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Shashikant
Ph.D Scholar, Division Soil Science
And Agricultural Chemistry,
University Banaras Hindu
University, Varanasi, Uttar
Pradesh, India

**Dr. Bhanu Pratap Singh
Raghubanshi**
Sr. Technical Officer, Department
of Soil Science, Rajmata Vijya Rajee
Scindhia Krishi Vishwavidyalaya,
Gwalior, Krishi Vigyan Kendra,
Lahar, Bhind, Madhya Pradesh,
India

Deependra Sharma
SRF, NICRA Project, Rajmata
Vijaya Rajee Scindhia Krishi
Vishwa Vidyalaya, Krishi Vigyan
Kendra, Lahar, Bhind, Madhya
Pradesh, India

Dr. Saurabh Kumar Verma
Assistant Professor (Guest faculty),
Department of Soil Science and
Agricultural Chemistry, College of
Agriculture Colonelganj Gonda,
A.N.D.U.A.T, Kumarganj,
Ayodhya, Uttar Pradesh, India

Akansha Tyagi
Ph.D. Research Scholar,
Department of Soil Science, Sardar
Vallabhbhai Patel University of
Agriculture and Technology,
Meerut, Uttar Pradesh, India

Dr. Biju Sidharthan
Scientist, Department of Plant
Breeding and Genetics, College of
Agriculture, Vellanikkara, Thrissur
680656, Kerala Agricultural
University, Kerala, India

Imtilemla
SMS, Soil Conservation, Krishi
Vigyan Kendra, Mokochung,
Nagaland, India

Arunima Goswami
Ph.D., Scholar, Department of
Agronomy, College of Agriculture,
OUAT, Bhubaneswar, Odisha,
India

Corresponding Author:
Shashikant
Ph.D Scholar, Division Soil Science
And Agricultural Chemistry,
University Banaras Hindu
University, Varanasi, Uttar
Pradesh, India

Biochar for soil carbon sequestration: Mechanisms, opportunities and challenges

Shashikant, Bhanu Pratap Singh Raghubanshi, Deependra Sharma, Saurabh Kumar Verma, Akansha Tyagi, Biju Sidharthan, Imtilemla and Arunima Goswami

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Abstract

Soil carbon sequestration has now become a key approach to reduce the effect of climate change and maintain soil fertility and agricultural sustainability. Among several treatments, biochar application has attracted increasing attention as a method to sequester carbon in soils over centuries to millennia. Biochar is a carbonaceous material produced by the thermochemical processing of biomass in an oxygen-limited environment. In addition to its chemical structure, biochar has unique physical and chemical characteristics such as high porosity, surface area, and oxygen containing functional groups which contribute to enhanced soil quality and long-term carbon sequestration. This review provides an in-depth analysis of how biochar enhances soil carbon sequestration through physicochemical stabilization, interactions with microbes, and associations with organo-mineral matter. Further, it presents promising potential of biochar in climate smart agriculture and waste management, soil fertility improvement and ecosystem recovery. Yet limitations such as the heterogeneity of feedstock, variable field results, economic considerations and insufficient long-term field data, need to be addressed for widespread implementation. The review also highlights potential future research areas such as biochar engineering, life cycle assessment and policy integration. Taken together, biochar is a promising soil carbon lever for maintaining sustainable soils and mitigating climate change.

Keywords: Biochar, soil carbon sequestration, climate change mitigation, soil organic carbon, sustainable agriculture

Introduction

Soil carbon sequestration has gained wide popularity as a mitigation mechanism for climate change, and biochar is considered the best amendment for long-term stabilization of soil organic carbon (SOC). *Biochar* is a carbonaceous and porous solid derived from the pyrolysis of biomass under oxygen-limited conditions (Lehmann *et al.*, 2021; Salma *et al.*, 2024) [36, 57]. The persistence of biochar in soils is attributed to its high aromatic carbon content, low H/C and O/C ratios and high resistance to microbial degradation for centuries to millennia. *Biochar* increases carbon sequestration via multiple pathways, a few of which are chemical recalcitrance (intrinsic), physical protection (e.g., within soil aggregates), complexation with organo-mineral stable complexes and indirectly through modulation of microbial community (Rai *et al.*, 2020). It affects soil carbon dynamics with diminished dissolved organic carbon losses, altered priming effects, and indirectly through increased carbon inputs via stimulated aboveground plant production and belowground root biomass. These processes, in turn, also promote a long-term C stabilization and improve soil physical structure and nutrient as well as water holding capacity, collectively (Gumo *et al.*, 2025; Joseph *et al.*, 2021) [21, 29].

