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Review Article

Assessing the Effects and Environmental Implications of Biochar Amendment in Agricultural Soils

Thomas Wilbur Davis*

Student, Doctor of Plant Health, Institute of Agriculture and Natural Resources, University of Nebraska - Lincoln, Plant Sciences Hall (PLSH), 279E, Lincoln NE 68583-0915, USA

*Corresponding Author E-mail: tdavis31@huskers.unl.edu

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ABSTRACT

In recent years, the production and use of biochar have been increasing rapidly, and the biochar market is projected to continue growing between 2019 and 2025. Given that biochar has a long residence time in the environment (soil), a systematic review was conducted to assess the major environmental impacts of its application in agricultural soils. The results were largely consistent in indicating the positive effects of biochar on soil fertility, moisture content, and microbial communities. Moreover, biochar has been shown to improve soil physical properties and provide habitats for soil microorganisms. Biochar application in soil has the potential to mitigate climate change and reduce human health risks. However, the oxidation and ageing process of biochar has the potential to lead to the absorption, accumulation, and release of environmental pollutants such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), dioxins, environmentally persistent free radicals (EPFRs), perfluorochemicals (PFCs), and volatile organic compounds (VOCs) depending on the type of biomass used. Therefore, when considering biochar application in soil for agricultural purposes, it is important to consider the biomass type and investigate the potential negative secondary environmental consequences.

Keywords: *Biochar; soil amendment; biochar oxidation; environmental effects; toxicity; heavy metals.*

INTRODUCTION

1.1. Study Context

Biochar, created by heating biomass in an oxygen-free environment, is a fine-grained, porous, highly aromatic, and very stable material estimated to persist in soil for hundreds to thousands of years (Herrmann et al., 2019). It is used for agricultural soil amendment, energy production, and other purposes. The biochar market has seen a rapid increase in recent years, with a projected further increase from 2019 to 2025.

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A report published by Zion Market Research in 2018 titled "Biochar Market by Feedstock Type (Woody Biomass, Agricultural Waste, Animal Manure, and Others), by Technology (Pyrolysis, Gasification, and Others), and by Application (Electricity Generation, Agriculture, and Forestry): Global Industry Perspective, Comprehensive Analysis, and Forecast, 2018–2025" states that the global biochar market was valued at USD 1.48 billion in 2018 and is projected to reach USD 3.82 billion by 2025, registering a compound annual growth rate (CAGR) of 14.5% between 2019 and 2025. Today, the usage of biochar for agricultural soil amendment is widespread globally. North America was the largest biochar market in 2018 due to the increasing demand for biochar. Due to high product awareness, the United States is the major contributor to and highest shareholder of the regional biochar market. North American countries are investing increasingly in biochar industries (pharmaceuticals, agriculture, etc.), which is projected to drive growth in this regional market in the years ahead. In 2018, Europe was the second largest market due to the increasing health awareness in the United Kingdom, France, and Germany. The Asia Pacific biochar market is anticipated to grow rapidly in the future due to the increasing demand from food, pharmaceutical, and agricultural sectors, particularly in India and China. The overall market's growth is largely attributed to the growing consumer awareness about biochar's application and the rising product demand for organic farming from the agricultural sector. According to Tarnik (2019), biochar has gained the attention of agronomists worldwide due to its effect on physical soil properties in recent years. The use of biochar in soil for agricultural purposes has grown significantly and is likely to continue to do so. Thus, it is necessary to evaluate the environmental consequences of using biochar in agricultural soils to determine whether it is a sustainable and environmentally-friendly agricultural practice. This systematic review is meant to uncover the major environmental effects of biochar application in agricultural soils.

1.2. Brief description of selected environmental issues

There are numerous environmental issues of concern. However, it is necessary to consider topics such as climate change, environmental pollution, and air quality when discussing them.

1.2.1. Climate Change: Climate change refers to long-term temperature and weather patterns changes. Natural causes, such as oscillations in the solar cycle, may contribute to climate change, but human activities, such as the burning of fossil fuels, have been the primary driver of climate change since the 1800s (UN, 2021). Fossil fuels such as coal, oil, and gas release greenhouse gases, such as carbon dioxide and methane, into the atmosphere when burned. These gases act as a blanket around the earth, trapping heat and raising global temperatures.

