SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V12I1P102

Volume 12 Issue 1, 7-15, January 2025

Review Article

Application of Biochar as a Sustainable Material for Soil Improvement and Contaminant Remediation - A Review

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Received: 17 October 2024 Revised: 18 November 2024 Accepted: 04 December 2024 Published: 26 December 2024

Abstract - *Biochar has gained an increasing interest among the scientific community as well as the public within the last few years. This article presents a comprehensive review of different applications of biochar to environmental and agricultural problems. It has become popular due to the competency of biochar pyrolyzed in improving the soil's quality and its ability to sequester carbon, as well as monitor activity remediation at contaminated soils. It is also a source of agricultural improvement by increasing nutrient retention and Cation Exchange Capacity (CEC) and fostering beneficial microbe growth in the soil, greatly affecting crop yields and future food security. Carbon-sequestering properties of biochar also aid in reducing climate change effects by lowering levels of CO_2 in the atmosphere. It may include remediation of polluted soils, immobilization, and degradation of pollutants, such as organic and heavy metal contaminants. Furthermore, biochar practices match sustainable agriculture principles in minimizing the use of synthetic fertilizers and conserving water through improved water retention. This study considered various biochar-related areas: production methods, chemical and physical characteristics, and gas and organic pollutant remediation applications. Specific Surface Area (SSA), porosity, and functional groups are all important properties of biochar that allow the application of the material to be adapted for different uses. Its adaptability is enhanced by using various feedstocks and production processes. The study also investigates biochar's role in soil stabilization. Biochar can improve soil strength in clayey soils, but its influence may vary depending on what biochar is used, its amounts applied, and the soil characteristics. Therefore, biochar applications have demonstrated it as an environmentally friendly, varied solution with a lot of potential to address diverse environmental and agricultural problems. Its versatile attributes, potential benefits for sustainability, and significant improvement in soil properties with the possibility of carbon storage and remediation of contaminated environments make it an object of great interest in today's research and sustainability initiatives. Further research will advance our understanding of the uses of biochar and its pivotal role in addressing global challenges.*

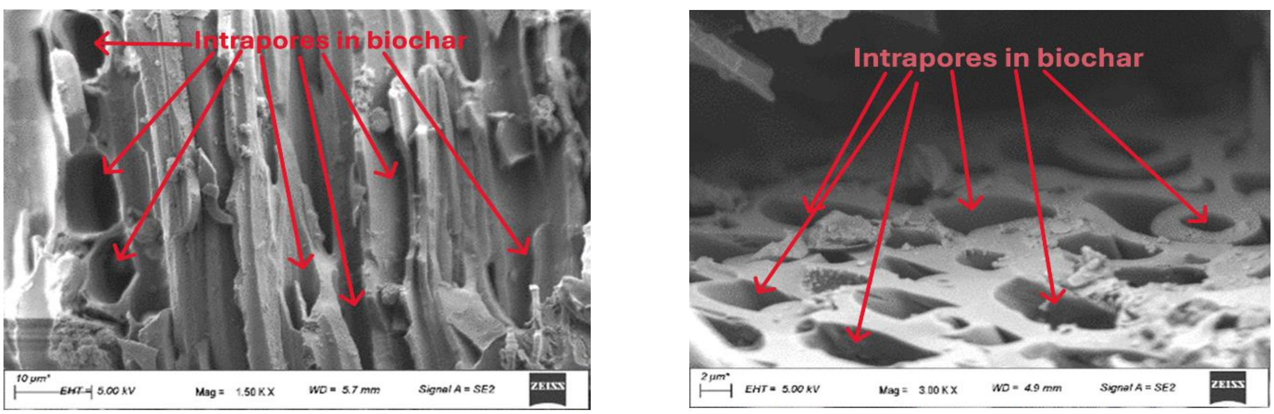
Keywords - *Biochar, Soil improvement, Pollution remediation, Carbon sequestration, Soil stabilization.*

1. Introduction

In recent years, there has been growing activity among scientists and the general public in using soils enriched with Pyrogenic-Carbonaceous Material (PCM) for biochar applications. There are possibly consequent advantages in using soil with such material to improve soil quality and sustainably manage natural resources (Glaser et al., 2000; Glaser et al., 2002; Lehmann et al., 2003). Biochar is essentially a porous carbon-rich substance manufactured by a process called pyrolysis, where organic materials, such as wood, leftover crops, and even kitchen scraps, to super high temperatures in an oxygen-poor atmosphere. People have become more interested in the wonderful thing that it is because it will help to improve soils, sequester carbon, and support methods of sustainable agriculture (Lehmann & Joseph, 2015). The need for sustainable solutions in various fields, such as chemicals, engineering, and agriculture, gave rise to exploring various materials with little to no environmental impact. Compared to harmful chemicals, biochar is useful as its substitute in pollution control and soil amendment; as such, biochar has gained a lot of publicity for its almost miraculous capacity to solve other significant problems such as pollution reduction, soil enrichment, and carbon sequestration. Indeed, biochar has begun emerging as the new panacea for many of today's troubled environmental issues. Among these, perhaps, the features that stand out include the ability of the biochar to hold on to many more nutrients, improve the Cation Exchange Capacity (CEC) of the soil, and better establish friendly microorganisms. All these translate to increased crop productivity and food security, which is quite good for agriculture (Lehmann et al., 2015). Biochar in soil modifies the soil structure in such a way that it increases its resistance against erosive forces. This quality is beneficial, especially in regions where wind or water erosion of the soil is possible (Novak et al., 2009). Carbon retention in the soil over the long term is another major way biochar contributes to carbon sequestration efforts and reduces atmospheric CO_2 levels, thus fighting climate change (Woolf et al., 2010). The special characteristics of biochar, such as possessing a huge surface area and increased adsorption capacity, enable it to immobilize and degrade pollutants, which may include organic pollutants and heavy metals, in highly contaminated soils (Chen et al., 2018). Not just for this, but the use of biochar in agricultural practices adheres to sustainable farming principles as it reduces nutrient runoff, improves soil health, and decreases dependency on chemical fertilizers-all of which safeguard invaluable water resources (Lehmann and Joseph, 2015). Biochar production mainly signifies the versatility of applying different kinds of organic waste materials included in the environmental-friendly recycling and repurposing of waste products, as well as reducing the overall impact this process has on the environment from waste disposal (Ronsse et al., 2013). Thus, biochar is a multifunctional means of acting for various problems being faced at present by making the issue of concern popular practically worldwide today in research and efforts regarding sustainability. Figure 1 shows the FESEM pictures of biochar, which shows a highly porous structure. In the present study, an investigation has been carried out to find biochar production methods, their chemical and physical properties, and the importance of using biochar in contamination remediation, soil stabilization, and agricultural use.

