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Biochar as an Agrifood Innovation: Evidence and Lessons for Integration into Agricultural Landscapes

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The authors

Tosin Somorin, International Water Management Institute (IWMI), Accra, Ghana
Chukwuebuka Akanno, University of Strathclyde, Glasgow, United Kingdom
Charity Osei-Amponsah, IWMI, Accra, Ghana
Solomie Gebrezgabher, IWMI, Accra, Ghana
Walter Mupangwa, IWMI, Sri Lanka, Colombo
Noah Adamtey, IWMI, Accra, Ghana
Eric G. Nartey, IWMI, Accra, Ghana
Richard Lord, Teesside University, Middlesbrough, United Kingdom
Chris Ennis, Teesside University, Middlesbrough, United Kingdom
Xiaolei Zhang, University of Strathclyde, Glasgow, United Kingdom
Ashleigh Fletcher, University of Strathclyde, Glasgow, United Kingdom
Leo Lue, University of Strathclyde, Glasgow, United Kingdom
Jun Li, University of Strathclyde, Glasgow, United Kingdom

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Front cover photograph: AI-generated image illustrating a biochar production facility with diverse biochar products derived from agricultural waste. *Source:* Anna Ivleva

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ACRONYMS AND ABBREVIATIONS

°C	Degrees Celsius
CEC	Cation exchange capacity
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
GHG	Greenhouse gas
HTC	Hydrothermal carbonization
HTG	Hydrothermal gasification
HTL	Hydrothermal liquefaction
LCA	Life cycle assessment
MSW	Municipal solid waste
N_2O	Nitrous oxide
NPK	Nitrogen, phosphorus, potassium
PTE	Potentially toxic element
SOC	Soil organic carbon
TEA	Techno-economic analysis

SUMMARY

This report examines the contested role of biochar as an agrifood innovation for enhancing soil health, valorizing organic waste and contributing to climate change mitigation and adaptation, in the context of smallholder agriculture in the Global South. While biochar—produced through pyrolysis and related thermochemical processes—offers a strategy for transforming organic waste into a stable, carbon-rich material, the delivery of environmental and agricultural benefits hinges on feedstock type, production conditions, application context and business model arrangements.

Key Takeaways: This report offers the following key takeaways:

Soil health and agronomic performance is context-specific. Biochar can improve nutrient retention, water-holding capacity and soil organic carbon in degraded, sandy or drought-prone soils, where smallholder farmers struggle with nutrient leaching and soil erosion. Reported agronomic outcomes vary, highlighting the importance of context-specific application. This underscores the need for site-specific trials, with clearly defined objectives and a careful matching of biochar type, application rates and soil–crop context, rather than assuming universal benefits.

Not all feedstocks are equal: performance and risks depend on objectives. While lignin-rich, low-ash, low-moisture woody residues often yield stable, carbon-dense biochars suitable for long-term carbon storage or soil structure improvement, they supply few nutrients and can therefore constrain immediate restoration efforts if the objective is the rapid recovery of soil fertility. If the biomass is derived from natural forests rather than organic residues, such feedstock choices risk contributing to deforestation and land-use change, undermining broader sustainability goals. Nutrient-rich organic residues such as manures can provide short-term fertility gains but often contain higher levels of labile carbon, the easily released fraction of organic carbon. This accelerates decomposition in soils and can lead to nutrient imbalances or greenhouse gas emissions. More so, sewage sludge and municipal waste may help address waste diversion objectives but can introduce heavy metals or persistent pollutants in the absence of stringent pre-treatment measures. Matching feedstock to a clear objective is therefore essential, as it directly influences both agronomic performance and environmental risk.

Technology choices shape outcomes: trade-offs between objectives, performance and risks. The type of technology used for the production of biochar strongly influences its yield, quality and carbon footprint. Slow pyrolysis remains the most accessible and cost-effective option for smallholder or community contexts, aligning with the objective of decentralization. However, it produces variable-quality biochar and often has low energy returns. Gasification can achieve higher efficiencies or tailored properties, but is capital-intensive, energy-demanding and largely viable only when linked to premium markets. Hydrothermal carbonization allows wet feedstocks to be processed without drying, expanding feedstock options, but requires high-pressure equipment and is inaccessible in most low- and middle-income country (LMIC) settings. Ultimately, the choice of technology must be guided by the objective—whether prioritizing low-cost soil restoration, long-term carbon storage, or energy recovery, since each pathway carries different agronomic benefits, financial viabilities, and environmental risks.

Climate co-benefits are context-dependent and contested. Biochar is widely promoted as a nature-based solution for both climate change mitigation and adaptation. It can sequester carbon in stable forms, reduce nitrous oxide (N_2O) and methane (CH_4) emissions, and improve drought resilience by enhancing soil water retention. These outcomes align with the objectives of long-term carbon storage or climate-resilient farming. However, performance varies. Certain biochars—especially those with high labile (easily decomposable) carbon—accelerate the decomposition of existing soil organic matter and increase carbon dioxide (CO_2) or N_2O emissions. Large-scale demand for feedstock can also divert biomass from other uses or incentivize deforestation, undermining net climate gains. Moreover, the slow accrual of carbon and soil fertility benefits poses challenges in insecure land tenure settings, where farmers lack the guarantee of reaping long-term rewards. In such contexts, adoption incentives are low, and market-driven demand for feedstocks may drive land grabbing or displacement, undermining livelihoods. Adaptation benefits are not universal: in alkaline or sandy soils, biochar can increase pH or hydrophobicity, leading to maladaptive outcomes that reduce crop performance rather than improve it. Ensuring climate-positive outcomes, therefore, requires matching technology and feedstock choices to explicit objectives, supported by robust life cycle assessments and tenure safeguards. Without these, biochar’s climate role risks being undermined by both biophysical uncertainties and social inequities.

1

INTRODUCTION

Agrifood landscapes face growing challenges from the dual pressures of feeding a rising global population and coping with climate change. Addressing these demands calls for resilient and sustainable farming systems. Yet, many current practices—such as intensive monocultures, extractive land use and heavy agrochemical use—prioritize short-term gains over long-term viability (FAO 2017; Mbow et al. 2019; FAO and UNFCCC 2024). While these approaches have significantly boosted food production and yields, they have also contributed to deforestation, overgrazing and excessive tillage, resulting in soil degradation, erosion and the loss of organic matter. These harmful practices are disrupting soil ecosystems, contaminating water sources, aggravating climate impacts and reducing the resilience of farming systems. Global food systems are already, directly and indirectly, responsible for 21%–37% of total anthropogenic greenhouse gas emissions, primarily driven by unsustainable production and land-use practices (FAO 2017). The consequences are especially severe for smallholder farmers—who form the backbone of global food production—as they face greater risks of crop failure, economic instability and loss of livelihoods.

One innovation that can potentially enable the restoration and resilience of agricultural landscapes is biochar—a carbon-rich material produced through the controlled thermochemical conversion of organic biomass under low-oxygen conditions (Tomczyk et al. 2020). Evidence suggests that when biochar is applied appropriately to soils, it can improve soil structure (El-Naggar et al. 2018), enhance water retention (Liu et al. 2017a; Thao et al. 2023), and boost microbial activity and nutrient availability (Ding et al. 2016), thus helping to reverse land degradation. In addition to improving soil fertility and agricultural productivity, biochar can contribute to climate mitigation by sequestering carbon and reducing greenhouse gas emissions (Matovic 2011; Jiang et al. 2016). For smallholder farmers, this offers a scalable and locally adaptable solution to enhance both soil health and livelihood resilience, making it a vital, climate-smart agrifood innovation for multifunctional landscapes. The capacity of biochar to increase water retention can also help reduce irrigation needs, particularly in drought-prone regions facing erratic rainfall patterns. Beyond its agricultural benefits, biochar supports sustainable resource recovery by transforming agricultural and organic waste into valuable soil amendment, reducing the accumulation of waste and closing nutrient loops. It also presents economic opportunities for small-scale farmers by enabling them to generate additional income streams and participate in bioeconomy markets—ultimately contributing to sustainable development and actions that enhance climate mitigation, climate adaptation and the resilience of local communities (Scholz et al. 2014; Bhattacharyya et al. 2024; Naeem et al. 2024).

However, despite its promising potential, biochar is not a one-size-fits-all solution, and its effectiveness depends on various contextual factors. A few studies have cautioned against its universal application, as the impacts of biochar use can vary, depending on soil type, feedstock material, pyrolysis conditions and application rates (Semida et al. 2019). In some cases, biochar may fail to improve soil quality and even have unintended adverse effects, such as altering soil pH unfavorably or immobilizing specific nutrients, making them less available to plants (Brtnicky et al. 2021; Kalu et al. 2021). Additionally, the long-term impacts of large-scale biochar application on soil ecosystems and biodiversity are still poorly understood (Woolf et al. 2018; Yin et al. 2022).

Other critical considerations in biochar innovation are its scalability, accessibility and broader sustainability. While small-scale production can effectively valorize waste, large-scale operations demand significant infrastructure, energy inputs and sustainable biomass supply—posing risks of deforestation or resource competition, if poorly managed. Economic barriers also limit adoption among smallholder farmers, who may lack the technical capacity or financial means to use biochar effectively. Beyond these logistical and financial hurdles, social and gender inequities often restrict access to land, labor and decision-making roles in biochar initiatives, sidelining women, youth and marginalized groups. Meanwhile, enabling environments remain weak, with limited regulatory frameworks, market incentives and inclusive financing models to support adoption at scale. These constraints highlight the need for context-sensitive, equity-oriented approaches to ensure that biochar contributes meaningfully to sustainable agriculture and climate resilience.

This report presents biochar as a strategic agrifood innovation for advancing multifunctional landscapes and

Biochar application in a vegetable garden. Photography by Toni Jardon

outlines the key mechanisms through which it enhances soil health, supports climate adaptation and mitigation, and contributes to circular bioeconomy transitions. Drawing on empirical studies, the report provides a balanced, evidence-based analysis of biochar's benefits and limitations, including considerations of economic viability, scalability, and the enabling policy and institutional frameworks required for its integration into sustainable food systems. In terms of its structure, the report begins by outlining the scientific foundations of biochar innovation, exploring its contributions to soil fertility, agricultural productivity and climate mitigation, adaptation and resilience. It then presents targeted recommendations in the realms of policy, research and implementation to support adoption and scaling up, reinforced by illustrations or case studies that highlight pathways for the sustainable integration of biochar into agrifood systems.

1.1. Biochar as a Circular Bioeconomy Solution

Biochar presents a compelling win-win strategy for sustainable agrifood waste management within circular bioeconomy frameworks (Figure 1), which aim to close resource loops and minimize environmental impacts (Facchini et al. 2023). Through the thermochemical conversion of organic residues into a stable, carbon-rich material, biochar enables the integration and cascading use of diverse organic waste streams, maximizing the value of biomass for multiple functions across the agrifood system. This sequential approach embodies the key principles of a circular economy: (i) eliminate waste and pollution; (ii) circulate products and materials at their highest value; and (iii) regenerate natural systems (Velenturf and Purnell 2021). It addresses the dual challenges of waste disposal and the need for soil regeneration (Morseletto 2020; Cheng et al. 2022), providing the opportunity to recycle nutrients and supporting long-term soil health and carbon sequestration.

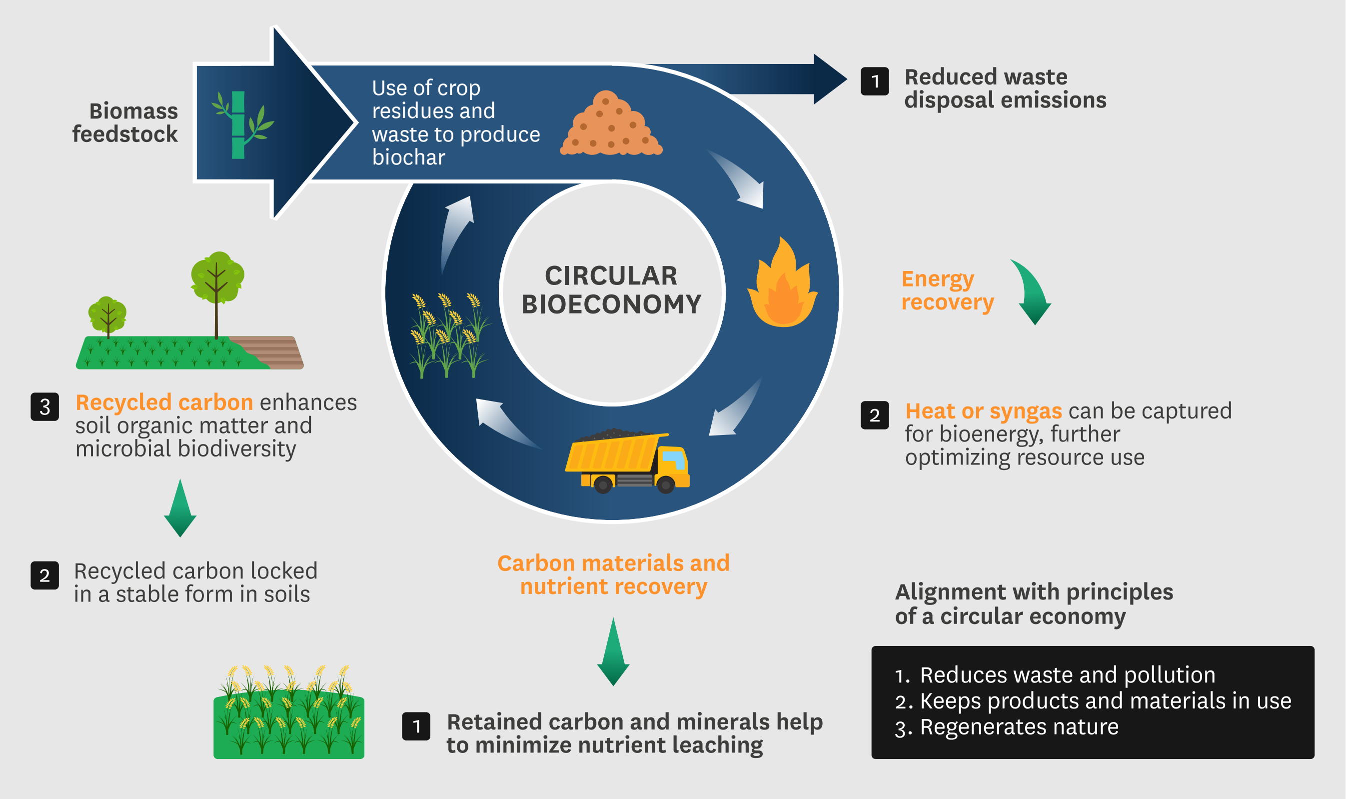

FIGURE 1. Biochar as a circular bioeconomy solution.

Source: Authors

The versatility of biochar as a waste valorization pathway does not imply that every type of waste is suitable for conversion to biochar. The feasibility of converting a given waste stream into high-quality biochar depends heavily on factors such as feedstock composition and contamination levels (Shahid et al. 2022). For instance, edible food waste—like slightly bruised fruits or misclassified vegetables—may be more sustainably repurposed for direct human consumption, a concept often described as food rescue or upcycling (Thorsen et al. 2023). Utilizing organic waste, especially leftover fruits and vegetables, as feed for animals is an effective and eco-friendly approach to minimizing waste, cutting down operational and production costs, and enhancing animal well-being. Different technologies, such as wet, dry and fermentation methods, can be employed to safely transform these wastes into nutritious animal feed (Hasan and Lateef 2024), delivering direct social and economic benefits without the need for energy-intensive thermal processes. Additionally, organic waste that contains heavy metals, synthetic residues or pathogenic organisms requires stringent pre-treatment to avoid transferring any pollutants into soils or food systems (Chen et al. 2015; Ndirangu et al. 2018). Therefore, there is a need for the careful selection of feedstock and processing control to ensure the environmental and agronomic benefits of biochar are not compromised.

The following section provides an overview of the suitability of different organic waste streams for biochar production. It focuses on how feedstock characteristics, including moisture level, the presence of contaminants and structural composition, determine the quality, safety and functional properties of the resulting biochar. By analyzing compositional attributes across diverse feedstocks, including agricultural residues, food processing by-products, animal manures and municipal organic waste, waste types can be more effectively matched with appropriate end-use applications.

2

VALORIZATION OF ORGANIC WASTE INTO BIOCHAR

Biochar can be produced from a diverse range of organic waste feedstocks, including food waste, woody biomass, municipal solid waste (MSW) and sewage sludge (Figure 2). Each of these feedstocks has unique structural and chemical compositions, as well as different levels of contaminants (El Barkaoui et al. 2023; Ahmed et al. 2024). For example, woody biomass (including forestry and agricultural residues) is typically rich in lignin and low in moisture and ash, making it ideal for producing high-quality, stable biochar with a high carbon content and large surface area (Tomczyk et al. 2020). Such characteristics make lignin-rich feedstocks particularly suitable for applications such as carbon sequestration, soil enhancement and pollutant adsorption (Ahmed et al. 2024). In contrast, non-woody biomass feedstocks such as food waste, MSW and sewage sludge often have higher moisture levels and a greater load of inorganic and organic contaminants, including heavy metals and persistent organic pollutants such as polycyclic aromatic hydrocarbons (PAHs), dioxins and polychlorinated biphenyls (PCBs) (Xiang et al. 2021). These impurities can significantly compromise the safety of the resulting biochar and require careful pre-treatment of feedstock or post-treatment of biochar to prevent environmental risks (Li and Skelly 2023; Ahmed et al. 2024). Table 1 provides a comparative overview of common biochar feedstocks, highlighting how their structural composition influences the quality, stability and functionality of the biochar produced.

FIGURE 2. Typical feedstocks and organic waste streams suitable for biochar and hydrochar production, including (from top left): (a) coffee husks, (b) forest residues, (c) wood shavings, (d) food waste, (e) livestock manure with or without agricultural residues, and (f) sugarcane bagasse.

TABLE 1. Influence of common biochar feedstocks on biochar quality.

