Journal of Soil, Environment & Agroecology

Journal homepage:
https://karyailham.com.my/index.php/sea/index
ISSN: 3030-5497

The Potential of Biochar as a Soil Detoxifier: A Review

Ramijur Rahman[1,*], Kulendra Nath Das[1]

[1] Department of Soil Science, Assam Agricultural University, Jorhat, Assam, 785013, India

ARTICLE INFO

Article history:
Received 20 February 2025
Received in revised form 18 March 2025
Accepted 30 March 2025
Available online 15 June 2025

Keywords:
Soil contamination; biochar; detoxification; soil health; efficiency

ABSTRACT

Soil contamination by heavy metals and organic pollutants has become a major environmental concern due to industrialization, mining, urbanization, and excessive agrochemical use. These contaminants pose serious risks to human health through the food chain. Conventional soil remediation techniques are often costly and less sustainable, necessitating alternative solutions. Biochar, a carbon-rich material produced through pyrolysis of organic waste under oxygen-limited conditions, has gained attention as a potential soil detoxifier. Its high surface area, porosity, cation exchange capacity (CEC), and negative surface charge enable pollutant removal through adsorption, electrostatic interactions, and redox reactions. Additionally, biochar improves soil's physical, chemical, and biological properties. The effectiveness of biochar in soil remediation depends on factors such as feedstock type, pyrolysis temperature, and application methods. However, concerns remain regarding its long-term stability, aging effects, and potential release of toxic compounds like polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs). Further research is needed to evaluate its impact on microbial communities and nutrient dynamics. Future studies should focus on biochar functionalization, nanocomposite synthesis, and microbial inoculant integration to enhance its remediation potential. Despite certain limitations, biochar offers a promising, cost-effective, and sustainable strategy for soil detoxification, requiring further interdisciplinary research and regulatory frameworks.

1. Introduction

Over the past decades, the increasing population has created a high demand of resources necessary for the survival of lives. As a results, to meet global food demands, urbanization and intensification of agricultural practices also increased. Several anthropogenic activities, such as mining, smelting, and sewage sludge application, contribute to heavy metal accumulation in soil. The industrial runoff, improper treatment of waste water, municipal and household waste, over

* *Corresponding author.*
E-mail address: ramijur.rahman.amj23@aau.ac.in

https://doi.org/10.37934/sea.5.1.118

application of agrochemicals pose serious risk to ecosystem and human well-being. Contaminated soils often contain heavy metals, such as Pb, Cd, Cu, Zn, and As and their mobility and bioavailability raise a serious global concern in uptake by plants and then to human through food chain [1]. To reduce the effect of contamination, many studies have found that a component made up of bio-waste through the process of pyrolysis termed as biochar [2]. When organic matter (wood, manure, or leaves) is heated in a closed container with little or no available air, charcoal is produced by a process called pyrolysis.

Biochar is a carbon-rich, fine-grained and porous material produced under oxygen-limited conditions [3] at temperatures between 350 and 700 C. It can be defined as the solid residue obtained from the thermochemical decomposition or pyrolysis of plant and waste feedstocks, and can be specifically used for application to soil as part of an agronomic or environmental management plan. Its unique properties, such as high surface area, cation exchange capacity, and functional groups, enable it to adsorb and immobilize various contaminants like heavy metals, pesticides, and organic pollutants. Biochar has high potential for carbon (C) sequestration due to its stable aromatic structure, which makes it resistant to microbial degradation. Additionally, biochar improves soil structure, nutrient retention, and microbial activity, making it an effective and sustainable solution for soil remediation [4]. Several studies suggest that biochar application can create win-win scenario by detoxifying soil, enhancing sustainability, and improving crop productivity [4-6]. Healthier the soil.

Despite its potential, knowledge gaps remain regarding biochar's long-term stability, interactions with soil microbial communities, and field-scale effectiveness. This review aims to evaluate biochar's role in soil detoxification, identify associated risks, and propose future research directions.

2. Methodology

To gather information about the concept of biochar and its application in soil remediation, various search engines, including Google Scholar, Elsevier, ScienceDirect, Scopus, and ResearchGate, were used. Relevant literature published in the last 15 years (2010–2025) was collected using keywords such as *biochar*, *soil remediation*, *soil contamination*, and *heavy metal contamination*. The primary sources of data for this review were peer-reviewed research and review articles, ensuring the inclusion of high-quality and credible studies. Priority was given to experimental studies and field trials that provided quantitative data on the effectiveness of biochar in improving soil quality and mitigating heavy metal contamination.

Studies that were not peer-reviewed, published before 2010, or focused on biochar applications unrelated to soil remediation, such as energy production or water treatment, were excluded. Additionally, articles that lacked experimental validation or were purely theoretical discussions were also omitted. This selection process ensured that the review remained focused on recent, scientifically validated findings that are directly relevant to the remediation of polluted soils using biochar.

3. Results and Discussion

3.1 Properties of Biochar

Biochar, a carbon-rich material produced from biomass pyrolysis, has gained attention for its potential benefits in agriculture and environmental management [1]. Physically, biochar is a fine-grained, porous material with high surface area. It has a high surface area that make biochar more capable to adsorb ions on its surface. Depending on the feedstock types and production methods, the properties of biochar varies and its influence on the soil also alter [7]. The chemical properties of biochar include that biochar is alkaline in nature due to high inorganic content and ash content ranging its pH from 6.5 to 9 depending on the temperature applied during the pyrolysis process [8]. Due to its high cation exchange capacity (CEC), biochar develops both positive and negative surface charges, which can reduce the leaching of cationic and anionic contaminants in soil [7]. Biochar differs from other organic matter lies in its significantly higher proportion of aromatic carbon structures, which contribute to its stability and sorption capacity. Unlike the aromatic structures found in soil organic matter, such as lignin, biochar's fused aromatic structures can take various forms. At lower pyrolysis temperatures, amorphous carbon predominates, whereas turbostratic carbon forms at higher temperatures. It is evident that the nature of these carbon structures is the main reason for biochar's high stability [9]. Biochar exhibits key biological properties that enhance soil health and productivity. Its porous structure fosters microbial colonization, boosting nutrient cycling and soil fertility. It also influences soil enzyme activities essential for nutrient dynamics and affects soil fauna by altering habitats [10]. Figure 1 depicts various properties of biochar.