Apart from the potential for carbon sequestration, biochar has also been reported with many other chances for sustainable agriculture, waste management, and environmental restoration (Manikandan *et al.*, 2023) [41]. It enhances soil fertility by stimulating the cation exchange capacity, nutrient availability, leaching loss of nutrients, and reduces emissions of greenhouse gases such as CO₂, N₂O, and CH₄ (Ran *et al.*, 2023; Shrestha *et al.*, 2023) [54, 59]. *Biochar* also promotes climate-smart agriculture as it enhances drought tolerance, crop

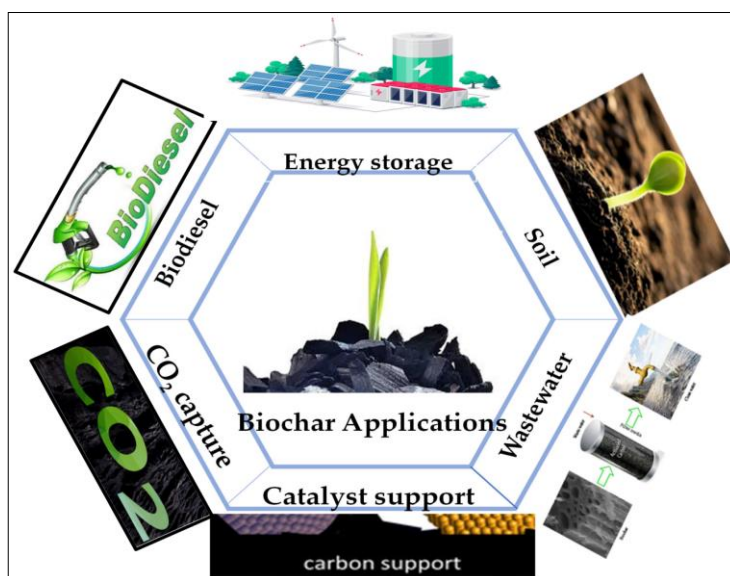
production, and soil quality in degraded, acidic and saline-affected lands (Bo *et al.*, 2023; Babu *et al.*, 2023) ^[11, 6]. Nevertheless, its widespread dissemination is hindered by feedstock heterogeneity, production costs that are too high, variable performance in the field, a lack of long-term experimental data, and uncertainties in life cycle carbon calculation. Other issues involve contamination with heavy metals, polycyclic aromatic hydrocarbons, poor policy and carbon market integration. The next-step advancements in engineered biochar, carbon credit systems, circular bioeconomy models, and AI-driven precision soil management would enhance its potential and scaling up. Ultimately, biochar is both a powerful and an emerging approach for sustainable soil carbon management and climate change mitigation (Kumar *et al.*, 2025; Gryta *et al.*, 2023) ^[33, 20].

2. Biochar production and characteristics

2.1 Production process

Biochar is generated by thermochemical transformation of biomass in oxygen-restricted environment through

pyrolysis, gasification, and hydrothermal carbonization (Leng *et al.*, 2019; Tomczyk *et al.*, 2020) ^[37, 63]. In pyrolysis, biomass is subjected to heat in the absence or near absence of oxygen resulting in its breakdown into solid biochar, liquid bio-oil and gaseous derivatives. Pyrolysis is classified as slow, intermediate or fast based on heating rate and residence time, which in turn affect biochar yield and properties (Bridgwater, 2012; Tripathi *et al.*, 2016) ^[13, 64]. At higher temperatures, gasification with a limited supply of oxygen generates more syngas and less carbonaceous solid residue, while wet biomass can be converted to hydrochar via hydrothermal carbonization at high pressure and moderate temperature, hydrochar varies in stability and soil reaction from pyrolytic biochar. Slow pyrolysis, which is generally conducted at 350-700 °C with longer residence time, is the most utilized method among these for soil due to this reason, *i.e.*, it generates biochar with higher fixed carbon content and more aromatic structure and thermal stable, in that this makes biochar resistant to degradation by microbes and very appropriate for long term soil carbon storage (Liu *et al.*, 2025) ^[40].