Parameter	Category	Palm shell	Sugarcane bagasse	Rice husk	Coconut shell	Wheat straw	Cotton stalk	Olive pomace	Coconut fiber
Biomass properties*									
Carbon, C (%)[a]	Feedstock	53.1	45.9	42.5	52.6	48.1	46.0	49.2	44.7
Hydrogen, H (%)[a]	Feedstock	7.1	6.7	6.5	6.2	6.8	7.6	6.8	7.5
Nitrogen, N (%)[a]	Feedstock	0.7	0.9	1.3	2.0	1.8	5.6	2.0	0.8
Sulphur, S (%)[a]	Feedstock	N/A-	0.2	N/A-	N/A--	N/A--	N/A-	N/A--	N/A-
Oxygen, O (%)	Feedstock	46.8	59.2	46.0	53.1	49.0	54.5	45.8	61.8
H/C	Feedstock	1.6	1.7	1.8	1.4	1.7	2.0	1.6	2.0
O/C	Feedstock	0.7	1.0	0.8	0.8	0.8	0.9	0.7	1.0
Moisture (%)	Feedstock	3.0	5.8	5.7	5.7	5.6	6.1	5.7	7.5
Volatile carbon (%)[b]	Feedstock	74.1	85.3	80.9	77.2	85.9	93.1	80.5	85.3
Fixed carbon (%)[b]	Feedstock	25.9	14.7	19.1	22.8	14.1	6.9	19.5	14.7
Ash (%)	Feedstock	2.0	4.4	19.6	0.6	7.9	4.2	4.5	5.3
HHV (MJ/kg)	Feedstock	19.9	14.6	15.5	17.2	17.3	16.8	18.2	14.9
Biochar properties**									
Biochar yield (%)	Biochar	31.8	27.7	39.0	28.2	30.3	28.0	30.5	30.8
Oil yield (%)	Biochar	50.3	50.3	33.5	43.7	50.0	53.6	44.8	47.8
Gas yield (%)	Biochar	17.9	23.6	21.8	28.1	17.6	18.4	29.2	25.1
Carbon, C (%)[a]	Biochar	90.6	88.6	54.5	93.9	75.3	83.2	71.8	82.6
Hydrogen, H (%)[a]	Biochar	2.8	2.8	2.1	3.0	2.6	3.2	2.8	2.7
Nitrogen, N (%)[a]	Biochar	0.9	1.3	1.1	0.4	1.0	4.8	1.9	2.4
Sulphur, S (%)[a]	Biochar	N/A-	0.1	N/A-	N/A--	0.2	0.1	N/A--	N/A--
Oxygen, O (%)	Biochar	7.9	13.7	5.4	2.6	4.5	14.2	11.6	12.8
H/C	Biochar	0.4	0.4	0.5	0.4	0.4	0.5	0.5	0.4
O/C	Biochar	0.1	0.1	0.1	0.0	0.0	0.1	0.1	0.1
Moisture (%)	Biochar	2.2	3.7	5.7	7.1	8.1	8.5	10.0	10.4
Volatile carbon (%)[b]	Biochar	11.5	30.1	13.9	8.1	21.2	28.8	20.9	25.1
Fixed carbon (%)[b]	Biochar	88.5	69.9	86.1	91.9	78.8	71.2	79.1	74.9
Ash (%)	Biochar	6.7	13.0	47.0	4.1	23.4	9.5	18.1	13.5
HHV (MJ/kg)	Biochar	33.6	30.1	19.3	33.7	26.5	31.4	24.1	26.6
Pore volume (cc/g)	Biochar	0.2	0.2	0.1	0.2	0.0	0.1	0.0	0.0
Surface area (m2/g)	Biochar	220.0	149.1	114.9	222.5	6.3	121.2	1.2	23.2
pH	Biochar	6.1	8.6	9.9	8.5	11.6	10.3	10.5	9.6
Recalcitrance index, R_{50}	Biochar	0.6	0.5	0.5	0.6	0.5	0.5	0.6	0.5
Carbon sequestration (%)	Biochar	32.5	27.3	26.0	28.7	21.3	23.8	24.5	26.8

Source: Windeatt et al. 2014

Notes: ***Biochar production conditions**: Each kind of biomass was ground and sieved to 1.4–2.8 millimeters (mm) for most; some (for example. coconut shell, palm shell) ranged from 3.35 mm to 10 mm. Biochars were produced in a laboratory-scale, fixed-bed slow pyrolysis reactor (250 mm length × 30 mm internal diameter) at a heating rate of 5°C/min and nitrogen atmospheric conditions with a flow rate of 200 ml/min, and at a peak temperature of 600°C for 1 hour.

****Description of biochar characteristics:** Pore volume (cc/g) is the total internal void space within the biochar per gram of material, indicating its capacity to retain water or adsorb substances. Surface area (m^3/g) is the total surface area available per gram of biochar, which influences its adsorption properties. Char yield (%) is the proportion of the original biomass mass that remains solid biochar after pyrolysis. Oil yield (%) is the percentage of biomass converted into liquid condensates during pyrolysis. Gas yield (%) is the fraction of the biomass transformed into gaseous products (for example, carbon monoxide, carbon dioxide, methane) during pyrolysis. R_{50} is a metric that compares the temperature at which 50% of the biochar oxidizes to graphite. It indicates the stability and degradation potential of biochar in soils. Carbon sequestration (%) is a theoretical estimation of the share of the original feedstock carbon that remains stored long term in the biochar after application to soils. H/C and O/C ratios are atomic ratios of hydrogen to carbon and oxygen to carbon, respectively. Lower values indicate higher aromaticity and stability of biochar.

[a]Elemental composition; [b]Proximate composition

2.1. Influence of Feedstock Composition on Biochar Quality

The structural composition of the organic waste, particularly the relative proportions of cellulose, hemicellulose and lignin in woody biomass, significantly affects the yield, physicochemical properties and functional characteristics of the resulting biochar. This composition also influences the fate of carbon (that is, how carbon behaves) in the final biochar and its potential applications. For example, hemicellulose decomposes at lower temperatures (220°C–315°C), whereas cellulose breaks down at intermediate temperatures (300°C–400°C). These feedstocks yield more volatile compounds, including light oxygenates, acetic acid, furfural, levoglucosan and water, leading to more gases and bio-oil. Their biochars tend to have lower stability and less porosity, though they can offer higher oxygen-containing functional groups that are useful in a soil remediation context. In contrast, lignin decomposes over a broader temperature range (150°C–900°C), resulting in biochar that is rich in aromatic carbon and thermally stable (Waters et al. 2017; Amalina et al. 2022). Such biochar has higher carbon content, greater porosity, higher surface area, and enhanced stability and adsorptive properties, making it ideal for soil improvement and pollutant adsorption.

The chemical composition of feedstocks, particularly the proportions of volatile matter and fixed carbon, plays a fundamental role in determining the quality and quantity of the biochar produced. Fixed carbon refers to the solid carbonaceous residue that remains after the volatile compounds are released during pyrolysis. A high fixed carbon content is generally associated with biochars that have greater thermal stability, higher porosity and enhanced adsorption capacity, making them suitable for applications such as pollutant removal, carbon sequestration and long-term soil amendment (Amalina et al. 2022; Ahmed et al. 2024). In contrast, volatile matter, which includes organic compounds that vaporize under heat, contributes primarily to forming bio-oil and syngas rather than the solid char fraction. Feedstocks with high volatile content tend to produce lower biochar yields and generate biochars with less structural integrity and reduced carbon stability (Nasrullah et al. 2022). The ratio of volatile matter to fixed carbon also influences the reactivity and surface chemistry of biochar. For example, biochars derived from feedstocks with moderate volatile content and processed at lower pyrolysis temperatures tend to retain more oxygen-containing functional groups, which enhance their nutrient exchange capacity and microbial compatibility in soil applications (Mishra et al. 2023). On the other hand, feedstocks rich in fixed carbon, such as woody biomass and lignin-dense materials, yield biochars with more aromatic structures, lower reactivity and greater durability, traits desirable for carbon-rich amendments and contaminant immobilization (El Barkaoui et al. 2023; Ahmed et al. 2024).

Moisture content also plays a critical role and influences both the efficiency and quality of biochar production. High-moisture feedstocks, including food scraps, animal manure and sewage sludge, can be used for biochar production, but the energy needed for drying the feedstock reduces the thermal efficiency of the process. This not only increases operational costs but also results in biochar with less structural integrity and lower fixed carbon content. In contrast, dry, lignocellulosic materials produce more stable and carbon-rich biochar under the same conditions (Ahmed et al. 2024). The presence of contaminants in feedstocks, particularly in MSW, directly affects the safety of the biochar. These materials often carry heavy metals such as cadmium (Cd), lead (Pb) and mercury (Hg), plasticizers and pharmaceuticals, which can remain in the biochar matrix after production. While certain treatment techniques can enhance biochar's sorptive performance, they do not always eliminate contaminants effectively. Therefore, feedstocks rich in such pollutants must be used with caution, especially when the intended application involves soil amendment (El Barkaoui et al. 2023).

2.2. Biochar Production Methods

Biochar is produced using a variety of thermochemical processes, including pyrolysis, gasification, torrefaction and hydrothermal methods (Figures 3 and 4). These processes convert biomass into a stable, carbon-rich material by applying heat in environments with limited or no oxygen. Each method operates under distinct temperature ranges, heating rates, residence times and pressure conditions, which directly influence the yield, structure and functionality of the resulting biochar.

2.2.1. Pyrolysis

Pyrolysis is a thermochemical process that converts carbon-rich materials into useful products such as biochar, bio-oil and biogas. In essence, pyrolysis is a complex process that involves various chemical reactions occurring inside the heated material, including depolymerization, fragmentation and cross-linking, which occur at specific temperatures (Balogun et al. 2017). These chemical reactions transform the organic waste components into solid, liquid or gaseous products. The solid product is biochar, the liquid is bio-oil and then gases which include carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), hydrogen (H_2) and small amounts of hydrocarbons, collectively known as syngas. Temperature is a critical factor that influences product efficiency in this process (Armah et al. 2023), with the process operating in an environment with little or no oxygen (anaerobic conditions) and at moderate-to-high temperatures (between 300°C and 1,200°C) (Borel et al. 2018). The absence of oxygen does not promote waste combustion but instead breaks down the feedstock into smaller molecules as different materials. The product obtained from this process is affected by the temperature used. Generally, when the pyrolysis temperature increases, biochar yield decreases, and more syngas is produced. Lower temperatures, in the range 300°C–700°C, favor the production of more biochar, while the production of biogas and bio-oil occurs more at higher temperatures (above 700°C). Generally, lower pyrolysis temperatures produce higher biochar yields because less organic material is converted into gas and vapor.

Additionally, the agricultural residues often used for pyrolysis comprise three main components, including cellulose, hemicellulose and lignin. These components influence the characteristics of the pyrolysis products because they break down at different temperatures. For example, cellulose starts to break down at 350°C, while lignin requires even higher temperatures (Al Arni 2018). Prolonged heating can further break down the feedstock, but excessively long dwell times, especially at higher temperatures, may reduce yields due to carbon loss.

Different types of pyrolysis reactors are used in biochar production, depending on whether the process is operated under slow, intermediate or fast conditions. Figure 3 illustrates the schematics of various fast pyrolysis reactor configurations commonly used. These include fluidized bed systems (bubbling and circulating), rotating cone and ablative reactors for efficient heat transfer, twin-screw mixers for enhanced solid–gas contact, and vacuum pyrolysis units designed for lower-temperature conversion and improved oil yields (Dahmen et al. 2009). Each configuration offers distinct advantages in heat integration, product selectivity and scalability.

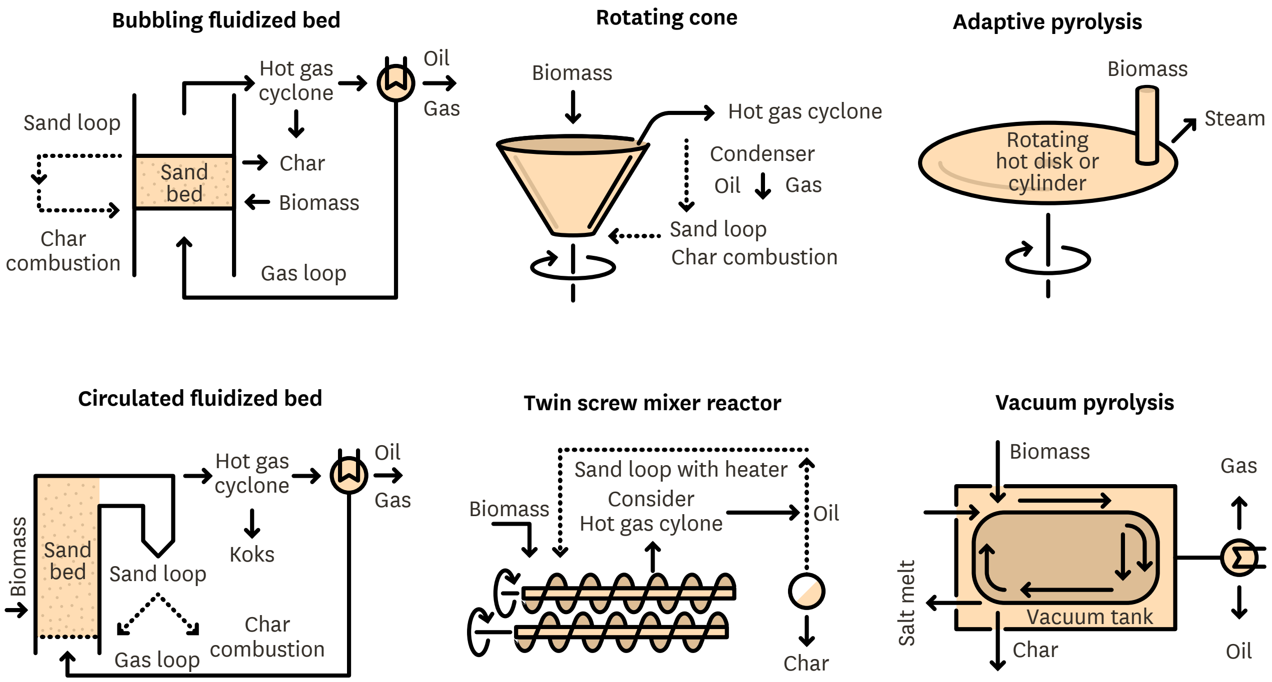

FIGURE 3. Schematics of various fast pyrolysis reactor configurations commonly used.

Note: In the figure, 'Koks' refers to coke.

Slow Pyrolysis

Slow pyrolysis is a conventional process that takes long to complete. Carbon-rich materials are heated slowly, at temperatures ranging between 300°C and 500°C, with a heating rate of 5–7°C per minute (Li et al. 2020), requiring extended hold times of more than 1 hour to allow the reactions to complete (Liu et al. 2015). The slow heating process and long reaction time promote secondary reactions, enabling the formation of more biochar. Although slow pyrolysis produces 35%–45% biochar in the total output as the main product, it also produces some bio-oil (25%–35%) and syngas (20%–30%) (Liu et al. 2015). Therefore, slow pyrolysis is an effective method to generate relatively high biochar yields while still producing some amounts of bio-oil and gas products.

Fast Pyrolysis

Unlike slow pyrolysis, fast pyrolysis is a quick and effective process that converts carbon-rich materials into high quantities of bio-oil, with lower outputs of biochar and syngas (Chang et al. 2021). The process is completed in just a few seconds at temperatures typically above 500°C and heating rates exceeding 300°C per minute, and without oxygen (Armah et al. 2023). Fast pyrolysis yields approximately 60%–75% bio-oil, 15%–20% biochar and 10%–20% syngas (Dai et al. 2017). The high temperatures result in the quick breakdown of the biomass used; however, though some biochar is still produced, it is in much smaller amounts compared to slow pyrolysis because of the short reaction time.

2.2.2. Torrefaction

Torrefaction is a low-temperature pyrolysis process often used as a step in pre-treatment to refine raw biomass for use in energy and chemical technologies, such as gasification (Armah et al. 2023). It operates under anaerobic conditions at temperatures of 200–300°C, with a heating rate of approximately 50°C/min, and residence times of 20–60 minutes, depending on the feedstock and desired product properties. Torrefaction yields 30%–70% of biochar, 5%–15% of liquids and 5%–10% of gases (Sarker et al. 2021). Unlike conventional pyrolysis, torrefaction is primarily used to gently heat biomass and remove some of its moisture and volatile components, without completely breaking it down. This process retains most of the original carbon in a solid, carbon-rich material, also known as torrefied biomass. The process yields a dry, dark material that does not absorb water easily, burns more efficiently due to its higher energy content, is easier to grind and does not break down quickly (Zhang et al. 2022). These modifications make biomass easier to store, transport and utilize in other energy processes, such as gasification. Overall, torrefaction improves the quality of solid biomass more efficiently than slow pyrolysis due to its lower temperatures and shorter residence times, thereby reducing costs.

2.2.3. Gasification

Gasification is a thermochemical process that converts carbon-rich materials into primarily syngas, comprising carbon monoxide, carbon dioxide, methane, hydrogen and small amounts of hydrocarbons (Dasappa and Shivapuji 2022). These gases can be used as fuel sources. This process occurs at high temperatures, between 700°C and 900°C, in the presence of limited amounts of oxygen or other gasifying agents, such as air, steam and carbon dioxide. The main product, syngas, is about 85%; the rest comprises about 10% biochar and 5% liquid products (Bisht and Thakur 2020).

2.2.4. Hydrothermal Processes

One major challenge of pyrolysis is that it requires dry biomass before processing, which can significantly increase operational costs due to the extra drying stage. However, when dealing with wet waste materials, like municipal solid waste, hydrothermal processes offer a more efficient alternative. Hydrothermal conversion processes create hydrochars, named after hydrothermal processes, where biomass is heated under high temperature and pressure. There are three types of hydrothermal processes:

Hydrothermal Carbonization

Hydrothermal carbonization (HTC) is a thermochemical process that involves mixing biomass with water. HTC uses hot, pressurized water to break down the biomass, producing hydrochar, as well as some gases and water-soluble by-products (Hoekman et al. 2011). HTC is carried out at 180–260°C and 2–6 megapascals (MPa) for 30–240 minutes, producing a 40%–60% hydrochar yield with low surface area, high energy content and an oxygen-rich composition, that is less stable than biochar from pyrolysis (Wang et al. 2025). The hydrochar is separated from the liquid by filtration and then dried.

Hydrothermal Liquefaction

Hydrothermal liquefaction (HTL) is a thermochemical process that converts wet biomass into biocrude oil under high temperature and pressure. The water in the system acts as a solvent, reactant and catalyst, and the process uses higher temperatures (280–360°C) and pressure (5-20 MPa) than hydrothermal carbonization to break wet biomass into biocrude oil and chemicals (Ponnusamy et al. 2020). HTL can process various feedstocks, including algae, sewage sludge and agricultural residues. The main outputs are an aqueous phase, gas, a small amount of solid residue and biocrude, which can be further processed into renewable fuels.

Hydrothermal Gasification

Hydrothermal gasification (HTG) is a thermochemical process that converts wet biomass into syngas (hydrogen-rich gas), which is useful for energy production. It operates at high temperatures (typically 373–700°C) and high pressure (22–30 MPa). It utilizes water in its supercritical state (above 374°C and 22.1 MPa) to convert biomass primarily into gaseous products (Wang et al. 2021). In this state, water behaves as a unique solvent and reaction medium, enabling a rapid breakdown of the biomass. The hydrochar yield in HTG is typically low because the process conditions favor a complete gasification of the biomass used, with hydrochar yields decreasing as the temperature increases.