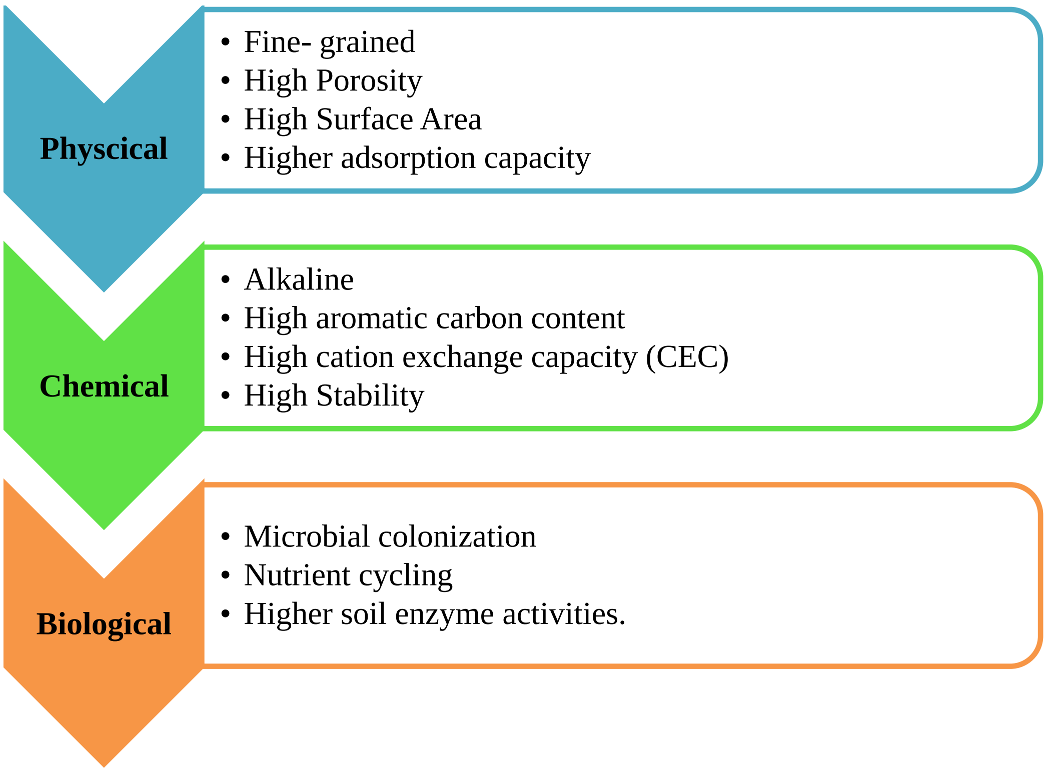

Fig. 1. Properties of biochar

3.2 Mechanisms of Biochar in Improving Soil Health

Biochar improves soil health through various mechanisms. Its high surface area and porosity enhance water holding capacity (WHC), soil porosity and structure, and aeration, creating an optimal habitat for soil microbial populations. The porous structure reduces runoff and increases the infiltration of moisture enhancing available water of soil [11]. High porosity of Biochar also contributes to water retention and slow discharge that enhances the conservative properties of degraded soils. Additionally, biochar raises soil pH due to its base cation composition, which includes Na^+, K^+, Mg^{2+} and Ca^{2+}. Ashes of biochar also accelerate pH enhancement in the acidic condition by the dissolutions of carbonate and hydroxides. The negatively charged functional groups present in the surface of biochar adsorb cations increasing cation exchange capacity (CEC) of soil [12]. It leads to immobilization of metal ions that reduces their bioavailability and support soil reclamation in contaminated areas [13]. Biochar is rich in essential nutrients (Ca, Mg, K, P, and N), that are necessary for the growth and development of plants. Although, the nutrient content of biochar varies with the feedstock used for preparing it, influencing nutrient dynamics and reduces nutrient leaching. Biochar also stimulates formation of root nodule and enhances nitrogen immobilization, promoting growth of plant [3]. Moreover, biochar improves microbial habitats by enhancing the structure, diversity, and activity of microorganisms present in soil. Biochar produced by Low-temperature, support microbial growth due to higher nitrogen and dissolved organic carbon (DOC) content. By rectifying the soil environment, biochar enhances nutrient cycling, structure of microbial community and Plant – Rhizobial interactions, making it a valuable material for the ecological reclamation of contaminated soils [14]. Figure 2 illustrates how biochar interacts with soil components, improving water retention, nutrient cycling, and microbial diversity while reducing heavy metal mobility.

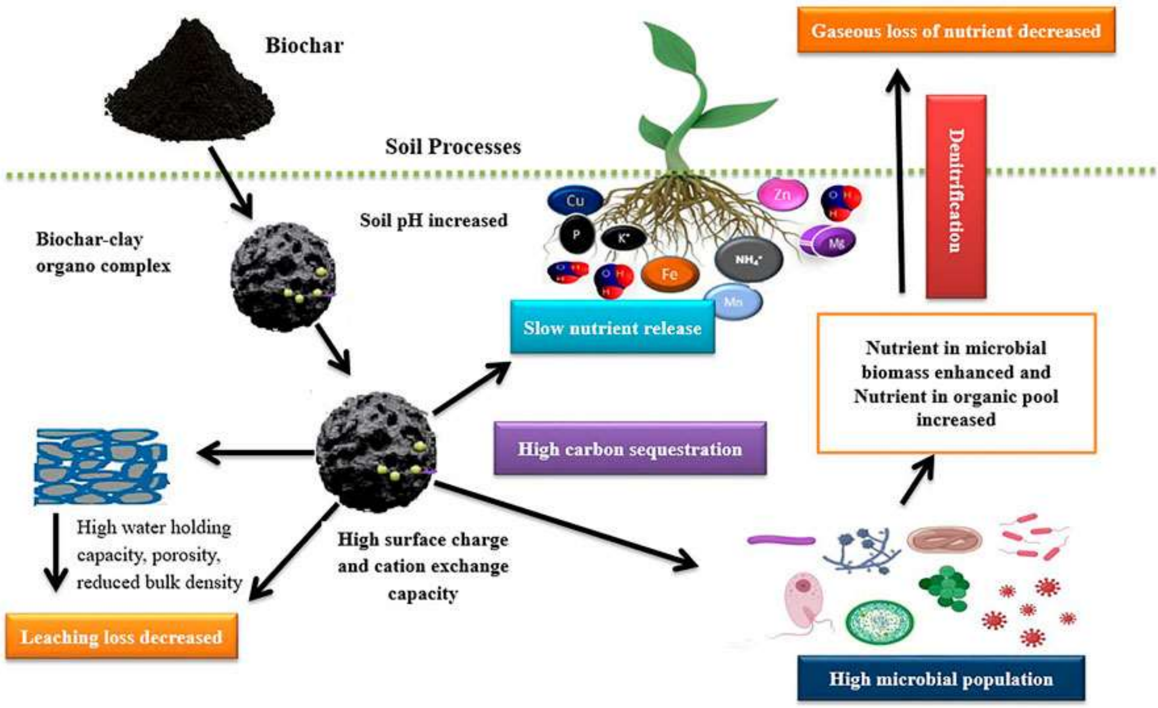

Fig. 2. Processes of biochar after its introduction to soil [75]

3.3 Mechanism of Biochar in Detoxifying Soil

Biochar has emerged as a promising tool in reducing concentration of various contaminants from soil due its unique physical, chemical and biological properties [15]. The aforementioned properties of biochar play a crucial role in the immobilization of heavy metals in soil which includes adsorption, complexation, precipitation, ion exchange, electrostatic interaction and redox potential [16]. The physical adsorption mechanism, also known as van der Waals adsorption, occurs due to intermolecular forces between the adsorbent and adsorbate molecules. This process is typically reversible and is influenced by various factors such as pore volume, surface energy, and the surface area of biochar. Biochar produced at high temperature pyrolysis tends to have a larger pore volume and higher surface area that provide an extensive binding area for heavy metal ions to be bound. As a result, these biochars has enhanced van der Waals adsorption capacity, immobilizing heavy metals effectively [17]. Furthermore, the microporous and mesoporous structures of biochar significantly influence its ability to bind contaminants, as smaller pore sizes contribute to stronger van der Waals interactions [18]. Various studies have shown that biochar derived from lignin and cellulosic biomass have higher adsorption potential due to their well-developed pore structures and high thermal stability [19]. Figure 3 illustrates the key processes involved in biochar detoxification, including physical adsorption, electrostatic interaction, and precipitation of heavy metals as stable complexes.

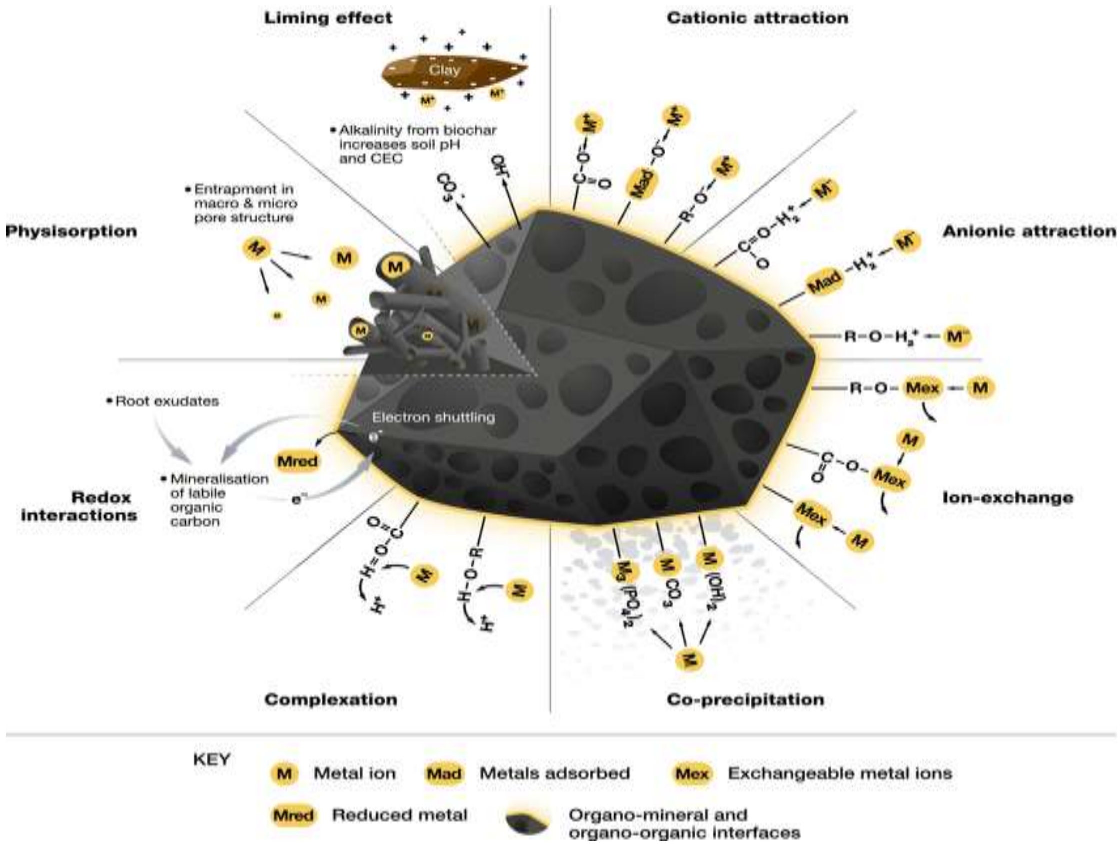

Fig. 3. Detoxification of heavy metals by biochar [76]

