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Unlocking the environmental potential of biochar: production, applications, and limitations

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Biochar is a solid, alkaline, and porous material characterized by a high specific surface area, low bulk density, and strong adsorption capacity, produced through the pyrolysis of biomass under limited oxygen conditions. Due to its favourable physicochemical properties, biochar has gained attention as a potential renewable resource for managing soil fertility and improving crop yield. Numerous studies have shown that biochar application improves the soil fertility, increases the dry matter content of various crops and enhances crop yields, particularly when used in combination with inorganic or organic fertilizers. Biochar has been widely recognized as a promising tool for addressing various environmental challenges, including soil degradation, carbon sequestration, and remediation of organic pollutants and heavy metals. It is important to recognize specific limitations linked with biochar utilization, such as its variable effects across different soil types and the high cost and scalability challenges associated with its production and application. These concerns must be carefully considered when integrating biochar into soil and agricultural management practices. This review examines the production methods, physiochemical properties, and the agronomic potential of biochar, with a particular focus on its role in enhancing soil fertility and crop productivity. In addition, it explores the environmental benefits, the feasibility of biochar production in developing countries, and the potential limitations associated with its application.

KEYWORDS

soil degradation, organic matter, productivity, carbon sequestration, persistent organic pollutant

1 Introduction

Soil degradation poses a significant threat to global agriculture, leading to reduced fertility and increased erosion (Prăvălie et al., 2021). Prolonged cultivation often results in adverse effects such as acidification, severe erosion, and the depletion of organic matter. Additionally, the injudicious use of chemical fertilizers has been linked to declining soil health, particularly in arid and semi-arid regions (Hassan and Rashid, 2023; Gnanaprakasam and Vanisree, 2022). The Green Revolution significantly improved crop yields through increased use of chemical fertilizer; however, it also contributed to a decline in soil fertility and quality, ultimately disrupting the sustainability of soil ecosystems (Gnanaprakasam and Vanisree, 2022). The depletion of organic matter reduces overall soil stability (Li et al., 2023). Soil degradation driven by intensive agricultural practices and climate change poses a serious threat to global food security, thereby encouraging the adoption of innovative and eco-friendly strategies to improve soil health (Wijerathna-Yapa and Pathirana, 2022; Saleem et al., 2024). Several studies have shown that organic amendments can enhance soil quality and boost agricultural productivity across various regions (Ramzani et al., 2017). Biochar, being a renewable resource, is a potential tool for managing soil fertility with several other economic and environmental benefits. It is seen as an important tool for addressing issues such as soil degradation, greenhouse gas emissions, waste management, and crop water productivity (Allohverdi et al., 2021; Kundu and Kumar, 2024). According to the International Biochar Initiative (IBI), biochar is a carbon-rich, stable, and porous solid produced through the thermochemical conversion of biomass under limited or no oxygen conditions, typically referred to as pyrolysis. Updated IBI guidelines (2021) emphasize that biochar is intended primarily for use as a soil amendment to enhance soil health, sequester carbon, and mitigate environmental pollution. It must meet specific quality standards including thresholds for organic carbon content, heavy metals, ash, and potential contaminants, ensuring its safety and effectiveness in agricultural and environmental applications. (IBI Biochar Standards, 2015). It is a permeable, alkaline substance with a high specific surface area, low bulk density, and strong adsorption potential (Qiu et al., 2021). Adding biochar to soil can enhance soil structure by promoting aggregation and water retention (Kang et al., 2022; Jia et al., 2024). Moreover, a mixture of biochar with ammonium, nitrate, and phosphate has been recommended as a slow-release fertilizer to improve soil fertility (Wang et al., 2022). Biochar has been shown to enhance not only the physicochemical properties of soil but also its microbial characteristics. Specifically, it improves the soil microbial community structure and enzymatic activity (Zhou et al., 2019). Furthermore, biochar enhances the microbial biomass of C, N, and P (Manirakiza et al., 2019), and promotes the growth of soil bacteria, particularly certain microbial guilds (e.g., diazotrophs) (Liu et al., 2020). It has also been shown to boost the overall composition of the soil biological community (Amoakwah et al., 2022). In addition to enhancing microbial biomass and enzymatic activity, biochar also supports the proliferation of beneficial fungi such as arbuscular mycorrhizal fungi (AMF). Its porous structure and large surface area create protective microhabitats that facilitate fungal colonization and root symbiosis, further contributing to nutrient uptake and plant health (Zhou et al., 2019; Videgain-Marco et al., 2021; Javeed et al., 2023).

Sustainable soil management and climate change are two major global concerns, and the application of biochar to soil may serve as an effective tool to address both issues (Abbas et al., 2018). Biochar can persist in soil for centuries (Lehmann et al., 2006) and contributes to C sequestration; therefore, it has the potential to mitigate the challenge of greenhouse gas emissions (Yin et al., 2022). As biochar contains a high amount of organic carbon, it has the potential to rapidly increase soil-organic C content (Zhang et al., 2022). In addition to its significant role in soil C sequestration and quality improvement, studies have shown that biochar can enhance hydro-physical properties of soil, such as water holding capacity (Alghamdi et al., 2022), by improving physical attributes like structure, texture, porosity, and aggregate stability (Das and Ghosh, 2022).