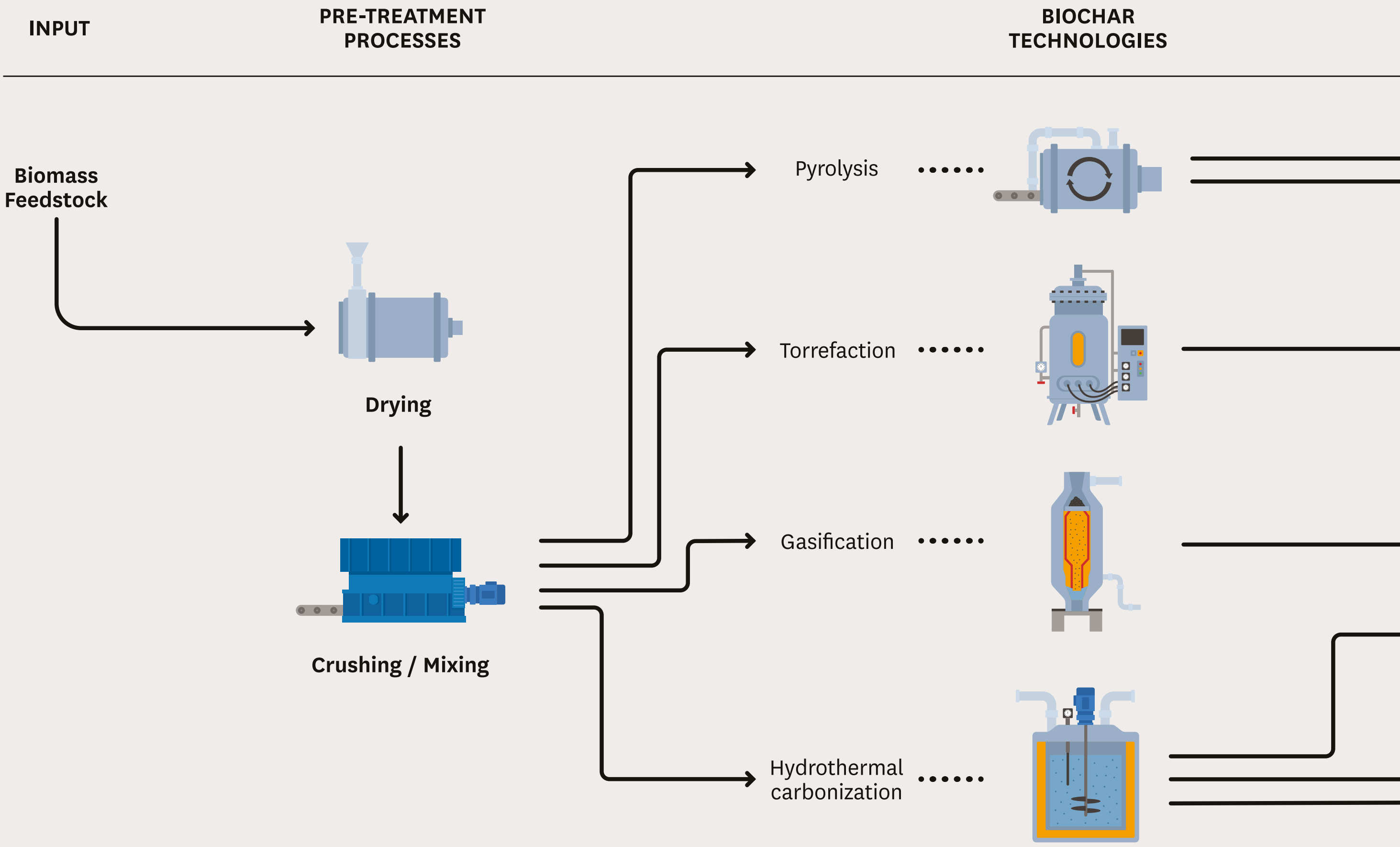

FIGURE 4. Types of biochar technologies, process conditions and properties.

Data sources: Dai et al. 2017; Borel et al. 2018; Ponnusamy et al. 2020; Sarker et al. 2021; Wang et al. 2021; Armah et al. 2023

Potato fields in an agricultural landscape.
Photography by Andrii Yalanskyi

TECHNOLOGY VARIANT	PROCESS CONDITIONS	BIOCHAR YIELD	BIOCHAR PROPERTIES
Slow Pyrolysis	Temperature: 500-700°C Heating rate: 300°C/min	15-20%	High porosity and stability due to enhanced carbon retention and structural changes
Fast Pyrolysis	Temperature: 300-600°C Heating rate: 5-7°C/min	35-45%	Low stability and porosity
	Temperature: 200-300°C Heating rate: 50°C/min	30-70%	High energy content but less stable and less porous than pyrolysis biochar
	Temperature: 700-900°C	~10%	High surface area and porosity, but lower carbon content than pyrolysis biochar
Hydrothermal carbonization	Temperature: 180-260°C Pressure: 2-6 MPa Tine: 30-240 min	40-60%	Low surface area, higher energy content. More oxygen-rich and less stable than pyrolysis biochar
Hydrothermal liquefaction	Temperature: 280-360°C Pressure: 5-20 MPa Tine: 15-60 min	20-40%	Low surface area, and porosity
Hydrothermal gasification	Temperature: 373-700°C Pressure: 22-30 MPa	5-15%	High surface area and porosity, enhancing absorption capacity

2.3. Influence of Process Conditions

All the above production methods have defined operating ranges for temperature and residence time, which critically shape the yield and physicochemical properties of the resulting biochar, including pH, surface area, pore volume, elemental composition and the presence of active functional groups. Higher temperatures (typically above 500°C) decrease overall biochar yield and increase gas production, as more volatile matter is released at elevated temperatures (Amalina et al. 2022; Mishra et al. 2023). This enhances biomass properties such as surface area, porosity and aromaticity, traits associated with improved structural stability and adsorption capacity (El Barkaoui et al. 2023; Mishra et al. 2023; Ahmed et al. 2024). However, these elevated temperatures also reduce the retention of surface functional groups and nutrients (Ahmed et al. 2024), often resulting in lower cation exchange capacity (CEC)[1] and diminished performance in soil fertility applications. Conversely, biochars produced at lower temperatures (300–450°C) tend to retain more oxygenated functional groups and nutrient elements, contributing to higher CEC, greater reactivity, and better support for microbial and plant-soil interactions (Mishra et al. 2023). Residence time further modulates these effects—longer durations at moderate temperatures favor more complete carbonization and improve biochar stability, while overly prolonged exposure at high temperatures can degrade beneficial surface functional characteristics (Amalina et al. 2022). On the other hand, shorter residence times, such as those used in fast pyrolysis, tend to yield less stable biochars with lower fixed carbon and underdeveloped pore structures (Ahmed et al. 2024). Thus, the combined influence of temperature and residence time is pivotal in optimizing biochar quality for specific environmental or agronomic applications.

Although pressure is not a primary consideration in low-cost or traditional pyrolysis systems, it becomes a critical factor in hydrothermal processes, particularly HTC and HTL, which operate under elevated pressures, ranging up to 45 MPa (Chandraratne et al. 2023). In these systems, the pressure allows biomass to be processed in water without prior drying, enabling the conversion of wet materials into hydrochar. The elevated pressure alters the physicochemical environment, influencing reaction kinetics, molecular rearrangement and the solubility of intermediates. As a result, hydrochars produced under high pressure tend to have lower surface area and porosity. However, they may retain more oxygen-containing functional groups, contributing to higher CEC and surface reactivity. High-pressure methods are less accessible for small-scale or decentralized applications due to greater complexity of equipment needed and the higher energy costs. For most low-cost biochar production scenarios, processes like slow pyrolysis—which operate at ambient pressure—remain more feasible and appropriate despite the lower control over specific product characteristics. Thus, while pressure has important implications for biochar quality in engineered systems, its practical relevance depends heavily on scale, access to technology and moisture content of the feedstock.

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[1] A measure of a soil's ability to hold and exchange positively charged ions (cations) such as calcium, magnesium, potassium and ammonium. Higher CEC indicates greater nutrient-holding capacity and enhanced buffer against nutrient loss.

3

ROLE OF BIOCHAR IN IMPROVING AGRICULTURAL SOILS

Biochar has emerged as a versatile soil amendment with unique physical, chemical and biological properties that can enhance soil health (Figure 5). Its role extends beyond basic soil conditioning, contributing to nutrient cycling, carbon sequestration and pollutant mitigation, making it a valuable tool in climate-resilient and circular agrifood systems. This section outlines the mechanisms through which biochar interacts with soil systems to deliver these benefits, particularly its contributions to water and nutrient retention, microbial activity and organic carbon stabilization.

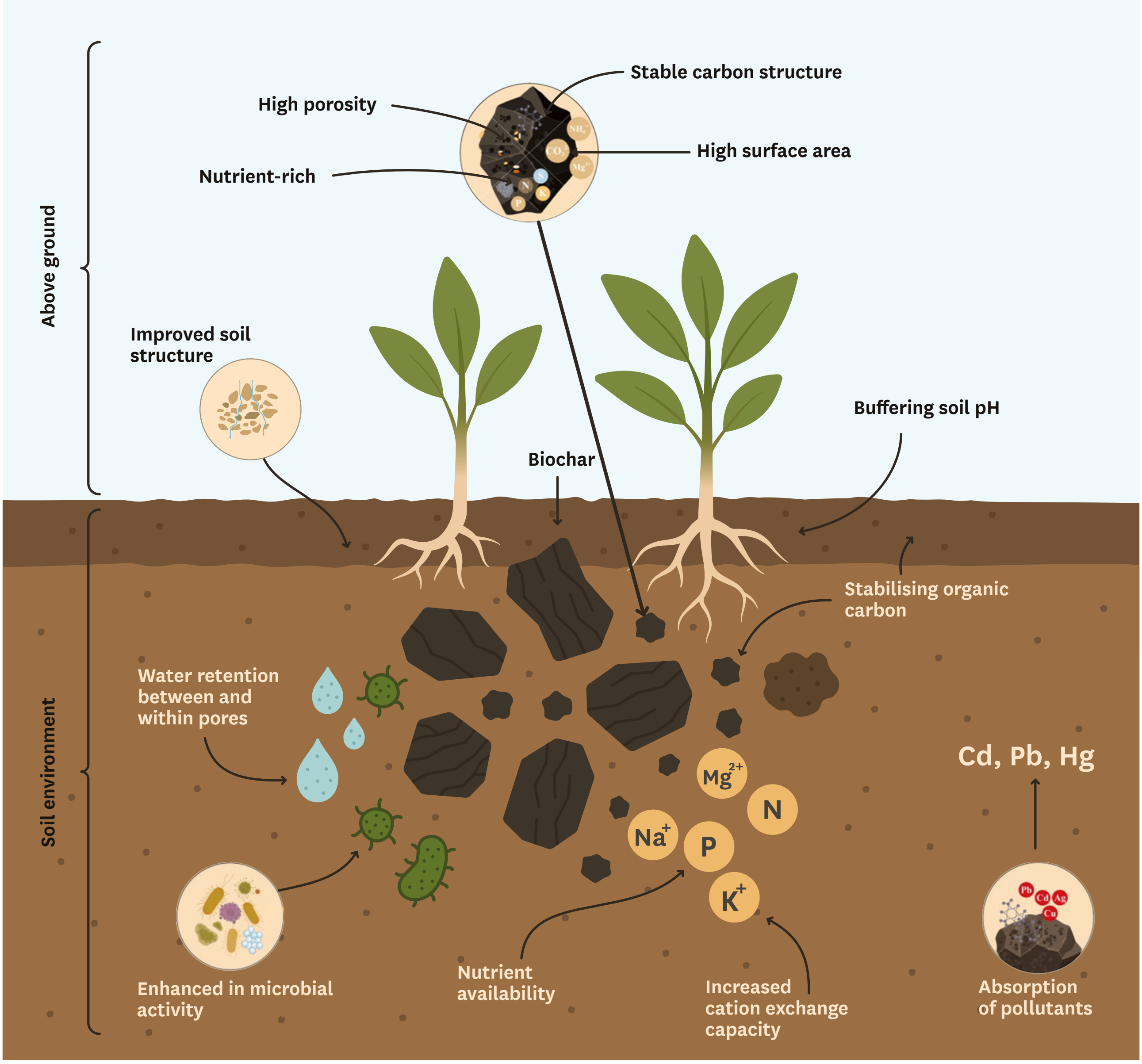

FIGURE 5. Multifunctional benefits of biochar in soil systems.

Source: Authors

3.1. Improving Soil Health and Fertility

Biochar is characterized by a high surface area, significant porosity and well-distributed pore sizes (Lehmann and Joseph 2015; Shakya and Agarwal 2020). These structural features are influenced by the feedstock type and pyrolysis temperature, with higher temperatures typically increasing surface area and microporosity (Downie et al. 2009). During pyrolysis, volatile compounds are released as gases, creating a porous, honeycomb-like structure that further enhances surface area. Smaller particle sizes and uniform pore distribution improve contact between the biochar and the soil, facilitating nutrient exchange and microbial colonization (Mukherjee et al. 2011). Collectively, these characteristics enhance soil aeration, moisture and nutrient retention, adsorption capacity and microbial activity, especially in coarse-textured soils (Glaser et al. 2002; Yuan and Xu 2011).

3.1.1. Improving Nutrient Retention

Biochar also enhances soil CEC by increasing surface negative charges, which attract and retain nutrient cations such as ammonium, potassium, calcium and magnesium, while releasing hydrogen ion to balance soil charge, thereby improving nutrient retention, reducing leaching and enhancing the uptake of nutrients by plants (Lehmann and Joseph 2015; Palansooriya et al. 2019a; Seleiman et al. 2021). This capacity improves over time due to surface oxidation and the formation of functional groups such as carboxyls and phenolics (Cheng et al. 2006; Liang et al. 2006). CEC is also influenced by feedstock type, pyrolysis conditions and soil properties (Mukherjee et al. 2011; Yuan and Xu 2011; Suliman et al. 2016). Generally, lower pyrolysis temperatures (300–450°C) yield biochars with higher CEC due to the preservation of functional groups, while higher temperatures reduce CEC.

3.1.2. Enhancing Nutrient Solubility and Availability

Soil pH affects the mobility and availability of different nutrients and chemical elements in the soil. Biochar is generally alkaline, and its pH increases with higher pyrolysis temperatures due to the loss of acidic functional groups and the accumulation of basic oxides and inorganic elements (Beesley et al. 2015; Shakya and Agarwal 2020; Singh et al. 2020). The pH also depends on the feedstock: lignin-rich sources such as nut shells produce biochar with a pH of around 8, while manure-, algae-, and waste-derived biochars can reach pH levels near 9.5 (Aller 2016). Biochar improves nutrient solubility indirectly by modifying soil pH and buffering capacity. In acidic soils, its alkaline nature (pH 7–9) raises the pH, creating a more favorable environment for the solubility and availability of essential nutrients such as phosphorus (P), calcium (Ca) and magnesium (Mg), which are often limited under low pH conditions. Biochar contributes to phosphorus availability in soils through acting as a direct source of phosphorus, altering soil pH, modifying P adsorption–desorption dynamics and promoting phosphorus-solubilizing microbial activity (Gao and DeLucia 2016). When biochar has been combined with nitrogen fertilizers, it has been shown to enhance fertilizer nutrient use efficiency (NUE) (Huang et al. 2018). For example, combining nitrogen at 50–150 kilograms per hectare (kg ha^{-1}) with biochar at 5–15 kg ha^{-1} increased both nitrogen use efficiency and the yields of maize in sandy soils. Omara et al. (2020) and Ibrahim et al. (2020) reported higher N uptake by plants following application of a biochar–N fertilizer compared to either biochar or N fertilizer alone.

3.1.3. Improving Soil Organic Carbon Stabilization

Soil organic carbon (SOC) is critical in maintaining soil health by enhancing microbial activity, nutrient cycling and water retention (Battaglia et al. 2021). Numerous studies have shown that biochar application can enhance soil carbon content (Diatta et al. 2020). Biochar contributes to SOC stabilization through several mechanisms. First, it provides physical protection to labile organic carbon by adsorbing it onto its porous surface, thus shielding it from microbial decomposition (Jiang et al. 2016). Second, the formation of organo-mineral complexes on biochar surfaces reduces SOC turnover by limiting its bioavailability (Lehmann et al. 2011). Furthermore, the aromatic carbon structure of biochar itself is resistant to microbial degradation, making it a long-term carbon sink in soils (Kuzyakov et al. 2014). Biochar produced at lower pyrolysis temperatures tends to retain a higher content of labile carbon than biochar produced at higher temperatures (Lévesque et al. 2018), indicating the presence of residual organic biomass.

The extent of biochar's effect on the soil depends on the feedstock material, pyrolysis conditions, application rate and soil type (El-Naggar et al. 2018). The extent of biochar's impacts on soil health and productivity is strongly influenced by the type of feedstock and the process conditions used in its production. Feedstock characteristics determine the biochar's chemical composition, nutrient content and structural properties, which in turn affect appropriate application rates and agronomic outcomes. Woody feedstocks typically produce biochars with high carbon content and structural stability but low nutrient levels, making them ideal for long-term carbon sequestration and improving soil structure—though they may require higher application rates or co-application with fertilizers to meet immediate crop nutrient demands. In contrast, biochars derived from nutrient-rich sources such as manure or crop residues contain elevated levels of nitrogen, phosphorus and potassium (NPK). These nutrient-dense biochars can enhance soil fertility, microbial activity and water retention, often at lower application rates due to their immediate nutrient benefits. However, high nutrient levels in such biochars can lead to nutrient imbalances, salt accumulation or leaching—especially in sensitive soils or poor drainage conditions—potentially harming soil microbiota or groundwater quality. Overall, biochar's benefits to the soil are promising but highly context-dependent, requiring clear objectives and tailored application strategies to avoid maladaptive outcomes. Therefore, selecting the appropriate feedstock and tailoring application strategies to specific soil and crop requirements is essential to maximize both the agronomic and environmental benefits of biochar use.

Table 2 provides examples of biochar feedstocks, application rates and effects on soil fertility and crop yields. The findings show that agronomic outcomes vary across sites: while many studies show gains in yield, others report negligible or even adverse effects, including nutrient imbalances, shifts in soil chemistry (for example, pH) or limited crop responses. This variability underscores the importance of site-specific trials, with clearly defined objectives and a careful matching of biochar type, application rates and soil–crop context, rather than assuming universal benefits.

TABLE 2. Effects of biochar feedstock and application rate on soil fertility and crop yields.

