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# Biochar Enhancing Soil Resilience: A Dual Strategy for Mitigating Heavy Metal Contamination and Drought Stress

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**Abstract:** Drought and heavy metals are abiotic stressors that affect soil fertility and plant growth excessively and have significant toxic consequences, threatening agricultural sustainability. Plants ' accumulation of heavy metals in soil uptake leads to disrupting physiochemical and biochemical metabolisms. Biochar has attracted major attention for potential and sustainable soil amendment. Biochar is a complex carbon-rich organic substance whose properties vary depending on the manufacturing process and feedstock. Application of biochar reduces drought stress by increasing the water holding capacity through modification of soil properties, helps in the retention of moisture, absorbs heavy metals, inhibits harmful bacteria, improves soil pH, and also significantly modifies the Reactive Oxygen Species (ROS) scavenging enzymes and provide an efficient electron transferring mechanism to reduce the toxic effects in plants. The review focuses on the effects of drought and heavy metals on soil fertility and plant growth, biochar counteracting the drought and as a soil improver, and the various direct and indirect interaction mechanisms of biochar with the soil. This article also focuses on the potential role of biochar in ameliorating drought and heavy metal stress.

**Keywords:** biochar; drought stress; metal toxicity; crop productivity.

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## 1. Introduction

"Black Gold" refers to biochar due to its special properties. Biochar is a porous carbonaceous solid material made from biomass pyrolysis under an inert atmosphere. Depending on the source material, the amount and chemical makeup of the carbon component differ. Biochar principally contains five elements: hydrogen, oxygen, nitrogen, Sulphur, and carbon. Various feedstocks, such as agricultural waste, wood waste, animal waste, and sewage sludge, have been used to make biochar [1-4]. Because of its broad surface area, high porosity, and abundance of functional groups, biochar is an appealing choice for environmental remediation. It can be used as an adsorbent and catalyst material to remove various harmful pollutants in soil and wastewater [5,6]. Biochar contains large charge densities, low bulk densities, a highly porous structure, high organic carbon content, and many other properties that help in increasing the soil's biological and chemical properties like its pH, cation exchange capacity (CEC), zeta potential, soil fertility, etc. [7-10]. Biochar plays a significant role in environmental management, such as the sorption of organic and inorganic pollutants, greenhouse gas emissions, and effective reduction in abiotic stresses like drought and salinity [11-13,123-124]. Because of the presence of negatively charged particles on its surface, it attracts polar molecules, which assists in immobilizing the heavy metals and agricultural contaminants on its adsorbing surface, thus limiting their intake by crops [14,125]. Existing treatment methods, encompassing primary and secondary processes, fall short of adequately addressing and eliminating pollutants. Consequently, there is a pressing need for an efficient, economical, and environmentally friendly tertiary treatment approach. Biochar emerges as a promising solution with diverse applications in environmental processes, including pollutant remediation, greenhouse gas reduction, and wastewater and soil treatment. Research indicates the utilization of various types of adsorbents, such as native and engineered biochar, to effectively remove or mitigate heavy metals, polycyclic aromatic hydrocarbons (PAHs), pesticides, and disinfectants from contaminated sites, contributing to improved environmental management. [15]. This review study discusses the potential toxicity of heavy metals (HMs) through drought stress from soil and how they adversely affect the soil's various properties. Biochar-based remediation technique has been utilized in recent years for HMs removal from the soil; thus review also includes the analysis of such a technique and what possible results have been obtained from it, shown in figure1.