Source: Varkolu *et al.*, 2025 ^[65]

Fig 1: Diagram showing various biochar applications

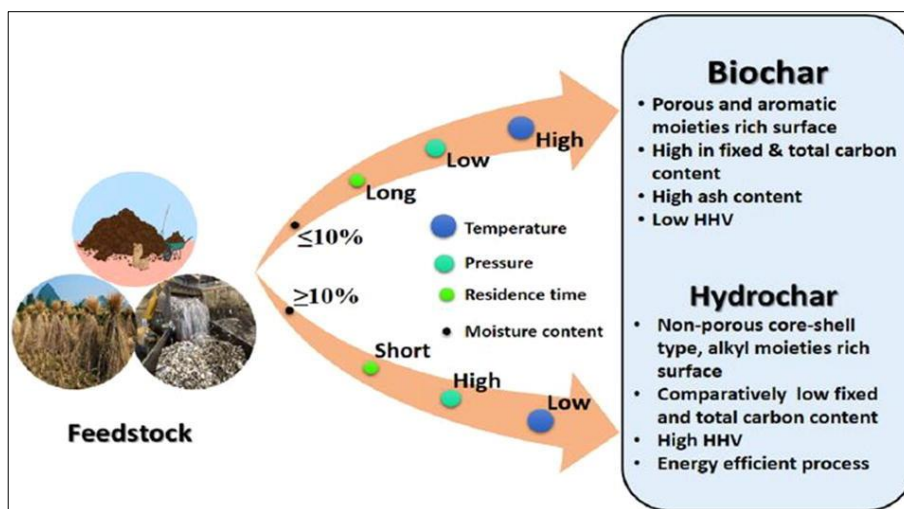
2.2 Feedstock sources

The types of biomass used to produce biochar can vary according to availability and application. Typical feedstock are agricultural by-products such as rice husk, wheat straw, corn stover, and sugarcane bagasse which are abundantly found in agricultural systems and have a great potential in waste valorization (Manikandan *et al.*, 2023; Yadav and Ramakrishna, 2023) ^[41, 68]. Another major source of forestry waste, including wood chips, sawdust, bark, and branches trimmings, produces an usually higher carbon stability biochar due to its abundant lignocellulosic content. Manure from animals is also utilized as a feedstock, resulting in a biochar rich in nutrients that has the potential to improve soil health, though its characteristics are dependent on the types of animal and conditions of processing. Furthermore, city green waste (consisting of lawn clippings, leaves, park residues, etc.) is being experimented with more and more as a green (in every sense of the word) feedstock alternative, providing a means to dispose of waste while promoting

environmental sensibility (Ippolito *et al.*, 2020) ^[27]. Particular source biomass selection significantly impact on physicochemical properties of biochar, such as the carbon content, nutrients composition, the surface area, and stability in soil systems (Tomczyk *et al.*, 2020) ^[63].

2.3 Physicochemical properties

A number of physico-chemical properties of biochar govern its fate in soil and its contribution to carbon storage. It usually has a high carbon content (60–90%), which is partly responsible for its high potential for long-term carbon sequestration. Its structure is mainly aromatic, and is also resistant to microbial decay and environmental degradation. In addition, biochar has a 3D network structure, which is highly porous with a large surface area, it could improve retention of water and nutrients as well as provide shelter for soil microbes (Rizwan *et al.*, 2023; Lehmann and Joseph, 2024) ^[55, 35].