Feedstock	Application rate (tonne/ha)	Effect on crops or soil	Reference
Cocoa pod biochar	5	Increase in the yields of maize by 56% compared to un-amended soil	Yeboah et al. 2022
Maize cobs	7.5–10	Significant increase in soil properties (pH, organic carbon, total nitrogen, available phosphorus, and water retention). Correspondingly, crop yields increased by 183% and 176% at application rates of 10 t/ha and 7.5 t/ha, respectively, compared to the baseline of 608 kg/ha	Frimpong et al. 2025
Rice husk + straw	10	Significantly increased growth and wheat yields	Sharma et al. 2025
Groundnut husk	8	Increase in soil fertility and maize yields by up to 218% in Ghana	Abdul-Aziz et al. 2024
Sawdust	15	Significantly improved water holding capacity by 70%–72%; increased growth and yield of sesame to 676 kg/ha compared to the average yield in Nigeria	Eifediyi et al. 2022
Sawdust or rice husk	10	Produced the highest moisture content (10.7% and 10.77%), 36.47% and 35.58% of soil porosity and 50% and 50.6% soil water-filled pore space. In addition, a significant impact on soil chemical (CEC, pH, OC, TN, P, K, Mg, Na) properties	Ndor et al. 2015
Corn husk biochar + corn cobs biochar + inorganic fertilizer (N60P60K0)	15 + 15 + 10	Increased fertility of clayey soil (pH, CEC and nutrient status) and maize growth	
Maize cobs	7.5–10	Increased soil pH, SOC,TN and water retention ability. Greater amaranthus growth and increased yields	Christian 2021

Feedstock	Application rate (tonne/ha)	Effect on crops or soil	Reference
Maize cobs biochar + compost + NPK	Each at 10	Increased yields of maize, okra and cassava	Christian 2021
Poultry manure or swine dung manure	10 or 15	Increased cowpea growth, nodulation and productivity, which is comparable to inorganic P at 30 kg P ha^{-1}	Adekanmbi et al. 2022
Sewage sludge	40	Increased total carbon (TC), TN, available K, and C:N, and decreased soil bulk density (BD) and pH. Variable effects on DOC. Increase in microbial biomass and the proportion of gram-positive bacteria, gram-negative bacteria, fungi and Actinomycetes, along with a decrease in the ratios of groups of bacteria. Produced highest peanuts yields	You et al. 2019

3.2. Promoting Beneficial Microbial Activity

As discussed in sections 3.1–3.3, biochar enhances soil fertility by inducing modifications in both chemical properties (such as soil pH and CEC) and physical properties (such as soil water holding capacity) (Glaser et al. 2002; Jeffery et al. 2011; Chintala et al. 2014; Dai et al. 2017; Cairns et al. 2022). These changes have a direct or indirect impact on soil microbial communities, which are crucial to soil quality and health. The mechanisms behind enhanced soil microbial communities are explained below.

3.2.1. Establishing a Habitat and Microenvironment for Soil Microbial Communities

Biochar's porous structure provides protective habitats and favorable micro-environments for soil microorganisms, particularly bacteria and fungi, by offering refuge from predation and environmental stress (Warnock et al. 2007; Wang and Zhou 2013). Its pores—typically larger than microbial cells of most soil bacteria, fungi and protozoa—facilitate colonization while excluding larger predators such as arthropods (Wong and Ogbonagya 2021). The pore structure of biochar offers protection to both endomycorrhizal and ectomycorrhizal fungi from external environmental stress (Warnock et al. 2007). Biochar surfaces also contain functional groups—hydroxyl, carboxyl and amino—that enhance microbial adhesion and proliferation (Bolan et al., 2023). These functional groups make biochar an effective carrier for microbial inoculants, supporting microbial survival and activity in soil and around roots of plants. Additionally, biochar improves water retention, increases surface area for colonization, and raises soil pH—creating a more favorable environment for microbial processes critical to nutrient cycling, soil fertility and overall ecosystem function (Huang et al. 2023; Sharma et al. 2025). The extent of microbial colonization also depends on the biochar's degree of ageing. Freshly applied biochar can release harmful contaminants (for example, cadmium and lead) into soils, which may inhibit microbial activity and reduce their colonization rate on the biochar (Xiang et al. 2021). In contrast, aged biochar—with reduced contaminant release and more stable surface characteristics—offers a more conducive environment for microbial growth (Mukherjee et al. 2014; Wang et al. 2017). Thus, by modifying both the physical structure and chemical environment of the soil, biochar plays a key role in influencing soil biochemical functions, microbial communities, and the nutrient and carbon cycles, with implications for soil health, water and nutrient availability, and long-term agricultural productivity (Bolan et al. 2023, 2024; Huang et al. 2023).

3.2.2. Promoting Nutrient Availability and Cycling for Microbial Populations

The application of biochar modifies the nutrient composition of soils, subsequently affecting soil microorganisms. It contains nutrients like potassium, magnesium, sodium, nitrogen and phosphorus, which support microbial growth when released into the soil (Rodríguez-Vila et al. 2016). CEC is a crucial indicator of soil nutrient retention and fertility, and is closely linked to the abundance of soil microorganisms and plant growth. Biochar is particularly effective in enhancing CEC in soils with low organic matter (Lehmann 2007; Zhu et al. 2017). Improved CEC resulting from biochar application can increase the presence of nitrogen-fixing bacteria, rhizobacteria, as well as nitrifying and denitrifying bacteria within the soil. This supports plant growth and enhances the ability of plants to manage environmental stressors (Glaser et al. 2002; Qin et al 2021).

Biochar also influences other soil nutrients and the microbial community. Gao et al. (2021) demonstrated that applying biochar increases potassium levels and affects the fungal community structure by adsorbing nutrients and providing an environment conducive to fungal growth, thereby increasing their relative abundance. Zheng et al. (2016) observed that biochar application elevates total nitrogen levels in paddy soils and alters the microbial community structure, with bacterial communities being less impacted compared to those of *Ascomycota* (sac fungi) and *Basidiomycota* (club fungi). Additionally, some biochars contain labile carbon and have an alkaline pH, which can affect the relative abundance of microorganisms. The microporous and mesoporous domains of biochar offer a suitable and protective habitat for microorganisms, particularly because they store soluble compounds like sugars, alcohols, acids and water, which further enhance microbial activity and alter microbial composition (Jaafar et al. 2015; Adnan et al. 2020).

3.2.3. Altering Soil Properties for Microbial Community Enhancement

Biochar can influence soil microbial activity and community structure through its key properties such as pore space, surface area, porosity, mineral content, functional groups, volatile compounds, free radicals and pH (DeLuca et al. 2015a, 2015b; Gao and DeLuca 2016; Zhu et al. 2017). It has alkaline properties, which can increase soil pH, particularly in acidic soils. Palansooriya et al. (2019b) showed that biochar raises soil pH and positively influences the metabolic activity and community structure of soil microorganisms. The raw material used in biochar production plays a significant role in determining its pH, with wood-based biochar typically having a higher pH than biochar made from other materials, making it more effective in regulating soil pH. Additionally, the pyrolysis temperature impacts the pH of biochar, as higher-temperature pyrolysis conditions generally produce biochar with a higher pH compared to low-temperature conditions (Al-Wabel et al. 2013; Gul et al. 2015; Wang et al. 2020). Biochar significantly affects microorganisms in acidic soils. Sheng and Zhu (2018) found that applying biochar to acidic soils substantially increases soil pH and significantly alters the composition of the soil microbial community, resulting in notable increases in *Bacteroides* and Gemmatimonadetes and a significant decrease in Acidobacteria. They attributed this change in the soil microbial community structure primarily to biochar's regulation of soil pH. The application of biochar influences soil density and the stability of aggregates, thereby directly or indirectly affecting soil microorganisms (Lehmann et al. 2011; Blanco 2017; Chen et al. 2018). Biochar decreases soil bulk density, enhances the soil's water-holding and moisture retention capacity, impacts nitrous oxide (N_2O) emissions from the soil, and affects soil nitrifying and denitrifying bacterial communities (Liu et al. 2017b, 2017c). The application of biochar reduces methane production by altering soil aeration, which decreases the abundance of methanogenic bacteria and increases that of methanophilic bacteria, thereby reducing CH_4 emissions (Jia et al. 2012; Chen et al. 2018; Wang et al. 2019).

In summary, the type of feedstock used in biochar production and the dosages applied significantly influence the abundance and diversity of soil microorganisms (Zhou et al. 2020). While biochar can enhance microbial communities, research indicates that its effects can vary widely due to the diverse properties of biochar produced under different conditions, which impact the soil environment and microorganisms differently (Huang et al. 2023). Documented variations in microbial responses to biochar primarily manifest through changes in microbial community abundance, structures and metabolic activities (Zhu et al. 2017), presenting further research opportunities regarding biochar applications in soil environments. The considerable abundance (up to 1 billion cells per gram of soil) and diversity (up to 1 million species per gram) of soil microbial communities (Fierer 2017) are essential for maintaining the ecological quality of the soil and agricultural productivity. These functions include organic matter mineralization, soil structure maintenance, pesticide degradation and the competitive exclusion of pathogenic species (Prevost-Boure et al. 2011; Philippot et al. 2013; Tardy et al. 2014; Sadet-Bourgeteau et al. 2019; Abis et al. 2020; Christel et al. 2021). At the same time, shifts in soil microbial communities can have mixed outcomes, highlighting the need for site-specific evaluation rather than assumed benefits.

3.3. Enhancing Soil Water Retention and Drought Resilience

Biochar enhances soil porosity and water retention by encouraging the aggregation of soil particles, particularly in sandy or light-textured soils (Figure 6). This process results in the development of various pore structures, including macropores (>80 micrometers [μm]), mesopores (30–80 μm) and micropores (5–30 μm), which improve the circulation of air and water throughout the soil profile. These structures also provide essential microhabitats for soil organisms and serve as reservoirs for moisture, oxygen and nutrients. For instance, biochar-amended light soils show an increase in macropores, mesopores and micropores, leading to significantly improved water-holding capacity (Li et al. 2021). This improvement is significant in drought-prone regions, as it enhances the soil's ability to retain water and sustain crops during dry spells and extended periods of low rainfall.

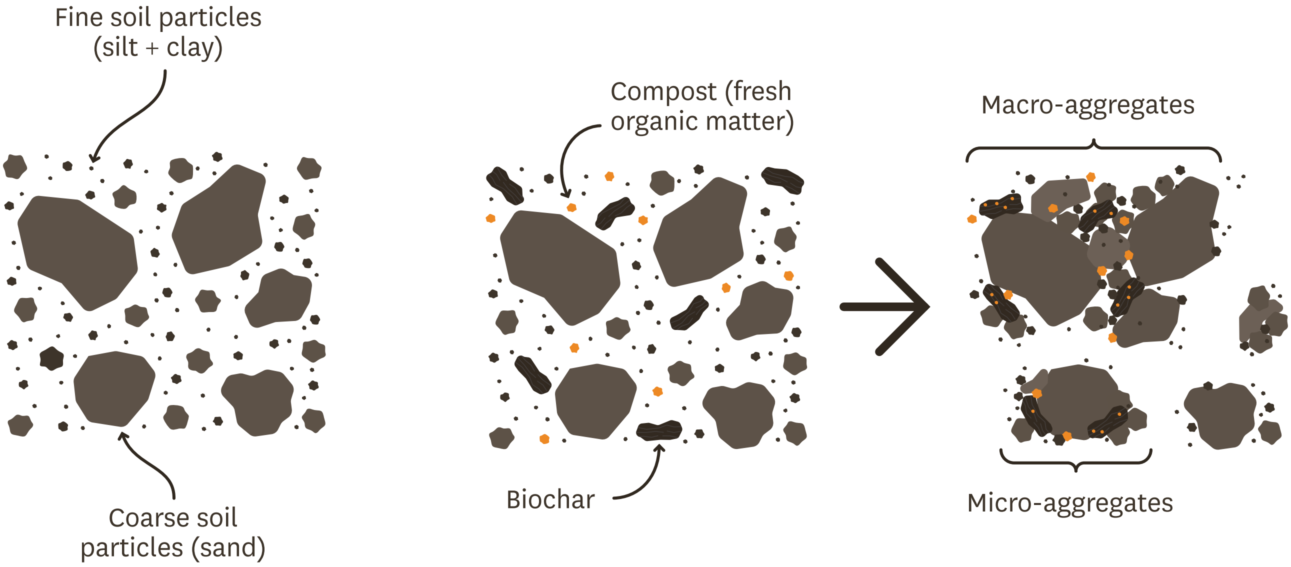

FIGURE 6. Biochar-enhanced soil aggregation and pore development.

Source: Lee et al. 2021

Biochar improves soil moisture retention through multiple mechanisms linked to its porous structure and interaction with soil aggregates. Water molecules are adsorbed onto the surface of biochar particles, while the different pore sizes play complementary roles in regulating water movement and availability. Macropores enable the rapid infiltration of rainwater or irrigation water into the soil under gravity, supporting deep soil recharge (Zhang et al. 2021). Mesopores function as intermediate storage zones, allowing the water to be redistributed gradually from wetter to drier zones and making moisture available to plant roots over time. Micropores, on the other hand, retain water through capillary action, extending the residence time of moisture in the root zone after rainfall or irrigation events (Li et al. 2021; Zhang et al. 2021). These combined effects enhance both the soil’s capacity to absorb water during precipitation or after irrigation and its ability to retain and supply that water over time. Notably, pore sizes between 5–9 μm are especially effective for capillary retention, making biochar with such characteristics particularly suitable for managing soil moisture in agricultural systems (Kameyama et al. 2019; Li et al. 2021).

Building on its influence at the pore scale, biochar also improves soil water retention through higher application rates, though outcomes vary depending on soil texture and structure (Zhang et al. 2024). In coarse-textured soils such as sandy loams, biochar-induced aggregation enhances water retention by increasing the number of mesopores and micropores. In contrast, in fine-textured clayey soils, aggregation improves water infiltration and percolation by reducing compaction and improving pore connectivity. In both cases, improved aggregation contributes to reduced surface runoff and erosion, enhancing water conservation. Empirical studies (see Figure 7) highlight this relationship: in sandy loam soils, an application of 12.5 Mg/ha of biochar increases water retention in the top 10 centimeters (cm) under near-saturated conditions (matric potential <10 kilopascals [kPa]). Under drier conditions, a higher application rate of 25 Mg/ha proves more effective, sustaining water availability over a longer period.

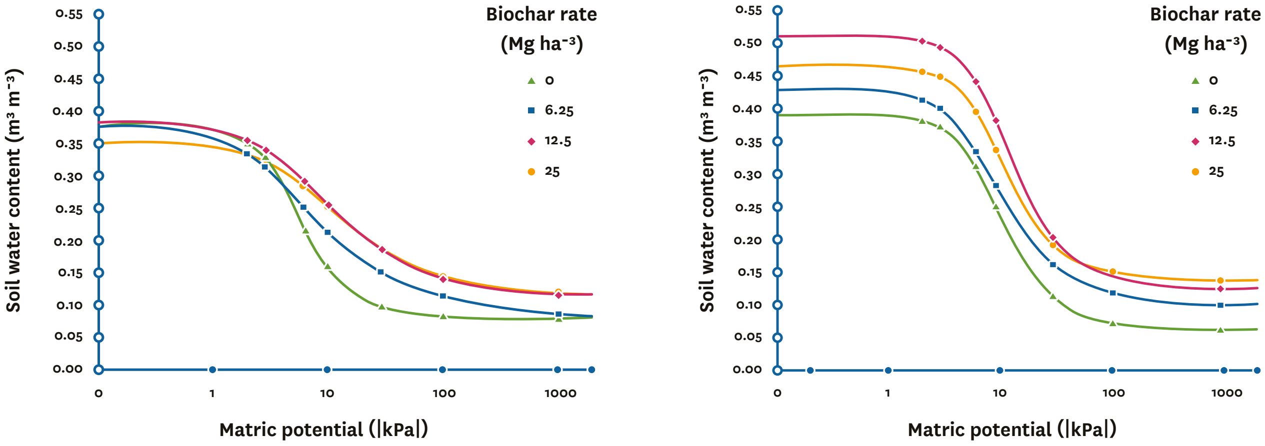

FIGURE 7. Soil water retention in near-saturated (<10 kPa matric potential) top 10 cm-layer and dry (>10 kPa matric potential) sandy loam soil after applying biochar (0, 6.25, 12.5 and 25 Mg ha^{-1}) evaluated (a) 50 days and (b) 150 days after incorporation into the 10-cm soil depth (n = 4).

Source: Carvalho et al. 2020

Note: The biochar was produced from mixed agricultural residues – cotton husks, sugarcane cakes and pig manure.

Beyond its effects on soil structure, biochar's internal porosity—its intrapores—also plays a crucial role in water retention. These internal pores store water within the biochar matrix itself, supplementing the water held in the surrounding soil. The degree of water retention is influenced by the feedstock material and pyrolysis conditions. For example, biochar derived from sugarcane bagasse, pyrolyzed at 600–800°C for two hours, exhibits a high concentration of micropores, offering greater water-holding capacity than biochars made from bamboo, sewage sludge, rice husks or poultry manure (Kameyama et al. 2019). These characteristics are particularly beneficial in semi-arid conditions or during extended dry spells and droughts in rainfed agricultural systems (Thao et al. 2023). In these contexts, biochar helps slow the soil's drying cycle by holding moisture in both soil micropores and its own intrapores, thereby prolonging the availability of water to plant roots. It also increases the wettable surface area in soils and enhances the affinity between soil and water particles (Leng et al. 2021). This enhanced interaction between soil and water particles enables plants to access moisture more efficiently, boosting resilience during periods of drought and water stress (Kameyama et al. 2012; Major et al. 2012).

3.4. Reducing Pollutant Leaching and the Immobilization of Potentially Toxic Elements

Biochar is increasingly recognized for its potential application in addressing soil contamination with potentially toxic elements (PTEs), such as those commonly referred to as 'heavy metals' — cadmium, chromium (Cr), copper (Cu), mercury, nickel (Ni), lead and zinc (Zn), together with metalloids such as arsenic (As). This reflects biochar's particular physical structure and chemical properties, as well as its role in supporting biological processes (Ennis et al. 2012).

Biochar's large surface area and porous structure offer extensive sites for physical adsorption of these contaminants, effectively reducing their mobility and bioavailability in soils. It effectively adsorbs a wide range of soil contaminants, including heavy metals, pesticides and excess nutrients, due to its high surface area, porosity, CEC, surface charge variability and functional group diversity (Ahmad et al. 2014). These physicochemical properties enable biochar to prevent pollutants from moving through the soil or being readily taken up by plants. For example, the porous structure, particularly in biochar produced at high temperatures, allows for the physical adsorption of metal ions (for example, lead, cadmium, arsenic). However, these low-energy interactions can be reversible. In addition, surface functional groups—such as carboxyl, hydroxyl and carbonyl—form chemical complexes with metal ions, enhancing their immobilization (Qiu et al. 2021). Biochar's alkalinity also plays a key role by raising soil pH upon application, which leads to the precipitation of dissolved metals as insoluble hydroxides or carbonates (for example, $Pb(OH)_2$, $CdCO_3$). Furthermore, increased soil CEC due to biochar allows for a stronger binding of cationic metals (for example, copper, zinc) through interactions with negatively charged groups like carboxyl and phenol, further reducing their bioavailability—especially in tropical, arid or semi-arid soils with naturally low CEC (Beesley et al. 2011).