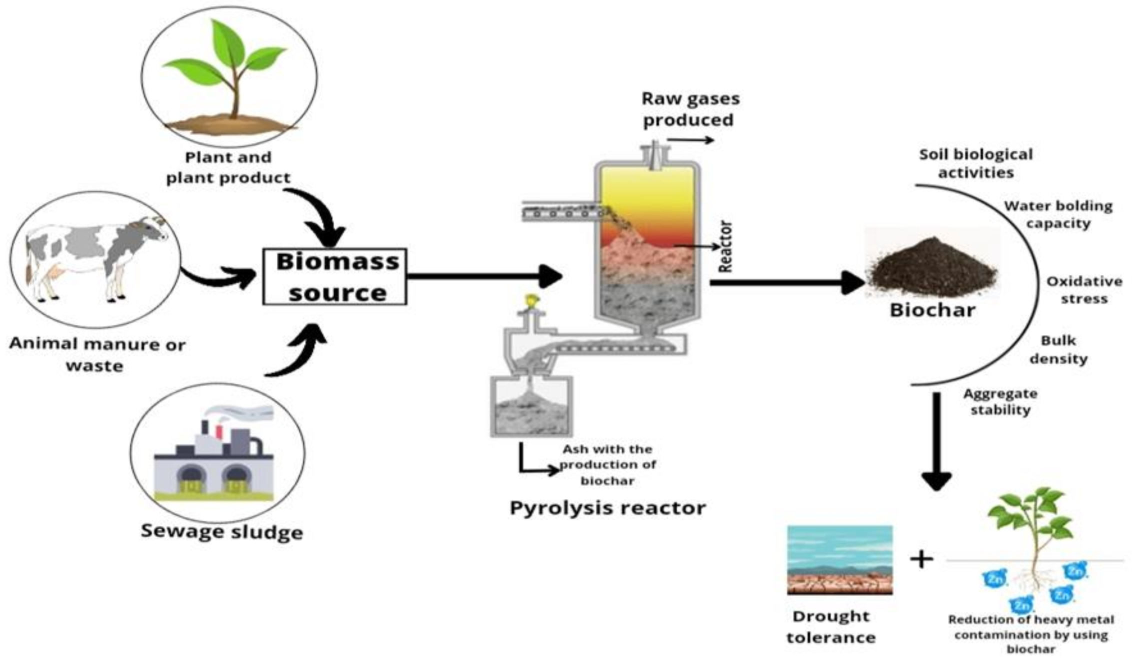


**Figure 1.** The illustration depicts the procedure for producing biochar from various biomass sources, including plant materials, animal manure or waste, and sewage sludge. It also presents the features of biochar, such as its ability to resist oxidation, capacity to boil water, and bulk density. Biochar can be valuable in mitigating heavy metal contamination in soil.

## 2. Effects of heavy metals of soil

### *2.1. Various heavy metals and their effect on soil.*

Contamination of soil by heavy metals is one of the most important apprehensions throughout the industrialized world [16]. Heavy metals are a major source of soil pollution caused by various heavy metals such as Cu, Ni, Cd, Zn, Cr, and Pb [17]. Heavy metals affect not only plant yield and quality but also soil microbial activities [18]. The diversity and activity of soil microbes play an important role in various processes, like replenishing soil nutrients, controlling pests, and detoxifying toxic chemicals [19,20]. Heavy metals greatly affect the soil microbial biomass population and their activities [21]. Heavy metal-contaminated soil negatively affects various properties of soil microbes, including underlying soil respiration rate and enzyme activities that are mainly dependent on soil pH, organic matter, and other chemical properties of soil [22,23,126]. Chromium(Cr) is known to have a toxic effect on the soil microbial population; it causes harmful effects on the metabolism of microbial cells [24]. Heavy metals also cause a change in the diversity, population size, and overall activity of the soil microbial community. Heavy metals indirectly affect the soil enzymatic activity by shifting the microbial community synthesizing enzymes [24,25]. As the concentration of heavy metal increases, most of the enzymes are significantly reduced, and this decrease in their activity can be caused by the interaction of enzymes and heavy metal [26,127]. Heavy metals affect soil biota by affecting key microbial processes and decreasing the amount of activity in the soil [27]. The effects of these heavy metals on plants can vary depending on the concentration and duration of exposure. High levels of heavy metals in soil can inhibit plant growth and development, reduce seed germination, and decrease overall plant health. Lead, for example, can reduce plant growth and chlorophyll production, while cadmium can interfere with plant nutrient uptake and reduce root growth, as shown in Table 1. Mercury can also reduce plant growth and chlorophyll production and accumulate in plant tissues, posing a potential health risk to animals that consume those plants. Arsenic, found in some pesticides and fertilizers, can be toxic to plants at high concentrations, leading to reduced growth, chlorosis, and necrosis. While essential micronutrients for plants, copper and zinc can become toxic at high concentrations, leading to reduced growth, chlorosis, and root damage. Overall, the accumulation of heavy metals in soil can have significant negative effects on plant growth and development, ultimately impacting the health of the ecosystem as a whole. Therefore, monitoring soil heavy metal levels and taking steps to reduce contamination when necessary is important. Heavy metals inhibit growth and reproduction, further affecting microbial enzymatic activity's synthesis and metabolism [28]. The enzymatic activities are affected in different by different heavy metals; for example, Cadmium(Cd) is a heavy metal which, if present in toxic quantity, may cause inhibition of b-glycosidase activity; Pb is found to decrease the activity of enzymes like urease and catalase and acid phosphatase, Cd is also found to affect the protease, urease, alkaline phosphatase and arylsulfatase [29-31]. Each soil has a different effect on each heavy metal, or we can say that each soil is sensitive to heavy metal in a specific way. As the heavy metal concentration reaches a toxic level, the primary effect is on the bacteria, fungi, actinomycetes, and other microbial communities. Heavy metals affect the soil microbial community in quality and quantity parameters [32]. They also affect the decomposition and conversion processes of the soil. It may cause a reduction in the diversity of the soil microbial population [128,129]. Due to heavy metals, there was a decrease in the carbon biomass that accepts lead (Pb). It was found that symbiotic nitrogen fixers showed high sensitivity to heavy metals like Cd, Pb, Hg, Cu, Cr, Mn, and Zn [33].