1.2.2. Toxic Environment: Toxic pollution is the presence of hazardous or poisonous contaminants in the air, land, and water, including sewage and particulates from power plants, industrial wastes such as hazardous metals from mining, and chemicals from companies. This is distinct from pollution from higher levels of carbon dioxide, which affects climate change but does not have immediate health effects. Drinking water, fish in rivers and ponds, and food grown on contaminated soil can all be contaminated by toxic substances (World Bank, 2015). According to the WHO (2021), an estimated 355,000 people die each year from unintentional poisonings across the globe, with two-thirds of these deaths occurring in low-income countries. In many of these places, toxic chemicals are released into the soil, air, and water from industrial processes, pulp and paper mills, tanning operations, mining, and unsustainable agricultural practices, often at levels or rates that are detrimental to human health (WHO, 2021).

1.2.3. Air Quality: Air quality is an indicator of how clean or dirty the air is. Because unclean air can be damaging to both human health and the environment, it is essential to monitor air quality regularly. Air pollution is one of three main types of pollution – air, land, and water – which occurs when any chemical, physical, or biological factor contaminates the indoor or outdoor environment, altering the natural properties of the atmosphere. Common causes of air pollution include household combustion devices, motor vehicles, industrial operations, and forest fires. Particulate matter, carbon monoxide, ozone, nitrogen dioxide, and sulfur dioxide all present public health concerns. When applied to agricultural soils, biochar may be a major contributor, particularly the emission of particulate matter into the atmosphere. Air pollution, both outside and inside, is a major cause of respiratory and other illnesses and a substantial source of morbidity and mortality. According to WHO (2021), the vast majority of the world's population (99%) breathes air that exceeds WHO guideline limits and contains high levels of pollutants, with low- and middle-income countries shouldering the majority of the burden.

1.3. Research Question

What are biochar amendment's effects and associated environmental implications in agricultural soils?

2.0. Methodology

A systematic computer-based electronic search of peer-reviewed and high-impact scientific publications in databases such as Web of Science and Scopus was conducted to identify all journal articles related to biochar application in soil published between 2016 and 2022. The search terms used either separately or in combination were "Impact," "biochar," "application," "agricultural soil," and "environmental effect."

A total of 67 studies were collected before removing duplicates, and these were evaluated using an abstract review before proceeding to final assessment to increase the review's credibility. The final assessment of the review was based on specific inclusion and exclusion criteria, which required that the article present biochar as a single treatment in order to be included. All research published between 2018 and 2022 that examined the effect of applying biochar to agricultural soils was included in the review. The reference list of cited studies in outstanding articles was checked to ensure that the sources used are reputable and up-to-date. After the screening process, 5 relevant studies were selected for the systematic review (Figure 1). Studies of high quality which examined environmental effects, but did not meet the inclusion and exclusion criteria, were mainly cited during the discussion.

Table1. Inclusion and Exclusion Criteria

No.	Exclusion Criterion	No.	Inclusion Criterion
1.	The article is a review paper	1.	The article is original and was published in a scientific journal (peer-reviewed)
2.	The article was published in 2016, 2017 or earlier	2.	The article was published between 2018-2022 (Except Support & Discussion)
3.	The article presents biochar in an integrated or compound treatment (e.g. biochar and compost amendment in soil)	3.	The article presents the impact of biochar application in soil as a 'single soil treatment' and for agriculture purpose
4.	The article was not published as original research and/or in a scientific journal	4.	The article was fully written in English
5.	The article was not fully written in English		