Source- Kumar *et al.*, 2020 [34]

Fig 2: Diagram comparing biochar and hydrochar

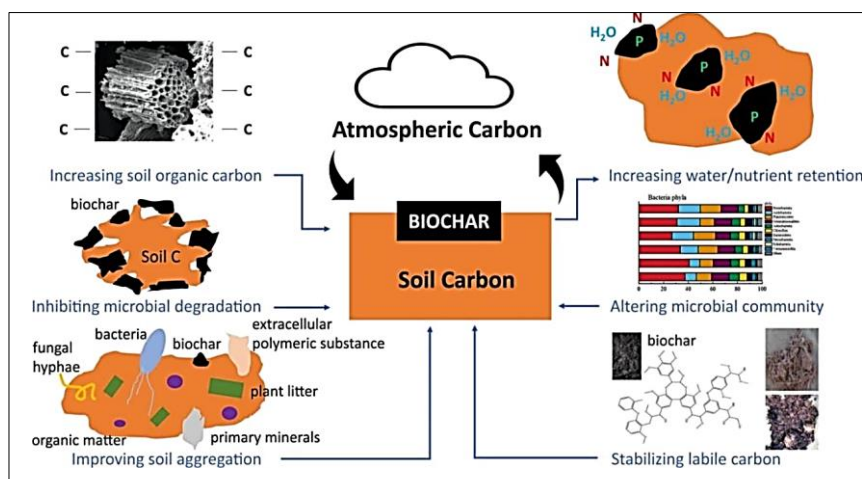
Most often it has an alkaline pH that can neutralize acidic soils and enhance soil chemical status. Furthermore, the reactivity and the interaction with soil nutrients and minerals are enhanced by the presence of some functional groups, *e.g.*, the carboxyl (-COOH), and hydroxyl (-OH) groups. Together these characteristics define its interactions with soil C dynamics via effects on carbon stabilization, nutrient cycling, and microbial dynamics in the soil ecosystem (Blanco- Canqui, 2021; Khan *et al.*, 2024) [10, 32].

3. Mechanisms of soil carbon sequestration by biochar

3.1 Recalcitrant carbon stability

Biochar harbors strongly condensed aromatic carbons, which are very resistant to microbial degradation. This chemical recalcitrance is what allows it to survive for so long in soils, implying that carbon can ages to centuries to millennia. The stability of biochar is largely controlled by the extent of its molecular structure especially the high level of aromatization that is occurred during pyrolysis which

forms condensed aromatic ring structures are strongly bonded and these rings are very difficult for soil enzyme and microorganism to decompose. In addition, biochar is characterized by low H:C and O:C ratios, which are well-known predictors of the degree of carbonization and long-term stability of the material (Spokas, 2010) [61]. These low ratios imply a material with substantial carbon and that is thermally modified, and thus with less reactive sites that can be attacked up on by oxidation. These ratios are indicative of a very carbonaceous material, which has undergone high temperatures and hence contains less reactive sites to attack for degradation. Moreover, recalcitrance to enzymatic degradation further restricts microbial access and consequently retards C turnover in soil systems. Altogether, these metrics characterize biochar as highly recalcitrant and thus promising for long-term soil carbon sequestration (Kane, 2022) [30], which explains a substantial part of its success.



Source: Li and Tasnady, 2023 [38]

Fig 3: Diagram of biochar soil interactions

3.2 Physical protection within soil aggregates

Biochar can be physically incorporated into soil aggregates, where it contributes to the protection of organic carbon against microbial decomposition. *Biochar* particles are progressively enmeshed in soil microaggregates and macroaggregates upon introduction to soil, which physically

protect them from direct microbial attack. This physical protection constrains the decomposers and the extracellular enzymes access to carbon substrates, resulting in slower decomposition. Aggregation also limits the diffusion of oxygen to the protected microsites further suppressing the activity of microbes and the rate of carbon mineralization. In

addition, biochar improves soil aggregation by working as binding agent and interacting with the organic and the mineral soil fraction, which promotes the stability of the soil structure. By these physical and bio-structural pathways biochar not only enhances soil resilience but contradictorily also increases soil organic carbon (SOC) longterm stabilization (Velasquez-Pinas *et al.*, 2025) ^[66].

3.3 Organo-mineral interactions

Biochar is highly reactive with soil minerals, especially clay minerals and metal oxides, and the resultant mineral–biochar or organo-mineral–biochar complexes are a key part of long-term carbon sequestration. These interactions take place frequently by cation bridging, in which multivalent cations (*e.g.* Ca^{2+} and Fe^{3+}) serve as bridging ligands between negatively charged surfaces of biochar and soil minerals and that also stabilizes the soil structure. *Biochar* surfaces also offer active sites for the adsorption of organic compounds, reducing their mobility and vulnerability to microbial degradation. The porous structure of biochar as well as its functional groups may also be involved in physical and chemical interactions with mineral surfaces. Collectively, these events facilitate the protection of organic carbon in soil particles, guarding against rapid turnover and possibly enabling long-term soil carbon pool persistence (Gholamahmadi *et al.*, 2026) ^[19].