Biochar immobilizes heavy metals such as Pb^{2+}, Cd^{2+} and Zn^{2+} through a combination of electrostatic interactions, complexation and precipitation (Beesley et al. 2011). These decrease the competition with H^+ ions for exchange sites (Novotny et al. 2015; Aller 2016) and minimize their interference with nutrient uptake. Additionally, biochar can retain organic pollutants—such as polycyclic aromatic hydrocarbons and pesticides—via hydrophobic interactions and electron donor–acceptor bonding (Lou et al. 2016), thereby reducing bioavailability and ecological risks. Finally, biochar supports microbial communities that contribute to the transformation and stabilization of contaminants. Some microbes can reduce metal toxicity via redox reactions (for example, Cr(VI) to Cr(III)) or secrete extracellular polymers that bind toxic metals such as copper, mercury, lead, cadmium, zinc and chromium (Kondakindi et al. 2024). These combined mechanisms make biochar a valuable amendment for remediating contaminated soils and minimizing pollutant impacts on plant and microbial health.

Practical considerations are critical to the successful use of biochar for contaminant immobilization. The feedstock type and pyrolysis conditions significantly affect performance. For instance, wood-based biochars produced at high temperatures (>500°C) tend to have more stable, aromatic structures with enhanced physical adsorption capacity, while lower-temperature biochars retain more oxygen-containing functional groups beneficial for cation binding. The characteristics of the receiving soil also play a major role. Soils vary widely in pH, CEC, organic matter content and clay fraction, all of which influence the effectiveness of biochar. Acidic soils, for example, may require higher application rates to neutralize pH and immobilize metals, whereas high-pH soils may experience adverse effects, such as increased arsenic mobility. Likewise, biochars with low CEC may offer limited benefits in soils already rich in exchange sites. Biochar's metal-specific immobilization mechanisms also mean that it is more effective for certain contaminants, such as lead and cadmium, than others like arsenic, whose mobility can increase under alkaline conditions (Beesley et al. 2015). While biochar can immobilize heavy metals already present in soils, the biochar itself—especially when derived from certain feedstocks such as municipal solid waste—may contain persistent pollutants. Thus, without stringent feedstock pre-treatment, these contaminants can enter soils (Xiang et al. 2021). Long-term field evidence also remains limited; ageing of biochar and changing soil conditions can alter surface chemistry and potentially remobilize previously immobilized metals, which raises questions about the permanence of these remediation effects and the effectiveness and safety of contaminant immobilization (Tan and Yu 2024). For example, in alkaline soils, further pH increases from biochar application can alter nutrient availability or mobilize other elements, creating potential trade-offs (Lehmann et al. 2011). Therefore, site-specific risk assessments are essential to ensure safe and effective use of biochar.

Another related consideration is the long-term stability of biochar-metal complexes. Although biochar itself is a stable form of carbon, environmental changes such as shifts in pH levels or flooding may disrupt these complexes and remobilize metals, underscoring the need for periodic monitoring. Moreover, biochar offers a suite of co-benefits beyond detoxification, including enhanced water retention, nutrient cycling, microbial activity, soil structure and plant productivity. These benefits are particularly valuable in combination with compost or mineral fertilizers (for example, phosphate), and they support soil resilience in remediated landscapes. In such systems, biochar can complement phytoremediation (Figure 8) or phytostabilization approaches, where plants chemically reduce or mechanically stabilize soil contaminants that get released through mobility or root exudates. This biomass—grown on marginal or contaminated land—can be converted into biochar, creating a self-reinforcing remediation cycle (Evangelou et al. 2012; Buss et al. 2016). However, plant biomass from polluted sites may carry residual contamination via wind-blown or rain-splashed soil particles (Nunn et al. 2025), so this should be screened before use in more sensitive soil applications. Furthermore, species that accumulate metals such as nickel, copper or zinc may concentrate these in their leaves, roots, bark or woody material, and because pyrolysis conserves most metal PTEs, these elements remain in the resulting biochar (Dickinson et al. 2009; Fletcher et al. 2014). This could restrict the reuse of such biochar in sensitive or uncontaminated environments for environmental or regulatory reasons. These combined mechanisms make biochar a valuable amendment for remediating contaminated soils and minimizing pollutant impacts on plant and microbial health—Box 1.

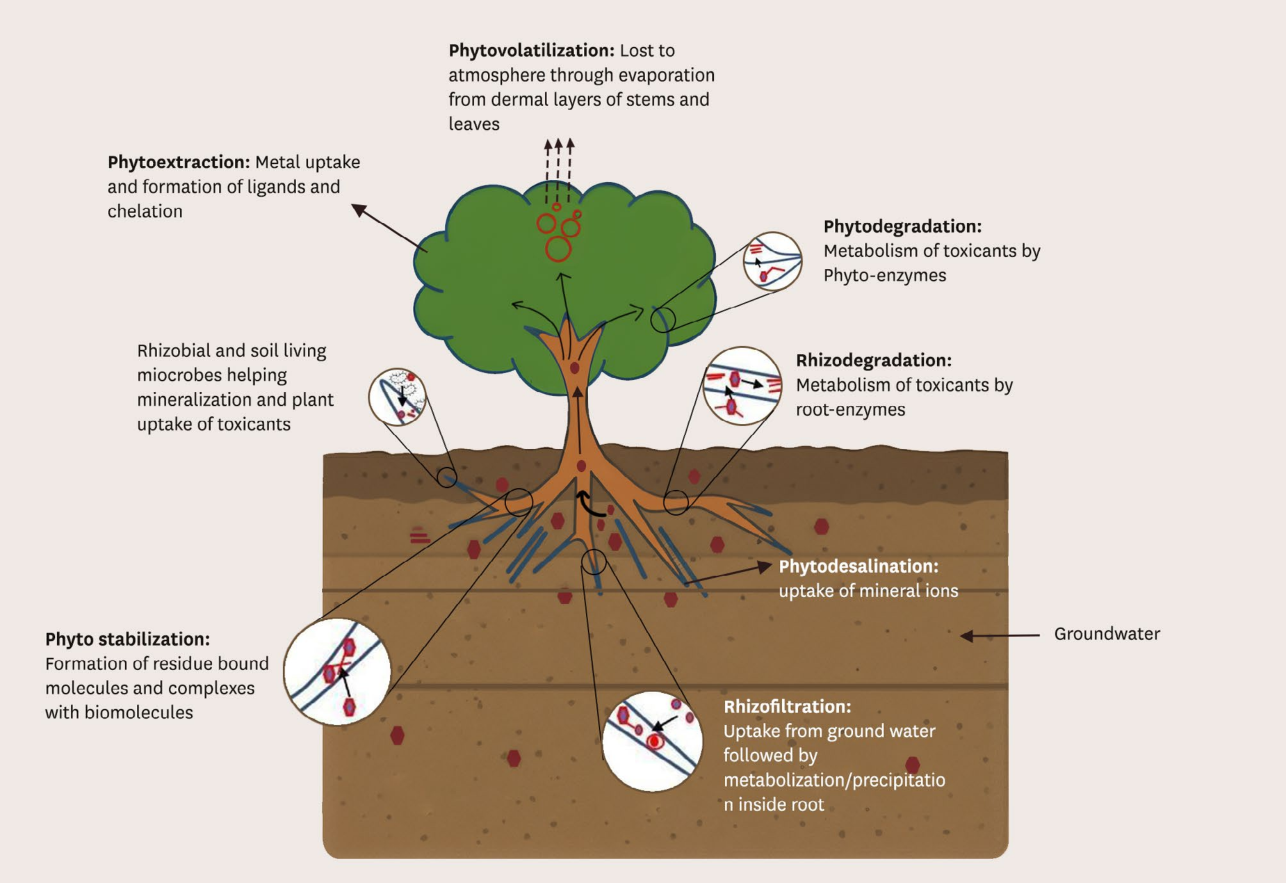

FIGURE 8. Mechanisms of phytoremediation and the practical role of biochar in contaminant management.

Source: Kafle et al. 2022

Charcoal. Photography by Uros Petrovic

Box 1. Biochar Applications for Heavy Metal Remediation in Gold Mine-affected Soils

Mining activities, particularly artisanal and small-scale gold mining (ASGM), often lead to soil contamination with heavy metals and metalloids such as mercury and arsenic. While mercury and cyanide are commonly used in gold recovery processes, the hard-rock gold ores and resulting tailings frequently contain elevated levels of arsenic. Addressing these contaminants is crucial for environmental restoration and reducing health risks.

Laboratory studies have explored the potential of biochar—produced from local agricultural wastes—as a remediation strategy. In West Sumbawa, Indonesia, biochar produced from corn cob, rice husk and coconut shell was applied at a 5% rate to mercury-contaminated soils collected from former ASGM sites (Kusnarta et al. 2024). Corn cob biochar proved most effective in reducing mercury concentrations in leachate, likely due to its greater porosity and higher hydroxyl group content compared to the other feedstocks. Similarly, in the eastern Amazon region of Brazil, biochars made from palm kernel cake, Brazil nut shells and açaí seeds were applied to mine tailings and cyanidation residues. At a 5% application rate, these biochars reduced arsenic bioavailability by up to 20%, based on sequential extraction methods (Dias et al. 2024). These findings suggest that biochar amendments can play a significant role in immobilizing heavy metals and metalloids in contaminated soils.

Field-based evidence further strengthens these results. As part of the CERESiS project, phytostabilization field trials were conducted at a historical lead mining site in Wanlockhead Village, Scotland, known for its legacy contamination with lead, zinc, copper, cadmium and arsenic (Figure 9). The trials applied biochar and compost to highly eroded mine tailings to restore vegetation and improve soil stability. Complementary restoration trials in Cherniakhiv, Ukraine, applied native energy crops such as *Miscanthus × giganteus* and *Phalaris arundinacea* to contaminated soils, resulting in significant reductions in mobile and total concentrations of heavy metals, pesticides and petroleum-derived pollutants (Romantschuk et al. 2024). These grasses not only stabilize and remediate degraded soils but also offer the potential for circular recovery: harvested biomass can be converted to biochar, while extracted metals may be reclaimed, creating a regenerative system for land restoration.

Taken together, these examples demonstrate that biochar can serve as an effective amendment to remediate metal-contaminated soils. It offers a circular opportunity for marginal lands to be transformed into productive systems—generating biomass for further biochar production and enabling continuous soil improvement, while supporting the recovery of metals and long-term ecosystem restoration through a regenerative, low-input remediation cycle.

FIGURE 9. Application of biochar and compost to a barren area of eroding lead mine tailings during CERESiS Project phytostabilization field trials in Scotland.

4

BIOCHAR’S ROLE IN CLIMATE MITIGATION, ADAPTATION AND RESILIENCE

4.1. Role of Biochar in Climate Change Mitigation

One of the most mentioned environmental benefits of biochar is its capacity to contribute to climate mitigation, both by reducing greenhouse gas (GHG) emissions and removing carbon dioxide from the atmosphere and storing it long term in soils. Studies have shown that biochar could sequester up to 1.8 billion tonnes (Gt) of carbon dioxide equivalent (CO_2-eq) per year, which is approximately 12% of anthropogenic greenhouse gas emissions (Woolf et al. 2010). This hinges on the nature of carbon in biochar, the thermally altered carbon structures, predominantly aromatic compounds, which decompose 1–2 orders of magnitude slower than unpyrolyzed (raw) biomass (Woolf et al. 2018). The slower decomposition rate makes biochar exhibit exceptional stability, enabling long-term carbon storage in soils and reducing the atmospheric return of previously sequestered carbon. Beyond this, there are various ways in which biochar contributes to carbon sequestration in soils and mitigating greenhouse gas emissions. These mechanisms collectively enhance biochar's role as a nature-based climate mitigation strategy.

4.1.1. Enhanced Soil Carbon Retention

Biochar not only stores carbon within its structure but also enhances the stability of native soil carbon, positioning soil as a potential carbon sink. The process, often referred to as 'negative priming', is a crucial mechanism through which biochar enhances carbon sequestration (Yin et al. 2022). Once biochar is applied to soils, it may stimulate the decomposition of native soil organic carbon; however, over a period of two years or more. Evidence shows that biochar can reduce carbon losses by 0.5–1.2 tonnes of carbon per hectare annually (Blanco-Canqui et al. 2020). While there are no long-term, century-long or millennial field studies, results from Yin et al. (2022), using a biogeochemical field modelling approach, show that biochar retains 651–725 kg of carbon per tonne of biochar–carbon (BC-C) in the soil


Source: Neirfy

after 500 years despite natural decomposition processes. This long-term persistence highlights biochar's potential as a durable carbon sequestration mechanism in soil systems.

Biochar's carbon stabilization in soils occurs through multiple adsorption and complexation mechanisms (Figure 10): its high surface area and porous structure allow dissolved organic carbon to be adsorbed. This facilitates the physical protection of SOC, promotes microaggregate formation with soil minerals and, in some cases, releases compounds that suppress microbial activity. Additionally, biochar supports plant growth by improving soil water retention, regulating nutrient cycling and exerting a liming effect, all of which contribute to greater carbon capture through increased photosynthesis and organic inputs, such as root secretions and leaf litter. These combined processes reduce the availability of labile carbon that microbes typically use for respiration, slowing down the microbial breakdown of native soil organic matter, respiration rates and CO_2 emissions. It enhances the longevity of soil carbon storage, amplifying biochar's climate mitigation potential beyond its own inherent stability.

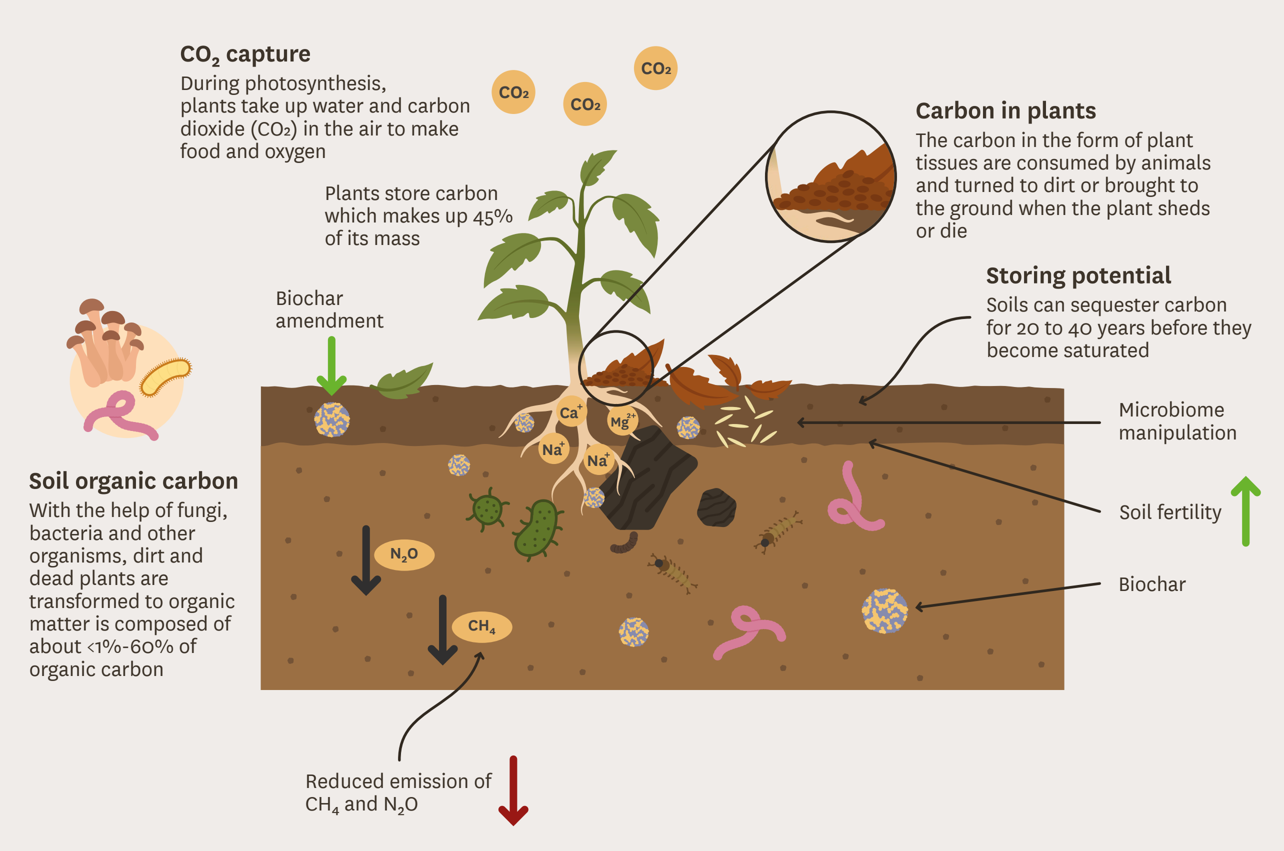

FIGURE 10. Biochar's pathways to carbon sequestration.

Source: Yadav and Ramakrishna (2023)

While biochar induces negative priming, positive priming can also occur under certain conditions. This can increase the decomposition rate of native soil carbon following the application of biochar, potentially releasing more CO_2 than would have been emitted otherwise. This effect is typically observed when biochar is mixed or provides a labile carbon source that stimulates microbial activity, accelerating the breakdown of existing soil organic matter (Woolf et al. 2018). Additionally, in nutrient-limited soils, biochar may enhance microbial growth and enzyme production, inadvertently promoting the mineralization of native carbon stocks (Lehmann et al. 2021). The occurrence and magnitude of positive priming depend on biochar properties, soil type and environmental conditions, highlighting the need for careful assessment before large-scale biochar deployment. For enhanced soil carbon retention, high-temperature biochar (above

Two men with a shovel removing charcoal in a drum for biochar application in a vegetable garden. Photography by Toni Jardon

500°C) generally exhibits stronger negative priming effects than low-temperature biochar (Woolf et al. 2018). The magnitude of negative priming is more pronounced in sandy or degraded soils but may be negligible in soils with high levels of organic matter. Factors such as moisture, temperature and the type of microbial communities and their activities can influence the strength and persistence of negative priming effects. For example, fungal-dominated systems promote more stable carbon pools due to slower decomposition rates than bacterial-dominated ones.