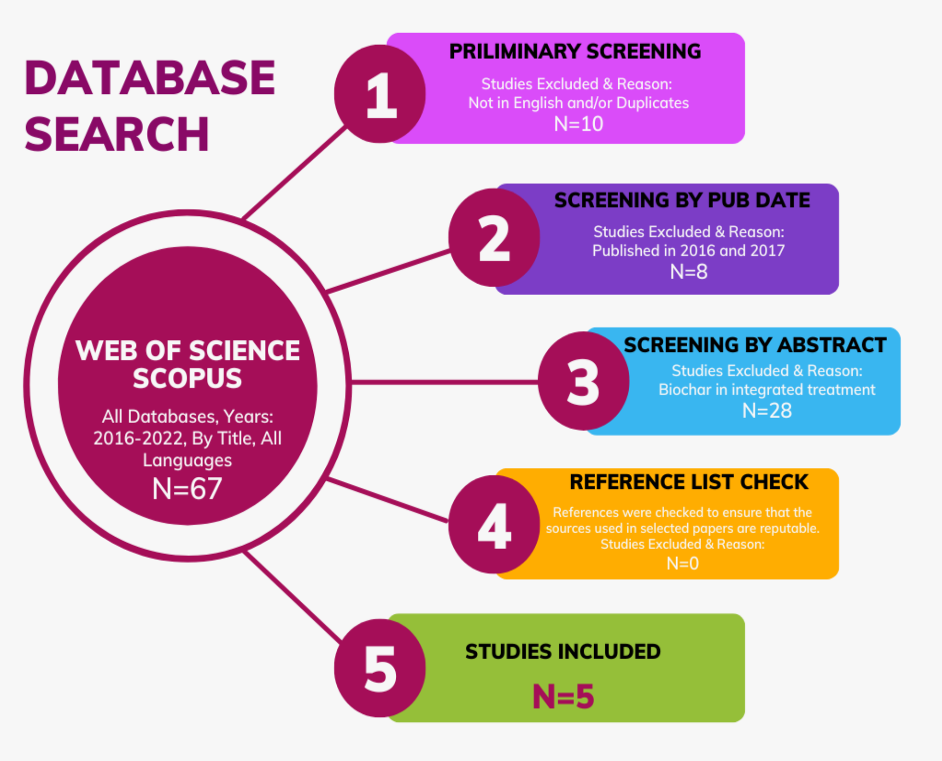


Figure 1: Research strategy - illustrating the screening and selection of relevant studies

3.0. Results

The systematic review showed that biochar application in soil has various positive effects on physical soil properties, such as water content (Tarnik, 2019), on microbial communities (Herrmann et al., 2019), and as a possible climate change mitigation strategy (Abujabhah et al., 2018). It also has the potential to reduce human health risks (Li et al., 2020) (Table 2). However, it is associated with the release of heavy metals and other pollutants that can be toxic to the environment (Xiang et al., 2021; & Freddo et al., 2012).

Table2. Summary of main findings

No.	Research Aim	Key Findings	References
1	Biochar derived from wood was applied to three different soil types (brown sandy loam, red loam, and black clay loam) as a single treatment, and its loading effects on the eukaryotic community were evaluated.	Biochar amendment had a minimal influence on diversity parameters in both brown sandy loam and red loam soils. However, there were noteworthy changes in the eukaryotic community composition of these soils when biochar was added due to the elapsed time and the improved soil porosity, which affects many aspects, including moisture content. Furthermore, it was determined that biochar application has varying effects on microeukaryotes depending on the amount applied.	Abujabhah et al. (2018)
2	The effects of increasing doses of biochar on microbial communities in a rubber tree plantation were investigated by applying it as a single soil treatment.	An investigation was conducted to examine the effects of increasing doses of a single soil treatment on microbial communities in a rubber tree plantation. Biochar application in soil was found to be beneficial, enhancing soil pH and nutrient content and altering both bacterial and fungal communities. Although changes in microbial composition and structure were observed, fungal communities were affected to a greater extent than bacterial communities. Moreover, the magnitude and nature of these changes were strongly correlated with soil properties such as pH, soil moisture, and phosphorus content. Nevertheless, further research is needed to better understand biochar application's impacts on soil microbial communities.	Herrmann et al. (2019)
3	The potential of biochar to reduce the presence of pharmaceuticals in radish plants grown in sandy loam soil and, in turn, reduce potential risks to human health was evaluated.	An experiment was conducted to determine the effect of biochar amendment on the uptake of pharmaceuticals (acetaminophen, carbamazepine, sulfadiazine, sulfamethoxazole, lamotrigine, carbadox, trimethoprim, oxytetracycline, tylosin, estrone, and triclosan) in radish grown in a sandy loam soil. The uptake of these pharmaceuticals can cause potential health risks to humans. The results showed that the concentration of these pharmaceuticals in pore water decreased by 33.3-83.0% when biochar was applied, and the concentration of lincomycin was increased by 36.7-48.2%. This indicates that biochar amendment has the potential to reduce the health risks associated with these pharmaceuticals, making it a valuable soil treatment.	Li et al. (2020)
4	Biochar was applied to soil in a greenhouse setting as a single soil treatment in order to investigate its effects in a greenhouse environment.	The results demonstrated that using biochar in soil has potential as a beneficial practice in greenhouse agriculture, as it positively impacts soil respiration, nitrogen mineralization, and nitrification. It was emphasized, however, that further experimentation is necessary to guarantee improved crop productivity and soil quality.	Marzaioli et al. (2018)
5	The physical soil properties (water content, temperature) were studied to assess the impact of repeated biochar doses applied as a single soil treatment.	Biochar application resulted in an increase in soil water content. Compared to plots with a short-term or no application of biochar, plots with a longer-term application of biochar had a significantly higher soil water content.	Tarnik (2019)