3.4 Microbial community modulation

Biochar affects the microbial ecology of the soil by changing the habitat and the resources available to microorganisms in the soil. Due to its porous structure, it provides protective microhabitats that protect microorganisms from predation and environmental pressures and allows for greater microbial colonization. This enhanced quality of habitat often results in an increase in overall microbial diversity, since a variety of microbial taxa can find suitable microenvironments within biochar pores (Kerner *et al.*, 2023) ^[31]. Its effect on fungal:bacterial ratios in the soil however can vary with soil type and biochar characteristics, and environmental conditions. In many instances, it increases microbial carbon-use efficiency as more organic substrates are converted into microbial biomass rather than lost as carbon through respiration. Together, such microbial shifts enhance soil organic C stabilization and long-term carbon storage in soil (Bolan *et al.*, 2024; Palansooriya *et al.*, 2019) ^[12, 48].

3.5 Priming effect regulation

Biochar can affect the dynamics of soil organic carbon through the priming effect, which may be either positive or negative depending on soil conditions, biochar characteristics and soil microbial community response. During negative priming, biochar amendments inhibit the decomposition of indigenous soil organic carbon by limiting the access of microbes to those substrates that are more easily degradable or by redirecting soil microbial activity from matrix surfaces to biochar surfaces, resulting in an overall increase in carbon stabilization (Zheng *et al.*, 2018; Han *et al.*, 2025) ^[69, 23]. On the other hand, transient positive priming may be induced in the short term due to the stimulation of microbial activity by biochar, and enhanced degradation of soil organic matter can be explained by the presence of labile compounds or increased nutrient accessibility. However, despite these opposing early

responses, the long-term field observations suggest that biochar generally promotes carbon stabilization by increasing levels of recalcitrant carbon and decreasing total carbon loss from soil systems (Qu and Ahammed, 2026) ^[52].

3.6 Dissolved organic carbon (DOC) interactions

The strong adsorption capacity of biochar makes it a key factor affecting the dynamics of DOC in soil. Compared with other types of natural organic materials, biochar has a unique ability to adsorb DOC due to its high specific surface area and different functional groups, which can effectively capture DOC molecules and impede their movement in soil profile. This adsorption also hinders the DOC from being leached into deeper layers of soil and run off into the groundwater and eventually contributes to increase carbon retention in the root zone. Moreover, by binding DOC, biochar limits the accessibility of DOC to microbial mineralization and the transformation of readily available carbon to CO_2 (Xie *et al.*, 2026) ^[67]. In combination, these mechanisms decrease carbon losses from soil systems and improve long-term soil C sequestration and/or stability (Hameed *et al.*, 2019; Nemes *et al.*, 2026) ^[22, 44].

3.7 Enhanced root biomass contribution

Plant growth are promoted by biochar, which indirectly led to increased soil carbon inputs and enhanced carbon sequestration in soil. Through increasing soil physical, chemical and biological properties, biochar ameliorates soil environment for root growth, which results in a better root growth with more root biomass and deeper root penetration. This greater belowground biomass adds substantial carbon to the soil via root turnover and decomposition. Meanwhile, enhanced plant vigor leads to greater aboveground biomass, which contributes to the accumulation of litter on the soil surface, thereby improving soil organic carbon pools. *Biochar* also promotes increased rhizodeposition, where plants emit more organic compounds including sugars, amino acids, and organic acids into the rhizosphere, which serve as additional carbon sources for soil microbes. These processes collectively enhance total carbon inputs to the soil system and hence long-term soil carbon storage (Liao *et al.*, 2023) ^[39].