Besides physical adsorption capacity of biochar, the highly negative charge on the biochar surface enhances electrostatic interactions between metal cations and soil particles, contributing to the immobilization of heavy metals through electrostatic attraction. The effectiveness of this interaction is largely influenced by factors such as the point of zero charge (PZC) of biochar, the pH of the soil solution, and the ionic and valence radii of the metal ions [20,21]. Biochar application increases soil pH and cation exchange capacity (CEC), enhancing electrostatic attraction between soil particles and metal ions. This process reduces the mobility and bioavailability of heavy metals [22]. Precipitation plays a crucial role in remediating soil. Its alkaline nature helps to increase soil pH, promoting the hydrolysis of heavy metals and leading to the formation of metal hydroxide precipitates, hence reduces their mobility. Studies have shown that biochar amendments, especially those derived from wood and manure, increase soil pH and significantly decrease extractable heavy metals like Pb, Zn, Cu, and Cd [23,24]. This pH elevation also facilitates the formation of Fe/Al hydroxide precipitates in paddy soils, co-precipitating metal ions onto iron plaques on plant roots. Moreover, biochar introduces phosphates, carbonates and sulphates, that reacts with metal ions to form stable precipitates, such as pyromorphite and hydroxypyromorphite in Pb-contaminated soils [25].

The metal immobilization influence differs with the biochar type because manure-based biochars are richer in phosphates, and they help to precipitate the metals, while wood-based biochars enhance carbonate and oxyhydroxide developments [26]. The aromatic structure of biochar makes it more stable, increases adsorption, and enhances interaction with organic and inorganic pollutants. The extremely compacted aromatic rings within biochar allow it to remain persistent in the soil for an extended period of time, allowing for a solid matrix for the immobilization of contaminants [27]. The structures enhance hydrophobicity and render biochar highly efficient at adsorbing non-polar organic pollutants such as pesticides, polycyclic aromatic hydrocarbons (PAHs), and persistent organic pollutants (POPs). Xiang *et al*., [28] reported that interactions of the π-electron in the aromatic framework enable the adsorption of heavy metals and organic contaminants that aids in detoxification of contaminated soils. As per Palansooriya *et al*., [29] investigation, the aromatic structure of biochar also enhanced its resistance to degradation of microbial population that allow it to maintain its remediation potential over a long period. Microbial habitat and nutrient availability of soil is improved by application of biochar while immobilizing potentially toxic elements (PTEs) and reduces their harmful effects on soil microorganisms. Biochar application also enhances bacterial diversity and increases the abundance of beneficial microbial groups like Actinobacteria, Proteobacteria, and Firmicutes [9,18]. The decrease in heavy metal toxicity, as well as enhanced nitrogen and phosphorus availability, is critical in enhancing microbial populations. Biochar amendments have also been associated with greater fungal and actinomycete populations, which are responsible for the degradation of contaminants and organic matter [30]. Microorganisms also act synergistically with biochar to enhance soil detoxification further. For example, co-inoculation with fungal-bacterial and biochar has been identified to minimize heavy metal bioavailability of elements like Ni, Mn, and Cr by reducing it through redox reactions [31,32].

Analogously, plant growth-promoting bacteria, i.e., *Neorhizobium huautlense*, have also been reported to diminish metal buildup in crops. Combination of biochar with microbial inoculants like Bacillus subtilis or Pseudomonas aeruginosa makes the immobilization of heavy metals even more efficient compared to single-use biochar. But in some interactions, like that of biochar with arbuscular mycorrhizal fungi, the remediation value might not always be substantial. These processes all lower the bioavailability of toxic metal, so biochar can be seen as a potential tool in soil remediation and stabilization of heavy metal [30].

3.4 Effectiveness of Biochar in Detoxifying soil

3.4.1 Removal of heavy metals

Heavy metal contamination is a major environmental threat resulting from industrial activities, mining, and agricultural practices. It reduces soil fertility and poses health risks through plant uptake and groundwater contamination. Traditional remediation methods are costly and time-consuming, highlighting the need for sustainable alternatives. Biochar has been found to be very effective in immobilizing heavy metals in polluted soils, lowering their bioavailability and inhibiting plant uptake. Studies indicate that the addition of 5% biochar from chicken dung reduced Cu uptake in *Oenothera picensis* plants from 66.9 mg/kg to 36.6 mg/kg, while significantly increasing shoot biomass by 3.5 times and root biomass by 3.1 times [33]. Sulfur-amended rice husk biochar increased Hg^{2+} adsorption by 73% to a capacity of 67.11 mg/g and reduced freely available Hg by 95.4%, 97.4%, and 99.3% at rates of 1%, 2%, and 5%, respectively [34]. In another research, rice hull biochar was superior to wheat straw biochar in minimizing Hg accumulation in rice, lowering Hg content below the Chinese government's limit of 20 ng/g [35]. In addition, sewage sludge biochar (SSB) lowered methylmercury (Me-Hg) and total Hg (THg) accumulation in rice tissues by 73.4% and 81.9%, respectively [36]. Casuarina-derived biochar at 4% effectively lowered Cd, Co, Cr, Cu, Ni, Pb, and Zn content in plant roots by 25.7%, 52.1%, 12.1%, 32.3%, 31.0%, 85.0%, and 25.2%, respectively [37]. Apart from immobilizing metals, biochar enhances soil fertility, structure, and microbial activity, hence supporting plant growth and preventing soil erosion. Nonetheless, long-term consequences of the use of biochar in metal-polluted soils are to be studied to determine its efficiency and stability over time [38]. The type of biochar produced by different feedstocks affects the removal of heavy metals from soil. Table 1 lists the various types of biochar that are used for heavy metal remediation and their effectiveness in the polluted soil. Biochars that are derived from various sources such as chicken dung, rice husk, wheat straw, and sewage sludge, exhibit varying capacities for adsorption of metal and their stabilization. Research has indicated that the use of biochar can minimize heavy metal uptake by plants, improve soil quality, and restrict metal mobility. In general, biochar is a cost-effective and sustainable method for remediating heavy metal-polluted soils and thus is a promising agricultural and environmental restoration amendment.

Table 1
Types of biochar that are used for heavy metal remediation and their effectiveness in the polluted soil

Biochar types	Heavy metals	Reduction of heavy metal concentration in %	Key observation	Study
Chicken dung biochar	Cu	45.5	Reduced Cu uptake by plants, increasing biomass	Meier *et al*., [33]
Sulfur-modified rice husk biochar	Hg	73	Enhanced Hg adsorption capacity, reduced freely accessible Hg	O'Connor *et al*., [34]
Sewage sludge biochar (SSB)	Hg	73.4% (MeHg), 81.9% (THg)	Reduced MeHg and THg accumulation in rice	Zhang *et al*., [36]
Casuarina biochar	Cd, Co, Cr, Cu, Ni, Pb, Zn	Greatly reduced	4% Casuarina biochar most efficient in reducing heavy metal adsorption by roots and shoots	Ibrahim *et al*., [37]
Biochar (straw, willow)	PAHs in willow soil	70.3% (biochar-straw), 29.3% (biochar-willow)	Different biochars exhibit varying reduction levels	Oleszczuk *et al*., [39]
Biochar (eucalyptus, wood, bamboo, rice husk)	Al toxicity	Varied reduction	Alleviating soil Al toxicity	Shetty *et al*., [40]
Cotton straw biochar	Cd	65-87	Reduction in Cd accumulation in plant organs	Zhu *et al*., [41]
Vegetable wastes biochar	Pb	87	Achieved Pb immobilisation of 87%.	Igalavithana *et al*., [42]
Wheat straw	Cd, Pb	55-71 (Cd) and 65-80% (Pb)	Soil extractable Cd decreased by 55-71% and Pb by 65 80%.	Bian *et al*., [43]
Agriculture residues	Pb, Cd	Varied reduction	Achieved reduction of expendable Pb and Cd by 28.68% and 85.14%, respectively	Alaboudi *et al*., [44]