2. Biochar Production

Biochar production is done by heating organic materials under regulated conditions, transforming biomass into stable carbon. Lehmann and Joseph (2015) found that its porous structure and large SSA may differ with the pyrolysis condition and feedstock type. Hydrothermal carbonization, torrefaction, microwave, gasification, slow pyrolysis, quick pyrolysis, flash carbonization, mid-pyrolysis, and torrefaction are among the several means of biochar production (Sahar Safarian, 2023). Biochar can also be made through biochemical conversion methods, the current most popular biomass-energy transformation route, and 80% of global biofuels produced through this process (Osman et al., 2023). Though not as mainstream, thermochemical conversion techniques, including but not limited to pyrolysis, also contribute about 20% to the world's biofuel production (Herviyanti et al., 2022). Many biomass materials can be used to make biochar, including grapefruit peel, bamboo, avocado peel, avocado seed, brown seaweed, and date palm seeds (Granados et al., 2022; Hussain Sait et al., 2022). Biochar characteristics or attributes such as moisture content, carbon concentration, and elemental composition can depend on feedstock and method. Figure 2. represents some techniques for biochar production.



(a) (b)

Fig. 1 FESEM images of biochar: (a) Mustard biochar, (b) Prosopis juliflora.

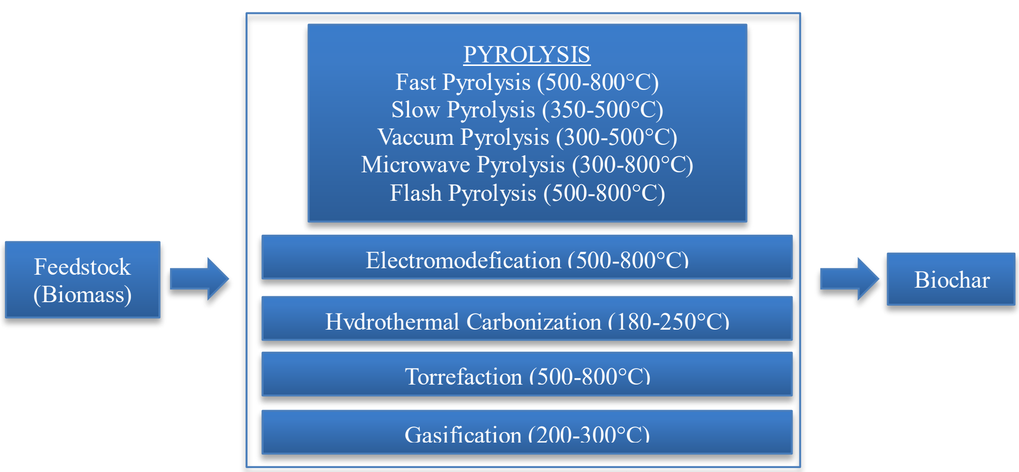


Fig. 2 Production methods of Biochar

3. Biochar Properties

3.1. Chemical Properties

Biochar has chemical properties that vary with its source material, production conditions, and the application for which it is used. Biochar is generally made up of carbon, and the carbon content ranges between 50% and 90% of its weight (Lehmann and Joseph, 2015). The high carbon content explains its capacity for sequestering carbon and long-term soil improvement. Several other biochar qualities are associated with SSA and porosity. For example, the SSA determines the Cation Exchange Capacity (CEC), which also impacts the accessibility of surface charges. CEC is the ability of the soil to transfer cations from the soil to the solution to promote the nutrient cycle in the system (Liang et al., 2006). The amount of water a biochar can hold depends substantially on its porosity and pore connectivity (Chesworth, 2008). Active sites and biochar reactivity are strongly correlated; as such, these active sites require a large available SSA (Weber and Quicker, 2018). High SSA significantly increases biochar's ability to adsorb and hold assorted molecules, such as nutrients and contaminants. SSA and porosity vary with variables such as biomass type and pyrolysis temperature. Optimal conditions include lignocellulosic materials, wood, and moderate temperatures of 400°C to 700°C (Leng et al., 2020). As represented by the Fourier Transform Infrared spectroscopy (FTIR) spectra, carbohydrate structure in cellulose and hemicelluloses is highly dominated by functional groups for oxygenated hydrocarbons within the biochar (Ghani et al. 2013). These functional groups would thus affect its reactivity during reactions within soil and interactions with their constituents. Due to this, the pH level of biochar is therefore dependent on the type of feedstock used and production temperatures. Biochar may be alkaline or acidic, and its pH can have significant effects on soil pH when incorporated (Jeffery et al., 2011). The ability of biochar to transport pH-dependent (changing) charge-typically a negative charge-creates CEC. Biochar's oxygen-containing functional groups (lactone, phenolate, and carboxylate) are the main source of biochar CEC (Steiner et al., 2007; Berek et al., 2018; Hue, 2020; Lehmann and Rondon, 2006). Biochar typically consists of mineral ash residues that result from the partial combustion of feedstock. The ash components can determine its nutrient content and pH (Cheng et al., 2008).