**Table 1.** Effects of different heavy metals on plants accumulated in soil [34].

| Heavy metal | Plants | Heavy metal toxicity effects | Reference |
|---|---|---|---|
| Co | Mung bean (*Ingratiate*) | Antioxidant enzyme activity is reduced, and plant starch, amino acids, sugar, and protein levels are reduced. | [35] |
| | Radish (*Raphanussativus*) | Root length, shoot length, and total leaf area are all reduced, as are chlorophyll concentration, nutritional content, antioxidant enzymatic activities, and plant amino acid, sugar, and protein levels are reduced. | [36] |
| | Tomato (*Lycopersiconesculentum*) | Reduced nutritional content in plants | [37] |
| As | Canola (*Brassica napus*) | Wilting, chlorosis, and stunted growth | [38] |
| | Rice (*Oryzasativa*) | Seed germination is reduced, seedling height is lowered, and leaf area and dry matter output are reduced. | [39,40] |
| | Tomato (*Lycopersiconesculentum*) | Fruit output is decreased, and leaf fresh weight is also reduced. | [41] |
| Zn | Pea (*Pisumsativum*) | Chlorophyll content decreases; chloroplast structure changes; decrease in photosystem II activity; decrease in plant growth. | [42] |
| | Rye grass (*Loliumperenne*) | Accumulation of Zn plant leaves; growth inhibition; decreases in plant nutritional content; less efficiency in photosynthetic energy conversion. | [43] |
| | Cluster bean (*Cyamopsistetragonoloba*) | Germination % is lower; plant height and biomass are lower, and carotenoid, chlorophyll, starch, sugar, and amino acid content is lower. | [43] |
| Pb | Portia tree (*Thespesiapopulnea*) | Plant height, number of leaves, and leaf area are all reduced | [44] |
| | Oat (*Avenasativa*) | $CO_2$ fixation was restricted by the inhibition of enzyme activity. | [45] |
| | Maize (*Zea mays*) | Reduced germination %; stunted development; lower plant biomass; lower plant protein content | [46] |
| Mn | Pea (*Pisumsativum*) | photosynthetic O2 evolution activity is reduced, and photosystem II activity; lower chlorophylls a and b content; reduced relative growth rate | [47] |
| | Tomato (*Lycopersiconesculentum*) | Plant development is slower, and the concentration of chlorophyll is reduced. | [48] |
| | Broad bean (*Viciafaba*) | Plant development is slowed, and the concentration of chlorophyll lowers | [48] |
| | Spearmint (*Menthaspicata*) | Accumulation of Mn in plant roots; Chlorophyll a and carotenoid levels reduced. | [49] |
| Ni | Rice (*Oryzasativa*) | Root growth is inhibited. | [50] |
| | Wheat (*Triticum* sp.) | Plant nutrient uptake is reduced. | [51,52] |
| | Rye grass (*Loliumperenne*) | Reduced nitrogen uptake by the plant; relatively low shoot output; chlorosis | [53] |
| Hg | Rice (*Oryzasativa*) | Plant height decreases; tiller and panicle development decreases; yield decreases; seedling shoot and root bioaccumulation. | [54,55] |
| | Tomato (*Lycopersiconesculentum*) | Chlorosis, reduced plant height, germination percentage, flowering, and fruit weight are also lower. | [56] |
| Cu | Bean (*Phaseolus vulgaris*) | Accumulation of Cu in plant roots causes root deformity and reduction of roots. | [57] |
| | Rhodes grass (*Chloris Guyana*) | Reduced root growth | [58] |
| | Black bindweed (*Polygonum convolvulus*) | Biomass and seed output is reduced due to plant mortality. | [59] |
| Cd | Garlic (*Allium sativum*) | Accumulation of Cd causes a reduction in shoot growth. | [60] |
| | Maize (*Zea mays*) | Shoot growth is slowed, and root growth is stifled. | [61] |
| | Wheat (*Triticum* sp.) | Germination of seed is reduced, plant nutritional content is lowered, and shoot and root length are reduced. | [62,63] |