3.1. Effects of biochar application on soil properties

The physical properties of soils play an integral role in the retention and accessibility of water in the soil and its surrounding environment (Tarnik, 2019). Soil water content is an essential indicator of climate change and the sustainability of life (Tarnik, 2019). Biochar, a solid, porous material which is produced through the thermal modification of organic matter by pyrolysis, is high in carbon content (Abujabhah et al., 2018). The application of this material into agricultural soil modifies the physical properties of the soil, resulting in changes in the soil's hydraulic properties, such as water retention and permeability, leading to a higher soil moisture content (Li et al., 2020). The structure of biochar also alters the soil's porosity, pore size distribution, and bulk density (Tarnik, 2019). Moreover, the addition of biochar to soil can increase crop yield, improve soil quality, optimize nutrient cycling, decrease nutrient leaching, and stimulate microbial activity (Tarnik, 2019). Thus, biochar can be used to improve soil quality while optimizing irrigation management and decreasing irrigation needs, especially in dryland regions (Tarnik, 2019). The application of biochar in a greenhouse environment has been demonstrated to influence soil respiration, nitrogen mineralization, and potential nitrification. These findings suggest that soil amendment with biochar could be a beneficial practice in greenhouses, although further experimentation is needed to determine the optimal amount and to assess long-term effects on soil productivity and quality (Marzaioli et al., 2018). Therefore, continued research into the effects of biochar is essential.

3.2. Effects of biochar application on soil microbial communities

There is limited knowledge of the effects of biochar application on soil biota, particularly microbial communities. In a study conducted by Herrmann et al. (2019) in a rubber tree plantation in Thailand, increasing doses of biochar were applied to investigate its impact on microbial communities. The application of biochar caused an increase in soil pH and nutrient contents, as well as changes in both bacterial and fungal communities. Fungal communities were more notably affected than bacterial communities. Additionally, research by Abujabhah et al. (2018) demonstrated that soil microeukaryotes responded to short-term carbon amendment, although to a minimal degree. The limited impact of biochar loading rates on soil microbiology was attributed to the short incubation period, the lack of fertilizer nutrients, and the inherent stability of the soil eukaryotic community. It was observed, however, that important plant symbiotic organisms were affected. The results indicated that biochar applications at different loading levels had differential effects on soil microeurokaryotes depending on soil properties, particularly clay content. A study by Herrmann et al. (2019) revealed that microbial composition and structure changes were strongly related to soil properties such as pH, soil moisture, and phosphorous content.

3.3. Biochar application in soil reduces potential human health risks

Over time, food crops can absorb and accumulate many pharmaceuticals from soils that are exposed to wastewater, biosolids, or animal manure (Li et al., 2020). The potential health risks related to the long-term consumption of a combination of pharmaceuticals is of great concern to both the public and scientific communities, as the continued release of pharmaceuticals into agricultural fields or agroecosystems could lead to further unintentional contamination of food crops. Biochar amendment in soil, however, could be a strategy to adopt in order to reduce crop uptake of pharmaceuticals from soils, ensuring food safety. The study by Li et al. (2020) found that adding 1.0% biochar to soil led to a 33.3-83.0% decrease in plant uptake of 15 pharmaceuticals (acetaminophen, carbamazepine, sulfadiazine, sulfamethoxazole, lamotrigine, carbadox, trimethoprim, oxytetracycline, tylosin, estrone, and triclosan) when radish was used as the crop of focus. This effect was attributed to a decrease in pharmaceutical concentrations in pore water due to the presence of biochar. The estimated daily intake data suggests that biochar amendment could potentially reduce total human exposure to a mixture of pharmaceuticals, thus reducing potential human health risks.