The volatiles released during pyrolysis can modify the characteristics of biochar through the nature and amount released (Spokas et al., 2011). The hydrophobic nature of some biochars initially renders them repellant to water. However, with the passage of time and exposure to environmental conditions, most of the biochar turns out to be hydrophilic and improves their water-holding capacity (Uchimiya et al., 2010). Biochar is highly stable and resistant to breakdown. This allows it to survive for extended periods in soils and aid in carbon sequestration (Liang et al., 2006). The immobilization and degradation of hazardous metals, insecticides, and organic pollutants in polluted soils can be achieved using biochar due to its adsorption capacity (Beesley et al., 2011). Altogether, all these chemical characteristics contribute to the versatility of biochar in agriculture, environmental remediation, and carbon management.

3.2. Physical Properties

Volatile substances like lignin, hemicellulose, and cellulose are volatile and escape biomass as the temperature rises for biochar synthesis, thereby increasing the SSA and forming tubular honeycomb structures during pyrolysis (Kim et al., 2013; Ahmad et al., 2012; Chen et al., 2011). The porous structure and SSA of biochar are enhanced by such design channels (Li et al., 2012). It was observed that carbonization increases porosity due to the volatile emissions (Ahmad et al., 2012). The methods that are used in manufacturing may influence the particle size in biochar. Finer particles would have a greater SSA, which can enhance their effectiveness in amendment with the soil (Lehmann and Joseph, 2015). The bulk density of biochar also affects how it is handled and applied, and it has been found that lower bulk density makes mixing biochar easier with soil (Novak et al., 2009).

4. Advantages of Using Biochar

Biochar effects through soil addition tremendously reduce nutrient losses from the soil, which is one of its benefits among all other effects. It has been found that applying biochar considerably diminishes the emissions of dangerous greenhouse gases such as N_2O. With a potential reduction of up to 83%, it is indeed an excellent supplement for soil management. Apart from that, biochar has several benefits, such as being used as an organic fertilizer, improving soil quality, sequestering carbon, enhancing soil fertility, encouraging useful microbe activity, balancing pH levels, recycling essential plant nutrients, increasing soil water retention, and aiding in lowering pollution levels in soil (Nguyen et al., 2014; Sedlak, 2018). With biochar additives, the physical properties of soil could also change. It increases soil moisture retention by lowering density and increasing pore size. Different in its composition, biochar can have particular features like acidic, hydrophobic against water, hydrophilic for water absorption, or alkaline. Such parameters contribute toward the capacity of soil to retain nutrients and have added advantages for improving the nutrient adsorption capacity of the soils. For example, biochar derived from the heat treatment of wood at 450°C can potentially absorb 250-520 mg phosphorus/g (Zimmerman et al., 2011; McBeath et al., 2011).

Biochar is even effective in capturing natural carbon and sequestering atmospheric carbon (Roy and McDonald, 2015). Biochar also improves soil quality for agricultural purposes. This becomes very significant because as continuous cultivation proceeds, the organic carbon content in the soil will steadily deplete with time (Xia et al., 2017). Organic carbon is essential in the soil for good agriculture production since it stores most major nutrients like nitrogen, phosphorous, and potassium and provides habitat for microbes that improve soil structure. Biochar would then be useful for purposes of sorption by acting in the elimination of dangerous contaminants from contaminated soils. Note that biochar itself has a large content of organic carbon, which is very often even high (up to 90%) according to the source of its material. Hence, biochar becomes a very useful content carbon sequester for reducing carbon emissions (Ippolito et al., 2017).

5. Biochar Application in Soil Stabilization

Soil applications of biochar inspired changes in several mechanical properties such as shear and cyclic shear strength, UCS, and tensile strength. Note that the quantity of biochar required for soil strengthening may differ depending upon the applied consolidation pressure. These conclusions are very important and have to be kept in mind while framing the initial procedures for the realistic application of biochar in real life. Additional studies (Reddy et al., 2015; Sarkar et al., 2020) have also shown an enhancement in the strength of clayey soil by adding biochar.

The inference from these findings is that soil amended with biochar becomes stronger, especially in soils high in clay but low in fine and coarse particles. Interestingly, studies by Zong et al. (2014) have pointed out that incorporating waste sludge, wood chips, and wheat straw-derived biochar has variable effects on soil strength parameters. For example, it was observed that the shear strength and compressive strength of expansive clay soils decreased while increasing cohesion and the frictional angle decreased with the increasing biochar concentration. Yang and Lu (2021) researched and justified the condition that biochar amendments applied onto soils will affect compressive properties, cohesion, and the angle of internal friction in soils that are amended with biochar. Reduced interlocking is possibly one reason biochar and soil-biochar do not contact well with each other. At the same time, the main contributor towards improved cohesive quality looks like water retention in mesopores of biochar. Some results are inconsistent with adding wood biochar into lean clay obtained by Zong et al. (2014). Also, Patwa et al. (2022) state that the introduction of biochar reduces the cohesiveness factor and then subsequently reduces soil strength, too.

