acidic soils. This leads to the metal's immobilization and reducing their bioavailability to plants [171]. For instance, Jing et al. [105] found that BC made from wheat straw has been demonstrated to raise soil pH, which lowers rice's absorption of Cd. Again, BC produced from manure, with its higher Ca content, can attract and immobilize metals like Cd and Cu through ion exchange [172]. BC derived from bamboo residues has been found to effectively adsorb Cr, decreasing its bioavailability to wheat [80]. Advanced BC forms, like nano-engineered versions, are better at trapping metals due to their small pores and surface oxygen groups [173]. The metal-binding effectiveness of BC depends on factors like the material source, surface area, nutrient content, and the presence of functional groups, with advanced BC types offering even greater metal-adsorption capacity. In addition to reducing metal uptake, BC improves root development, nutrient and water availability, general plant vigor, and HM tolerance in plants [174]. Furthermore, BC strengthens plant defense mechanisms against oxidative stress brought on by metals. It has been demonstrated to increase the activity of several antioxidant enzymes, including CAT and SOD, which are essential for reducing oxidative damage in plants subjected to metal stress [175]. Small peptides rich in cysteines, known as phytochelatins (PCs), have the ability to bind metal(loid)s through SH-groups. While a variety of metal(loid)s can trigger PC production *in vivo*, PCs are primarily implicated in the detoxification of mercury, Zn, Pb, and Cu ions, as well as Cd and As(III), all of which have strong affinity for S-containing ligands [176]. BC stimulates phytochelatins synthesis, metallothionein's, and other metal-binding peptides that sequester toxic metals, thereby reducing their harmful effects on plant cells. Furthermore, BC modified with transition metals or metal oxides has gained prominence as a catalyst in SR-AOPs due to its large surface area, high stability, and catalytic efficiency [177] (Fig. 2).

BC assists plants in scavenging ROS by releasing free radicals and functional groups involved in ROS neutralization [178]. Furthermore, studies on molecules have demonstrated that BC therapies can regulate the expression of a metal confronting gene (*OsFSD1*) linked to stress tolerance, including those that code for antioxidant enzymes (*OsSOD*, *OsPOD*, *OsCAT*, and *OsAPX*) [179]. Bamboo BC, according to Sarraf et al. [15] and Hannan et al. [161], effectively reduced Ni stress by upregulating the levels of *CAT*, *APX*, and *GR* genes and downregulating the expression of *SOD* genes and Ni transporter genes (*BnNi-T*, *BnNRAMP3*, and *BnIRT1*). It accomplishes this by reducing cellular membrane damage, lowering ROS levels, reducing chlorophyll degradation, and boosting antioxidant activity [180]. Overall, BC is a multipurpose instrument in sustainable agriculture, providing advantages that go beyond improving soil quality, such as lowering the bioavailability of metals and increasing plant resistance to stress caused by metals (Fig. 2).

5 Limitation of BC Application in HMs Contaminated Soil

HM stress in polluted soils can be effectively managed by BC, but there are a number of restrictions and difficulties that need to be taken into account. A number of variables, including the kind of soil, production circumstances, and feedstock, can affect how effective BC is at immobilizing HMs [181]. Different types of BC have varying adsorption capacities, and some may be less effective due to their chemical and physical properties [182]. BC can also interact with soil amendments, which may exceed its metal-binding capacity

and release HMs back into the soil. Additionally, BC can alter soil pH, making some HMs more soluble and reducing their effectiveness [183].