Several researchers have reported that the addition of biochar to soil improves net primary crop production, grain yield, and dry matter accumulation (Sarwar et al., 2023; Yang et al., 2023; Pinnamaneni et al., 2023). When applied in combination with inorganic or organic fertilizers, biochar can further enhance crop productivity, particularly in tropical soils (Bai et al., 2022). It has been shown that crop productivity increased by 10% after adding biochar to the soil (Melo et al., 2022). Depending on the features of biochar, methods of application, and background soil conditions, a negative to positive crop response has been found (Chen et al., 2019). For example, biochar has been shown to significantly enhance crop yields in degraded, acidic, or nutrient-poor soils, where its ability to improve pH, cation exchange capacity (CEC), and water retention can address critical fertility constraints. However, in nutrient-rich or well-structured soils, its benefits are often limited or even negative. El-Naggar et al. (2019) reported that in high-fertility soils, biochar amendments produced negligible yield gains, and in some cases, caused nutrient imbalances by immobilizing nitrogen and micronutrients. Similarly, Rajkovich et al. (2012) found that corn grown in fertile soils with high organic matter showed a decrease in nitrogen uptake and growth after biochar addition, likely due to its strong adsorption capacity. These findings highlight the need for site-specific assessments before recommending biochar applications, especially in systems that are already performing well under conventional management. Studies have revealed that adding biochar with other farm management approaches, could perform better under changing climatic scenarios, especially in water-stressed areas (Fischer et al., 2019).

Furthermore, the potential of biochar to absorb chemicals and other contaminants that are used in agriculture is a crucial process that has direct impacts on the agronomic efficacy of these agricultural chemicals (e.g., insecticides, herbicides, and supplements) as well as on their environmental fate and ecotoxicological effects. However, there are certain drawbacks associated with biochar that need to be addressed during its application to soils. This review article offers a novel and region-specific synthesis by focusing on the potential and challenges of biochar application in developing countries, particularly India and East Africa—areas often overlooked in previous reviews. In addition, it incorporates recent advances in feedstock selection, microbial interactions, and biochar-soil dynamics. Unlike earlier literature, this review emphasizes practical limitations, such as soil-specific responses and environmental safety concerns, offering a critical and holistic view that aims to inform both policy and practice. By synthesing current knowledge, the review seeks to inform researchers, policy-makers, and practitioners about the opportunities and limitations of integrating biochar into sustainable soil and environmental management practices.

2 Production process of biochar

Biochar is produced as a solid material through pyrolysis of biomass. Figure 1 illustrates the step-by-step process of biochar production via pyrolysis, during which biomass is thermochemically decomposed at high temperatures in a limited-oxygen environment. During this process, the biomass is first dried. The dried material is then heated to elevated temperatures, resulting in the release of volatile substances from the solid matter. The volatile substances produced may be either permanent gases like carbon monoxide, carbon dioxide, methane, and hydrogen, or condensable organic compounds, like acetic acid and methanol. Subsquent reactions in the gaseous phase, including cracking and polymerization, can alter the overall product structure. Three types of products can be generated; permanent gases, one or more liquid forms (such as water and tar), and a solid residue. The differentiation of these products depends on process temperature and residence time (RT). Moreover, the reaction pathways leading to the formation of these products are to some extent, competing. In order to generate a

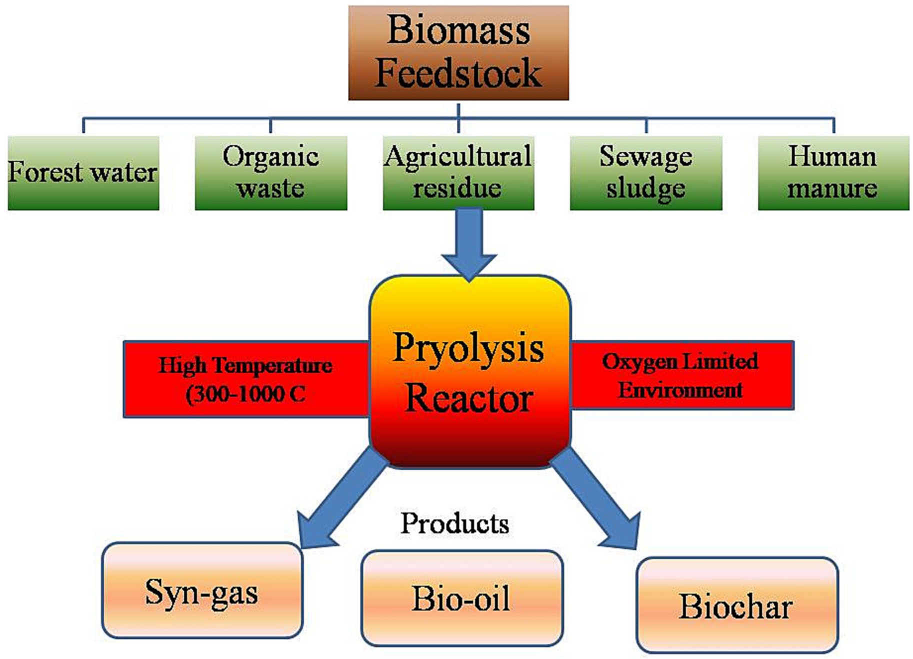

FIGURE 1
Steps in biochar production.