More studies are required to reveal what leads to different results concerning the strength of biochar. Micro-level investigations within the different components are important. Examples of these would include the soil-biochar one, the soil-soil one, and the blanket soil-biochar-water-air.

6. Use of Biochar in Agriculture

The likely advantages of biochar in agriculture need to be evaluated based on soil productivity, including an array of soil attributes and processes that determine the physical criteria jointly affecting soil structure, such as pore size, pore continuity, and stability through aggregation. Other significant characteristics include chemical characteristics such as pH, availability of nutrients and organic content and biological characteristics such as microbial concentration (Cassman, 1999). Jeffery et al. (2011), for example, conducted a meta-analysis that analyzed data obtained from various investigations, providing a broad estimate of the influence of biochar on the productivity of crops. Thus, it is a more conclusive method dealing with the area, creating room for elucidating positive effects and further areas of study. Biochar thus consists of charged surface functional groups with surface area. When biochar is produced at rather low temperatures, the possibility of very high CECs is possible. While this structure still retains a sufficient quantity of functional groups to provide negative charges, the overall surface area also dramatically increased upon pyrolysis compared to the feedstock before processing. The CEC of biochar thus tends to be lower when produced at higher pyrolysis temperatures, such as temperatures >500°C (Rasse et al., 2017). The CEC is defined by the ability of biochar to adsorb cations such as ammonium (NH_4^+) and calcium (Ca_2^+), which are essential for plants. Thus, high CEC biochar can minimize the leaching losses of nutrients in soils and help conserve these nutrients for plants. Soil SSA is majorly responsible for all essential soil fertility aspects, like soil retention of water and nutrients, aeration adequacy, and microorganisms' activity (Zwieten et al., 2009). The increased SSA due to biochar mixtures with soil can be ascribed to the increased agronomic productivity of biochar-amended soils. Biochar presents a huge SSA such that one can envisage the creation of complexes and bonds by cations, anions, and other soil elements over its surface. Therefore, the soil's potential for nutrient retention is improved (Liang et al., 2006; Hammes et al., 2009; Atkinson et al., 2010). Very little information is found on the SSA of soil-biochar amendments despite various research presenting SSA data of different biomass sources used in biochar production and pyrolysis conditions. Nevertheless, SSA may be greatly increased by adding biochar, in some cases up to 4.8 times greater than that of the neighbouring, untreated soils when soil is treated with biochar (Liang et al., 2006). Table 1 shows the porosity and SSA of soil amended with biochar.

7. Biochar in Gas Mitigation

Biochar has proven itself efficient in remediating toxicants from gases. The varieties of biochar, i.e., bamboo, rice hulls, camphor, etc., effectively remove any hydrogen sulfide (H2S) from biogas. Above 96% removal efficiency, biochar reaches an excellent adsorption capacity of 110 to 370 mg H_2S/g of biochar. Moisture (>85 by vol), pH (>8.0), available SSA, and some chemical reactions involving functional groups like OH and COOH at the surface affect the adsorption of H_2S. Alkali biochar surfaces interact with H_2S in water and an oxygenated environment to react with the OH and COOH groups. This reaction produces substances like $(K, Na)_2SO_4$, which may be available to the plant as sulfate (SO_4^{2-}) (Lehmann and Joseph, 2015). Biochar derived using soybean straw (SBC) and peanut shells (PBC) at different pyrolysis temperatures from 350°C to 750°C were screened to eliminate trichloroethylene. While trichloroethylene was found to be eliminated efficiently by biochar produced at increased pyrolysis temperature levels (SBC700 and PBC700), it could not do the same on the biochars generated at lower pyrolysis temperatures (SBC300 and PBC300). Both SBC700 and PBC700 did not even make a spare comparison against commercially available activated charcoal. Regarding application doses, 0.28 g/l of PBC700 exhibited the highest removal efficiency, crossing 88% even when the recovery concentration was as much as 9 mg/l. The removal efficiencies are attributed to increased hydrophobicity with oxygen removal of about 10%, increased surface area (varying from 12 to 410 square meters per gram), and reduced polarity of biochar (PBC700 and SBC700) as compared to PBC300 and SBC300 (Lehmann et al., 2006).

Table 1. Impact of biochar on the soil's porosity and surface area (adopted from Mukherjee and Lal, 2013)

Biochar Type	Soil	Study Condition	Biochar application in % (g/g)	Specific Surface Area (m^2/g)	Porosity %	Reference
Betula pendula, 400 °C	Silty-loam	Field	0 1.2	- -	50.9 52.8	Karhu et al., 2011
Eucalyptus marginata, 600°C	Sandy soil	Greenhouse	0 0.45 2.27	1.3 2.7* 8.4*	56.1 57.6 62.1	Dempster et al., 2012
Mixed hardwoods (Quercus species, Carya species), 500°C	Clarion fine loamy	Laboratory	0 0.5 1.0 2.0	130 133 138 153	- - - -	Laird et al., 2010
Municipal green waste, 450 °C	Sandy soil	Laboratory	0 2.6 5.2	- - -	0.46 0.48 0.51	Jones et al., 2010

8. Biochar in the Removal of Organic Contaminants

Applying biochar to soil to eliminate organic contaminants is of utmost importance, especially when dealing with a wide range of contaminants. This includes fungicides, herbicides, pesticides, and insecticides like atrazine and chlorpyrifos, among others (Spokas, 2010). Additionally, biochar can effectively target antibiotics and pharmaceuticals such as sulfamethazine, sulfamethoxazole, industrial chemicals like (PAHs) including biphenyl, catechol, polychlorinated, naphthalene, volatile organic compounds like furan, benzene, as well as cationic aromatic dyes such as methyl-violet, rhodamine, and methylene blue (Herath et al., 2015). Indeed, biochar's application extends to addressing various specific organic compounds found in different waste streams.