According to Yin et al. (2022), several factors can limit carbon storage in soils. Physical disturbances, such as ploughing and excessive tillage, can accelerate the decomposition of biochar by increasing its exposure to oxygen and microbial activity. Biological erosion from plant root exudates containing organic acids such as malic acid and citric acid can destabilize biochar, while microbial activity can initially enhance the mineralization of soil organic carbon. Climatic conditions also play a role, with high temperatures and precipitation increasing microbial respiration and the loss of carbon. Over time, nutrient depletion limits plant productivity, reducing long-term carbon inputs into the soil. Additionally, biochar can contribute to anaerobic conditions in humid environments with poor drainage, increasing CO_2 and N_2O emissions. These factors demonstrate the complex interactions influencing long-term carbon sequestration in soils.

4.1.2. Reduction of Potent Greenhouse Gas Emissions

The effectiveness of biochar as a climate mitigation tool also depends on its influence on other potent GHGs in the soil, including methane and nitrous oxide. Both gases have a higher global warming potential, approximately 28–36 and 265–298 times that of CO_2 over 100 years, respectively (Vallero 2019). A meta-analysis by He et al. (2016), covering studies from 1900 to 2015, showed that biochar application can enhance carbon sequestration but has mixed effects on soil GHG fluxes, depending on soil conditions and management practices. The study confirms that biochar introduces recalcitrant organic carbon into soils, providing a long-term carbon sink. However, its impact on soil CO_2 fluxes varies; while some studies reported increased soil respiration due to biochar's labile carbon, others found that biochar suppressed CO_2 emissions in fertilized soils, likely due to nutrient interactions that reduced microbial decomposition.

Additionally, biochar significantly reduced nitrous oxide emissions by more than 30%, contributing to a lower overall GHG impact. Its effects on methane fluxes were negligible, although in some cases, it suppressed methane production by improving soil aeration and promoting methanotrophic activity (He et al. 2016). Another study revealed that soils amended with biochar can emit significantly less nitrous oxide, with reductions of up to 80% in some instances. These improvements were attributed to improved aeration, altered microbial dynamics and the facilitation of electron transport (Woolf et al. 2018). The analysis shows that aside from pyrolysis temperature and feedstock type, biochar's long-term sequestration potential depends on soil conditions and application methods. The maximum climate mitigation benefits can be derived when biochar is applied under optimal soil conditions, such as in combination with nitrogen fertilizers and high-stability biochar formulations.

Some of the mechanisms by which nitrous oxide and methane emissions are reduced include improved soil aeration, which limits the anaerobic microsites and conditions required for methanogenesis and denitrification, key processes that generate these gases (He et al. 2016). Biochar also adsorbs nitrogen compounds, such as ammonium, and nitrate, reducing their availability for microbial transformations that produce nitrous oxide. Additionally, biochar raises soil pH and facilitates electron transfer between microbial communities. These conditions can suppress nitrifying and denitrifying bacteria producing nitrous oxide, favoring nitrous oxide-reducing bacteria, or decreasing nitrous oxide emissions.

In the case of methane, biochar reduces water saturation and increases gas exchange. This inhibits methanogenic (methane-producing) microbes while stimulating methanotrophic (methane-oxidizing) bacteria, enhancing methane oxidation. Evidence shows that in flooded rice cultivation, incorporating biochar into soils reduces methane emissions by up to 90% in some cases by shifting microbial populations toward methane oxidation (Woolf et al. 2018). Another study (Dong et al. 2020), showed that biochar promoted complete denitrification, facilitating the conversion of nitrous oxide to nitrogen gas (N_2), which is environmentally neutral. Since agriculture is a major contributor to nitrous oxide and methane emissions, integrating biochar into farming systems offers a practical solution to reduce emissions without requiring drastic changes in management practices. These combined effects and multiple emission reduction potentials make it a valuable tool for carbon mitigation.

Nevertheless, climate-mitigation benefits must be weighed against possible trade-offs: for example, large-scale application of dark biochar can alter soil albedo and surface energy balance, potentially offsetting part of the intended greenhouse gas reduction (Tan and Yu 2024). In addition, large-scale biochar programs would require vast and sustained supplies of biomass; securing this feedstock could lead to land-use changes or even land grabbing, with associated ecological and societal damage and loss of biodiversity. The production process itself is energy- and emission-intensive—high pyrolysis temperatures, biomass drying and long-distance transport all add to the life cycle greenhouse gas footprint (Jeffery et al. 2011). More so, black carbon can be lost from soils through riverine transport to the oceans, undermining the permanence of carbon sequestration (Coppola et al. 2018).

4.1.3. Increased Plant Biomass and Carbon Uptake

Earlier sections highlighted the role of biochar's porous structure in increasing the soil's water-holding capacity and enhancing the retention and cycling of soil nutrients. They also highlighted their role in supporting beneficial soil microbes, including mycorrhizal fungi and nitrogen-fixing bacteria, which enhance nutrient uptake by plants. These positive contributions from biochar use increase biomass production and promote higher plant productivity, contributing to further carbon sequestration as more carbon dioxide is drawn down from the atmosphere via photosynthesis and converted into plant-derived carbon. For example, Vaccari et al. (2011) showed that biochar application increased aboveground biomass by up to 39% in durum wheat, with significant yield improvements of 28%–39% compared to control plots. The increase was consistent over two growing seasons, even without reapplication of biochar in the second year, demonstrating sustained productivity benefits. In the long term, it was estimated that 95%–97% of biochar carbon remained in the soil after 50–100 years, reinforcing its role in long-term carbon storage (Vaccari et al. 2011). The persistence of higher crop biomass and increased root growth suggests that biological carbon sequestration is reinforced.

The greater return of organic material (root deposits, litterfall) further contributes to the soil's organic carbon pool over time. While biochar is a promising strategy for long-term carbon sequestration, its life cycle—from sourcing feedstock and production methods to soil applications—needs careful evaluation to ensure that the net benefits outweigh any unintended environmental emissions or trade-offs.

4.2. Role of Biochar in Climate Adaptation and Resilience

The role of biochar in climate adaptation and resilience is based on its ability to enhance critical soil functions, such as soil fertility, soil structure and the water-holding capacity of soils, for sustaining agricultural productivity under increasing climatic stress. These attributes position biochar as a key tool for building adaptive capacities to climate change, particularly when integrated with other sustainable practices such as composting, mulching and cover cropping (Olawepo et al. 2024).

Biochar improves crop tolerance to climate-induced stressors such as heatwaves, droughts and irregular rainfall by enhancing the soil structure, increasing water retention and moderating temperature fluctuations in the root zone. Its porous structure and high surface area enhance soil aggregation, porosity and water retention, key traits for moderating soil temperature and reducing loss of moisture during dry spells. For example, Shyam et al. (2025) reported that biochar-amended soils exhibited significantly improved water-holding capacity and root-zone aeration, allowing crops to maintain physiological functions under water stress. In drought-prone regions, biochar contributes to more stable soil moisture dynamics by increasing mesopore and micropore volumes, which retain and slowly release water to plant roots, reducing the risk of desiccation and enhancing photosynthesis efficiency during heatwaves. Furthermore, biochar's positive effects on soil fertility are crucial for plant resilience. By improving CEC and nutrient retention, biochar makes essential nutrients such as nitrogen, potassium and phosphorus more available under stress conditions. Kundu and Kumar (2024) emphasize that biochar enhances microbial habitats and supports beneficial microbial communities, including nitrogen-fixing and phosphate-solubilizing bacteria, which boost nutrient cycling and plant vigor. These microbial benefits also support the development of stronger root systems and improved plant immune responses, making crops more resistant to pests and pathogens whose prevalence is increasing due to changing climatic conditions.

In terms of adaptation, field trials in Tanzania showed that biochar use increased maize yields from 1 tonne to 3 tonnes per hectare, which farmers attributed to enhanced soil moisture and nutrient conditions, even during periods of erratic rainfall (Rogers et al. 2022). The study showed that food security and increased incomes were the main reasons farmers adopted biochar. Similarly, Adu et al. (2022) documented a 78.4% increase in crop yields when pyrolyzed oil palm empty fruit bunches were applied as soil amendments. Together, these findings reinforce the role of biochar as a powerful climate adaptation strategy, particularly in smallholder and rainfed systems where resilience to drought, temperature stress and soil degradation is critical to food security.

The role of biochar in enhancing SOC is also pertinent in climate adaptation and resilience, particularly in tropical and sub-tropical regions where soils are often degraded and vulnerable to climate variability. The application of biochar significantly increases SOC by contributing recalcitrant carbon that remains stable in soils over long periods. According to Olawepo et al. (2024), this long-lived carbon pool improves soil health by enhancing microbial activity, boosting nutrient cycling and increasing water retention, critical components of resilience in smallholder systems facing drought and irregular rainfall. Incorporating biochar with organic inputs such as compost and cover crops creates synergistic effects, facilitating deeper root development, microbial diversity and aggregate stability. This integrated approach regenerates degraded soils more effectively than single amendments, thus strengthening the adaptive capacity of farming systems over time.

In the long term, biochar supports climate-resilient agroecosystems by stabilizing soil functions critical to productivity and ecological balance. Shyam et al. (2025) report that biochar can sequester carbon in soils for up to 2,000 years, acting as a durable carbon sink that buffers against climate-induced losses of soil organic matter. Furthermore, biochar improves resistance to erosion and nutrient leaching, an essential adaptation trait in sloped, sandy or weather-exposed landscapes, where runoff and topsoil loss are intensified by climate change. These properties collectively reduce the vulnerability of agricultural soils to climatic shocks while enhancing their capacity to absorb, store, and recycle water and nutrients. When biochar is contextually matched with appropriate feedstocks and application strategies, it becomes a cornerstone of adaptive soil management, with both immediate and lasting benefits for food security and landscape restoration in the Global South.

4.3. Risks of Maladaptation Associated with Biochar Use

Despite its many benefits, biochar can lead to maladaptive outcomes when applied without appropriate safeguards or context-specific considerations. One such risk is soil over-alkalinization, especially in arid or alkaline soils where high-pH biochars may push pH levels beyond agronomic thresholds. This can reduce the availability of essential micronutrients such as zinc and iron, impairing crop performance and contradicting adaptation goals (Shyam et al. 2025). Another maladaptive scenario involves biochar hydrophobicity. Certain biochars produced at high pyrolysis temperatures or from specific feedstocks such as rice husks and miscanthus straw can repel water rather than retain it. These hydrophobic characteristics lead to poor wetting, reduced hydraulic conductivity and lower soil moisture availability, particularly in sandy or drought-prone soils, where increased water retention is a primary objective (Shyam et al. 2025). Further concerns arise from contaminated feedstocks. Over-application or poorly matched biochar types can disrupt soil nutrient balance. For instance, Shyam et al. (2025) highlighted a study that found that 30 t/ha of biochar combined with manganese sulfate ($MnSO_4$) led to a 42% reduction in manganese levels in the soil, affecting nutrient availability. Similarly, corn planted in biochar-amended soils showed a 33% drop in nitrogen uptake, posing risks to yields. Biochars derived from municipal waste, sewage sludge or industrial residues may contain persistent toxins or heavy metals. If such biochars are applied without treatment or quality control, they risk transferring pollutants into soils, threatening crop safety and soil health.

Finally, in some cases, biochar may increase greenhouse gas emissions rather than reduce them. When biochar contains labile carbon or is applied to soils with high microbial activity under anaerobic conditions, it may stimulate microbial decomposition of existing soil organic matter, resulting in greater CO_2 or N_2O fluxes. Such "positive priming" effect, together with riverine export of black carbon, can reduce the permanence of carbon sequestration (Coppola et al., 2018). Large-scale biochar production could divert biomass from other uses or incentivize land-use changes, such as deforestation for biochar plantations. This threatens biodiversity, reduces natural carbon stocks, and increases emissions, directly undermining both adaptation and mitigation aims. Ethical trade-offs due to unsustainable biochar production—via deforestation, air pollution from pyrolysis or nutrient runoff—could harm ecosystems and marginalized communities, for example, leading to competition with food crops for land or exclusion of women and smallholders from value chains. Expanding the definition of 'waste' to justify large-scale biomass sourcing can also deplete residues needed for compost, mulch or animal fodder, undermining local nutrient cycles and traditional farming practices. Such outcomes underscore the need for context-specific application and appropriate safeguards to avoid maladaptation issues. The following sections outline the inclusive financing models, and institutional, technical and policy levers that must be activated to maximize the benefits of biochar while minimizing the risks of maladaptation.

AI-generated image of a tractor ploughing through a field, spreading a layer of dark, crumbly biochar on top of the soil. Source: Justlight

5

TECHNO-ECONOMIC AND LIFE CYCLE CONSIDERATIONS

The economic viability and environmental feasibility of biochar innovations is influenced by a complex interplay of factors, including the sourcing of feedstock, production technologies, agronomic benefits, carbon market dynamics and system integration strategies. Techno-economic analysis (TEA) and market studies remain essential tools for assessing costs, revenues and scalability. However, when considered in isolation, TEA overlooks critical environmental trade-offs across the biochar value chain. More so, most existing TEA studies to date originate in Global North contexts—such as North America and Europe—where regulatory, infrastructural and financial conditions differ significantly from those in LMICs. In LMIC settings, where smallholder producers, informal markets and decentralized systems dominate, there is a persistent lack of disaggregated, context-specific data at the agrifood system scale. This report underscores the need for both techno-economic and life cycle considerations when evaluating biochar systems in LMIC contexts.

5.1. Economic Feasibility and Production Costs

Evidence from LMIC contexts offers growing insights into locally viable biochar systems. For example, pilot projects in Kenya, Ethiopia and Vietnam indicate that the unit cost of biochar production using flame curtain kilns or traditional earth kilns ranges from USD 10 to USD 80 per tonne, depending on the costs of feedstock, labor and transport, and kiln efficiency (Owsianiak et al. 2021). These low-tech systems are broadly accessible but may produce biochar of inconsistent quality in the absence of adequate process control, operator training and post-production handling protocols. Slightly more advanced systems, such as top-lit updraft gasifiers or retort kilns, entail higher capital and operational expenditures, leading to estimated production costs between USD 150 and USD 300 per tonne—especially when feedstocks have high moisture content or are used intermittently.

In Tanzania, micro-gasifier cookstoves demonstrated low operating costs, but their widespread adoption was constrained by limited awareness of biochar's agronomic value and the logistical burdens of handling, transporting and applying the product (Eltigani et al. 2022). Despite these challenges, Robb et al. (2020) found that cost-effective scenarios for smallholder farmers emerge at less than USD 100 per tonne, particularly when the biochar is integrated into daily farming routines and produced from locally-sourced dry agricultural residues such as maize stalks, rice husks or coconut shells. Labor costs in LMICs, while variable, tend to be lower relative to industrialized countries, providing a comparative advantage for small-scale systems that rely on manual feedstock collection and kiln operation. However, the economic feasibility of biochar innovations remains highly sensitive to the quality of feedstock, the distance it needs to be transported and whether the biochar is a primary or secondary product (for example, cookstove use).

In contrast, evidence from the Global North suggests that higher production costs are associated with larger-scale, capital-intensive systems. For instance, converting orchard waste into biochar in California's Central Valley incurs costs ranging from USD 448.78 to USD 1,847 per tonne, with a 90% probability interval between USD 571 and USD 1,455 per tonne (Nematian et al. 2021). In Idaho, on-site conversion of cattle manure using portable refinery units yields lower costs at approximately USD 237 per tonne (Struhs et al. 2020). These variations are largely attributable to differences in economies of scale, automation, feedstock transport costs and regulatory overheads.

Sensitivity analyses from these studies confirm that biochar production rates are the most influential cost factor, and that system efficiencies—such as reducing feedstock moisture or optimizing on-site processing—can significantly improve economic performance (Struhs et al. 2020; Nematian et al. 2021). In forested areas, portable systems for converting forest residues into biochar have a minimum selling price (MSP) of USD 1,044 per tonne (on an oven-dry basis). However, technological improvements could lower this to USD 470 per tonne (Sahoo et al. 2019). Labor costs remain a significant component of production and application phases both, with its economic feasibility often hinging on achieving optimal application rates (Patel and Panwar 2024). Application rates of around 8 tonnes per hectare tend to maximize cost-benefit ratios and internal rates of return, while rates exceeding 20 tonnes per hectare can become economically prohibitive. Even where labor is inexpensive, the technical demands of high-temperature pyrolysis, together with the need to dry and transport bulky biomass, make production energy-intensive and can quickly push total costs beyond what low-income producers can afford (Jeffery et al. 2011).

These insights highlight the need for locally grounded economic and value-chain assessments in LMIC settings, especially those that focus on decentralized, low-cost and labor-intensive technologies that smallholders can realistically adopt. Future analyses should break down cost components in detail (labor, transport and feedstock conditioning), explore alternative market scenarios and identify business models that match local capacities and financing options. Such evidence can guide context-appropriate investments and help determine the scale of technology needed for agronomic integration. Regional economic modelling further shows that well-designed policy initiatives—such as incentives linked to carbon-sequestration benefits—can stimulate job creation, strengthen rural incomes and generate value-added products (Nematian et al. 2021; Campion et al. 2023).

5.2. Economics of Producing Technologies

Building on the cost variations discussed above, the choice of biochar production technology—including conventional pyrolysis, microwave pyrolysis, gasification and hydrothermal carbonization—also significantly influences overall economic feasibility. Life cycle assessment studies show that the choice of both process and feedstock influences not only the quality and quantity of biochar produced but also the overall system costs.

Among these, gasification technology is often more advantageous in economic terms due to its lower energy consumption and relatively high conversion efficiency compared to pyrolysis and hydrothermal carbonization (Li et al. 2024). Conventional slow pyrolysis, meanwhile, remains more economically viable in many settings due to its operational simplicity and lower capital requirements. Reported MSPs for conventional pyrolysis systems range from EUR 436 to EUR 863 per tonne, depending on scale, feedstock and system design (Haeldermans et al. 2020). While microwave pyrolysis can offer higher yields and improved biochar quality, it is more capital-intensive and typically feasible only when premium markets exist for biochar with specific functional properties. In LMIC contexts, where upfront capital investment and electricity access may be limited, such technologies are less likely to be viable without significant support or value-added use cases.

Recent developments in portable and on-site systems—including containerized units and mobile kilns—have shown promise for reducing both production and transportation costs. These systems are particularly relevant for rural and peri-urban areas where feedstock availability is decentralized and market access is constrained. Moreover, integration with other technologies, such as anaerobic digestion or composting, can increase system-wide efficiency and financial viability by spreading capital costs across multiple value streams. Finally, the development of standardized, high-value biochar products—for example, nutrient-enriched biochar, biochar compost blends or pelletized formulations—offers additional routes for enhancing profitability. Such innovations are especially promising when coupled with capacity-building, market development and policy support for quality certification and end-user awareness (Sahoo et al. 2019; Kochanek et al. 2022).