3.4. Effects of biochar application on climate change

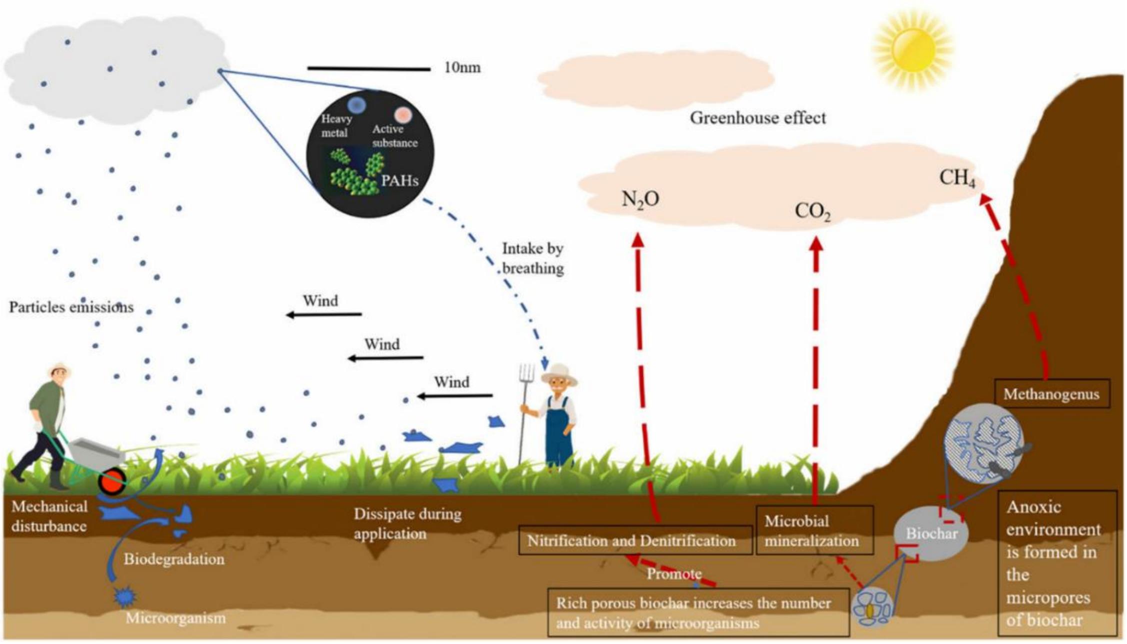
The Intergovernmental Panel on Climate Change (IPCC, 2014) has reported that global greenhouse gas (GHG) emissions have risen to unprecedented levels, despite growing efforts to combat climate change. In order to keep global mean temperature rise below 2 degrees Celsius, the IPCC (2014) suggests that greenhouse gas emissions be decreased by 40–70% by mid-century and brought to nearly zero by the end of the century. The term "biochar" was not associated with climate change mitigation until 2005. Since then, it has been recognized that the application of biochar in soil for agricultural purposes is essential for the fight against global warming due to its ability to retain soil water content. Biochar has been identified as a potential tool to limit climate change by enhancing Carbon sequestration in soils, while its utility as a soil amendment to improve soil fertility and crop yields is still highly regarded (Herrmann et al., 2019). Studies have suggested that when biochar is incorporated into soil, the Carbon can be stored for long periods of time, up to 1000 years, thus preventing the release of Carbon dioxide that would occur when biomass breaks down. Carbon sequestration through biomass conversion to biochar has been proposed as a way to reduce global agriculture's contribution to climate change. It has been reported that biochar and its storage in soil can help reduce global anthropogenic Carbon dioxide emissions by up to 12% (Brassard et al., 2016). For biochar to be sustainable, it must be produced from materials that would otherwise degrade, such as forestry slash, dead biomass, crop residues, and urban yard wastes, and not compete with food production. Additionally, biochar should be created inefficient reactors that emit minimal to no greenhouse gases. Agricultural land has the potential to contribute considerably to GHG emissions and thus has an important role in achieving the goal of limiting temperature increase to 2 degrees Celsius. In addition to avoiding carbon dioxide and methane emissions from normal decomposition of feedstocks, research has shown that the use of biochar as a soil amendment can reduce or suppress greenhouse gas emissions from agricultural soil. Biochar may also help reduce indirect greenhouse gas emissions by decreasing the nitrogen fertilizer needed for agricultural production.