Inhibitory substances like furfural and phenolic compounds can impede the decomposition of biomass. It helps decrease estrogenic chemicals, mostly in sewage and animal manure, and hazardous organic compounds in landfill leachate. It can deal with a wider variety of organic pollutants, which underlines its versatility in cleaning environments (Xia et al., 2017). The effectiveness of these pollutants' removals is greatly influenced by the mode of their interaction with the various components of biochar cell walls. Two types of bioprocesses are mainly recognized: physisorption and chemisorption, which are related to electrophilic interactions. This can involve hydrogen bond formation, π-π electron sharing, hydrophobic connections, and electrostatic attraction or repulsion associated with such functional groups as carboxylic acids, diols, and alcohols discussed previously when considering the broader aspects of interactions. All these have much importance (Spokas, 2010) when taken collectively because of their close-surface activities combined with the functional groups mentioned before. Biochar has various other mechanisms for removing pollutants. Partitioning is one in which the contaminants are mainly retained within the biochar and separated from the soil or water phase, while chemical transformation may be generated from electrical conductivity alterations and reductive reactions due to biochar effects.

Biodegradation is the process in which many contaminants naturally associated with charcoal come to be mineralized. The microorganisms living on the surface and in the micropores of this biochar become part of the community and evolve their effects on the contaminants in due time (Yin et al., 2014). Several variables influence how biochar and organic contaminants interact, such as pH levels, pyrolysis temperature, feedstock source, and biochar-to-pollutant ratios. Biochar produced at higher pyrolysis temperatures is likely to have a greater SSA and greater microporosity, which makes it particularly effective for removing nonpolar organic pollutants. On the other hand, low-temperature-subjected biochar will probably not conjure such exceptional features, which may affect its adsorption efficiency for some contaminants (Awad et al., 2018). Certainly, the functional equation of effects reveals that as biochar pyrolyzes at temperatures above 500°C, it becomes more aromatic, less polar, and less acidic. This causes the number of functional groups containing O and H on the surface of biochar to decrease. The reduction in the number of these O-bearing groups increases the propensity of biochar to engage in hydrophobic interactions and, thus, makes it likely effective in adsorbing nonpolar organic materials.

Contrary to this assumption, biochar pyrolyzed at temperatures below 500°C may have more such polar O-bearing functional groups. By their ability to form hydrogen bonds and other polar associations, these transform the biochar into a material with an affinity for attachment to polar organic compounds (IBI, 2015). This author agreed with previous studies that biochar can be very effective in removing specific polar insecticide and herbicide compounds through its interaction. Specific properties and processes that characterize biochar will be crucial when dealing with different organic contaminants, especially agrochemicals, in soils. It's amazing how biochar can reduce the number of organic pollutants that become bioavailable in soil and, therefore, their accessibility to plants and microorganisms. This, in turn, helps mitigate the potential for these contaminants to be taken up by plants and negatively impact the environment. Table 2 shows the removal of organic contaminants using biochar.

Table 2. Biochar removal of persistent organic pollutants in soil (adopted from Oni et al., 2020)

Biochar	Soil tested	Pyrolysis condition	Contaminants	Remediation effect	Author Ref.
Wood bark	Loamy	300˚C, 1h	Phenanthrene	Increase metabolite accumulation in soil and reduce the degradation of pollutants in soil.	El-Naggar et al., 2018; Rhodes et al.,2008
Sugar beet tailing/Pinewood/ Woodchips	Sandy	500˚C, 1h	Polychlorinated biphenyl; PAHs	Biochar of this kind removes PHAs and other contaminants in the soil and replenishes the bioavailability of the soil, compared to unamended soil.	Spokas, 2010; Wang et al. 2018; Lehmann et al., 2006.
Dairy/poultry/human manure	Clay	300˚C, 1h	2,4, dichlorophenol; Pyrene	Removes heavy metals and aromatic compounds from soil that may contaminate soil productivity in plants.	Lynd et al., 1999
Organic wastes/plant residues/Empty fruit bunches	Sandy-Loam	600˚C, 1h	PAHs	PAH accumulation was reduced with regard to organic waste/plant residues. Thus, it enhances soil modification on application.	Zeng et al., 2018; Spokas, 2010
Rice Hull	Loamy	500˚C, 1h	Oxyfluorfen	The degradation of Oxyfluorfen is more rapid in soil containing biochar than in soil without biochar.	Maestrini et al., 2014; Hansen et al., 2016

9. Discussions

The article examines the expansive applications of biochar in agriculture and different spheres of the environment. Biochar is a pyrogenic carbon-rich material- the new darling because of its numerous advantages, which will be noted in detail later. Probably the best of these is the improvement of the soil. Biochar improves the soil by increasing its ion exchange capacity, fostering beneficial microorganisms, and enhancing the retained nutrients from the soil. These, in turn, contribute to greater agricultural yields and a more stable food supply. Biochar also serves as soil for erosion-prone areas not only because of its capability but also because it shapes the soil. Besides, the ability of biochar to sequester carbon is a plus for a climate change battle against atmospheric CO_2. Biochar has its applications beyond the agricultural field. It is very efficient for the remediation of contaminated soils and immobilizing and degrading several pollutants, including organic and heavy metal ones. It is, however, a perfect match for the principles of sustainable agriculture, as it keeps reusing organic waste materials, protects water resources, and reduces the demand for chemical fertilizers.