desired product from the process, several general procedures can be applied to maximum yield of that specific product (Weber and Quicker, 2018). Biochar can be produced as a co-product of various processes, such as fast pyrolysis (FP), slow pyrolysis (SP), and gasification (Table 1). Various factors affect the pyrolysis process, including temperature, pressure, moisture content, and RT (Al-Rumaihi et al., 2022).

The transformation process and the properties of the resulting product are also influenced by the characteristics of the biomass feedstock used in the biochar production. Biochar typically contains three major types of organic compounds—hemicellulose, cellulose, and lignin. During the pyrolysis process, these compounds behave differently, and thus, the composition of biomass directly affects both the properties and yield of the final product. Hemi-cellulose is a group of branched chain polysaccharides. Among the three major organic compounds in biomass, hemicellulose is the most reactive and least thermally stable, decomposing at temperatures ranging from 220 to 315°C (Huang et al., 2023). Cellulose, being the most abundant organic compound on earth, has been extensively studied; however its thermal disintegration is still not fully understood. In contrast, lignin processes a complex three dimensional structure with a variety of chemical bonds, which results in its breakdown occuring over a broad temperature—unlike the more defined decomposition ranges of hemi-cellulose and cellulose. Lignin contains a large number of functional groups with varying thermal stabilities. As a result, it decomposes over a broad temperature range. Its thermal degradation begins around 200°C and may require temperatures as high as 900°C for complete decomposition, depending on the residence time (Yang et al., 2007). Animal wastes and sewage residual biomass contain negligible amount of these compounds due to their different origins; therefore, they require distinct processing methods (Weber and Quicker, 2018).

3 Pyrolysis conditions and feedstock type influence the biochar physio-chemical properties

Pyrolysis processes and various feedstock sources considerably influence the properties of biochar, like pH, CEC, particle size, pore size, surface area, biochar yield, and charge. Biochar properties can vary widely depending on the feedstock and pyrolysis conditions, and they act differently in different soil types. For instance, manure-derived biochar, which has a higher cation exchange capacity (CEC) and nutrient content, is particularly effective at enhancing nutrient retention and water-holding capacity in sandy soils, whereas woody biochars may be better suited for improving aeration and pH in acidic or compacted clay soils. (Ighalo et al., 2023; Balmuk et al., 2023). Downie et al. (2012) discussed in detail the properties of newly produced biochars as determined by production processes and the type of feedstock used. Various feedstock, like forest wastes, rice husks, sugar beet tailings, empty fruit bunches and other crop wastes, wood bark, and different types of manure, are used in biochar production (Amalina et al., 2022). The ash content of biochar, which consists mainly of mineral elements such as calcium, magnesium, potassium, and phosphorus, contributes significantly to its alkaline nature (Whalen et al., 2024). Biochars with high ash content, especially those derived from manure or agricultural residues can exhibit pH values ranging from 8 to 11, making them effective liming agents in acidic soils. For example, Yuan and Xu (2011) reported that adding poultry litter biochar raised soil pH by up to 1.2 units within a single growing season. Similarly, Van Zwieten et al. (2010) found that applying sugarcane bagasse biochar to acidic soils significantly increased pH and enhanced base saturation. This pH-modifying effect not only improves nutrient availability but also reduces aluminum toxicity and creates more favorable conditions for microbial activity and root

TABLE 1 Comparison of pyrolysis methods, conditions, and resulting product yields.

Methods of pyrolysis	The key reaction parameters			Solid product (Biochar)	Liquid product (Tar)	Gas product (H_2, CO, CH_4)	Reference(s)
	Temperature	Gas/Vapour residence time	Heating rate: (°C/s)				
Slow	400–660°C	5–30 min	Not rising heating rate (0.1–1°C/S)	25–25%	20–50%	20–50%	Shareef and Zhao (2016), Uzun et al. (2016)
Intermediate	500–700°C	10–20 s	1–10	25–40%	35–50%	20–30%	
Fast	About 500°C	Less than 2 s	Fast heating rate (10–200°C/S)	10–25%	60–75%	10–30%	
Gasification	More than 800°C	Less than 1 s	Fast heating rate (1,000°C/S)	About 10%	60%	About 80%	

development. Biochar produced from animal residues typically has a lower specific pore surface compared to biochar produced from plant materials under similar pyrolysis conditions and RT. This is due to the higher ash content and increased inorganic concentrations found in biochars produced from animal dung (Ok et al., 2015). Consequently, biochar from animal manure has a greater potential as a nutrient source, enhancing crop production in the agricultural sector (Hou et al., 2022).