3.5. Environmental toxicity associated with biochar application in soil

The application of different types of biochar in soil can lead to a toxic environment due to the presence of heavy metals, Polycyclic aromatic hydrocarbons (PAHs), dioxins, Environmentally Persistent Free Radicals (EPFRs), Perfluorochemicals (PFCs), and volatile organic compounds (VOCs) (Xiang et al., 2021; & Freddo, et al., 2012). These pollutants have a range of adverse impacts on human health, and their toxicity, persistence, and bioaccumulation make heavy metals particularly concerning. The concentration and bioavailability of heavy metals in biochar is determined by the type of biomass used, with those with a higher content resulting in a greater risk of environmental contamination. Miscanthus, an energy crop, grows on soils fertilized with sewage sludge or wastewater and has a high accumulation of trace metals. According to Xiang et al. (2021), Miscanthus-derived biochar has a higher hazardous metal content than other biochar, which could release heavy metals into the environment.

Additionally, high Zinc (Zn) and Manganese (Mn) levels are found as monovalent and divalent cations in wood biochar produced from pin wood chips, bamboo, or oak. These heavy metals are weakly bound to the biochar matrix and are easily released, even under mild conditions such as irrigation. As wood-derived biochar has a large surface area (180–270 m2/g), and the exchangeable/acid-soluble fraction often contains more than 50% of the total metal content, this may lead to an increased bioavailability of heavy metals. The careful analyses and observations suggest that biochar application in soil has a severe negative impact on the environment. The degree of impact depends on the type of biochar. Biochar application can cause air pollution and greenhouse gas emissions and can have adverse effects on health due to its effects on the atmosphere (Figure 2). Wind-borne particulate matter and particles can also cause air contamination when biochar is applied mainly on a large scale.

Figure2. Negative environmental effect of biochar on the atmospheric environment (Xiang et al., 2021)



DISCUSSION

The studies reviewed in this article uncovered both positive and negative environmental impacts associated with the use of biochar in agricultural soils. While the use of biochar can lead to beneficial changes in soil porosity, water retention, fertility, permeability, pore size distribution, and bulk density, it is not a universal 'cure-all' (Baronti et al., 2013). Different biochar types have varied effects on soil microeukaryotes depending on soil properties, and some biochar-soil combinations can lead to earthworm mortality (Weyers & Spokas, 2011). In addition, the inconsistent results across studies suggest that biochar's impacts on soil may depend on soil conditions. Additional research is needed to gain a more thorough understanding of the effects of biochar application on soil microbial communities and their subsequent effects on ecosystem functions. Different results are expected to emerge when studying a range of soil types across varying conditions. While biochar amendment generally increases the soil's capacity to sorb pharmaceuticals, it may not always reduce the uptake of certain pharmaceuticals, such as caffeine, monensin, and lincomycin (Li et al., 2020). This can be attributed to the increased sorption of pharmaceuticals leading to a decreased dissipation rate and possibly an increased amount of bioavailable pharmaceuticals in soil pore water, leading to higher plant uptake. In this case, the reduced uptake of these pharmaceuticals by radish with the addition of 1% biochar is likely the reason for the reduction in human health risk (Li et al., 2020). Biochar has been suggested as a possible tool to help mitigate climate change due to its ability to reduce nitrogen fertilizer use. Additionally, when applied to soil, biochar can store Carbon for a long period of time, preventing the release of CO2 that would otherwise be emitted as biomass decays (Sparrevik et al., 2013). Reports have suggested that carbon sequestration from biomass conversion to biochar could reduce global agricultural emissions by up to 12%, making biochar a viable option for improving environmental sustainability.

When biochar is added to an environment, it is subjected to physical, chemical, and biological reactions, which cause it to change significantly over time. This process, known as physical ageing, involves the biochar diminishing in size due to environmental factors such as wind or wear. Herbaceous plant biochar is more susceptible to these physical stresses than woody plant biochar. In addition, chemical ageing occurs due to biochar being exposed to chemical oxidation, leading to oxygen-containing functional groups forming on its surface. This could potentially increase the biochar's ability to exchange ions with heavy metals. Although biochar has various positive environmental impacts, it also has several drawbacks, which can have a negative impact on the environment (Wu et al., 2021).

The cation exchange capacity and adsorption capacity of Copper (II) oxide (Cu (II)) on old biochar were lower than those on new biochar across a pH range of 5.0-6.8. This is likely due to the process of biological ageing, where microorganisms use biochar as a substrate for oxidative respiration and other living functions. This process involves the secretion of extracellular enzymes that cause Carbon-Carbon bonds in the aromatic structure of biochar to break, resulting in biochar degradation - ageing and oxidation (Figure 3).