The study on biochar is quite extensive, as it deals with biochar's production, chemical, and physical attributes and its application in organic and gaseous pollutant remediation. Such features, together with functional groups, porosity, and surface area, are strong correlates of biochar's hold-up and adsorption ability. These characteristics render biochar a very versatile tool that can be tailored to a particular use since it can be affected by production procedure and the type of raw material used.

Studies have found that biochar can improve soils with fewer large and microscopic particles, particularly clayey ones. However, biochar impacts on soil strength vary according to biochar type and dosage and unique soils. This work shows that biochar is a highly flexible and sustainable tool for addressing numerous environmental and agricultural challenges. It is central to the sustainability agenda because biochar improves soils while sequestering carbon and cleaning up contaminated places. More research is needed to clarify how biochar interacts with soil strength and to explore the complex micro-level interactions in soil-biochar systems.

10. Conclusion

The study presents these possibilities concerning biochar's addressing of a number of agricultural environmental issues. Biochar is a quite flexible and sustainable solution, which can be attributed to its soil-improving quality, carbon base, and polluted site cleaning potential.

- Biochar has proven to improve crop yield, nutrient retention, and soil health in agriculture. Its beneficial influence on soil structure, recycling of nutrients, and retention of water makes it a significant tool in sustainable agricultural practices.
- Biochar is also important beyond agriculture, for it both stores and captures carbon to mitigate climate change. Biochar has a significant stake in environmental restoration projects where contaminated soils are cleaned because of its unrivalled capacity to both absorb and neutralize most pollutants.
- An investigation was conducted on different properties of biochar, notably its chemical and physical properties, which play significant roles in biochar efficacy for various purposes, thus necessitating the need to harmonize biochar production with an intended purpose.
- The present study investigates how biochar might be used to help stabilize soils, especially how it might improve the properties of clayey soils. However, certain contradictions in the findings would suggest the possibility of an impact brought about by several influences and recognize the need for future research in that area.

Ultimately, the study reveals that biochar is a probable remedy for all or part of the numerous problems surrounding agriculture and the environment. It is a point of curiosity at this present time in sustainability research and initiatives because of its versatility, which benefits the environment. Continued research and a better understanding of its uses will influence the extent to which biochar will alleviate pressing problems facing our global community.

Acknowledgements

The author, Mr. Dinken Paksok, would like to acknowledge the supervisors cum co-authors, Dr. Ajanta Kalita and Dr. K. Ravi, for their constant support and direction in the preparation of this report.

Author Contributions

All the authors contributed to the preparation of this report. Mr. Dinken Paksok, Dr. Ajanta Kalita and Dr. K. Ravi conceptualized the idea of this review work. Mr. Dinken Paksok prepared the original draft, and Dr. Ajanta Kalita and Dr. K. Ravi reviewed and provided valuable suggestions for modification of the final draft.

References

[1] Mahtab Ahmad et al., "Effects of Pyrolysis Temperature on Soybean Stover-and Peanut Shell-Derived Biochar Properties and TCE Adsorption in Water," *Bioresource Technology*, vol. 118, pp. 536-544, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[2] Christopher J. Atkinson, Jean D. Fitzgerald, and Neil A. Hipps, "Potential Mechanisms for Achieving Agricultural Benefits from Biochar Application to Temperate Soils: A Review," *Plant and Soil*, vol. 337, no. 1, pp. 1-18, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[3] Yasser Mahmoud Awad et al., "Carbon and Nitrogen Mineralization and Enzyme Activities in Soil Aggregate-Size Classes: Effects of Biochar, Oyster Shells, and Polymers," *Chemosphere*, vol. 198, pp. 40-48, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[4] Luke Beesley et al., "A Review of Biochars' Potential Role in the Remediation, Revegetation and Restoration of Contaminated Soils," *Environmental Pollution*, vol. 159, no. 12, pp. 3269-3282, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[5] Arnoldus Klau Berek et al., "Biochars Improve Nutrient Phyto-Availability of Hawai'i's Highly Weathered Soils," *Agronomy*, vol. 8, no. 10, pp. 1-18, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[6] Sander Bruun, Erik S. Jensen, and Lars S. Jensen, "Microbial Mineralization and Assimilation of Black Carbon: Dependency on Degree of Thermal Alteration," *Organic Geochemistry*, vol. 39, no. 7, pp. 839-845, 2008. [CrossRef] [Google Scholar] [Publisher Link]

[7] Kenneth G. Cassman, "Ecological Intensification of Cereal Production Systems: Yield Potential, Soil Quality, and Precision Agriculture," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 96, no. 11, pp. 5952-5959, 1999. [CrossRef] [Google Scholar] [Publisher Link]

[8] Jinquan Chen et al., "Characterization of an Hg(II)-Volatilizing Pseudomonas Sp. Strain, DC-B1, and Its Potential for Soil Remediation when Combined with Biochar Amendment," *Ecotoxicology and Environmental Safety,* vol. 163, pp. 172-179, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[9] Yingquan Chen et al., "Biomass-Based Pyrolytic Polygeneration System on Cotton Stalk Pyrolysis: Influence of Temperature," *Bioresource Technology*, vol. 107, pp. 411-418, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[10] Chih-Hsin Cheng, Johannes Lehmann, and Mark H. Engelhard, "Natural Oxidation of Black Carbon in Soils: Changes in Molecular Form and Surface Charge along a Climosequence," *Geochimica et Cosmochimica Acta*, vol. 72, no. 6, pp. 1598-1610, 2008. [CrossRef] [Google Scholar] [Publisher Link]