In fine-textured soils, the addition of wood and animal-based biochar improves soil aggregation (Yang et al., 2024), soil aeration, and overall physical structure. This enhances the moisture ratio creating a better environment for root growth and development. During pyrolysis, the concentration of the macronutrients in biochar increases, whereas volatile compounds and water are removed from its structure. Organic acids like acetic acid, formic acid, propionic acid and butyric acid are some of the volatile compounds that are present in biochar, and the discharge of these substances and the deposition of important elements like Ca and Mg as a result of an increase in the temperature of pyrolysis processes lead to high pH values in different biochars. These characteristics of biochar justify its use as a tool for soil improvement, a source of nutrition, and a liming factor in soils (Pandian et al., 2024).

4 Biochar improves soil fertility and crop yield

The fertility of soil decreases either from erosion and depletion or from an imbalance in organic matter, thereby affecting agricultural productivity worldwide. Modern agricultural practices have been successful in increasing food production in the short run, but in the long run, they cause damage to agricultural productivity (Ramzan et al., 2022). Modern agricultural land use practices include the everlasting excessive use of inorganic fertilizers, which may increase soil acidification, which in turn affects the soil biota and biogeochemical processes, thus creating an environmental risk and a decrease in crop yield. In this regard, organic remediation such as biochar is a useful tool to feasibly balance soil organic matter, preserve and improve soil fertility, and increase crop production (Jatav et al., 2021). Biochar has been proven to increase soil water holding capacity (WHC) as well as have significant impacts on soil nitrogen retention capacity and nutrient cycling via indirect effects on numerous biogeochemical processes in the soil (Nkoh et al., 2021; Yin et al., 2022). The specific surface area, highly porous character, and total pore size of biochar define the WHC of biochar, but its effectiveness varies significantly with soil texture. In sandy soils, which are typically low in organic matter and have large pores, biochar improves WHC by increasing microporosity and adding a high surface area structure that slows water drainage and enhances moisture retention. In contrast, clay soils, which already retain water efficiently due to their fine particles and small pores, may experience minimal or even negative effects. In some cases, the addition of biochar can clog soil pores or disrupt aggregate structure, reducing infiltration and aeration. Therefore, while biochar application generally benefits coarse-textured soils, its use in fine-textured or compacted soils requires careful assessment of particle size, application rate, and pyrolysis temperature to avoid undesirable impacts on soil hydrology (Jia et al., 2024). Moreover, biochar, when added to soils, modifies or improves soil quality by amending various properties of soil (Figure 2). It may augment the microbial population of the soil and modify the profile of soil microbial communities by selectively enriching some specific microbial populations, such as eubacteria, archaebacteria, and fungal communities, and reducing the diversity of some other communities (Dong et al., 2024). These changes in soil microbial populations are ascribed to an extra nutrient supply coming from the readily breakable carbon source of biochar. Biochar favours the living environment of microbes and consequently guards them against the grazers or adversaries in biochar pores (Janardhan and Krishna, 2021). This microbial augmentation may promote the degradation of organic pollutants in soils (Sun et al., 2024). Biochar contains minerals, some volatile organic compounds, and free radicals that can further restructure the soil microbial communities, affect their activities, and alter the soil enzymatic activity (Rasul et al., 2022). Enzymes in soil catalyze different biogeochemical pathways comprising elemental (N, P, and S) cycles and soil organic matter production (Daunoras et al., 2024). Hence, biochar influences the various soil processes in a prospective way.

Applying various forms of compost or biochar combined with fertilizers to fields can boost crop productivity. Nutrients are stored in biochar because of its specific properties like pore structure and functional groups. Surplus nutrients, for example, nitrate, phosphate, and ammonium, could be deposited on the surface of biochar. Biochar improves nutrient cycling and lessens the chance of nutrient leaching in soils, which has a favourable effect on crop yields (Siedt et al., 2021). Furthermore, biochar has the potential to reduce NO and NO_2 emissions, resulting in increased soil fertility. Several positive results

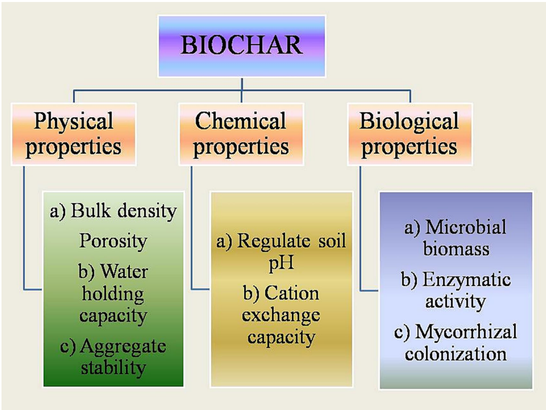

FIGURE 2
Biochar improves soil quality by improving various features of soil.

have been observed in a variety of crops after amending soils using biochar (Table 2). At higher pyrolyzing temperatures, the pH of biochar increases, and crop productivity is remarkably increased by biochar produced at higher temperatures (Rajkovich et al., 2012).