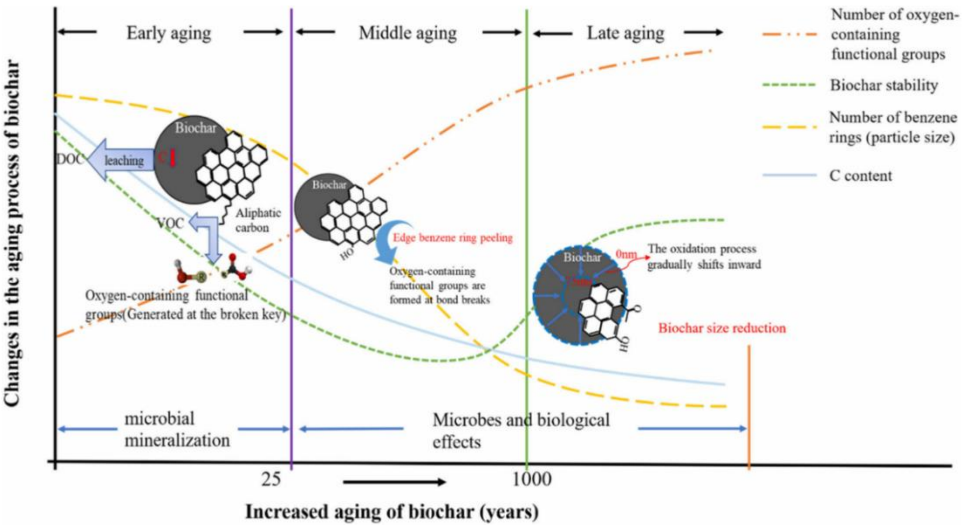


Figure 3: Changes in biochar during oxidation and ageing (Xiang et al., 2021)

The physical and chemical properties of biochar and its effect on environmental media change in the natural environment due to the combined effects of physical, chemical, and biological ageing. The dissociation of oxygen-containing functional groups shifts as biochar ages, which could be why Cu (II) adsorption is impeded. Functional groups (phenolic hydroxyl) that are harder to dissociate had a large impact in a high pH range (5.0–6.8) compared to a low pH range (3.3–5.0). The ageing process of biochar may make it difficult to dissociate functional groups on its surface, limiting the adsorption of copper (II). It is, therefore, essential to consider the medium's pH and the internal mechanism of heavy metal adsorption by biochar when calculating its capacity to absorb heavy metals. Additionally, some heavy metal ions, such as Chromium (Cr), undergo a reduction reaction and form precipitates under acidic conditions, reducing the amount of adsorbed heavy metals. Moreover, polycyclic aromatic hydrocarbons (PAHs) are adsorbed onto biochar through the π–π interaction between the benzene ring of PAHs and the aromatic Carbon structure of biochar. However, the oxidation of aromatic Carbon rings rich in π–π electrons during the ageing process of biochar may lead to the release of organic contaminants which were originally adsorbed, resulting in secondary environmental pollution (Xiang et al., 2021). Biochar that has aged is more susceptible to both biodegradation and physical disintegration, resulting in the release of biochar components such as dissolved Organic Materials and soluble black Carbon as well as endogenous contaminants such as heavy metals. Cui et al. (2021) found that ageing activates heavy metals in biochar, increasing the leaching rate and bioavailability of the heavy metals and presenting environmental risks.

CONCLUSION

The application of biochar to agricultural soils has numerous positive impacts and advantages in terms of agricultural production. Its potential to mitigate climate change and reduce greenhouse gas emission, as well as its ability to improve soil properties, have been widely documented. However, its sustainability and environmental safety have been called into question, as the oxidation and ageing process of biochar can result in the release of heavy metals and other environmental contaminants into the environment, which can be detrimental to the health of both humans and other organisms. Consequently, it is not accurate to say that biochar application is an inherently sustainable and environmentally friendly practice, as some environmental risks are associated with its use. Before determining its sustainability, further research is needed on the long-term environmental impact of potential biomass for biochar production.

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This paper and everything connected was written and done by the sole author.

Declarations:

Data availability:

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

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Competing Interest

The author (s) have no financial or proprietary interests in any material discussed in this article.

REFERENCES

Abujabhah, I. S., Doyle, R. B., Bound, S. A., & Bowman, J. P. (2018). Short-term impact of biochar amendments on eukaryotic communities in three different soils. *Antonie van Leeuwenhoek (2019) 112*, 615–632

Baronti, S., Vaccari, F. P., Migliettaa, F., Calzolari, C., Lugato, E., Orlandini, S., Pini, R., Zulianf, C., & Genesioa, L. (2013). Impact of biochar application on plant water relations in Vitis vinifera (L.). *European Journal of Agronomy*.