Despite these technological options, mainstreaming biochar production continues to face several persistent challenges, including high production costs, high energy intensity, feedstock affordability and environmental trade-offs. The biochar market also remains limited and fragmented, with weak demand signals and price volatility that discourage widespread adoption. This highlights the need for expanded economic and market research to understand demand dynamics, stabilize prices and identify high-value applications (Donner and Vries 2021; Nematian et al. 2021).

Overcoming these barriers will require more systematic life cycle assessments and in-depth studies of the mechanisms underlying biochar's agronomic and carbon sequestration potential. Equally important are innovative business models that integrate technological and organizational innovations. These models must be underpinned by enabling policy frameworks, responsive market conditions and multi-sectoral collaboration to optimize the use of agricultural residues and other organic waste streams (Donner and Vries 2021). Value co-creation and coordination among actors across the biochar value chain—such as farmers, processors, technology providers and end-users—are essential for enhancing economic efficiency and environmental outcomes. Ultimately, realizing the full potential of biochar as a transformative agrifood innovation will depend on the convergence of technological advancement, policy support and inclusive business development. Strategic interventions in these areas can catalyze adoption, promote product standardization and stimulate investments in value-added applications such as soil enhancement, carbon markets and climate-smart agriculture (Kumar et al. 2020; Ayaz et al. 2021; Nematian et al. 2021; Li et al. 2024;).

5.3. Life Cycle Considerations

While TEA highlights financial feasibility, life cycle considerations capture the environmental sustainability of biochar systems. Evaluating each stage—from the sourcing of feedstock and processing to application and end-use—helps identify trade-offs in emissions, energy use and resource efficiency (Zilberman et al. 2023). Figure 11 applies a life cycle lens to illustrate these issues, enabling a clearer understanding of the synergies and trade-offs across the biochar value chain.

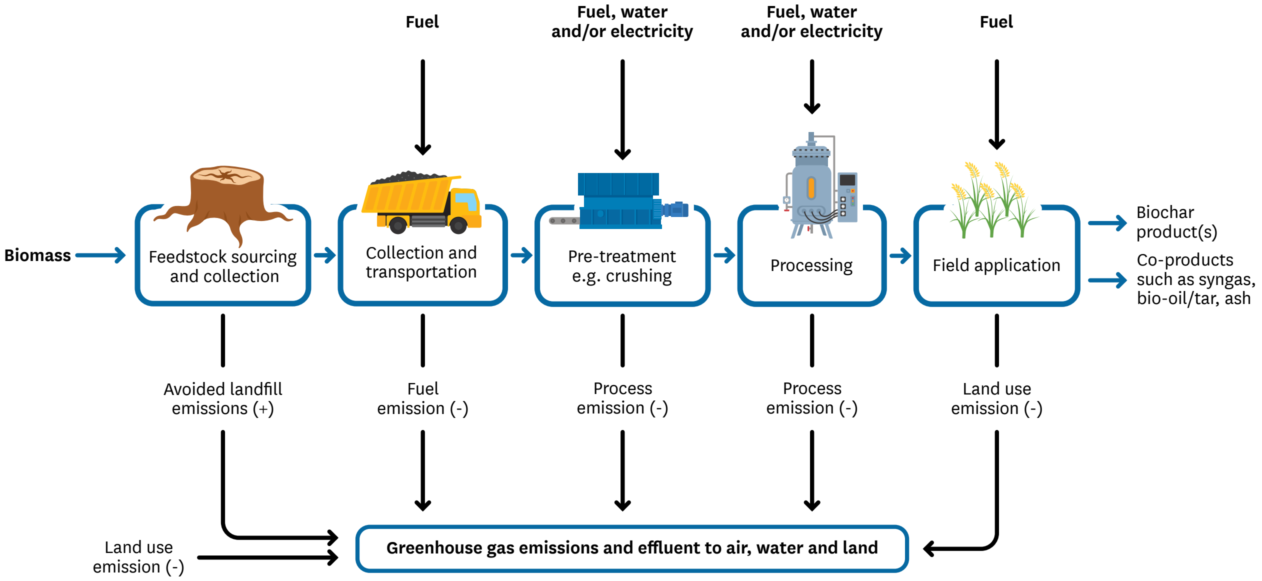

FIGURE 11. Biochar's life cycle stages.

Source: Authors

5.3.1. Feedstock Sourcing and Costs

The choice of feedstock determines both cost and environmental impacts. For example, sourcing biochar from forestry residues or agricultural by-products offers clear advantages; these materials are often underutilized and carbon-rich, and repurposing them can help avoid emissions from natural decomposition or open burning (Desjardins et al. 2024). In contrast, using land specifically to grow biomass for biochar—particularly through the conversion of natural ecosystems—undermines climate goals. This is because converting forests into plantations for biochar feedstock can lead to deforestation, land-use change and the depletion of soil organic carbon, significantly undermining biochar's potential as a climate mitigation tool. For example, Desjardins et al. (2024) showed that producing biochar from forest residues that would otherwise be pile-burned reduced emissions by approximately 0.85 t of CO_2-eq. per tonne of biochar, whereas leaving residues to naturally decay could increase emissions by about 6 t of CO_2-eq. per tonne of biochar. Feedstocks also differ in their opportunity cost: woody biomass yields stable, carbon-rich biochar but may compete with timber markets (Cornelissen et al. 2013), whereas manure-based biochars provide nutrient benefits but incur higher pre-processing costs. Feedstocks high in lignin typically yield biochar with greater porosity and adsorption capacity (Li et al. 2024), while herbaceous biomass, which contains more labile compounds, tends to decompose more rapidly, limiting its carbon sequestration potential to decades rather than centuries (Tu et al. 2022).

Ultimately, choosing the right feedstock involves balancing its potential for carbon sequestration, soil enhancement properties, energy efficiency and regional abundance. To reduce land-use emissions, biochar production should avoid feedstocks that require dedicated cultivation or involve the conversion of natural ecosystems. Instead, sourcing should focus on by-products that would otherwise decompose, be burned or go to waste, thereby ensuring that biochar contributes to a circular, low-emissions bioeconomy. Priority should be given to sourcing waste biomass, such as agricultural residues from sustainable forestry and agricultural practices, as these materials offer the best trade-off between environmental benefits and the minimization of the carbon footprint.

5.3.2. Collection, Transportation and Logistics

The collection and transportation of feedstock contribute directly to both costs and emissions. Low bulk density materials (for example, crop residues) require higher fuel inputs per tonne transported, leading to higher fuel use and emissions per unit of biochar produced (Thengane et al. 2020). Transport-related emissions are also sensitive to haul distance and fuel type, with long-distance movement using fossil fuels contributing significantly to overall greenhouse gas emissions (Desjardins et al. 2024). Based on EU-certified reference emissions using the VECTO model, long-haul, heavy-duty diesel trucks (5-LH class) emit an average of 52.7–56.6 grams of carbon dioxide per tonne-kilometer (Suzan et al. 2021). To enhance the carbon sequestration potential of biochar, it is therefore essential to prioritize locally-sourced feedstocks and optimize logistics to minimize travel distances and fuel use.

5.3.3. Pre-Processing and Production Methods

Sustainable biochar production requires integrated strategies, including careful feedstock selection, energy-efficient processing and robust emission control measures to maximize its climatic benefits. Upstream pre-processing (drying, chipping, sorting) incurs significant energy costs and emissions. Azzi et al. (2019) estimate that mechanized harvesting and chipping emit up to 48.6 kg of CO_2-eq per tonne of dry woodchips. This highlights the importance of minimizing energy use and emissions during upstream biomass handling. The choice of production technology also introduces cost–emission trade-offs (Gaunt and Lehmann 2008): slow pyrolysis offers high yields and long-term stability, but the need for higher temperatures ($>500°C$) increases energy inputs and production costs despite improved carbon retention. Traditional kilns, often low-cost, emit >2.6 kg of CO_2-eq per kilogram of biochar due to incomplete combustion (Cornelissen et al. 2013), whereas advanced retort kilns and top-lit updraft gasifiers require higher capital investment but significantly reduce emissions. Integrating heat and syngas recovery can offset fossil fuel costs, but only where the infrastructure supports energy recapture. Overall, choosing low-emission technologies and installing advanced gas capture and filtration systems can enhance carbon mitigation, but this may require high initial investments.

5.3.4. Post-processing and Distribution

Post-processing typically includes grinding, sieving, cooling, pelletizing or blending the biochar with other materials such as compost or soil. These steps are energy-intensive and may add operational costs and emissions, particularly if powered by fossil energy. Engel and Eriksson (2024) show that processing biochar for urban applications involved additional emissions due to the blending with compost and stones, resulting in a larger climate footprint than direct agricultural use. Transport logistics, often underestimated, can significantly affect the climate balance of biochar systems, especially when feedstock is sourced remotely, or biochar is distributed over large geographic areas. These stages should thus be optimized and integrated with local sourcing strategies and supply chain logistics to preserve biochar's net-negative carbon potential.

5.3.5. Application and Use-phase Benefits

The effectiveness of biochar in agricultural soils depends on application methods, soil type and the biochar's properties, all of which influence its role in carbon sequestration and climate mitigation. Cornelissen et al. (2013) state that incorporating biochar into the soil through deep mixing or trenching enhances its long-term stability and minimizes losses due to erosion or surface runoff, ensuring maximum carbon retention. Desjardins et al. (2024) found that broadcasting biochar on the soil surface leads to higher volatilization losses, while incorporating it into the root zone increases water retention and microbial interactions, optimizing nutrient availability and plant uptake. Studies show that a 2% biochar application by weight stabilizes soil organic carbon while enhancing productivity (Azzi et al. 2019). Ghimire (2020) found that the application of biochar in Norwegian soils delivered approximately 1.1–1.3 t of CO_2-eq avoided per tonne applied, alongside up to 50% reduction in nitrous oxide emissions. Furthermore, studies show that biochar combined with compost or manure improves soil CEC, reduces nitrogen leaching, and enhances microbial activity, reinforcing its role in sustainable agriculture.

However, if misapplied, biochar may lead to temporary nutrient imbalances or shifts in soil pH, affecting plant performance and causing unintended consequences. Environmental factors such as soil pH, microbial activity and moisture may influence the rate of biochar degradation. For example, poor water conservation or excess tillage can lead to erosion, causing biochar particles to be washed away or leached into deeper soil layers, which affects the long-term sequestration potential. This can lead to nitrogen immobilization, that is eutrophication from phosphorus-rich biochars, and increased particulate matter from poor handling. Site-specific guidelines are therefore critical to balance costs with long-term agronomic and climate benefits.

In sum, integrating life cycle considerations with techno-economic analyses ensures that biochar systems are not only financially viable but also genuinely climate positive. This dual approach highlights trade-offs, avoids unintended rebound effects and supports the design of policies and investments that maximize both economic feasibility and environmental sustainability.

6

BUSINESS AND FINANCIAL MODELS FOR BIOCHAR

The economic analysis of biochar production encompasses a range of factors to systematically evaluate the scale of the initial investment, production costs and long-term sustainability associated with potential economic benefits (Campion et al. 2023). The key determinants of economic viability include the scale of production, the type and quality of feedstock utilized, the production method, the logistics of transporting feedstock to the production facility and mechanisms of pricing and revenue diversification (Campbell et al. 2018). Yet, comprehensive economic feasibility studies remain limited, constraining evidence-based assessments of biochar's economic viability. Bridging this gap requires more than techno-economic analysis alone: as outlined in this section, enabling factors such as coherent policy frameworks, market incentives, institutional innovations and inclusive capacity-building are critical to convert promising economics into practice.

A number of countries have introduced policy programs that directly or indirectly support biochar production. These include financial incentives, non-financial policy support and research and development funding (Pourhashem et al. 2019) (refer to Section 7 for more details). Despite such policy measures, biochar markets remain underdeveloped and future pricing remains uncertain. This uncertainty is linked to variability in potential applications, differences in the characteristics of biochar and the diverse markets spanning the mining, horticultural and industrial sectors (Galinato et al. 2011). Campbell et al. (2018), drawing on information from the International Biochar Initiative, reported that biochar prices range from USD 80 to USD 13,480 per tonne. However, these figures do not differentiate between wholesale and retail prices, nor do they reflect post-conversion improvements. The biochar market is further characterized by its dependence on end use, leading to its classification as an intermediate good. Nonetheless, biochar can also be considered a final product given its role in climate change mitigation—particularly as a tool for reducing greenhouse gas emissions—and its application as a soil amendment (Anderson et al. 2016). These dynamics underscore the importance of examining biochar business models, which can provide practical insights into how production and market challenges are being addressed in different contexts.

Biochar business models vary widely depending on the scale of production, market orientation and the integration of co-benefits such as carbon credits, soil health improvements and waste management services. Four main typologies are often highlighted: (i) cooperative models, where farmer groups or producer organizations jointly invest in biochar facilities to reduce costs and share benefits; (ii) public–private partnerships (PPPs), which leverage government incentives and private sector investment to scale up production and strengthen market linkages; (iii) social enterprise models, which prioritize environmental and community benefits alongside financial sustainability; and (iv) carbon credit-driven models, in which revenue generation relies primarily on verified carbon removal credits.

In practice, these models operate differently across contexts. Cooperative models involve coordination among local organizations, communities and farmers to pool resources and distribute profits. This approach has been effectively applied in sub-Saharan Africa, where cooperatives produce cooking fuel briquettes, water filters and biochar for soil amendment, not only providing financial benefits but also contributing to social cohesion and environmental sustainability (Mohammed et al. 2024). In India, the cooperative biochar business model has been effectively demonstrated through innovative, community-driven approaches to agricultural waste management. In the northern Indian state of Punjab, the Punjab Agricultural University along with the Department of Agriculture installed medium-scale pyrolysis units processing 2–5 tonnes of biomass daily at centralized district facilities to process rice straw and wheat residue supplied by farmer cooperatives. Farmers received direct compensation for residue collection, ensuring strong participation, while the produced biochar was applied to wheat fields at the rate of 5–10 tonnes per hectare. This model led to a 30% reduction in residue burning, 15%–20% higher wheat yields, and carbon sequestration of around 3.5 tonnes of CO_2-eq per hectare, while also generating over 200 jobs in the collection, transport and processing of biomass (Sinha 2025). Similarly, in the southern Indian state of Tamil Nadu, the Tamil Nadu Agricultural University partnered with coconut producer companies to establish a cooperative biochar system utilizing coconut shells, abundant by-products of coconut cultivation. Continuous slow pyrolysis units with heat recovery systems were

Bamboo Charcoal . Photography by Wasana Jaigunta

employed, and the cooperative produced premium biochar-enriched compost branded as ‘CocoChar’, which was integrated into organic farming systems. This model enabled the conversion of 12,000 tonnes of coconut waste annually, improved vegetable yields by 22%, generated revenues of approximately USD 470,000 per year, and reduced greenhouse gas emissions by an estimated 5,600 tonnes of CO_2-equivalent (Sinha 2025). In Shahada in the western Indian state of Maharashtra, a similar cooperative model has been piloted with support from the CGIAR Initiative on Nature-Positive Solutions and the CGIAR Multifunctional Landscapes Program. Here, cotton stalks—traditionally burned, causing air pollution and soil nutrient loss—are repurposed into biochar through locally managed units. The Kanikansara Farmer Producer Company Limited oversees production, while 32 farmers in Sabalapani Village, were trained in unit installation, biochar production and application, residue management and marketing (CGIAR 2025). The initiative not only reduces open burning of agricultural residue, air pollution and greenhouse gas emissions but also enhances soil organic carbon, improves soil fertility and strengthens rural livelihoods. Together, these case studies highlight how cooperative biochar models provide scalable, climate-smart solutions that simultaneously address waste management, soil degradation and environmental challenges, while also enhancing soil health and yields, creating rural employment, and unlock new revenue streams through biochar valorization.

Similar to cooperative models, social enterprise plays an important role in developing countries, where small-scale, community-led initiatives address environmental challenges and create livelihood opportunities.
For example, in South India, social enterprises have established biochar systems, demonstrating biochar’s potential to drive socio-economic transformation (Müller et al. 2019). Building on these grassroots efforts, PPPs

extend circular bioeconomy business models by combining public funds and policy support with private sector expertise and infrastructure. For instance, municipal waste management programs have adopted PPPs to convert organic waste into biochar, reducing landfill dependency, generating revenue from biochar sales and supporting urban greening initiatives (Pavesi et al. 2024).

Finally, carbon credit-oriented models are increasingly central to the biochar value chain, linking production with emerging carbon markets (Box 2). These models involve a complex interplay of stakeholders, including governments, private companies and farmers, each with distinct and complementary roles. Governments establish enabling environments through policy frameworks, subsidies and financial mechanisms that reduce production costs and incentivize carbon sequestration (Elias et al. 2024; Cavallin 2025). They also support research, development and certification systems—such as the European Biochar Certificate and the International Biochar Initiative—to ensure quality and environmental integrity (Han et al. 2023). Private companies drive innovation, develop production facilities and build market linkages, while also participating in carbon credit markets. They often collaborate with governments and farmers by providing equipment and training, or acting as intermediaries between biochar producers and carbon credit buyers (Mohammed et al. 2024; Phelan et al. 2024). Farmers remain central, as primary producers of biomass feedstock and end-users of biochar. Through its adoption, they can improve soil health, increase yields and access new income streams via carbon credit schemes, though high initial costs, knowledge gaps and uncertain markets present significant barriers (Upadhyay et al. 2024).

BOX 2. Asaasepa Artisan Biochar Production: A Carbon Credit Model in Ghana

The Business Model: Asaasepa Limited is a private sector enterprise in Ghana which operates eight production sites that convert cocoa pod husks — a major agricultural residue in Ghana — into biochar while generating verified carbon credits. The company's model integrates waste valorization with carbon credit generation, positioning biochar as both a soil amendment, a carbon sequestration tool and a source of income generation. The enterprise works in collaboration with multiple partners such as C-Sink Manager Tachibana International, dMRV technology provider and broker Planboo, and other international brokers such as Puro Earth. It applies the bulk density method—certified with support from its C-Sink manager—for carbon credit accounting. Planboo plays a central role in monitoring, reporting and verification (MRV), including compliance processes, and the issuance of carbon credit certificates. Like many artisanal biochar producers, Asaasepa does not sell directly to end buyers; instead, international brokers mediate transactions. While this ensures access to global markets, it also creates information asymmetries and reduces price transparency along the value chain.

Benefits and Challenges: To date, Asaasepa has generated an estimated 30,207 tonnes of CO_2-eq, worth of carbon credits valued at approximately USD 130 per tonne. However, the farmers themselves rarely receive the proceeds from carbon credits due to high compliance costs. Structural challenges also persist, including limited understanding of the cocoa value chain among artisanal producers and financial barriers for smallholders to enter carbon credit markets independently. Their experiences highlight both the opportunities and barriers of the carbon credit-driven model. On one hand, it demonstrates how private sector innovation, partnerships and certification systems can enable artisanal producers to participate in global carbon markets. On the other hand, it underscores the need for greater funding support for smallholders and cooperatives, streamlined compliance processes and stronger local capacities to reduce dependence on intermediaries.