5 Environmental benefits of biochar

Biochar improve environmental quality by aiding in the mitigation of various pollutants. Its porous structure and high surface area make it an effective sorbent for contaminants like heavy metals and organic chemicals in soil systems (Khan et al., 2021).

5.1 Carbon sequestration

The process of absorbing and retaining carbon to stop it from being released into the atmosphere is known as carbon sequestration (Hu et al., 2021). Biochar has been essential for improving carbon sequestration in soil for hundreds to thousands of years (Graber, 2009; Das and Ghosh, 2020). A 250-hectare farm could sequester around 1900 metric tonnes of CO_2 per year (Sisay and Girma, 2021). When biochar in the soil gets mineralized, a portion of it persists in a relatively stable state, which makes biochar a significant carbon sink (Luo et al., 2023; Li and Tasnady, 2023). Carbon sequestration in biochar improves storage duration compared to other terrestrial sequestration technologies such as afforestation or reforestation (Jeswani et al., 2022; Yadav et al., 2023). The carbon content of biochar is usually inversely proportional to the ash content of the feedstock (Windeatt et al., 2014). Nan et al. (2018), investigated how natural minerals affect the pyrolysis of peanut husk, barley grass, sewage sludge, and cow dung. During pyrolysis, eliminating natural minerals may limit emissions of low-molecular-weight organic compounds and allow more carbon (3.5–30.1%) to be preserved in biochar (Nan et al., 2018). Biochar may be labile and recalcitrant depending on the concentration of carbon (Zheng et al., 2019). Soil microorganisms might readily use labile carbon in biochar applications, and carbon mineralization could be resumed. Recalcitrant carbon, on the other hand, is more difficult to degrade and may remain in the soil for longer periods (Chen and Frank, 2020). Soil organic carbon (SOC) may influence soil microbial activity, resulting in enhanced organic matter breakdown and CO_2 generation (Liu et al., 2020). In biochar applications, both increased and decreased carbon emissions were reported. Biochar applied in acidic settings, in particular, resulted in higher CO_2 emissions owing to biochar decomposition, but overall CO_2 emissions were lower in alkaline conditions (Sheng and Zhu, 2018). Biochar, on the other hand, when applied to the soil, helps in a dramatic decrease of CO_2, N_2O, and CH_4 emissions (Yang et al., 2020). The importance of biochar in reducing the consequences of climate change on a global scale has been scientifically validated (Lehmann et al., 2021). Biochar, according to the IBI, has the ability to reduce global warming by absorbing roughly 3.67 gigatonnes (Gt) of CO_2 each year.

5.2 Reduction in the emission of greenhouse gases (N_2O and CH_4 emissions)

The rise in emissions of greenhouse gases (GHGs) is one of the major causes of global warming and, ultimately, climate change. The application of biochar to soil has been suggested as a sustainable approach to mitigate GHG emissions from soil and contribute to efforts to combat climate change (Das et al., 2020). Biochar can sequester about 12% of GHGs from soils (Kaushik et al., 2024). At present, studies have demonstrated that biochar has the potential to reduce GHG emissions from soil, such as CH_4 and N_2O emissions, which are the potent gases for global warming that lead to climate change. For example, nitrous oxide emissions from an acidic ferrosol were reduced by biochar made from paper mill wastes, biosolids, green waste, and poultry remnants. The type of feedstock used for biochar synthesis, the temperature of the production process, and the amount of water available in the soil all influence the potential of biochar to reduce GHG emissions (Purakayastha et al., 2016). The soils of agricultural fields and pasturelands are one of the major sources of nitrous oxide emissions (Basheer et al., 2024). Biochar is able to reduce GHG emissions in agricultural soils by significantly decreasing N_2O emissions (Van Zwieten et al., 2024), and the lowering of N_2O and CH_4 emissions because of biochar usage in the soils is being viewed as an effective strategy to combat global warming as these gases have a much higher potential to cause global warming than CO_2. The basic mechanisms involved in the reduction of N_2O in biochar-added soils are that the application of biochar accelerates the action of microbes that are capable of reducing nitrous oxide into nitrogen, and the reason for this is the biochar alkalinity (Novak et al., 2010). Studies have shown that biochar has a large surface area and hence provides an immense number of sites for the adsorption of nitrous oxide and other GHGs (Ullah et al., 2024).

5.3 Mitigation of persistent organic pollutants from soil

Organic contaminants originating from a broad range of agricultural and industrial operations, as well as poor management and disposal of waste, are the prime factors leading to soil degradation. Various organic pollutants are non-degradable, and several are cancerous and mutagenic (Kishor et al., 2021). There are two major types of organic pollutants: persistent organic pollutants

TABLE 2 Biochar-induced yield enhancement in various crop plants.