4. Opportunities of biochar in agriculture and environment

4.1 Climate change mitigation

Biochar has a key role in climate change mitigation through increased soil carbon storage and abatement of greenhouse gas emissions. With its very stable aromatic carbon structure, biochar can sequester carbon for hundreds to thousands of years, thus removing CO_2 from the active carbon cycle. Besides storing carbon, applications of biochar to soil can reduce emissions of major greenhouse gases, such as carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4), by enhancing soil aeration, modifying soil microbial populations, and increasing soil nutrient retention. The collective outcomes of these effects are reduction in both the direct and indirect sources of GHG production in agricultural systems. And biochar is gaining prominence as a negative emissions technology not just because it prevents carbon emission from biomass decay, but because it actively locks atmospheric carbon in stable soil pools. Thus, biochar is considered a promising instrument in the pursuit of long-term climate mitigation and

the realization of global carbon neutrality/stability goals (Schmidt et al., 2023; Tisserant and Cherubini, 2019) [62].

4.2 Soil fertility improvement

Biochar is considered a powerful amendment for soil fertility improvement due to the improvement of its chemical properties, particularly cation exchange capacity (CEC), which enhances the soil's nutrient holding and supply capacity for plants. Its porous structure and surface functional groups provide various adsorption sites to adsorb important nutrients including nitrogen (N), phosphorous (P) and potash (K) and maintains their availability for longer durations for plant uptake. *Biochar* reduces nutrient losses by leaching (especially in sandy or highly weathered soils) by better retaining nutrients and water in the root zone. This enhanced nutrient retention contributes not only to improved fertilizer use efficiency, but also to sustained crop productivity and less frequent fertilizer application, which results in more sustainable soil management (Nepal et al., 2023; Ahmad et al., 2024; Alkharabsheh et al., 2021) [45, 2, 4].

4.3 Soil physical improvement

Biochar enhances the major physical quality of soil and so provides improved conditions for plant growth and function and ultimately soil quality. Because its structure is very porous, biochar can hold a lot of water, and as it holds moisture in its pores, it increases the water-holding capacity of the soil, making water more available to plants during dry periods. Nevertheless, the porosity of biochar particles enables the improvement of soil aeration, with the formation of a multi-porous system which facilitates oxygen availability and hence the root and microbial functions. The enhanced pore structure also plays a role in reducing soil bulk density and improving soil aeration, which ultimately leads to a lighter, less compact soil that is easier for roots to penetrate. These physical changes collectively enhance soil aggregation, improve root proliferation, and increase soil production potential (Blanco-Canqui, 2017; Ayaz et al., 2021) [9, 5].

4.4 Waste management

The production of biochar allows for the valorization of a wide range of organic waste materials, such as crop residues, forestry waste, and organic municipal waste. Rather than being burned in air or allowed to decay, these biomass products are transformed into a stable, value-added product in a matter of minutes. This helps not only to deal with large volumes of agricultural or urban waste but also to contain the environmental pollution due to open burning (particulates, greenhouse gases, etc). Amid the waste-to-bioleaching process, the nutrients and carbon contained in the waste can be stabilized as biochar and circulated back into soils, helping to close the loop around resource use, in line with circular economy and sustainable resource management concepts. The technology also allows for a solution to waste management, and to increase soil fertility while reducing climate change (Bukhtoyarov et al., 2024) [15].

4.5 Crop productivity enhancement

Application of biochar has been demonstrated to improve plant productivity and these improvements are attributable to changes in some physiological and soil related processes. It lays foundation for better seed germination and root growth early in the grow season by altering soil textures,

moisture holding capacity and aeration, which is critical for young plants. In addition, biochar enhances the efficiency of nutrient uptake by increasing the retention of nutrients in the root zone and reducing leaching losses, which makes the essential nutrients accessible to the plants for a longer duration. Its high porosity and water-holding capacity also increase drought tolerance by conserving soil moisture during water stress. As a result, these advantages contribute to increased plant growth, enhanced stress tolerance, and greater and more stable crop productivity under diverse environmental conditions (Hussain et al., 2017; Omidvar, 2021) [26, 46].

4.6 Soil restoration and land reclamation

Biochar is a solid product obtained from converting biomass through thermal decomposition in the absence of air (pyrolysis), which has been associated with multiple benefits in soil remediation and the recovery of soil functions. It can restore soil productivity because it improves soil structure, increases soil organic carbon, and makes nutrients available to plants, and these actions collectively contribute to restoring soil productivity under production. In soils impacted by mining, biochar is an excellent medium for sequestering toxic metals, enhancing microbial populations, and restoring soil organic matter, and thus, that application can facilitate ecosystem restoration. It is also good for treating faulty soils including saline and sour soils. *Biochar* promotes salt leaching and water retention in saline soils, while in acidic soils, it increases soil pH through its alkaline property and alleviates acid stress on the plants. By these multiple mechanisms, biochar is instrumental in enhancing soil function and the sustainability of degraded land ecosystems for a long time (Minhas et al., 2026; Bhattacharyya et al., 2024) [43, 8].