3.4.2 Removal of organic pollutants

Soil pollution with organic contaminants originates from diverse sources such as agricultural practices, ineffective waste management, and industrial activities. Most of these contaminants, like persistent organic pollutants (POPs) and new emerging organic pollutants, are hazardous to the environment and human health because they exhibit mutagenic and carcinogenic effects (WHO). Biochar is well researched as a remediation agent because it has a high specific surface area (SSA), microporosity, and rich functional groups, which are responsible for the adsorption of organic contaminants [45]. The effectiveness of biochar in the adsorption of organic pollutants is influenced by a number of factors, such as pyrolysis conditions, type of feedstock, and soil characteristics. Experiments have shown that biochar strongly inhibits the bioaccumulation of Polycyclic aromatic hydrocarbons (PAHs) in plants. Ni *et al*., [46] explored the impact of biochar on PAH absorption in *Daucus carota L*. (carrot) planted in contaminated soil. The research used two different biochars: CB300 from corn straw and BB700 from bamboo, both at a concentration of 2%. PAH bioaccumulation in carrot roots was significantly minimized after 150 days. The CB300 treatment lowered both total and bioavailable PAH amounts, while BB700 boosted total PAHs in the rhizosphere but lower bioavailable PAHs using adsorption processes. In addition to this, Oleszczuk *et al*., [39] investigated further the application of biochar and activated carbon (AC) in reducing PAH bio-accessibility in willow (*Salix viminalis*). PAH-contaminated soil was treated with 2.5 % wt straw or willow-derived biochar. The outcomes indicated a high decrease in the bio accessible fraction (C-bioacc) of PAHs after 18 months. The concentration of PAH dropped by 70.3% using straw biochar, 38.0% using AC, and 29.3% using willow biochar. Rajapaksha *et al*., [47] indicated that sulfamethazine (SMT) adsorption by BBC700, a burcucumber (*Sicyos angulatus L*.) derived biochar. The objective was to evaluate SMT accumulation in lettuce (*Lactuca sativa L*.) cultivated in contaminated soil treated with 5% BBC700. The results indicated that biochar application significantly increased SMT adsorption, reducing its bioavailability. Compared to untreated soil, lettuce grown in biochar-amended soil exhibited an 86% reduction in SMT uptake when treated with 5 mg kg^{-1} SMT and a 63% reduction when treated with 50 mg kg^{-1} SMT.

Overall, biochar demonstrates significant potential in remediating soil contamination by reducing the bioavailability of organic pollutants. High adsorption capacity of biochar and its ability to immobilize contaminants make it a crucial tool in remediation of contaminated soil. Though, the long-term environmental fate of sequestered pollutants remains uncertain, necessitating further research to assess the sustainability of biochar-based soil remediation strategies. While biochar has proven to be a valuable solution in reducing contamination risks to the human food chain and groundwater, future studies should explore its long-term impact on ecosystem health and pollutant degradation dynamics [16]. Table 2 provides a comprehensive overview of biochar's influence on the sorption of various organic pollutants.

Table 2
Overview of biochar's influence on the sorption of various organic pollutants

Biochar type	**Organic pollutants**	**Impact of biochar**	**Study**
Swine manure biochar	Norflurazon and fluridone	Biochar derived from swine manure exhibited strong adsorption properties for these herbicides, reducing their mobility in soil.	Rana *et al*., [48]
Pine needles biochar	PAHs	Higher pyrolysis temperatures enhanced PAH retention, minimizing their environmental impact.	Wang *et al*., [6]
Sugarcane residue biochar	Ethinylestradiol	Biochar effectively adsorbed steroidal pollutants, reducing their bioavailability and slowing microbial degradation.	Lian *et al*., [49]
Biochar (hardwood)	PAHs	Biochar treatment led to a reduction in both total and accessible PAHs, improving soil quality.	Kharel *et al*., [50]
Biochar (willow)	PAHs	Amended biochar decreased PAH exposure to soil organisms, reducing ecotoxicity without affecting plant health.	Godszad *et al*., [51]
Sewage slugde biochar	PAHs	PAH accumulation in soil was significantly reduced due to biochar's high adsorption capacity.	Tedoldi *et al*., [52]
Biochar (woftwood)	Polychlorinated biphenyls	Biochar application restricted PCB availability, lowering the risk of groundwater contamination.	Montagnoli *et al*., [11]
Maize stover biochar	Polychlorinated dibenzo-p-dioxins	Biochar immobilized toxic dioxins, preventing their spread through soil and water.	Lomaglio *et al*., [53]
Biochar (bamboo)	Pentachlorophenol	Biochar effectively trapped pentachlorophenol, limiting its leaching potential.	Simiele *et al*., [54]
Rice straw biochar	Petroleum	Petroleum hydrocarbons were degraded more efficiently in biochar-amended soils.	Nedjimi [55]
Biochar (hardwood)	Tylosin	Higher biochar concentrations enhanced tylosin adsorption, reducing its leaching in alkaline soils.	Katiyar *et al*., [56]
Olive residue biochar	Metalaxyl and tebuconazole	Biochar treatment reduced pesticide degradation rates, leading to prolonged retention in soil.	Liang *et al*., [57]
Biochar (hardwood)	Simazine	Simazine movement was restricted by biochar, decreasing groundwater contamination risks.	Lahori *et al*., [58]
Biochar (pinewood)	Phenanthrene	Phenanthrene adsorption increased in low organic-carbon soils treated with biochar.	Gu *et al*., [59]

3.5 Efficacy of Biochar in Detoxifying Polluted Soils

Biochar has proved to have a significant potential to adsorb inorganic and organic pollutants in the form of various contaminants due to its porous structure and large surface area. Biochar performs extremely well to desorb organic contaminants like pesticides, polycyclic aromatic hydrocarbons (PAHs), and drug residues [60]. Biochar is also able to immobilize some heavy metals, minimizing their bioavailability in soils. Yet, its efficiency depends on the characteristics of the biochar and the contaminants in question. While biochar effectively immobilizes metals such as lead and cadmium, its efficiency with other contaminants varies. Certain contaminants might not adsorb well, requiring the application of other remediation methods [61]. The efficiency of biochar also depends on varying soil types.

In sandy soils, biochar enhances water and nutrient retention, hence increasing soil fertility. In contrast, in clay soils where water and nutrient retention is already considerable, the effect of biochar might be minimal. The interaction of biochar with different soil minerals can influence its capacity to immobilize pollutants, so its effectiveness is not uniform in different soils.

Soil texture and the presence of organic matter are some of the key factors that determine its performance. Long-term efficacy of biochar, over a period of time, can be diminished by aging phenomena such as oxidation and microbial attack, which affect its surface properties. With passage of time, pores in biochar can become plugged with soil minerals or organic matter, thereby decreasing its adsorption capacity. While biochar in general is stabile in soils, its sorption and sequestration properties to bind inorganic contaminants are subject to reduce over time since it will also be interacting constantly with the native environment. Its long-term effects can only truly be evaluated and assessed through conducting field studies extending for many years.

The long-term efficacy of biochar can be lost through aging mechanisms such as oxidation and microbial processes, which alter its surface properties. With time, the porosity of biochar can be clogged by organic residues or soil minerals, reducing its adsorption capacity. Although biochar is stable in the soil, its ability to bind and sequester contaminants could decrease as it interacts with the environment. Biochar is effective in the treatment of moderately polluted soils by immobilizing contaminants and reducing their bioavailability. In cases of extreme pollution with high concentrations of heavy metals or persistent organic pollutants, though, the use of biochar alone might not be sufficient. It has limited adsorption capacity, and high pollutant loads can fill biochar's binding sites to the point of reducing its efficiency. In extremely contaminated sites, biochar is often used in combination with other remediation strategies, i.e., phytoremediation or chemical amendments, to get maximum benefits. Environmental parameters such as temperature, rainfall, and relative humidity are all influence the detoxification function of biochar. Under conditions of high rainfall, leaching can lead to the washing away of biochar particles, along with the impurities they have adsorbed, from where they were deposited to the groundwater, which could result in contamination. Temperature fluctuations may impact microbial activity within the soil, which in turn affects the stability of biochar and its capacity to retain contaminants. Furthermore, in cold regions, freeze-thaw cycles will alter the porosity and adsorption properties of biochar, which will overall reduce its efficiency. These are factors to consider when applying biochar for the remediation of soil under diverse environmental conditions.

3.6 Toxicity Associated with Biochar and Its Mitigation Strategies

While biochar has traditionally been considered a safe soil amendment, concerns about its toxicity have recently emerged. The pyrolysis process can generate dioxins, heavy metals, PAHs, and VOCs, all of which pose risks to plant health, soil microorganisms, and the environment. Organic Pollutants of biochar, such as dioxins, PAHs, and VOCs are produced as a result of pyrolysis of the biomass feedstock that are toxic to soil microecosystems. The contaminants can be immobilized in the biochar and leach in the environment and cause harm to microorganisms and plant growth. The existence of these substances poses a problem for the safe utilization of biochar in agriculture [62].

Production and effect of VOCs in biochar contains VOCs originating from the re-condensation of gasses and liquids that were produced during the pyrolysis absorption process, such as syngas and bio-oil. Types of feedstock biomass tend to have a major impact on the development of VOC and materials with high lignin usually produce higher concentrations [63]. Biochar may contain residual VOCs, which can limit its environmental applications. Research has shown that the content of VOC in biochar can be anything between 0.34 to 16000 µg /g, and this largely depends on the types of feedstocks and the conditions of pyrolysis [64]. Too high amounts of VOCs have the potential to stifle plant germination, block soil microbial activity and even disrupt cycling of nutrients [65].