Crop	Biochar feedstock	Dosage (tonnes/ hactare)	Increase in yield compared to control	Reference(s)
Maize/Soybean	Rice husk	10	10–40%	Duku et al. (2011)
Wheat	Paper mill sludge	10	30–40%	
Radish	Poultry litter	0–50	42%	Shareef and Zhao (2016)
Maize	Cow manure	15	150%	Uzoma et al. (2011)
Radish	Green waste	100	266%	Chan et al. (2007)
Durum wheat	Woodland of beech, hazel, oak and birch	60	30.4%	Vaccari et al. (2011)
Grapes	Woodchips from fruit trees	22	20%	Genesio et al. (2015)
Maize	Straw (corn Stover)	30	11.9	Genesio et al. (2015)
Maize	Waste wood	10	44.4%	Agbede and Adekiya (2020)
Maize	Waste wood	20	66.7%	
Maize	Waste wood	30	88.9%	
Rice	Wheat straw	40	14	Zhang et al. (2010)
Radish	Poultry litter	10	42	Chan et al. (2008)
Rice	Wheat straw	40	18.3	Bian et al. (2014)
Rapeseed	Wheat straw	40	36.02	Liu et al. (2014)
Rice	Peanut Husk	0.45	28.1	Qian et al. (2014)
Rice/sorghum	Forest waste	11	22	Steiner et al. (2008)

(POPs) and emerging organic pollutants (EOPs). Most of the organic pollutants were, in the past or at present, used as pesticides. Many of them are used in industrial activities for the manufacturing of various products like additives, solvents, and pharmaceuticals. Biochar has been found to be very capable of taking various man-made as well as natural organic compounds (Table 3). This ability of biochar to adsorb various organic compounds such as pesticides, PAHs, and emerging pollutants like steroid hormones has been found to be attributed to the large surface area, highly aromatic character, micropore size, and the existence of plenty of polar functional groups in biochar (Kookana et al., 2011). It has also been found that the higher organic carbon content in the biochar contributes to the higher uptake capacity of biochar for POPs (Taherymoosavi et al., 2018). The processes of absorption of POPs by biochar chiefly comprise division, surface adsorption, and pore impediment (Zheng et al., 2017). The major pathway for mineralizing and eliminating POPs from the soil is microbial degradation (Krithiga et al., 2022). Biochar produced at high temperatures has powerful sorption capability for POPs, but it can hamper the biodegradation of POPs in soils. Decreased accessibility of POPs to microbes may be the reason for reducing their biodegradation in soils amended with biochar produced at higher temperatures (Anyika et al., 2015). It has been demonstrated that 98% of the added acetochlor disappeared from the soil not amended with biochar, whereas 56% or 82% of the acetochlor got degraded in the soil mixed with biochar produced from rice hull or crofton weed at 600°C, respectively (Li et al., 2018). It was found that the soil, when mixed with wood biochar produced at a temperature of 800°C, decreased the availability of monoaromatic hydrocarbons and led to their biodegradation (Bushnaf et al., 2011). Biochars prepared at low temperatures have been detected to be capable of promoting POP degradation in the soil (Dong et al., 2019).

5.4 Toxic metal remediation

In ecosystems, pollutants (heavy metals) are being released by processes like mineral resource mining and smelting, solid waste disposal, sewage irrigation, and the use of pesticides and fertilizers. These pollutants are difficult to decompose in soil and lead to major health and environmental risks. In recent years, biochar has emerged as a viable remediation material. It offers minimal costs, great remediation efficiency, environmental friendliness, and soil enhancement (Wang et al., 2019). According to Mehmood et al. (2018), biochar derived from a variety of feedstocks, such as manure, agricultural waste, woody plants, or animal corpses, has the ability to immobilise heavy metals (such as Cd, Pb, Cr, Cu, and Zn) in soils and thereby reduce the accumulation of heavy metals in plants. However, not all heavy metals have responded well to the addition of biochar to the soil. In field studies in Hunan, for example, Zn (II) buildup in grains revealed no significant change when biochar was added (Chen et al., 2016). Biochar may be modified using techniques such as activation, magnetization, oxidation, and digestion to boost its heavy metal adsorption considerably (Wang et al., 2019). Biochar generated at 300°C improved Pb and Cu mobility in an alkaline environment. On the other hand, biochar generated at 700°C performed better in reducing Zn and Pb mobility in an acidic environment (100%) (Zhang et al., 2020). Moreover, the pH of the water may alter as a result of the addition of biochar. Changing the pH may aid in the immobilization of heavy metals (Schlögl et al., 2023). Biochar made from cow dung activates heavy metal-resistant bacteria to improve heavy metal immobilization in sheep manure compost (Liu et al., 2021). Pb immobilization might be improved by aromatic carbon groups. Richness in inorganic minerals (Ca^{2+}, K^{+}, Mg^{2+}, and Na^{+}) also aids in increasing metal trapping activity (Yang et al., 2018).