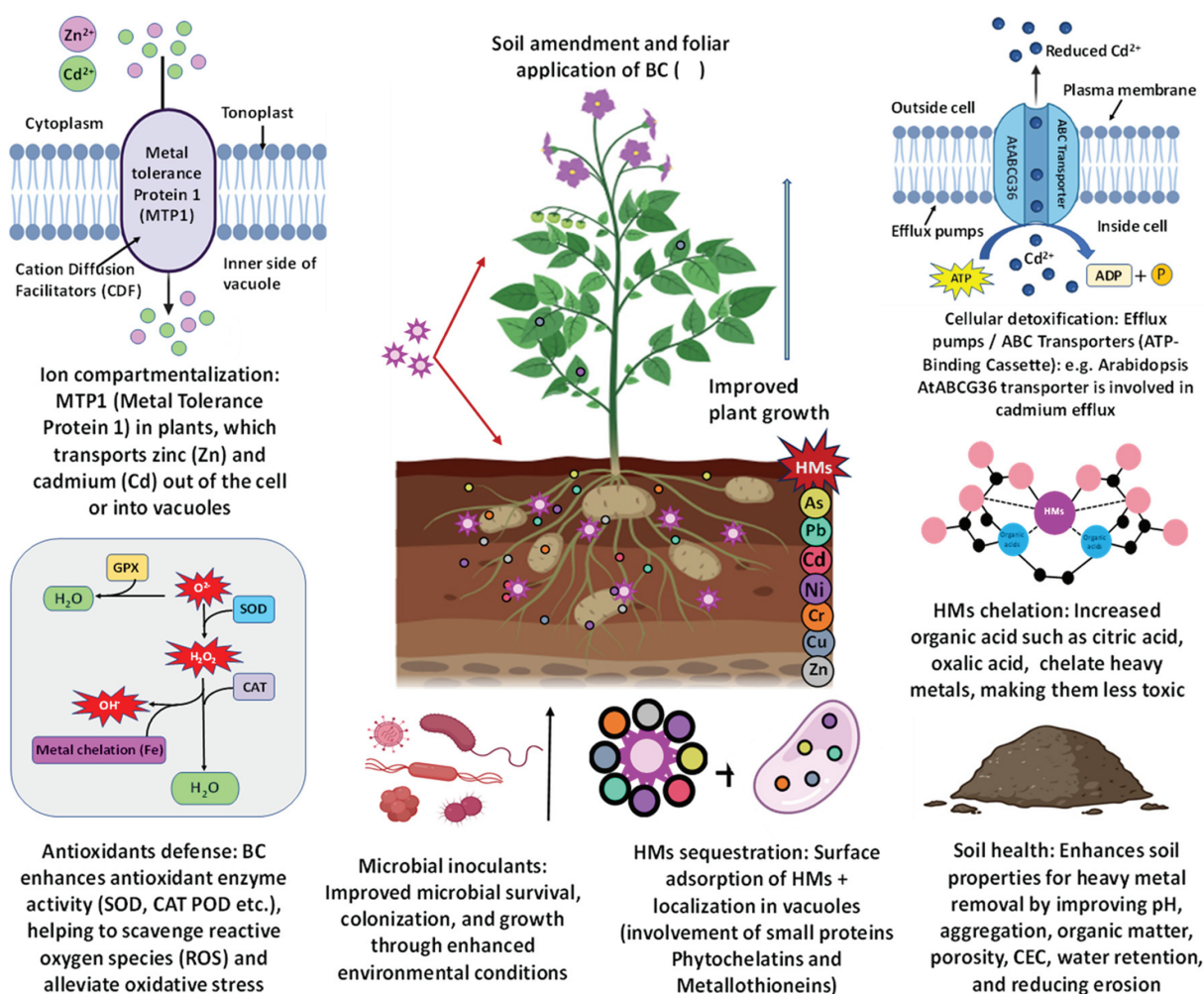


Figure 2: Mechanisms of HM stress mitigation in plants through BC application. BC enhances the detoxification of HMs in plants by influencing efflux pumps and metal transporters. Efflux pumps, such as RND, CDF, and ABC transporters, actively remove metals like Cd from cells. Metal transporters, including NRAMPs and HMAs, move metals across membranes and sequester them in vacuoles. BC reduces metal bioavailability, easing the load on these detoxifying processes and improving plant tolerance to metal toxicity

Moreover, the heating rate during pyrolysis, and the production conditions are some of the variables that can greatly affect the properties of biochar. The resulting biochar's chemical makeup, surface area, and nutrient content are significantly influenced by the feedstock material, which might include wood, agricultural waste, or animal dung [184]. The porosity, surface functional groups, and carbon content of the biochar can also be impacted by changes in the heating rates during pyrolysis [185]. Because biochar's efficacy in soil amendment, heavy metal adsorption, and plant growth promotion might vary based on the source material and manufacturing conditions, it is difficult to estimate how effective it will be in certain applications [110,186].

Excessive application of BC may disrupt nutrient availability in the soil which adversely affects plant growth. Also, uniform distribution of BC can be difficult to achieve and inconsistencies in application may limit its overall effectiveness [187]. The effectiveness of BC in sequestering HMs can also be impacted by variations in production conditions such as the temperature during pyrolysis [188]. Complex interactions exist between BC and the soil matrix, which can modify the pH and other aspects of the soil, thereby influencing the availability of metals and the health of plants. Furthermore, not all HMs can be effectively removed by BC, particularly those that have a poor affinity for its adsorption sites. Other important issues that must be addressed are the long-term stability of BC in the soil, possible nutrient imbalances, and the continuous expenditures associated with manufacturing and application [189]. Furthermore, recent studies indicate that BC's efficiency in HM remediation may be influenced by its interactions with soil microbial communities; this is an issue that has to be further investigated [190] (Fig. 3). However, the adsorption capacity of BC for HMs can be improved by refining its application techniques, such as controlled incorporation and activation [191]. BC's effectiveness in reducing soil contamination is increased by using high-carbon feedstocks and adding additives [192,193].