Polycyclic Aromatic Hydrocarbons (PAHs) in biochar are produced during the process of pyrolysis through thermal degradation of lignocellulosic biomass [66]. The concentration of PAHs in biochar depends on the temperature and time of the pyrolysis process. There have been some reports of low total PAH content, but there is deep concern over the existence of PAHs because of their known mutagenic and carcinogenic properties [67]. PAHs that exist in biochar are mobile and can diffuse into the surrounding environment, which causes a change in soil properties and even destroys the microbial population [68]. Research has demonstrated that biochar produced at temperatures of over 500°C contains less PAH than biochar produced at temperatures below that and with more harmful PAH to the environment [69].

Heavy metals in biochar heavy metals such as lead (Pb), cadmium (Cd), arsenic (As), and copper (Cu) are enriched in biochar through pyrolysis. Their enrichment depends on the original biomass material [56]. Animal manure and sewage sludge biochars are more heavily enriched with heavy metals compared to plant biochars [70]. While some heavy metals are trapped in stable mineral phases, others are present in bioavailable fractions that increase their environmental hazards. Application of heavy metal-enriched biochar in soil may result in metal leaching, polluting groundwater and inhibiting plant growth [21]. Dioxins in biochar, Polychlorinated dibenzo-p-dioxins and dibenzofurans are organochlorinated poisonous substances with acute toxicity produced through low-temperature pyrolysis. More dioxins in biochar are found from chlorine feedstocks based on studies [48,71]. Few studies, however, have been carried out to provide safe dioxin content in biochar. Reduced dioxin content below detection levels is reported by some studies, whereas others report their long-term environmental concerns.

3.7 Strategies to Reduce Toxicity Associated with Biochar

Mitigation strategies for biochar toxicity, has five ways which intent to minimize the risks associated with biochar toxicity as follows:

i. *Using Uncontaminated Biomass as Wood and Agricultural Residues* – selection of clean Feedstocks as puts forward uncontaminated wood and agricultural residues aims at reducing heavy metal and dioxin contamination.
ii. *Retaining and Enhancing Biochar Stability Through Higher Pyrolysis Temperatures* – optimization of pyrolysis conditions makes use of higher pyrolysis temperature's range of 500 – 700 degrees Celsius to reduce PAH and VOC content.
iii. *Composting Biochar* –Post treatment methods include washing and composting as techniques which further mutes the concentration of PAH, VOC, and heavy metals.
iv. *Improved Biochar Quality Through Contaminant Reduction* – Industrial scale production as controlled pyrolysis conditions within industrial reactors.
v. *Safe Use In Agriculture Through Better Regulation* - Application Guidelines as safe use of biochar in agriculture and environment remediation can be achieved through active regulation of PAHs, VOCs, and Heavy Metals in a prepared biochar [72].

3.8 Limitations of Biochar

3.8.1 Variable efficiency depending on feedstock and pyrolysis conditions

The effectiveness of biochar as a soil detoxifier depends significantly on the feedstock source and pyrolysis conditions. Different sources of biomass yield biochar of different physical and chemical natures, thus varying its capacity and efficiency as an adsorber of contaminants [2]. For instance, biochar from pyrolysis at high temperatures might be of high surface area but low in functional groups necessary to trap contaminants.

3.8.2 Potential nutrient deficiency

Although biochar can enhance soil fertility, it may also cause nutrient imbalances. Biochar has the potential to adsorb available nutrients such as nitrogen and phosphorus and therefore lower their availability to plants [3]. The carbon content in biochar can also lead to nitrogen immobilization, impacting microbial growth and plant development.

3.8.3 Impact on soil microbial communities

Soil biochar application may have indirect impacts on the soil microbial community. Although it can stimulate good microbes, it can suppress others, and this will disrupt the ecological balance of the soil [9]. There is much to be learned regarding the long-term effects of this microbial change on soil structure and contaminant degradation.

3.8.4 Limited use against specific pollutants

Biochar is better at the adsorption of hydrophobic organic pollutants and heavy metals but poorer in the removal of very soluble pollutants such as nitrates and certain pesticides [73]. Biochar adsorption of contaminants is pH, ionic strength, and soil type dependent, which can reduce its effectiveness in real-world applications.

3.8.5 Excessive application and production costs

Mass production and application of biochar are costly, hence making biochar less viable for large-scale soil detoxification. The use of high-tech machinery and energy-consuming pyrolysis increases costs, and the technology is therefore less competitive compared to conventional soil remediation technologies [74].

4. Conclusion

Biochar has proven to be a promising detoxifier for contaminated soil due to its high adsorption capacity and structural complexity. It has been observed to stabilize heavy metals such as cadmium (Cd), lead (Pb), zinc (Zn) and copper (Cu), thus reducing their bioavailability and plant. In addition, biochar adsorbs organic pollutants, including polycyclic aromatic hydrocarbons (PAH) and pesticides, effectively and prevent them from entering into groundwater. It has the ability to enhance soil structure, increase microbial activity and increase water retention. However, the efficiency depends on raw material, pyrolysis temperature and specific soil environments. Its variable efficiency, long-term stability, and potential toxicity risks must be addressed before large-scale implementation.

4.1 Research Gaps

Although there is a huge extent for the use of biochar in toxic soil, there are some important intervals in research to ensure long – lasting effect and environmental protection. Moreover, Biochar has shown promising consequences for heavy metal and organically polluting stabilization in the laboratory, the lack of studies of the long – standing field limits its endurance and effect under the real field state. In addition, environmental risk such as leaching of heavy metals and polycyclic aromatic hydrocarbons (PAH) should be the release of toxic compounds such as liberation and any unwanted effects thoroughly examined.

4.2 Future Perspectives

In order to increase the detoxification efficiency of biochar, advanced strategies such as biochar composites, functionalization and microbial vision strap should be detected. Including materials such as soil, iron oxide or gas can improve adsorption, while chemical modifications (e.g. acid treatment, magnetization, nanoparticle doping) increase the selection for specific environmental toxins. Microbial integration can speed up the decline in pollution, which can lead to more effective. In addition, accurate application strategies can maximize the efficiency of fit soil conditions and contaminated types. To ensure secure application of biochar, policies and regulation are necessary for development of control, risk assessment and application guidelines. Future research should integrate material science, microbiology and environmental technology to continuously optimize the therapeutic capacity of biochar.

Acknowledgement
The authors gratefully acknowledge the support received by the Department of Soil Science, Assam Agricultural University. Jorhat, Assam, India.

Author's Contribution
The manuscript was prepared by Rahman, R under the supervision of Das, K.N.

Funding
This research was not funded by any grant.

Consent for publication
All authors have consented for publication.

Conflict of interest
The authors declare no conflict of interest.

References

[1] Tiller, K. G. "Heavy metals in soils and their environmental significance." *Advances in Soil Science: Volume 9* (1989): 113-142. https://doi.org/10.1007/978-1-4612-3532-3_2

[2] Ahmad, Mahtab, Anushka Upamali Rajapaksha, Jung Eun Lim, Ming Zhang, Nanthi Bolan, Dinesh Mohan, Meththika Vithanage, Sang Soo Lee, and Yong Sik Ok. "Biochar as a sorbent for contaminant management in soil and water: a review." *Chemosphere* 99 (2014): 19-33. https://doi.org/10.1016/j.chemosphere.2013.10.071

[3] Liu, Xiaoyu, Afeng Zhang, Chunying Ji, Stephen Joseph, Rongjun Bian, Lianqing Li, Genxing Pan, and Jorge Paz-Ferreiro. "Biochar's effect on crop productivity and the dependence on experimental conditions—a meta-analysis of literature data." *Plant and soil* 373 (2013): 583-594. https://doi.org/10.1007/s11104-013-1806-x

[4] Lehmann, Johannes, and Stephen Joseph. "Biochar for environmental management: an introduction." In *Biochar for environmental management*, pp. 1-13. Routledge, 2015. https://doi.org/10.4324/9781003297673-1

[5] Dong, Shuangkuai, Wanli Xu, Fufei Wu, Cuixia Yan, Dianpeng Li, and Hongtao Jia. "Fe-modified biochar improving transformation of arsenic form in soil and inhibiting its absorption of plant." *Transactions of the Chinese Society of Agricultural Engineering* 32, no. 15 (2016): 204-212.