4.7 Integration with sustainable farming systems

Biochar can be successfully applied in nearly all forms of sustainable agriculture to improve soil quality and drainage. It acts as a soil conditioner in organic farming and organic matter that aids in retaining nutrients, boosting microbial activity and decreasing obligation on synthetic fertilizers. For example, biochar within conservation agriculture principles of minimum soil disturbance and permanent soil cover is now seen as a way to improve soil tilth, water holding capacity, and stable carbon storage in soils. In agroforestry, it enhances soil fertility, root growth, and nutrient cycling in multiagroecosystems, assimilating itself into tree-crop co-existence within these systems. Likewise, in precision agriculture, biochar is processable in a specified data-deterministic way to modulate soil variables, to increase precision farming of resources and crop stability as well as altitude adaptability. In general, their adoption in the agricultural systems in this review contributes to sustainable intensification and long-term resilience in agriculture (Pandian et al., 2024) [49].

5. Challenges and limitations

5.1 Feedstock variability

Among the key ticketing limitations in biochar application is its natural variability of properties which is mainly due to feedstock type and production parameters. The physical and chemical properties of biochar made from different biomass feedstock are usually dissimilar, which makes its behavior in soil systems unpredictable. Furthermore, differing

pyrolysis temperatures and processing methods may influence the stability of the carbon, impacting the extent to which it can be sequestered over the long term. Likewise the nutrient concentration of biochar is variable; some biochars are rich in nutrients and others are relatively inert, based on the composition of the original feedstock. Such variability creates challenges for standardization, quality control, and large-scale farming application (Abdulraheem *et al.*, 2024; Ahmed *et al.*, 2024; Freitas *et al.*, 2020)^[1, 3, 17].

5.2 Production cost and energy demand

The uptake of biochar is typically limited by financial and infrastructural barriers, especially involving the costs of production and the technology needed. The start-up costs for biochar production systems are relatively high, particularly those involving advanced pyrolysis units with the necessary process infrastructure. Such systems are energy demanding and need technical know-how and maintenance, hence they may add to the total costs of operation. Consequently, so far efficient pyrolysis technology is not accessible to small farmers and rural areas (Eskenazi, 2014). The absence of economical, small scale production units limits the potential of this technology to be widely adopted particularly in developing countries where resources for financing are limited. Therefore, promotion of biochar at the larger scale would also require cost-effective, easy-to-use technologies and the presence of conducive policies to enhance accessibility and feasibility (Silva *et al.*, 2022; Saldarriaga and Lopez, 2025)^[60, 56].

5.3 Limited long-term field data

Biochar adoption is constrained predominantly by economic and infrastructural factors. The capital cost of building pyrolysis facilities and the inventory of specialized equipment and technical know-how adds to the cost of production. These devices also have to be supplied with energy and maintained, resulting in higher operating costs. Hence, access to cost effective biochar production technologies has been out of reach for the smallholder farmers and rural communities. Small-scale units are thus scarce, which in turn limits dissemination and adoption on a larger scale particularly in developing countries, where financial and technical resources are already strained. Hence, the generalization of biochar production would be enhanced by the development of cost-effective production processes, as well as the implementation of best-practice guidance and incentives to improve accessibility and scalability (Bromark *et al.*, 2025)^[14].

5.4 Soil-specific responses

Responses to biochar application in agriculture are often inconsistent in sandy, clayey, and acidic soils, which are considered as soil types susceptible to biochar application. Biochar application frequently enhances water and nutrient-holding capacity in sandy soils, yet response magnitude is influenced by biochar properties and dosage. Effects may also be less evident in heavy clay soils where the nutrient holding capacity is already high and the soil structure relatively stable. Similarly improvement of pH and nutrient availability by biochar in acid soil was reported but crop yield responses were not always consistent. In some situations, increases in yield may be minimal despite enhancement of soil properties because of factors such as nutrient exhaustion, climatic conditions, or incompatibility

of the biochar with the soil. This variation emphasizes that the effects of biochar are highly site-specific and relate to the complex interactions between soil, crop, and climate (Bekchanova *et al.*, 2024)^[7].