*2.2. Usefulness of biochar in the reduction of heavy metal contamination.*

Biochar has proved to be a great asset in agriculture not only by increasing fertility, improving plant health, etc., but also by aiding in countering one of the major problems, i.e.

heavy metal contamination [64]. The presence of heavy metal I soil has affected not only the soil but also the soil microbial population , soil quality, and plant health, and it has also adverse effects on animals and human beings [65]. Heavy metals are very difficult to degrade and thus retain in the soil and the environment for a very long time. Recently, biochar has been proven to be a very effective and eco-friendly means to counter heavy metals [66]. Biochar can reduce the movement or mobility of heavy metals in soil, reducing plants' chances to uptake these heavy metals [67,68]. They can absorb heavy metals and reduce environmental risk; for example, the biochar composed of bamboo can absorb heavy metals like Cu, Hg, Ni, and Cr from soil [69]. The remediation process can be done by the use of different biochar and mechanisms for multi-element polluted soil; thus, while using biochar for the treatment of soil, we must ensure what type of heavy metal is present and the temperature used in the production of biochar, as these plays an important role in the selection of suitable biochar for the treatment of soil [70]. Biochar is very effective in decreasing the leakage of heavy metals by using the reduction reactions of metals; for example, Chromium is a heavy metal that exists in two forms, i.e., trivalent[Cr(III)] and hexavalent[Cr(VI)] [70]. [Cr(III)] is generally nontoxic and gets strongly bound to soil particles, whereas [Cr(VI)] is toxic and highly mobile in soil [71]. By the use of biochar, we could reduce the [Cr(VI)] to [Cr(III)], which in turn results in the detoxifying and stopping the mobility of the Cr in the soil, thus inhibiting its toxicity [72]. Heavy metals are generally found in very low concentrations, but their high or cumulative concentration causes toxic effects in soil. The bioavailability of heavy metals is generally concerned with the heavy metals present in a particular area [73]. The bioavailability of heavy metals helps in knowing the toxic effects on the soil and potential environmental risks, as shown in Figure 2. Due to the use of biochar, there is an increase in the pH, cation exchange capacity, and water-holding capacity and decreased bioavailability of some metals [74]. Application of biochar has significantly reduced the concentration of free heavy metals; biochar, being highly aromatic, has a large surface area, micropore volume, and abundant polar functional groups; biochar is effective in absorbing a wide range of organic compounds, including pesticides, hormones, etc. [75]. The type of biochar and carbon content of soil plays a major role in the remediation of heavy metals in the soil [76]. Thus, biochar significantly reduces the bioavailability and toxicity of heavy metals, as shown in Table 1[77].