Brassard, P., Godbout, S., & Raghavan, V. (2016). Soil biochar amendment as a climate change mitigation tool: Key parameters and mechanisms involved. *Journal of Environmental Management*. *181*(1), October 2016, Pages 484-497. https://doi.org/10.1016/j.jenvman.2016.06.06

Cui, H., Li, D., Liu, X., Fan, Y., Zhang, X., Zhang, S., Zhou, J., Fang, G., & Zhou, J. (2021). Dry-wet and freeze-thaw ageing activate endogenous copper and cadmium in biochar. *J. Clean. Prod. 288*, 125605.

Devi, P., & Saroha, A. K. (2014). Risk analysis of pyrolyzed biochar made from paper mill effluent treatment plant sludge for bioavailability and eco-toxicity of heavy metal. *Bioresour, Technol. 162*, 308-315

Freddo, A., Cai, C., & Reid, B. J. (2012). Environmental contextualization of potential toxic elements and polycyclic aromatic hydrocarbons in biochar. *Environmental Pollution 171*, 18-24.

Herrmann, L., Lesueur, D., Robin, A., Robain, H., Wiriyakitnateekul, W., & Brau, L. (2019). Impact of Biochar Application Dose on Soil Microbial Communities Associated with Rubber Trees in North East Thailand. *Science of the Total Environment 689*, 970-979.

Intergovernmental Penal on Climate Change (IPCC) 2014. (6th Janauary, 2022). Retrieved from: https://www.ipcc.ch/site/assets/uploads/2018/02/AR5_SYR_FINAL_SPM.pdf

Li, Y., He, J., Qi, H., Li, H., Boyd, S. A., & Zhang, W. (2020). Impact of biochar amendment on the uptake, fate and bioavailability of pharmaceuticals in soil-radish systems. *Journal of Hazardous Materials 398*, 122852.

Marzaioli, R., Coppola, E., Iovieno, P., Pentangelo, A., Pane, C., & Rutigliano, F. A. (2018). Impact of Biochar Amendment on Soil Quality and Crop Yield in a Greenhouse Environment. *Journal of Environmental Accounting and Management*. *6*(4), Pages: 313-324. Published: Dec 2018.

Sparrevik, M., Field, J. L., Martinsen, V., Breedveld, G. D., & Cornelissen, G. (2013). Life Cycle Assessment to Evaluate the Environmental Impact of Biochar Implementation in Conservation Agriculture in Zambia. *Environmental Science & Technology*.

Tarnik, A. (2019). Impact of Biochar Reapplication on Physical Soil Properties. IOP Conf. Series: *Materials Science and Engineering 603*, 022068. doi:10.1088/1757-899X/603/2/022068

United Nations – What is Climate Change? Retrieved (12th January 2022). Retrieved from: https://www.un.org/en/climatechange/what-is-climate-change

Weyers, S. L., & Spokas, K. A. (2011). Impact of Biochar on Earthworm Populations: A Review. *Applied and Environmental Soil Science*, Article ID 541592, 12 pages doi:10.1155/2011/5415

World Health Organization – Air Pollution (12 January 2022). Retrieved from: https://www.who.int/health-topics/air-pollution#tab=tab_1

World Health Organization – Toxic Hazard (12 January 2022). Retrieved from: https://www.who.int/heli/risks/toxics/chemicals/en/

Xiang, L., Liu, S., Ye, S., Yang, H., Song, B., Qin, F., Shen, M., Tan, C., Zeng, G., & Tan, X. (2021). Potential hazards of biochar: The negative environmental impacts of biochar applications. *Journal of Hazardous Materials 420*, 126611.

Zion Market Research (24 November 2021). (2018–2025) Global Biochar Market Size Worth USD 3.82 Billion By 2025 | CAGR 14.5%. Retrieved from: https://www.globenewswire.com/news-release/2019/07/13/1882255/0/en/2018-2025-Global-Biochar- Market-Size-Worth-USD-3-82-Billion-By-2025-CAGR-14-5.htm

World Bank (2015). What You Need To Know About Toxic Pollution: A Conversation with Richard Fuller. Accessed online 12 January 2022: https://www.worldbank.org/en/news/feature/2015/04/21/what-you-need-to-know-about-toxic-pollution-a-conversation-with-richard