[6] Wang, Liuwei, Yong Sik Ok, Daniel CW Tsang, Daniel S. Alessi, Jörg Rinklebe, Hailong Wang, Ondřej Mašek, Renjie Hou, David O'Connor, and Deyi Hou. "New trends in biochar pyrolysis and modification strategies: feedstock, pyrolysis conditions, sustainability concerns and implications for soil amendment." *Soil Use and Management* 36, no. 3 (2020): 358-386. https://doi.org/10.1111/sum.12592

[7] Beusch, Christine. "Biochar as a soil ameliorant: how biochar properties benefit soil fertility—a review." *Journal of Geoscience and Environment Protection* 9, no. 10 (2021): 28-46. https://doi.org/10.4236/gep.2021.910003

[8] Gai, Xiapu, Hongyuan Wang, Jian Liu, Limei Zhai, Shen Liu, Tianzhi Ren, and Hongbin Liu. "Effects of feedstock and pyrolysis temperature on biochar adsorption of ammonium and nitrate." *PloS one* 9, no. 12 (2014): e113888. https://doi.org/10.1371/journal.pone.0113888

[9] Lehmann, Johannes, Matthias C. Rillig, Janice Thies, Caroline A. Masiello, William C. Hockaday, and David Crowley. "Biochar effects on soil biota–a review." *Soil biology and biochemistry* 43, no. 9 (2011): 1812-1836. https://doi.org/10.1016/j.soilbio.2011.04.022

[10] Kocsis, Tamás, Marianna Ringer, and Borbála Biró. "Characteristics and applications of biochar in soil–plant systems: A short review of benefits and potential drawbacks." *Applied Sciences* 12, no. 8 (2022): 4051. https://doi.org/10.3390/app12084051

[11] Montagnoli, Antonio, Silvia Baronti, Danieli Alberto, Donato Chiatante, Gabriella Stefania Scippa, and Mattia Terzaghi. "Pioneer and fibrous root seasonal dynamics of Vitis vinifera L. are affected by biochar application to a low fertility soil: A rhizobox approach." *Science of the Total Environment* 751 (2021): 141455. https://doi.org/10.1016/j.scitotenv.2020.141455

[12] Amin, Muhammad Ahmar, Ghulam Haider, Muhammad Rizwan, H. Kate Schofield, Muhammad Farooq Qayyum, Muhammad Zia-ur-Rehman, and Shafaqat Ali. "Different feedstocks of biochar affected the bioavailability and uptake of heavy metals by wheat (Triticum aestivum L.) plants grown in metal contaminated soil." *Environmental Research* 217 (2023): 114845. https://doi.org/10.1016/j.envres.2022.114845

[13] Jain, Shilpi, Disha Mishra, Puja Khare, Vineet Yadav, Y. Deshmukh, and Abha Meena. "Impact of biochar amendment on enzymatic resilience properties of mine spoils." *Science of the Total Environment* 544 (2016): 410-421. https://doi.org/10.1016/j.scitotenv.2015.11.011

[14] Gul, Shamim, Joann K. Whalen, Ben W. Thomas, Vanita Sachdeva, and Hongyuan Deng. "Physico-chemical properties and microbial responses in biochar-amended soils: mechanisms and future directions." *Agriculture, ecosystems & environment* 206 (2015): 46-59. https://doi.org/10.1016/j.agee.2015.03.015

[15] Dhiman, Shalini, Mohd Ibrahim, Kamini Devi, Neerja Sharma, Nitika Kapoor, Ravinderjit Kaur, Nandni Sharma et al. "Biochar assisted remediation of toxic metals and metalloids." *Handbook of Assisted and Amendment: Enhanced Sustainable Remediation Technology* (2021): 131-162. https://doi.org/10.1002/9781119670391.ch7

[16] Murtaza, Ghulam, Zeeshan Ahmed, Sayed M. Eldin, Iftikhar Ali, Muhammad Usman, Rashid Iqbal, Muhammad Rizwan, Usama K. Abdel-Hameed, Asif Ali Haider, and Akash Tariq. "Biochar as a green sorbent for remediation of polluted soils and associated toxicity risks: a critical review." *Separations* 10, no. 3 (2023): 197. https://doi.org/10.3390/separations10030197

[17] Ghosh, Dipita, and Subodh Kumar Maiti. "Biochar-assisted eco-restoration of coal mine degraded land to meet United Nation Sustainable Development Goals." *Land Degradation & Development* 32, no. 16 (2021): 4494-4508. https://doi.org/10.1002/ldr.4055

[18] Han, Huawen, Muhammad Khalid Rafiq, Tuoyu Zhou, Rong Xu, Ondřej Mašek, and Xiangkai Li. "A critical review of clay-based composites with enhanced adsorption performance for metal and organic pollutants." *Journal of hazardous materials* 369 (2019): 780-796. https://doi.org/10.1016/j.jhazmat.2019.02.003

[19] Wang, Xi-yang, Zai-jun Xin, Xiao-hui Li, Liang Li, Xiao-yan Sun, and Fang-fang Min. "Effect of combination of rice-straw biochar and Pennisetum sinese on remediating Cu and Cd contaminated soil." (2021): 74-82.

[20] Guo, Mingxin, Weiping Song, and Jing Tian. "Biochar-facilitated soil remediation: mechanisms and efficacy variations." *Frontiers in Environmental Science* 8 (2020): 521512. https://doi.org/10.3389/fenvs.2020.521512

[21] Zaman, Anwar, Muhammad Irfan, Amir Muhammad Khan, Haidar Ali, Navid Iqbal, Ijaz Ahmad, Muhammad Fawad, and Fida Muhammad. "Toxicity assessment and phytostabilization of contaminated soil by using wheat straw-derived biochar in tomato plants." *Gesunde Pflanzen* 74, no. 3 (2022): 705-713. https://doi.org/10.1007/s10343-022-00646-x

[22] Głąb, Tomasz, Krzysztof Gondek, and Monika Mierzwa–Hersztek. "Biological effects of biochar and zeolite used for remediation of soil contaminated with toxic heavy metals." *Scientific Reports* 11, no. 1 (2021): 6998. https://doi.org/10.1038/s41598-021-86446-1

[23] Gong, Xiaomin, Danlian Huang, Yunguo Liu, Guangming Zeng, Sha Chen, Rongzhong Wang, Piao Xu, Min Cheng, Chen Zhang, and Wenjing Xue. "Biochar facilitated the phytoremediation of cadmium contaminated sediments: Metal behavior, plant toxicity, and microbial activity." *Science of the Total Environment* 666 (2019): 1126-1133. https://doi.org/10.1016/j.scitotenv.2019.02.215

[24] Gouma, Vasiliki, Charikleia Tziasiou, Anastasia D. Pournara, and Dimosthenis L. Giokas. "A novel approach to sorbent-based remediation of soil impacted by organic micropollutants and heavy metals using granular biochar amendment and magnetic separation." *Journal of Environmental Chemical Engineering* 10, no. 2 (2022): 107316. https://doi.org/10.1016/j.jece.2022.107316

[25] Qiao, Yuxi, Juan Wu, Yanze Xu, Zhanqiang Fang, Liuchun Zheng, Wen Cheng, Eric Pokeung Tsang, Jianzhang Fang, and Dongye Zhao. "Remediation of cadmium in soil by biochar-supported iron phosphate nanoparticles." *Ecological engineering* 106 (2017): 515-522. https://doi.org/10.1016/j.ecoleng.2017.06.023

[26] Shaheen, Sabry M., Nabeel Khan Niazi, Noha EE Hassan, Irshad Bibi, Hailong Wang, Daniel CW Tsang, Yong Sik Ok, Nanthi Bolan, and Jörg Rinklebe. "Wood-based biochar for the removal of potentially toxic elements in water and wastewater: a critical review." *International Materials Reviews* 64, no. 4 (2019): 216-247. https://doi.org/10.1080/09506608.2018.1473096

[27] Qi, Fangjie, Saranya Kuppusamy, Ravi Naidu, Nanthi S. Bolan, Yong Sik Ok, Dane Lamb, Yubiao Li, Linbo Yu, Kirk T. Semple, and Hailong Wang. "Pyrogenic carbon and its role in contaminant immobilization in soils." *Critical reviews in environmental science and technology* 47, no. 10 (2017): 795-876. https://doi.org/10.1080/10643389.2017.1328918

[28] Xiang, Nan, Chunxia Jiang, Tinghan Yang, Ping Li, Haihua Wang, Yanli Xie, Sennan Li, Hailong Zhou, and Xiaoping Diao. "Occurrence and distribution of Polycyclic aromatic hydrocarbons (PAHs) in seawater, sediments and corals from Hainan Island, China." *Ecotoxicology and environmental safety* 152 (2018): 8-15. https://doi.org/10.1016/j.ecoenv.2018.01.006

[29] Palansooriya, Kumuduni Niroshika, James Tsz Fung Wong, Yohey Hashimoto, Longbin Huang, Jörg Rinklebe, Scott X. Chang, Nanthi Bolan, Hailong Wang, and Yong Sik Ok. "Response of microbial communities to biochar-amended soils: a critical review." *Biochar* 1 (2019): 3-22. https://doi.org/10.1007/s42773-019-00009-2