**Table 2.** Biochar characteristics and efficiency of heavy metal remediation.

| S.no | Biochar | Pyrolysis Temperature | Target metal | Reduction Rate | References |
|---|---|---|---|---|---|
| 1 | Oakwood | Pyrolysis at the temperature at 400°C | Pb | Reduction of bioavailability by 75.8% | [78] |
| 2 | Rice straw | Pyrolysis temperature at 500°C | Zn | Removal efficiency by 36.9% | [79] |
| 3 | Green waste | Pyrolysis at the temperature 650 °C | Pb | Removal efficiency by 92.9% | [80] |
| 4 | Carrot pulp | Pyrolysis at temperature 550°C | Cu | Removal efficiency by 47.4% | [81] |
| 5 | Orange bagasse | Pyrolysis temperature 500°C | Cu | Removal efficiency by 28% | [82] |
| 6 | Sugarcane bagasse | Pyrolysis temperature at 500°C | Cr | Removal efficiency by 49.6% | [83] |
| 7 | Vegetable waste | Pyrolysis at 500°C | Pb | Removal efficiency by 87% | [84] |
| 8 | Soybean straw | Pyrolysis at 350°C | Cd | Removal efficiency by 65.7% | [85] |
| 9 | Bamboo | Pyrolysis at 600°C | Cu | Removal efficiency by 79.7% | [86] |
| 10 | Maize straw | Pyrolysis at 550°C | Cd | Removal efficiency by 50.4% | [87] |
| 11 | Wheat straw | Pyrolysis at 350-450°C | Hg | Increased by 26% | [88] |
| 12 | Kenaf bar | Pyrolysis at 600°C | Cd | Removal efficiency by 90.1% | [89] |

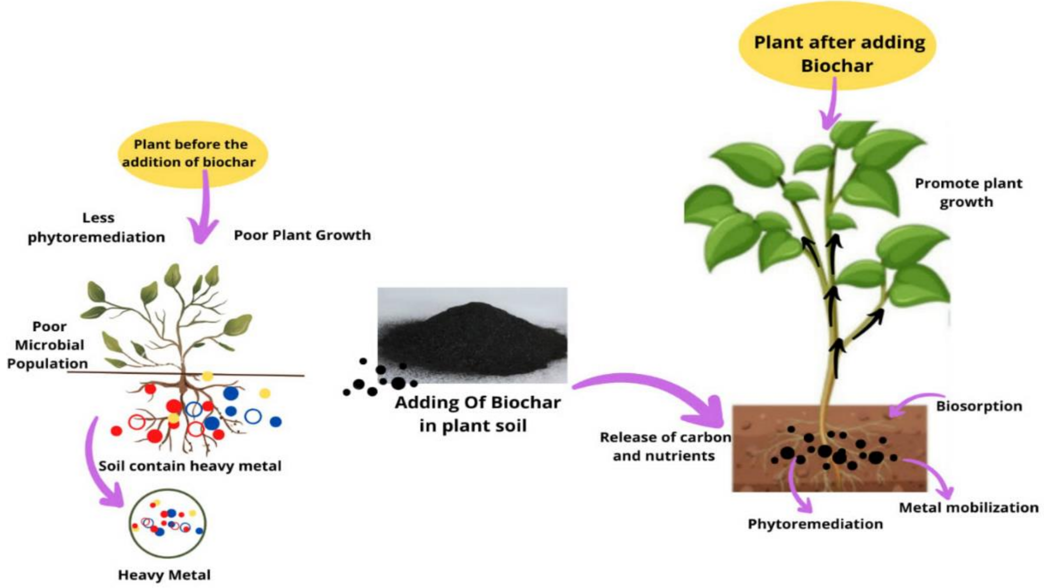


**Figure 2.** The alterations in the physical and chemical characteristics of plants subsequent to the remediation of heavy metals from soil utilizing biochar.