[11] Ward Chesworth, *Water Holding Capacity*, Encyclopedia of Soil Science, Springer, pp. 1-822, 2008. [CrossRef] [Publisher Link]

[12] Wan Azlina Wan Abdul Karim Ghani et al., "Biochar Production from Waste Rubber-Wood-Sawdust and Its Potential Use in C Sequestration: Chemical and Physical Characterization," *Industrial Crops and Products*, vol. 44, pp. 18-24, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[13] Bruno Glaser et al., "Black Carbon in Density Fractions of Anthropogenic Soils of the Brazilian Amazon Region," *Organic Geochemistry*, vol. 31, no. 7-8, pp. 669-678, 2000. [CrossRef] [Google Scholar] [Publisher Link]

[14] Bruno Glaser et al., "Potential of Pyrolyzed Organic Matter in Soil Amelioration," *12th ISCO Conference*, vol. 3, pp. 421-427, Beijing, China, 2002. [Google Scholar] [Publisher Link]

[15] Paola Granados et al., "Effects of Biochar Production Methods and Biomass Types on Lead Removal from Aqueous Solution," *Applied Sciences*, vol. 12, no. 10, pp. 1-10, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[16] Karen Hammes, and Michael W. I. Schmidt, *Changes of Biochar in Soil*, Biochar for Environmental Management, Routledge, 1st ed., pp. 201-214, 2009. [Google Scholar] [Publisher Link]

[17] I. Herath et al., "Immobilization and Phytotoxicity Reduction of Heavy Metals in Serpentine Soil Using Biochar," *Journal of Soils and Sediments*, vol. 15, no. 1, pp. 126-138, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[18] Herviyanti et al., "Characteristics of Biochar Methods from Bamboo as Ameliorant," *IOP Conference Series: Earth and Environmental Science*, vol. 959, no. 1, pp. 1-8, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[19] Nguyen Hue, *Biochar for Maintaining Soil Health*, Soil Health, Springer International Publishing, pp. 21-46, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[20] "*Standardized Product Definition and Product Testing Guidelines for Biochar that is Used in Soil*," International Biochar Initiative, Report, pp. 1-61, 2015. [Publisher Link]

[21] James A. Ippolito et al., "Soil Quality Improvement through Conversion to Sprinkler Irrigation," *Soil Science Society of America Journal*, vol. 81, no. 6, pp. 1505-1516, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[22] S. Jeffery et al., "A Quantitative Review of the Effects of Biochar Application to Soils on Crop Productivity Using Meta-Analysis," *Agriculture, Ecosystems and Environment*, vol. 144, no. 1, pp. 175-187, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[23] Woong-Ki Kim et al., "Characterization of Cadmium Removal from Aqueous Solution by Biochar Produced From a Giant Miscanthus at Different Pyrolytic Temperatures," *Bioresource Technology*, vol. 138, pp. 266-270, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[24] Johannes Lehmann, John Gaunt, and Marco Rondon, "Bio-Char Sequestration in Terrestrial Ecosystems - A Review," *Mitigation and Adaptation Strategies for Global Change*, vol. 11, no. 2, pp. 403-427, 2006. [CrossRef] [Google Scholar] [Publisher Link]

[25] Johannes Lehmann et al., "Nutrient Availability and Leaching in an Archaeological Anthrosol and a Ferralsol of the Central Amazon Basin: Fertilizer, Manure and Charcoal Amendments," *Plant and Soil*, vol. 249, pp. 343-357, 2003. [CrossRef] [Google Scholar] [Publisher Link]

[26] Johannes Lehmann, and Stephen Joseph, *Biochar for Environmental Management Science, Technology and Implementation*, Routledge, 2nd ed., pp. 1-976, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[27] Johannes Lehmann et al., "Biochars and the Plant-Soil Interface," *Plant and Soil*, vol. 395, pp. 1-5, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[28] Johannes Lehmann, and Marco Rondon, *Bio-Char Soil Management on Highly Weathered Soils in the Humid Tropics*, Biological Approaches to Sustainable Soil Systems, CRC Press, pp. 517-530, 2006. [Google Scholar] [Publisher Link]

[29] Lijian Leng et al., "An Overview on Engineering the Surface Area and Porosity of Biochar," *Science of the Total Environment*, vol. 763, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[30] Mi Li et al., "Cu(II) Removal from Aqueous Solution by Spartina Alterniflora Derived Biochar," *Bioresource Technology*, vol. 141, pp. 83-88, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[31] B. Liang et al., "Black Carbon Increases Cation Exchange Capacity in Soils," *Soil Science Society of America Journal*, vol. 70, no. 5, pp. 1719-1730, 2006. [CrossRef] [Google Scholar] [Publisher Link]

[32] Melanie Mayes et al., "Relation between Soil Order and Sorption of Dissolved Organic Carbon in Temperate Subsoils," *Soil Science Society of America Journal*, vol. 76, no. 3, pp. 1027-1037, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[33] Anna V. McBeath et al., "Determination of the Aromaticity and the Degree of Aromatic Condensation of a Thermosequence of Wood Charcoal using NMR," *Organic Geochemistry*, vol. 42, no. 10, pp. 1194-1202, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[34] Atanu Mukherjee, and Rattan Lal, "Biochar Impacts on Soil Physical Properties and Greenhouse Gas Emissions," *Agronomy*, vol. 3, no. 2, pp. 313-339, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[35] Jeffrey M. Novak et al., "Characterization of Designer Biochar Produced at Different Temperatures and Their Effects on a Loamy Sand," *Annals of Environmental Science*, vol. 3, pp. 195-206, 2009. [Google Scholar] [Publisher Link]