7

FROM POTENTIAL TO PRACTICE: ENABLING BIOCHAR INNOVATION

The adoption of biochar is being promoted by diverse stakeholders, including non-governmental organizations, private sector entities and research organizations. For instance, in Ghana, Solidaridad is introducing biochar technology to farmers, particularly in regions facing challenges of climate change impacts and soil degradation. Yet, the benefits of biochar have not been fully realized by farmers, agrifood experts, private sector stakeholders and government ministries of food and agriculture due to policy incoherence, limited attention to gender and social equity, and fragmented approaches across agrifood systems (Pierson et al. 2024). Therefore, supported by in-depth desk research, this chapter examines the enabling conditions required to move biochar from potential to practice, including policy reforms, financial incentives, inclusive strategies, innovation systems thinking, safeguards and evidence-based approaches. Table 3 outlines priority actions across stakeholder groups, highlighting opportunities for coordination and system-wide impacts.

7.1. Policy and Regulatory Landscape

The regulatory landscape surrounding biochar production and use is characterized by a lack of uniformity and specificity across different countries and regions (Van Laer et al. 2015). Various voluntary standards and certifications have been developed. For example, the World Biochar Certificate, the European Biochar Certificate and the International Biochar Initiative standards provide guidance, but these are not universally mandated (Lin et al. 2025). In the USA, the Clean Air Act regulates production technologies, and the United States Department of Agriculture (USDA) has introduced the Soil Carbon Amendment Conservation Practice Standard (CPS 336) (Rodriguez-Franco et al. 2024). Similarly, the European Union has included biochar in its Fertilizing Products Regulation (Štrubelj 2022).

These efforts mark progress, but the prevailing patchwork of regulations creates uncertainty, discourages investment and impedes cohesive market development. In LMICs, regulatory frameworks for biochar are often absent or fragmented, though some national standards are emerging. For instance, India's Bureau of Indian Standards has issued specifications for biochar as a soil amendment (Priyadarshi and Sharma 2025). Countries such as Kenya, Ghana, Nigeria and South Africa are also exploring regulatory guidance within their national soil fertility and renewable energy frameworks. However, such standards remain limited in scope and enforcement, and certification systems are rarely accessible, creating barriers for small-scale producers to access international carbon markets and limiting local uptake despite strong potential demand.

One significant obstacle is the unclear classification of biochar, which is often categorized as a by-product of waste, rather than a soil amendment, thereby restricting its agricultural use (Goh et al. 2018; Štrubelj 2022). Permit processes for production facilities can be particularly burdensome, with stringent air quality regulations raising costs (Pierson et al. 2024). Furthermore, inconsistent quality control protocols also make it difficult to ensure product consistency, weakening trust in emerging markets (Mou 2024). Ghana illustrates the practical challenges: while significant biomass resources exist for biochar production (Duku et al. 2011), there is a huge challenge regarding feedstock access, collection, and transport, as well as competition with livestock feed and household fuel, reducing availability (Rogers et al. 2021). Policy incoherence further exacerbates these issues. Biochar may be classified as waste under environmental regulations but simultaneously recognized for its agricultural benefits, creating confusion and disincentives (Anokye 2024). Likewise, inconsistencies between energy and carbon sequestration policies, with one accounting for biogenic emissions and the other not, create contradictions. This lack of a unified policy approach and integration into agricultural and climate frameworks discourages investment and slows scaling up.

7.2. Incentives and Institutional Innovations

Financial and institutional instruments can reduce barriers to the adoption of biochar. Countries such as Denmark have provided government investment to support agricultural biochar (Thomsen 2024), while the EU's Common Agricultural Policy (CAP) funds biochar projects that improve sustainability (Cavallin 2025). In the USA, the USDA's Environmental Quality Incentives Program (EQIP) offers financial assistance for soil carbon amendments, including biochar (Smith and Swanson 2025). These examples illustrate how financial incentives can offset the upfront costs of production and application, creating stronger incentives for adoption.

Despite such progress, adoption in many contexts is slowed by structural and institutional barriers. These include limited access to affordable finance for small producers, who face high capital costs for pyrolysis equipment (Pourhashem et al. 2019); weak farmer organization and limited cooperative structures which reduce bargaining power and access to carbon markets (Salgado 2021); fragmented research and development and extension systems, which constrain farmer knowledge and evidence regarding optimal application (Prochnow et al. 2024); and uncertain market mechanisms, where carbon credit prices and product quality standards remain inconsistent (Henderson et al. 2022; Salma et al. 2024). To address these barriers, a combination of institutional and market-based innovations that drive scaling up are needed. This includes bankable business models to mobilize resources and expertise for infrastructure and technology development; targeted subsidies and financial instruments to directly reduce adoption costs; market-based mechanisms, such as carbon credit schemes and product standards to create predictable revenue streams (Henderson et al. 2022; Salma et al. 2024); and continued research and development, supported by governments and non-profit organizations, to expand the evidence base and improve locally adapted practices. Also, blended finance, microcredit schemes and access to climate funds are crucial for overcoming cost barriers.

7.3. Gender and Social Dimensions

Biochar adoption is deeply embedded in social relations and gendered roles within agrifood systems. In many LMICs, women are often responsible for food production (Antriyandarti et al. 2024), while youth are central to sustaining agricultural innovation (Kote et al. 2024). However, access to land, finance and technical training remains uneven, limiting equitable participation in biochar initiatives (Paul and Meena 2016). Traditional gender roles may also dictate who is involved in various stages of biochar production and use, from collecting feedstocks to operating pyrolysis units and applying the final product to fields. Therefore, it is imperative that biochar initiatives are designed with a clear understanding of the existing gender roles, power relations and dynamics within communities to be able to ensure equitable participation and the fair distribution of benefits.

When inclusively designed, biochar initiatives can empower women and youth. For example, in Ghana, the GROW2 project trained and supported women's groups to produce biochar from agricultural waste, which improved soil fertility and generated income through carbon credits. Similarly, the ASA Initiative empowered rural women to integrate biochar into their agricultural practices (McGreevy and Shibata 2014). In Bangladesh, biochar application supported the production of indigenous vegetables and fruits (Sutradhar et al. 2021). Youth participation has also proven transformative, equipping them with skills in biochar production and creating employment opportunities in rural areas (McGreevy and Shibata 2014). These examples show that gender-transformative approaches can redistribute benefits, provide new income streams, enhance food security and improve family well-being (Njenga and Mendum 2018).

7.4. Social Inequalities and Land Tenure

While biochar presents numerous benefits, its production and use can potentially reinforce existing social or systemic inequalities if not carefully managed. For instance, large-scale industrial biochar production might favor established corporations with greater access to capital and resources, marginalizing smallholder farmers and local communities (Leach et al. 2010). Uneven access to information, technology and finance can exclude smallholders, further disadvantaging marginalized communities (Rogers et al. 2021). Insecurity of land tenure compounds these risks. In many LMICs, farmers operate under customary or informal systems without long-term guarantees. Because biochar's soil fertility and carbon benefits accrue over time, insecure tenure reduces incentives to invest. Furthermore, the expansion of biochar markets and demand for feedstocks may drive land grabbing and displacement, undermining local livelihoods and resilience (Leach et al. 2010).

Mitigating these risks requires deliberate safeguards. For example, supporting small-scale, community-led initiatives to help retain value locally. Embedding tenure protections into biochar and carbon market policies to ensure that smallholders are not displaced and can benefit from emerging markets. Providing targeted training and finance to marginalized groups to reduce exclusion. Leveraging biochar for environmental justice — for example, in remediating polluted sites and improving soil, air and water quality — can further deliver benefits to disadvantaged communities (Gwenzi et al. 2015; Ghosh and Maiti 2021). Such equity-focused and inclusive strategies can reduce systemic inequalities.

7.5. Innovation Systems and Building Capacities

Scaling up biochar requires systemic rather than piecemeal interventions. Innovation systems thinking highlights the importance of networks of actors, institutions and policies working together to enable technology adoption (Fischer 2001; Pierson et al. 2024). For biochar, this means adapting technologies to local contexts (Müller et al. 2019), while building strong platforms for dialogue and coordination among farmers, researchers, industry, government and civil society. Regarding institutional support, agricultural extension services play a central role in providing farmers with the technical knowledge and training necessary to apply biochar effectively (Colclasure et al. 2024). Digital tools such as Internet of Things-based monitoring, remote sensing and mobile platforms can strengthen both evidence collection and farmer training. They are also important in the provisioning of robust monitoring, reporting and verification frameworks, for example, for quantifying carbon sequestration and soil fertility benefits. Sustained investment in both fundamental and applied research is also needed to fill knowledge gaps and optimize production and application methods (Pierson et al. 2024).

7.6. Safeguards, Evidence and Market Diversification

In addition to policies and institutional mechanisms, enabling conditions include robust evidence generation, clear safeguards and diversified markets. For example, the unsustainable harvesting of feedstock may drive deforestation or competition with the demand for food, fuel and fodder, while poorly controlled emissions can cause local pollution, and competition may exacerbate existing inequalities. International experience shows that the early enthusiasm for biochar carbon credits has sometimes shifted towards speculative investment. Robust safeguards are needed to ensure that climate mitigation claims remain credible and are not primarily profit-driven. As such, safeguards must also be applied to ensure sustainability. This includes considerations for the full value chain and applying 'do no harm' principles that align with broader environmental justice goals (cleaner air, healthier soils and improved livelihoods) in project design. It is also important to diversify the end uses of biochar products, not only as soil amendment, but also in emerging applications — including animal feed additives, wastewater filtration, compost bulking and construction materials — thereby expanding its market potential and resilience. Encouraging entrepreneurship around these applications can further strengthen business models and reduce dependence on a single market.

TABLE 3. Thematic recommendations for policymakers, practitioners and private sector stakeholders.

Actors	Recommendations	
Policymakers	Regulatory frameworks and standards	→ Proactively design and implement adaptive regulations for biochar production and application, anticipating future innovations and market developments, including scenarios where demand might be low or absent. This should include setting up clear quality standards that evolve with scientific understanding and incentivizing best practices through feedback mechanisms, while also considering the opportunity cost of biochar compared to other proven soil ameliorants → Develop and implement a fast-track system to provide permits in a timely manner for setting up production facilities that meet sustainability criteria, ensuring efficient and sustained uptake rather than just initial setup → Establish a national biochar certification body
	Financial incentives	→ Establish dedicated financial mechanisms (for example, green bonds, blended finance initiatives) that explicitly value biochar's multifaceted benefits (soil health, carbon sequestration, waste valorization), acknowledging that these benefits must outweigh the opportunity costs of investing in alternative soil management practices
	Cross-sectoral biochar program development and integration	→ Integrate biochar into national climate finance strategies and explore innovative carbon accounting methodologies that accurately reflect its long-term benefits and impacts → Design cross-sectoral programs that synergize biochar with initiatives in climate-smart agriculture, the circular economy and renewable energy. For example, biochar production from agricultural waste can be linked to rural electrification projects → Develop a national soil health strategy with measurable targets, positioning biochar as a cornerstone solution → Mandate the consideration of biochar in relevant agricultural and land management programs and incentivize its adoption through performance-based payments
	Research, innovation and capacity-building support	→ Establish a national biochar research fund → Foster collaborative research networks that involve academia, industry and farmers to accelerate innovation and knowledge transfer, with defined research priorities → Develop digital extension platforms and training modules specifically on biochar production and use, leveraging data analytics and peer-to-peer learning networks → Establish demonstration farms and farmer-led research initiatives to facilitate the practical transfer of knowledge
	Equity and inclusion	→ Establish a multi-stakeholder Biochar Task Force with representation from marginalized groups, including youth, women and smallholder farmers—co-design policies and implement strategies → Implement gender-responsive budgeting and ensure equitable access to resources and benefits across the value chain, utilizing clear, gender-disaggregated data collection and analysis

Actors	Recommendations	
Practitioners (Farmers, producers)	Networks and partnerships	→ Actively participate in national and regional biochar networks to exchange best practices and explore opportunities for collaboration → Form or strengthen farmer cooperatives and producer associations to negotiate better prices collectively, access shared processing facilities and leverage collective voices to advocate for supportive policies. This includes establishing formal partnerships with research institutions and private sector actors
	Technological innovation and piloting	→ Investigate and pilot integrated bioenergy systems to generate additional revenue streams and explore the development of specialized biochar formulations tailored to high-value crops
	Resource management	→ Implement comprehensive feedstock management plans that prioritize locally sourced waste streams (agricultural residues, forestry byproducts) and actively monitor and minimize the environmental footprint of biochar production processes
	Market development	→ Conduct thorough market research to identify and target diverse end-use applications for biochar beyond agriculture, critically assessing potential demand fluctuations and the competitive landscape with existing, proven soil ameliorants. Develop tailored product specifications and marketing strategies that highlight biochar's unique value proposition where demand exists
	Financial viability (from a user's perspective)	→ Before adoption, farmers and other users should undertake a clear financial analysis comparing the cost–benefit ratio of biochar application versus existing, well-understood soil ameliorants. This analysis should consider initial purchase costs, application costs, potential increases in yields, input cost reductions (for example, of fertilizers) and long-term benefits to soil health, without relying on externalized benefits or subsidies. The decision to adopt should be based on a demonstrable return on investment within a reasonable timeframe
	Policy engagement	→ Engage with policymakers at all levels and showcase successful biochar initiatives to demonstrate its benefits and advocate for supportive policies and incentives
Private sector stakeholders (companies, investors)	Technology and product research and development	→ Increase research-for-development investment in new biochar production technologies that enhance efficiency, reduce costs and minimize environmental impacts, focusing on achieving cost-effectiveness that is competitive with established alternatives
	Collaborative innovation and commercialization	→ Partner with research institutions, policymakers and practitioners through joint research projects, technology transfer agreements, and participation in industry consortia to drive and accelerate the development and commercialization of novel biochar-enhanced products and services across diverse sectors
	Sustainability and ethics	→ Implement robust sustainability protocols throughout biochar operations, including transparent feedstock sourcing, environmental impact assessments, and fair labor practices
	Inclusive business models and policy advocacy	→ Prioritize investments in scalable and commercially viable biochar production facilities. Business models must demonstrate a clear profitability pathway based on market demand and competitive pricing, without dependence on subsidies or carbon credits for baseline operations. This includes rigorous analysis of production costs (feedstock, energy, labor), market prices, distribution channels and sales volumes → Develop inclusive business models that empower marginalized groups and ensure that benefits are shared equitably across the value chain, provided these models are financially sustainable → Engage with policymakers and advocate for supportive regulations and incentives

8

CONCLUSIONS

This report set out to assess the potential of biochar as an agrifood innovation within circular bioeconomy and multifunctional landscape frameworks, such as examining how it can restore soils, valorize waste, and contribute to climate mitigation and adaptation in smallholder contexts. The evidence presented underscores the dual nature of biochar: a promising regenerative tool when applied appropriately, but also one with contested, context-dependent outcomes. On the one hand, biochar can significantly enhance the soil structure, water retention and nutrient availability, while serving as a long-term carbon sink that aligns with nature-based climate solutions. It offers a viable pathway for turning agricultural and organic residues into bio-products, supporting waste diversion, soil rehabilitation and carbon sequestration goals. On the other hand, the report highlights important cautions, such as variability in agronomic performance, risks of contamination or maladaptation under certain soil conditions, feedstock competition and uncertain climate benefits when full life cycle impacts and land-use dynamics are not well considered. In essence, biochar is neither a silver bullet nor a flawed concept, but a technology whose benefits depend on how it is produced and used, where it is applied and for what purpose. Realizing its potential will require integrated approaches, including aligning technological innovation with local context, embedding inclusive business models, establishing and implementing clear regulatory frameworks and generating continuous evidence. When these enabling conditions are met, biochar can move beyond debate to become a transformative element in sustainable agrifood systems.

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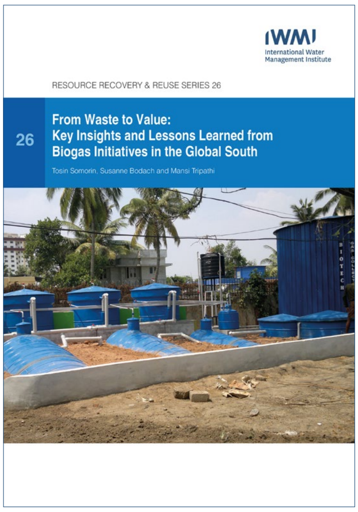

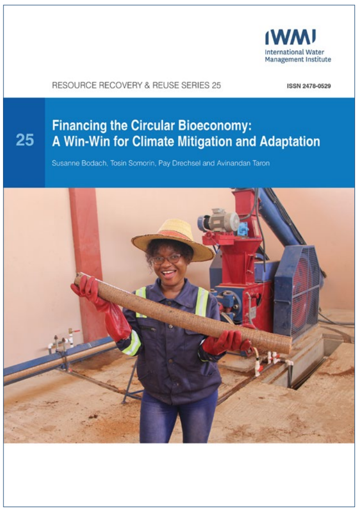

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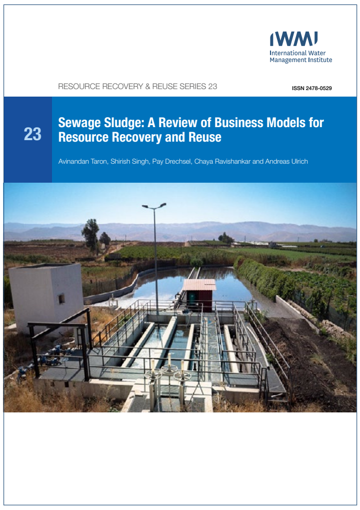

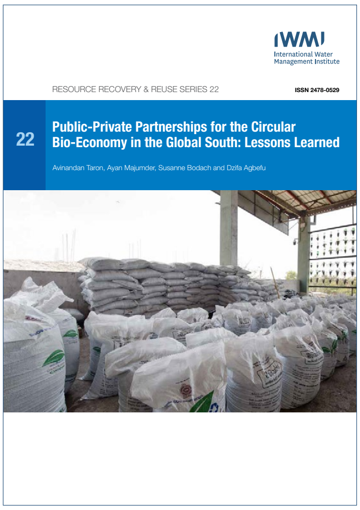

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International Water Management Institute (IWMI)
Headquarters
127 Sunil Mawatha, Pelawatte,
Battaramulla, Sri Lanka
Mailing address:
P. O. Box 2075, Colombo, Sri Lanka
Tel: +94 11 2880000
Fax: +94 11 2786854
Email: iwmi@cgiar.org
www.iwmi.org

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