## 3. Biochar efficacy in drought stress management

Drought is the most common abiotic stress that impacts crop growth and yield, diminishes crop production globally [90], and is a major issue in the world's arid and semi-arid zones. Biochar has recently gained popularity worldwide as a way to improve the physicochemical qualities of soil and, as a result, is being employed as an alternative technique to deal with the worrying situation. Biochar is a pyrolyzed natural material intended to be used as a soil amendment [91-94] to practically sequester carbon while improving soil characteristics and functions in the short and long term [95]. Treating the soil with biochar in various situations increases the soil's water-holding capacity [96]. Biochar supplements improve ion transfer ability, soil structure, and fertility while lowering crops' heavy metal toxicity [97,98]. It also boosted microbial activity, soil nutrient storage, and exchange capacity [99]. Biochar has a high porosity and surface area, which aids in drought stress reduction [100]. The use of biochar to promote the development and yield of various crops has been frequently recognized in drought-stricken areas [101-103]. Under drought conditions, biochar improved water consumption efficiency, stomatal conductance, chlorophyll content, photosynthesis, and relative water content of tomato leaves. Biochar application has been shown to boost plant leaves' drought defense mechanisms by raising the activity of protective enzymes and electron transport in crops, reducing the effects of drought mutilation on the photosynthetic machinery [104]. Most studies on biochar's impact on soil have found that biochar increases agricultural yield to varying degrees. These positive impacts can help to alleviate land stresses and are also relevant to land restoration and remediation [105]. Because of its ability to trap carbon in the soil for an extended period of time, biochar has the potential to help reduce global environmental change. Biochar addition can aid in restoration by enhancing soil carbon status and physical structure, thereby fostering soil microbial activity, which is critical for plant nutrient cycling [106].

### *3.1. Soil structure and porosity.*

Biochar improves the soil quality, including soil structure, porosity, fertility, pH, and density. The porous structure of biochar as a soil additive is an excellent soil improver; it reduces soil density, and biochar application effectively increases the thermal conductivity and diffusivity of soil [107].

During the process of pyrolysis, volatile compounds are emitted as gases, leading to the creation of a highly porous honeycomb structure that enhances the surface area of biochar. This increase in surface area corresponds to a linear improvement in Water Holding Capacity (WHC), nutrient retention, and their subsequent release [10,11,108,109]. The macropores (pore diameter >50 nm) and mesopores (2–50 nm) within biochar contribute to WHC and serve as habitats for soil microorganisms. In comparison, the micropores or nanopores (<0.9 nm) predominantly influence the chemical and sorption properties of biochar [12,110].

Furthermore, biochar's particle size and shape play a crucial role in soil's physiochemical and hydraulic properties. Fine and small biochar particles interact more readily with soil particles, facilitating the formation of aggregates [13,14,111,112]. This interaction enhances the overall effectiveness of biochar in influencing soil characteristics.

### *3.2. Soil pH control.*

Typically, biochars exhibit an alkaline nature, with their alkalinity intensifying as the temperature increases during the pyrolysis process [15,113]. Elevated temperatures in pyrolysis lead to eliminate of carboxyl, formyl, or hydroxyl groups, resulting in a higher concentration of inorganic elements and basic oxides in the biochar. The alkalinity and pH of biochar depend on the feedstock used. Moreover, the addition of the BC increases soil pH and total cation exchange capacity (CEC), thus facilitating better capture of nutrients by plants [16,17,114,115]. The pH of the soil is an important factor affecting soil fertility and, thus, the yield of cultivated plants. The effect of pH on the chemical properties of soil is as follows: it counteracts the impoverishment of soil sorption complex, ensures the availability of nutrients for plants, and prevents the leaching of toxic metals like Aluminium.

### *3.3. Ion Exchange capacity.*

The ion exchange capacity is the total amount of ions that can be adsorbed on the surface of biochar. The Cation Exchange Capacity (CEC) is generally affected by the preparation or modification temperature of biochar and biochar raw materials, i.e., the feedstock used and specific functional groups formed during pyrolysis. Biochars characterized by a high Cation Exchange Capacity (CEC) exhibit enhanced capabilities in nutrient retention, reducing nutrient leaching. Additionally, they facilitate the absorption of ions such as ammonium (NH4+), potassium (K+), calcium (Ca2+), and magnesium (Mg2+) from the soil to plant roots. This is achieved by releasing H+ ions to maintain a balanced charge in the soil [18,19,116,117]. High temperatures increase the synthesis of carboxyl functional groups and the oxidation of aromatic carbon [20,118]. As the pH increased, the zeta potential of carbon decreased. These results showed that dissociating the functional groups ($COOH^-$, $OH^-$) on the surface of biochar enhanced the negative charge on the surface while increasing the Cation Exchange Capacity [21,22,118,119]. The soil CEC can be significantly improved by applying biochar.