[36] Babalola Aisosa Oni, Olubukola Oziegbe, and Obembe O. Olawole, "Significance of Biochar Application to the Environment and Economy," *Annals of Agricultural Sciences*, vol. 64, no. 2, pp. 222-236, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[37] Ahmed I. Osman et al., "Optimizing Biomass Pathways to Bioenergy and Biochar Application in Electricity Generation, Biodiesel Production, and Biohydrogen Production," *Environmental Chemistry Letters*, vol. 21, no. 5, pp. 2639-2705, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[38] Deepak Patwa et al., "A Novel Application of Biochar Produced from Invasive Weeds and Industrial Waste in Thermal Backfill for Crude Oil Industries," *Waste and Biomass Valorization*, vol. 13, no. 6, pp. 3025-3042, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[39] Daniel P. Rasse et al., "Persistence in Soil of *Miscanthus* Biochar in Laboratory and Field Conditions," *PLoS ONE*, vol. 12, no. 9, pp. 1-17, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[40] Krishna R. Reddy et al., "Enhanced Microbial Methane Oxidation in Landfill Cover Soil Amended with Biochar," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 140, no. 9, pp. 1-11, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[41] Frederik Ronsse et al., "Production and Characterization of Slow Pyrolysis Biochar: Influence of Feedstock Type and Pyrolysis Conditions," *GCB Bioenergy*, vol. 5, no. 2, pp. 104-115, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[42] Mimi Roy, and Louis M. McDonald, "Metal Uptake in Plants and Health Risk Assessments in Metal-Contaminated Smelter Soils," *Land Degradation and Development*, vol. 26, no. 8, pp. 785-792, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[43] Sahar Safarian, "Performance Analysis of Sustainable Technologies for Biochar Production: A Comprehensive Review," *Energy Reports*, vol. 9, pp. 4574-4593, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[44] Hani Hussain Sait et al., "Hydrogen-Rich Syngas and Biochar Production by Non-Catalytic Valorization of Date Palm Seeds," *Energies*, vol. 15, no. 8, pp. 1-13, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[45] Arijit Sarkar et al., "Influence of In-House Produced Biochar on Geotechnical Properties of Expansive Clay," *IOP Conference Series: Earth and Environmental Science*, vol. 463, no. 1, pp. 1-6, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[46] David Sedlak, "Sifting Through the Embers," *Environmental Science and Technology*, vol. 52, no. 6, pp. 3327-3328, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[47] Kurt A. Spokas, John M. Baker, and Donald C. Reicosky, "Ethylene: Potential Key for Biochar Amendment Impacts," *Plant and Soil*, vol. 333, no. 1, pp. 443-452, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[48] Kurt A. Spokas et al., "Qualitative Analysis of Volatile Organic Compounds on Biochar," *Chemosphere*, vol. 85, no. 5, pp. 869-882, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[49] Christoph Steiner et al., "Long Term Effects of Manure, Charcoal and Mineral Fertilization on Crop Production and Fertility on a Highly Weathered Central Amazonian Upland Soil," *Plant and Soil*, vol. 291, no. 1-2, pp. 275-290, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[50] Lukas Van Zwieten et al., *Biochar and Emissions of Non-CO2 Greenhouse Gases from Soil*, Biochar for Environmental Management, 1st ed., Routledge, pp. 259-282, 2009. [Google Scholar] [Publisher Link]

[51] Minori Uchimiya et al., "Influence of Pyrolysis Temperature on Biochar Property and Function as a Heavy Metal Sorbent in Soil," *Journal of Agricultural and Food Chemistry*, vol. 59, no. 6, pp. 2501-2510, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[52] Kathrin Weber, and Peter Quicker, "Properties of Biochar," *Fuel*, vol. 217, pp. 240-261, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[53] Dominic Woolf et al., "Sustainable Biochar To Mitigate Global Climate Change," *Nature Communications*, vol. 1, no. 5, pp. 1-9, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[54] Tianjiao Xia et al., "Cation-Inhibited Transport of Graphene Oxide Nanomaterials in Saturated Porous Media: The Hofmeister Effects," *Environmental Science and Technology*, vol. 51, no. 2, pp. 828-837, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[55] C.D. Yang, and S.G. Lu, "Effects of Five Different Biochars on Aggregation, Water Retention and Mechanical Properties of Paddy Soil: A Field Experiment of Three-Season Crops," *Soil and Tillage Research*, vol. 205, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[56] Yun-feng Yin et al., "Effects of Rice Straw and Its Biochar Addition on Soil Labile Carbon and Soil Organic Carbon," *Journal of Integrative Agriculture*, vol. 13, no. 3, pp. 491-498, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[57] Andrew R. Zimmerman, Bin Gao, and Mi-Youn Ahn, "Positive and Negative Carbon Mineralization Priming Effects Among a Variety of Biochar-Amended Soils," *Soil Biology and Biochemistry*, vol. 43, no. 6, pp. 1169-1179, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[58] Yutong Zong, Danping Chen, and Shenggao Lu, "Impact of Biochars on Swell-Shrinkage Behavior, Mechanical Strength, and Surface Cracking of Clayey Soil," *Journal of Plant Nutrition and Soil Science*, vol. 177, no. 6, pp. 920-926, 2014. [CrossRef] [Google Scholar] [Publisher Link]