TABLE 3 Biochar-mediated degradation of organic pollutants.

Organic pollutant	Biochar feedstock	Effect	Reference(s)
Carbaryl and Atrazine	Pig manure	Both the pesticides hydrolyzed faster in the presence of biochar. In presence of biochar pyrolyzed at 700°C, carbaryl and atrazine decomposition rates reached 71.8 and 27.9%, respectively, within just 12 h	Zhang et al. (2013)
Bisphenol A	Sugarcane waste	Bisphenol A was effectively degraded at pH of 5–11 and temperatures of 25–45°C within 1 h.	He et al. (2021)
Acetaminophen, Bisphenol A, Phenol and Sulphamethoxazole	Saw dust and organic nitrogen conataining compounds	Organic pollutants were effectively oxidized.	Xu et al. (2020)
Monoaromatic hydrocarbons	Wood	Biochar produced at a temperature of 800°C, decreased the availability of monoaromatic hydrocarbons and led to their biodegradation.	Bushnaf et al. (2011)
4-nonylphenol	Bamboo and Fe_3O_4	At pH 3, 85% degradation efficiency was achieved for 4-nonylphenol with the dosage of 3.33 gL^{-1} of biochar in river sediments.	Dong et al. (2019)
Oxyfluorfen	Rice hull	Oxyfluorfen degraded more rapidly in soil treated with biochar compared to soil without biochar amendment.	Oni et al. (2019)

6 Potential of biochar production in developing countries

Almost every agricultural field or area has the capacity to produce adequate amounts of biomass feedstock for the production of biochar. In India, a large quantity of crop residues are produced in agricultural fields and other land uses, which can be used as a potential biochar feedstock. Roughly 500–550 metric tonnes (Mt) of residue from crops are generated every year in India (Gatkal et al., 2024). The primary sources include wheat, paddy, sugar cane, and maize, accounting for 63% of India's total residue output (Khare et al., 2021). Uttar Pradesh leads with 72 Mt., followed by Punjab with 45.6 Mt., and Haryana with 24.7 million tons, as the top crop residue-producing states in India. A major problem in rural farm areas as well as in urban areas is the inefficient and non-sustainable management of organic waste, and the majority of this waste is either destroyed by burning or eventually dumped in the land, which leads to environmental pollution and the generation of huge quantities of GHGs. The amount of residue burned in India ranges from 98.4 Mt. to 131.9 Mt. annually, with the greatest proportion coming from the combustion of residue (Khare et al., 2021). The application of biochar as a soil amendment tool provides an efficient way to combat climate change and build up sustainable agricultural systems in India. About 1,300 metric tonnes of bio-oil and 900 metric tonnes of biogas, which is equivalent to 31 terra joules of energy, can be generated if 1% of the biochar production process is done using modern instruments. Furthermore, women in rural India use wood and charcoal biomass to cook food on highly polluting stoves. A number of problems are associated with this custom, like deforestation; the collection of fuel wood is time-consuming; back pains; and other risks. Moreover, a significant amount of CH_4 emissions are generated in an earth-mound kiln through the inefficient production of charcoal. For that reason, the development of highly proficient biochar-producing cooking stoves and the pyrolysis of farm waste biomass, which is otherwise burned, can lead to the control of deforestation, enhanced crop yield, better management of crop residues, and the development of a carbon-negative approach by removing atmospheric carbon to counteract global warming (Srinivasarao et al., 2013).

Beyond India, East Africa also holds significant potential for biochar implementation, particularly in regions facing soil fertility constraints, deforestation, and declining agricultural productivity. Agriculture is still a dominant factor that contributes considerably to the economic development of East African countries like Burundi, Kenya, Uganda, Tanzania, Rwanda, and South Sudan and is a source of livelihood for more than 70% of the population of the area (Omulo, 2020). Maize is the most prominent crop produced in East Africa, as it is the staple diet of the people living there. In East Africa, about 8.1 million hectares of land are under the cultivation of maize, which generates a total of 13.5 million metric tonnes of maize, which leads to the production of about 33.3 million metric tonnes of crop residues annually that are potential feedstock for the production of biochar through the process of pyrolysis. Similarly, Ghana, in West Africa, has huge potential for producing biochar due to the abundance of biomass resources. Crop residues, agricultural by-products, forest litter, wood residues, byproducts of municipal solid waste, manures, and industrial wastewater are all examples of biomass resources in Ghana.