### *3.4. Soil microbial activity.*

Soil microorganisms are important in nutrient recycling, reducing pests and diseases, and maintaining soil structure. Application of biochar to the soil can affect the soil microbial activity and community structure with the help of its significant features, including pore size, surface area, porosity, minerals, surface volatile organic molecules, functional groups, free radicals, and pH [23,24,120-122]. Biochar contains many essential elements and other nutrients that can have long-term beneficial effects on microbial growth upon release into the soil solution [8,25]. Different varieties of bacteria grow and enhance the soil properties; one such species is Nitrogen-fixing bacteria, which are unique bacterial species. These bacteria contain nitrogen-fixing enzymes, which can convert molecular nitrogen in the atmosphere into nitrates ($NO_3^-$) by plants through nitrification. Moreover, biochar application to soil increases microbial growth and abundance.

## 4. Benefits of biochar techniques in recent times over drought stress and heavy metal problem

Biochar can improve soil water-holding capacity, which helps to reduce water stress in plants during drought conditions. This is because the porous nature of biochar allows it to hold onto water and nutrients, releasing them slowly to plants as needed. Biochar can improve nutrient availability in soil by increasing soil organic matter and microbial activity. Biochar has a high surface area that can adsorb nutrients and prevent them from leaching away. This property makes nutrients more available to plants and reduces the need for fertilizer application. This, in turn, helps to improve plant growth and resilience to drought stress. Biochar can bind heavy metals in soil, reducing their bioavailability and toxicity to plants. This is particularly important in areas where soil contamination from heavy metals is a major problem. Biochar can improve soil structure and stability, which can help prevent soil erosion and promote plant growth. This is because biochar helps to create pore spaces in soil, which improves soil aeration, drainage, and root penetration. Biochar can be produced through pyrolysis, which involves heating organic materials without oxygen. This process produces a type of charcoal that is rich in carbon and stable, which means it can sequester carbon in the soil for hundreds of years, reducing greenhouse gas emissions. Biochar is a stable form of carbon that can remain in the soil for thousands of years, reducing the amount of carbon dioxide in the atmosphere. This property makes biochar an effective tool for climate change mitigation.

## 5. Challenges and future aspects of biochar technique

One of the challenges of biochar techniques is the high cost of production. The feedstock, equipment, and labor costs can be a limiting factor for small-scale farmers. Biochar quality can vary depending on the feedstock, production conditions, and post-treatment. It is essential to ensure consistent quality to achieve the desired benefits. Biochar techniques have shown promising results at the small-scale level, but there are challenges in scaling up production and application to larger areas. Research is needed to optimize production and application methods for large-scale adoption. While biochar can have immediate benefits, its long-term effects on soil health, nutrient cycling, and carbon storage are poorly understood. Further research is needed to evaluate the long-term effects of biochar on the environment and its sustainability.

Biochar techniques can be integrated with other sustainable agriculture practices, such as agroforestry, conservation, and organic farming. Biochar can be used as a feedstock for other value-added products, such as activated carbon, soil amendments, and bioenergy. There is a need for innovative production methods that can reduce costs, increase efficiency, and enhance biochar quality. Collaboration among researchers, farmers, policymakers, and industry can enhance knowledge sharing and accelerate the adoption of biochar techniques.

## 6. Conclusion

Heavy metal contamination of the soil and other abiotic stresses like drought pose risks to the plant body, its growth, and development. It affects the plant body's various functions and is toxic so it can lead to plant death. , the incorporation of biochar is an effective remediation method. Modifying the physio-chemical characteristics of soil using biochar is beneficial. It raises the soil's capacity to bind to water, improves water and mineral intake, holds onto nutrients, absorbs heavy metals, increases soil fertility, and improves microbiota. The qualities of biochar are further influenced by the type of biomass and its production conditions for thermochemical conversion and how effective it is. A wide variety of soil heavy metals can be absorbed by biochar, which can also offer a repair method that is both safe for the environment and unlikely to result in any immediate ecological risks. Applying biochar to contaminated soils has the best effect when it leaves the soil's natural properties, like its biotic ecosystem and nutritional status, untouched. This descriptive literature helps us understand biochar-mediated tolerance effectively.


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## Conflicts of Interest

The authors declare no conflict of interest.

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