To evaluate the sustainability of this strategy, research on the long-term impacts of applying biochar (BC) on plant productivity and soil health is still crucial. Long-term use of BC may have unforeseen repercussions, including altered microbial populations, changes in soil pH, and possible nutrient imbalances, even while it can improve soil structure, promote nutrient retention, and reduce heavy metal toxicity [194]. Furthermore, BC's efficacy in soil fertility and carbon sequestration is influenced by its stability and degradation over time [195]. Its long-term effects are further complicated by variations in feedstock type, pyrolysis conditions, and application rates. Therefore, to ascertain if BC treatment continues to be advantageous or presents dangers over time, ongoing monitoring of soil characteristics, plant responses, and ecosystem interactions is crucial.

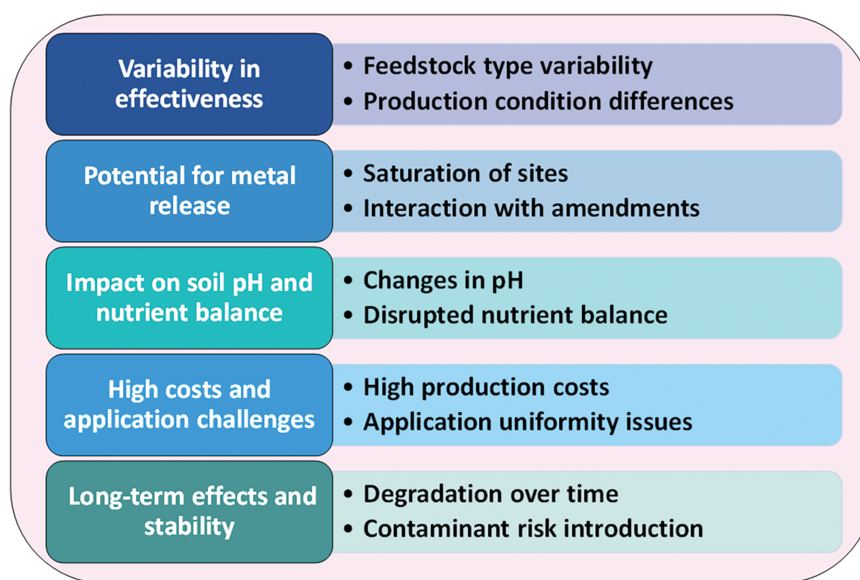


Figure 3: Limitation of BC application in HM contaminated soil

6 Conclusion and Future Perspectives

BC has emerged as a promising sustainable soil amendment to mitigate HM stress in agricultural systems. Its unique properties, such as high porosity, large surface area, and functional groups, improve soil quality by reducing HM mobility, enhancing pH, and increasing cation exchange capacity. BC effectively immobilizes metals like Pb, As, Cd, and Cr, reducing their bioavailability and uptake by plants, leading to improved growth, enhanced photosynthetic activity, and increased antioxidant defenses. Additionally, BC fosters beneficial microbial activity, aiding in HM detoxification through microbial processes like adsorption and ion exchange. Beyond its chemical stabilization effects, BC enhances nutrient availability, water retention, and soil structure, improving root growth and plant resilience under stress. It also promotes the formation of organo-mineral complexes that reduce HM solubility. These combined effects contribute to sustainable remediation and soil restoration, making BC a vital component of green agricultural practices.

However, several research gaps must be addressed to optimize BC's effectiveness in HM mitigation. Tailoring BC production for specific metals and soil conditions requires standardizing feedstock types, pyrolysis temperatures, and activation methods. Advanced BC formulations, incorporating metal-oxide nanoparticles or functionalized ligands, could enhance metal immobilization. Molecular studies should explore BC-induced regulation of metal transporter genes, antioxidant enzymes, and peptides like phytochelatins and metallothioneins. While BC impacts microbial communities, long-term studies on its synergistic effects with microbial consortia are needed for sustainable HM detoxification. Field trials should assess BC's stability, degradation, and secondary pollution risks. Integrating BC with phytoremediation plants offers a hybrid system for better metal uptake and stabilization, while its role in carbon sequestration and HM mitigation under varying climates remains underexplored. Advanced techniques, such as synchrotron-based spectroscopy and nuclear magnetic resonance, could refine our understanding of BC-metal interactions. Future research should explore BC's impact on soil enzymatic activity and signaling pathways related to HM tolerance. Developing BC composites with biodegradable polymers or bioactive coatings may improve durability and controlled release of beneficial compounds. Integrating BC into circular economy models using agricultural or industrial waste as feedstock promotes sustainability. Additionally, exploring BC's synergy with other amendments like compost and zeolites could offer broader solutions for soil health. Lastly, establishing global standards for BC quality and safety will accelerate its adoption in environmental cleanup and sustainable farming.

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