7 Limitations of biochar

Despite the fact that biochar has been proved to increase soil quality, crop production and have good environmental consequences by reducing various pollutants; in some cases, the use of biochar can be harmful, and it has some possible downsides. Biochar's positive benefits have been demonstrated to be soil specific. As a result, biochar addition may not always be beneficial to all soil types. For instance, Ghorbani and Amirahmadi (2024) reported that biochar application in certain well-structured soils showed no significant improvement in yield and, in some cases, caused nutrient imbalances. In clayey soils, Brtnicky et al. (2021) found that biochar may decrease water retention over time due to pore clogging and reduced capillary flow, eventually leading to adverse effects on plant growth. Conversely, sandy soils tend to benefit more due to their initial poor structure and low water-holding capacity. Due to the existence of multiple macropores in the biochar, adding biochar to soil causes immediate and long-term impact on soil water retention ability (Fischer et al., 2019). And based on particle size and distribution, it may significantly influence soil texture on a broad range. However, effect is likely to be predominantly transient because biochar seems to disintegrate quickly, resulting in tiny sized particles or silt. Impacts of biochar on available moisture are insignificant over time or may be potentially harmful in clayey soils (Brtnicky et al., 2021). Soil is defined as a nonrenewable resource due to its slower rate of formation, and even a moderate dose of biochar is anticipated to outpace the normal rate of soil formation (Verheijen et al., 2010). Therefore, extreme caution must be taken while adding biochar to a field in order to match the soil formation rate (Brtnicky et al., 2021). Biochar may release some organic pollutants like volatile organic compounds, polycyclic aromatic hydrocarbons, dioxins etc. These compounds are either normally found in the feedstock used to make biochar or are synthesized during the pyrolysis process, which might include faulty or partial pyrolysis (Hilber et al., 2017). The range of pollutants in the resultant biochar mainly depends on biomass used in its production (Krithiga et al., 2022), primarily for certain feedstocks like sludges or biomass derived from phytoremediation. The combination of potential hazardous compounds with biochar is a big concern in relation to soil pollution and health implications (Brtnicky et al., 2021). Biochar made at elevated temperatures often contains more ash than that made at relatively low temperatures. As a result, it was speculated that the negative effects may be triggered on plants cultivated in soils amended with biochar generated at elevated temperatures (Butnan et al., 2015). Another disadvantage of biochar is its ability to absorb nitrogen and also other important elements like Fe, which can be detrimental to plant development (Younas et al., 2024). Biochars produced at lower pyrolysis temperatures often contain more labile organic compounds that promote microbial immobilization of nitrogen, while high-temperature biochars tend to have a higher surface area and cation exchange capacity (CEC), leading to increased ammonium adsorption. Furthermore, fine biochar particles offer more adsorption sites and may enhance nitrogen retention but also delay its release, which can hinder plant uptake. In contrast, larger or coarser biochar particles typically reduce this immobilization effect and allow more immediate nitrogen availability. Strategic co-application of biochar with compost or nitrogen fertilizers can help balance this effect and improve overall nutrient use efficiency (Haider et al., 2024; Rajkovich et al., 2012).

8 Conclusion and recommendations

In comparison to chemical fertilizers, biochar has a significantly positive impact on soil fertility and crop production while minimizing adverse environmental effects. Furthermore, it contributes to environmental improvement through carbon sequestration, GHG reduction, and the management and mitigation of organic pollutants and toxic metals. Biochar fosters the proliferation of beneficial soil microbial fauna, enhancing overall soil quality. Notably, it can replace chemical fertilizers due to its slow-release nutrient properties and cost-effectiveness, making it a sustainable alternative. However, it's essential to acknowledge the potential drawbacks associated with its application. Harnessing the full potential of biochar in agriculture, particularly in developing countries, requires a multifaceted approach encompassing research, education, policy support, and collaboration. To begin with, there is a crucial need for investment in research and development to enhance biochar production technology. This involves improving the efficiency, scalability, and cost-effectiveness of production methods to make biochar more accessible to farmers. Simultaneously, initiatives to promote and educate farmers about the benefits of biochar are essential. Extension services, workshops, and demonstration farms can serve as effective platforms for disseminating knowledge and showcasing best practices in biochar integration. Moreover, integrating biochar production into existing organic waste management systems presents an opportunity to utilize agricultural and organic residues effectively, reducing waste while producing a valuable agricultural input. Collaboration between researchers, farmers, policymakers, and industry stakeholders is paramount for advancing the adoption of biochar. Research into the specific properties of different types of biochar and their effects on soil fertility could lead to the development of tailored biochar products for different soil types and crops. To ensure biochar benefits reach smallholder farmers, it is essential to promote low-cost, accessible pyrolysis technologies that convert crop residues into biochar on-site. Training through agricultural extension services, farmer field schools, and demonstration plots can build local capacity for biochar application. Community-based models, such as cooperatives or rural entrepreneurs, can facilitate biochar production and distribution at the village level. These approaches, combined with tailored agronomic guidance, will help integrate biochar into existing farming systems, enhancing soil health, reducing input costs, and improving resilience to climate variability. Thus, by combining scientific insight with grassroots implementation and supportive policy environments, biochar can serve as a transformative technology for regenerative agriculture. Such efforts will not only improve soil health and agricultural productivity but also contribute significantly to global goals on climate change mitigation and sustainable development.

Author contributions

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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