[30] Bandara, Tharanga, Ashley Franks, Jianming Xu, Nanthi Bolan, Hailong Wang, and Caixian Tang. "Chemical and biological immobilization mechanisms of potentially toxic elements in biochar-amended soils." *Critical Reviews in Environmental Science and Technology* 50, no. 9 (2020): 903-978. https://doi.org/10.1080/10643389.2019.1642832

[31] Wang, Lu, Jun Meng, Zhangtao Li, Xingmei Liu, Fang Xia, and Jianming Xu. "First "charosphere" view towards the transport and transformation of Cd with addition of manure derived biochar." *Environmental Pollution* 227 (2017): 175-182. https://doi.org/10.1016/j.envpol.2017.04.024

[32] Li, Hongbo, Xiaoling Dong, Evandro B. da Silva, Letuzia M. de Oliveira, Yanshan Chen, and Lena Q. Ma. "Mechanisms of metal sorption by biochars: Biochar characteristics and modifications." *Chemosphere* 178 (2017): 466-478. https://doi.org/10.1016/j.chemosphere.2017.03.072

[33] Meier, Sebastián, Gustavo Curaqueo, Naser Khan, Nanthi Bolan, Mara Cea, González María Eugenia, Pablo Cornejo, Yong Sik Ok, and Fernando Borie. "Chicken-manure-derived biochar reduced bioavailability of copper in a contaminated soil." *Journal of Soils and Sediments* 17 (2017): 741-750. https://doi.org/10.1007/s11368-015-1256-6

[34] O'Connor, David, Tianyue Peng, Guanghe Li, Shuxiao Wang, Lei Duan, Jan Mulder, Gerard Cornelissen, Zhenglin Cheng, Shengmao Yang, and Deyi Hou. "Sulfur-modified rice husk biochar: a green method for the remediation of mercury contaminated soil." *Science of the total environment* 621 (2018): 819-826. https://doi.org/10.1016/j.scitotenv.2017.11.213

[35] Xing, Ying, Jianxu Wang, Jicheng Xia, Zhenmei Liu, Yonghang Zhang, Ying Du, and Wanli Wei. "A pilot study on using biochars as sustainable amendments to inhibit rice uptake of Hg from a historically polluted soil in a Karst region of China." *Ecotoxicology and Environmental Safety* 170 (2019): 18-24. https://doi.org/10.1016/j.ecoenv.2018.11.111

[36] Zhang, Jin, Shengchun Wu, Zhentao Xu, Minyan Wang, Yu Bon Man, Peter Christie, Peng Liang, Shengdao Shan, and Ming Hung Wong. "The role of sewage sludge biochar in methylmercury formation and accumulation in rice." *Chemosphere* 218 (2019): 527-533. https://doi.org/10.1016/j.chemosphere.2018.11.090

[37] Ibrahim, Ehab A., Mohamed AA El-Sherbini, and El-Metwally M. Selim. "Effects of biochar on soil properties, heavy metal availability and uptake, and growth of summer squash grown in metal-contaminated soil." *Scientia Horticulturae* 301 (2022): 111097. https://doi.org/10.1016/j.scienta.2022.111097

[38] He, Lizhi, Huan Zhong, Guangxia Liu, Zhongmin Dai, Philip C. Brookes, and Jianming Xu. "Remediation of heavy metal contaminated soils by biochar: Mechanisms, potential risks and applications in China." *Environmental pollution* 252 (2019): 846-855. https://doi.org/10.1016/j.envpol.2019.05.151

[39] Oleszczuk, Patryk, Paulina Godlewska, Danny D. Reible, and Piotr Kraska. "Bioaccessibility of polycyclic aromatic hydrocarbons in activated carbon or biochar amended vegetated (Salix viminalis) soil." *Environmental Pollution* 227 (2017): 406-413. https://doi.org/10.1016/j.envpol.2017.04.064

[40] Shetty, Rajpal, and Nagabovanalli Basavarajappa Prakash. "Effect of different biochars on acid soil and growth parameters of rice plants under aluminium toxicity." *Scientific Reports* 10, no. 1 (2020): 12249. https://doi.org/10.1038/s41598-020-69262-x

[41] Zhu, Yongqi, Haijiang Wang, Xin Lv, Yutong Zhang, and Weiju Wang. "Effects of biochar and biofertilizer on cadmium-contaminated cotton growth and the antioxidative defense system." *Scientific reports* 10, no. 1 (2020): 20112. https://doi.org/10.1038/s41598-020-77142-7

[42] Igalavithana, Avanthi Deshani, Eilhann E. Kwon, Meththika Vithanage, Jörg Rinklebe, Deok Hyun Moon, Erik Meers, Daniel CW Tsang, and Yong Sik Ok. "Soil lead immobilization by biochars in short-term laboratory incubation studies." *Environment international* 127 (2019): 190-198. https://doi.org/10.1016/j.envint.2019.03.031

[43] Bian, Rongjun, Stephen Joseph, Liqiang Cui, Genxing Pan, Lianqing Li, Xiaoyu Liu, Afeng Zhang et al. "A three-year experiment confirms continuous immobilization of cadmium and lead in contaminated paddy field with biochar amendment." *Journal of hazardous materials* 272 (2014): 121-128. https://doi.org/10.1016/j.jhazmat.2014.03.017

[44] Alaboudi, Khalid A., Berhan Ahmed, and Graham Brodie. "Effect of biochar on Pb, Cd and Cr availability and maize growth in artificial contaminated soil." *Annals of Agricultural Sciences* 64, no. 1 (2019): 95-102. https://doi.org/10.1016/j.aoas.2019.04.002

[45] Mahmud, Upoma, Md Tareq Bin Salam, Abu Shamim Khan, and Md Mizanur Rahman. "Ecological risk of heavy metal in agricultural soil and transfer to rice grains." *Discover Materials* 1 (2021): 1-13. https://doi.org/10.1007/s43939-021-00010-2

[46] Ni, Ni, Yang Song, Renyong Shi, Zongtang Liu, Yongrong Bian, Fang Wang, Xinglun Yang, Chenggang Gu, and Xin Jiang. "Biochar reduces the bioaccumulation of PAHs from soil to carrot (Daucus carota L.) in the rhizosphere: a mechanism study." *Science of the Total Environment* 601 (2017): 1015-1023. https://doi.org/10.1016/j.scitotenv.2017.05.256

[47] Rajapaksha, Anushka Upamali, Meththika Vithanage, Jung Eun Lim, Mohamed Bedair M. Ahmed, Ming Zhang, Sang Soo Lee, and Yong Sik Ok. "Invasive plant-derived biochar inhibits sulfamethazine uptake by lettuce in soil." *Chemosphere* 111 (2014): 500-504. https://doi.org/10.1016/j.chemosphere.2014.04.040

[48] Rana, Anuj, Meena Sindhu, Ajay Kumar, Rahul Kumar Dhaka, Madhvi Chahar, Surender Singh, and Lata Nain. "Restoration of heavy metal-contaminated soil and water through biosorbents: A review of current understanding and future challenges." *Physiologia Plantarum* 173, no. 1 (2021): 394-417. https://doi.org/10.1111/ppl.13397

[49] Lian, Jiapan, Longfei Zhao, Jiani Wu, Hongxia Xiong, Yanyu Bao, Aurang Zeb, Jingchun Tang, and Weitao Liu. "Foliar spray of TiO2 nanoparticles prevails over root application in reducing Cd accumulation and mitigating Cd-induced phytotoxicity in maize (Zea mays L.)." *Chemosphere* 239 (2020): 124794. https://doi.org/10.1016/j.chemosphere.2019.124794

[50] Kharel, Gyanendra, Oumar Sacko, Xu Feng, John R. Morris, Claire L. Phillips, Kristin Trippe, Sandeep Kumar, and James W. Lee. "Biochar surface oxygenation by ozonization for super high cation exchange capacity." *ACS Sustainable Chemistry & Engineering* 7, no. 19 (2019): 16410-16418. https://doi.org/10.1021/acssuschemeng.9b03536

[51] Ghodszad, Larissa, Adel Reyhanitabar, Mohammad Reza Maghsoodi, Behnam Asgari Lajayer, and Scott X. Chang. "Biochar affects the fate of phosphorus in soil and water: A critical review." *Chemosphere* 283 (2021): 131176. https://doi.org/10.1016/j.chemosphere.2021.131176

[52] Tedoldi, Damien, Rayan Charafeddine, Philippe Branchu, Eric Thomas, and Marie-Christine Gromaire. "Intra-and inter-site variability of soil contamination in road shoulders–Implications for maintenance operations." *Science of the Total Environment* 769 (2021): 144862. https://doi.org/10.1016/j.scitotenv.2020.144862

[53] Lomaglio, Tonia, Nour Hattab-Hambli, Florie Miard, Manhattan Lebrun, Romain Nandillon, Dalila Trupiano, Gabriella Stefania Scippa et al. "Cd, Pb, and Zn mobility and (bio) availability in contaminated soils from a former smelting site amended with biochar." *Environmental Science and Pollution Research* 25 (2018): 25744-25756. https://doi.org/10.1007/s11356-017-9521-4

[54] Simiele, Melissa, Manhattan Lebrun, Florie Miard, Dalila Trupiano, Philippe Poupart, Olivier Forestier, Gabriella S. Scippa, Sylvain Bourgerie, and Domenico Morabito. "Assisted phytoremediation of a former mine soil using biochar and iron sulphate: Effects on As soil immobilization and accumulation in three Salicaceae species." *Science of the Total Environment* 710 (2020): 136203. https://doi.org/10.1016/j.scitotenv.2019.136203

[55] Nedjimi, Bouzid. "Phytoremediation: a sustainable environmental technology for heavy metals decontamination." *SN Applied Sciences* 3, no. 3 (2021): 286. https://doi.org/10.1007/s42452-021-04301-4

[56] Katiyar, Ravi, Chiu-Wen Chen, Reeta Rani Singhania, Mei-Ling Tsai, Ganesh D. Saratale, Ashok Pandey, Cheng-Di Dong, and Anil Kumar Patel. "Efficient remediation of antibiotic pollutants from the environment by innovative biochar: current updates and prospects." *Bioengineered* 13, no. 6 (2022): 14730-14748. https://doi.org/10.1080/21655979.2022.2108564

[57] Liang, Jinsong, Junpei Ye, Chuan Shi, Panyue Zhang, Jianbin Guo, Mohammad Zubair, Jianning Chang, and Lian Zhang. "Pyrolysis temperature regulates sludge-derived biochar production, phosphate adsorption and phosphate retention in soil." *Journal of Environmental Chemical Engineering* 10, no. 3 (2022): 107744. https://doi.org/10.1016/j.jece.2022.107744

[58] Lahori, Altaf Hussain, G. U. O. Zhanyu, Zengqiang Zhang, L. I. Ronghua, Amanullah Mahar, Mukesh Kumar Awasthi, S. H. E. N. Feng et al. "Use of biochar as an amendment for remediation of heavy metal-contaminated soils: prospects and challenges." *Pedosphere* 27, no. 6 (2017): 991-1014. https://doi.org/10.1016/S1002-0160(17)60490-9
[59] Gu, Shiguo, Wei Zhang, Fei Wang, Zhanhang Meng, Yu Cheng, Zexuan Geng, and Fei Lian. "Particle size of biochar significantly regulates the chemical speciation, transformation, and ecotoxicity of cadmium in biochar." *Environmental Pollution* 320 (2023): 121100. https://doi.org/10.1016/j.envpol.2023.121100
[60] Xu, Wei, Yuan Jin, and Gang Zeng. "Introduction of heavy metals contamination in the water and soil: A review on source, toxicity and remediation methods." *Green Chemistry Letters and Reviews* 17, no. 1 (2024): 2404235. https://doi.org/10.1080/17518253.2024.2404235
[61] Duwiejuah, Abudu Ballu, Abdul Halim Abubakari, Albert Kojo Quainoo, and Yakubu Amadu. "Review of biochar properties and remediation of metal pollution of water and soil." *Journal of Health and Pollution* 10, no. 27 (2020): 200902. https://doi.org/10.5696/2156-9614-10.27.200902
[62] Alhar, Maysaa AM, David F. Thompson, and Ian W. Oliver. "Mine spoil remediation via biochar addition to immobilise potentially toxic elements and promote plant growth for phytostabilisation." *Journal of Environmental Management* 277 (2021): 111500. https://doi.org/10.1016/j.jenvman.2020.111500
[63] Rinklebe, Jörg, Sabry M. Shaheen, Ali El-Naggar, Hailong Wang, Gijs Du Laing, Daniel S. Alessi, and Yong Sik Ok. "Redox-induced mobilization of Ag, Sb, Sn, and Tl in the dissolved, colloidal and solid phase of a biochar-treated and un-treated mining soil." *Environment international* 140 (2020): 105754. https://doi.org/10.1016/j.envint.2020.105754
[64] Ren, Xinwei, Jingchun Tang, Lan Wang, and Hongwen Sun. "Combined effects of microplastics and biochar on the removal of polycyclic aromatic hydrocarbons and phthalate esters and its potential microbial ecological mechanism." *Frontiers in microbiology* 12 (2021): 647766. https://doi.org/10.3389/fmicb.2021.647766
[65] Murtaza, Ghulam, Zeeshan Ahmed, Sayed M. Eldin, Iftikhar Ali, Muhammad Usman, Rashid Iqbal, Muhammad Rizwan, Usama K. Abdel-Hameed, Asif Ali Haider, and Akash Tariq. "Biochar as a green sorbent for remediation of polluted soils and associated toxicity risks: a critical review." *Separations* 10, no. 3 (2023): 197. https://doi.org/10.3390/separations10030197
[66] Patel, Anil Kumar, Reeta Rani Singhania, Anugunj Pal, Chiu-Wen Chen, Ashok Pandey, and Cheng-Di Dong. "Advances on tailored biochar for bioremediation of antibiotics, pesticides and polycyclic aromatic hydrocarbon pollutants from aqueous and solid phases." *Science of the Total Environment* 817 (2022): 153054. https://doi.org/10.1016/j.scitotenv.2022.153054
[67] Varjani, Sunita, Gopalakrishnan Kumar, and Eldon R. Rene. "Developments in biochar application for pesticide remediation: current knowledge and future research directions." *Journal of environmental management* 232 (2019): 505-513. https://doi.org/10.1016/j.jenvman.2018.11.043
[68] Zhang, Guixiang, Xiaofang Guo, Yuen Zhu, Xitao Liu, Zhiwang Han, Ke Sun, Li Ji, Qiusheng He, and Lanfang Han. "The effects of different biochars on microbial quantity, microbial community shift, enzyme activity, and biodegradation of polycyclic aromatic hydrocarbons in soil." *Geoderma* 328 (2018): 100-108. https://doi.org/10.1016/j.geoderma.2018.05.009
[69] Duan, Chengyu, Tianyu Ma, Jianyu Wang, and Yanbo Zhou. "Removal of heavy metals from aqueous solution using carbon-based adsorbents: A review." *Journal of Water Process Engineering* 37 (2020): 101339. https://doi.org/10.1016/j.jwpe.2020.101339
[70] Zheng, Xuemei, Weihua Xu, Jie Dong, Ting Yang, Zichen Shangguan, Jing Qu, Xin Li, and Xiaofei Tan. "The effects of biochar and its applications in the microbial remediation of contaminated soil: a review." *Journal of Hazardous Materials* 438 (2022): 129557. https://doi.org/10.1016/j.jhazmat.2022.129557
[71] Lu, Kouping, Xing Yang, Gerty Gielen, Nanthi Bolan, Yong Sik Ok, Nabeel Khan Niazi, Song Xu et al. "Effect of bamboo and rice straw biochars on the mobility and redistribution of heavy metals (Cd, Cu, Pb and Zn) in contaminated soil." *Journal of environmental management* 186 (2017): 285-292. https://doi.org/10.1016/j.jenvman.2016.05.068
[72] Haider, Fasih Ullah, Xiukang Wang, Usman Zulfiqar, Muhammad Farooq, Saddam Hussain, Tariq Mehmood, Muhammad Naveed et al. "Biochar application for remediation of organic toxic pollutants in contaminated soils; An update." *Ecotoxicology and Environmental Safety* 248 (2022): 114322. https://doi.org/10.1016/j.ecoenv.2022.114322
[73] Beesley, Luke, Eduardo Moreno-Jiménez, and Jose L. Gomez-Eyles. "Effects of biochar and greenwaste compost amendments on mobility, bioavailability and toxicity of inorganic and organic contaminants in a multi-element polluted soil." *Environmental pollution* 158, no. 6 (2010): 2282-2287. https://doi.org/10.1016/j.envpol.2010.02.003

[74] Pandey, V., P. Kumar, and P. Dutta. "Thermo-hydraulic analysis of compact heat exchanger for a simple recuperated sCO2 Brayton cycle." *Renewable and Sustainable Energy Reviews* 134 (2020): 110091. https://doi.org/10.1016/j.rser.2020.110091

[75] Murtaza, Ghulam, Zeeshan Ahmed, Muhammad Usman, Waseem Tariq, Zia Ullah, Muhammad Shareef, Hassan Iqbal et al. "Biochar induced modifications in soil properties and its impacts on crop growth and production." *Journal of plant nutrition* 44, no. 11 (2021): 1677-1691. https://doi.org/10.1080/01904167.2021.1871746

[76] Joseph, Stephen, Annette L. Cowie, Lukas Van Zwieten, Nanthi Bolan, Alice Budai, Wolfram Buss, Maria Luz Cayuela et al. "How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar." *Gcb Bioenergy* 13, no. 11 (2021): 1731-1764. https://doi.org/10.1111/gcbb.12885