5.5 Potential contaminants

Biochar can contain some undesirable substances, including contaminants, that may have environmental implications depending on the feedstock and production conditions. One of the major issues in this regard is heavy metals, particularly when biochar is derived from contaminated biomass (e.g. industrial waste or sewage sludge or some municipal residues). These metals may reside in soil and potentially flow into the food chain if unregulated. Another significant issue is the PAHs (polycyclic aromatic hydrocarbons) that are formed – these are organic pollutants that are formed when combustion is incomplete or in low efficiency pyrolysis processes. The levels of PAHs in biochar are largely influenced by the pyrolysis temperature, the residence time, and the oxygen availability during the manufacturing process. While most properly produced biochars have minimal levels of such contaminants, the risk can be compounded by inappropriate feedstock choices and/or adverse production conditions, underscoring the need for quality control standards in biochar production to ensure safety in agricultural application (Meng *et al.*, 2025; Dong *et al.*, 2025)^[42, 16].

5.6 Carbon accounting uncertainty

Biochar-based carbon accounting is extremely challenging given the complexity of life cycle assessment (LCA) and the uncertainties surrounding full accounting of its actual climate benefits. Performing an entire LCA is challenging as it needs to consider different phases such as biomass production, transportation, energy consumption during pyrolysis, biochar use, and long-term soil activities. Variable emissions and efficiencies characterize each of these levels, coupling, if ever so slightly, the ease of standard assessment with curse of complexity. "There is also uncertainty in how to calculate the net carbon negativity of a biochar system because the carbon sequestration from the stable biochar can be offset by emissions from production and application, and the stability of biochar may vary under different soil and environmental conditions. These uncertainties complicate precise quantification of the entire carbon balance and underline the need for more suitable methodologies and standardized protocols including long-term field data to reliably assess the biochar climate mitigation potential (Pscherrer and Krommes, 2025)^[51].

5.7 Policy and market barriers

Broad-scale application of biochar is also hindered by a range of policy and institutional barriers. One of the major constraints is the absence of well defined carbon credit system that can adequately quantify the gains of long-term carbon sequestration through biochar application. In the absence of standardized procedures for carbon accounting, utilization of biochar in conventional carbon markets may be challenging. Moreover, poor knowledge among farmers on the benefits, usage and long-term advantages with biochar acts as a bottleneck in terms of field scale uptake. Many farmers still do not know its role in soil health, climate change. In addition, commercialization networks remain weak and supply chains are less established to

support efficient production, distribution, and marketing of biochar products. These joint challenges slow its scaling and call for enhanced policy support, extension services and market development strategies (Herath Bandara, 2025) ^[25].

6. Factors influencing biochar efficiency

The efficiency of biochar is affected by several factors such as pyrolysis temperature, residence time, feedstock, soil type, climate, and mode of application. Higher pyrolysis temperatures enhance carbon stability and aromaticity but reduce nutrient content and surface reactivity. Feedstock type has a great influence on the chemical makeup and quality of biochar while soil texture and pH influence how biochar interacts with soil processes, for example nutrient retention and soil microbial activity. Climatic conditions control its long-term stability under field conditions, while application rate and method determine its distribution in and effectiveness to the soil. Cumulatively, these attributes define the efficacy of a biochar to stimulate soil carbon sequestration and to benefit soil health (Ahmed *et al.*, 2024; Harasim *et al.*, 2026) ^[3, 24].

7. Future prospects

7.1 Engineered biochar

Upcoming developments in biochar technology are aimed at improving its performance and the efficiency of its use through the application of tailored modifications. Nutrient-enriched biochar results from loading biochar with important plant nutrients (*e.g.*, N, P, K) that also enhance its value as a fertilizer and facilitate slow nutrient delivery. Nano-modified biochar refers to biochar modified in the form of nanostructures or at its surface at the nanoscale, such as by using metalbased nanoparticles to increase surface area, reactivity and adsorption capacity which improves its capability for nutrient and contaminant retention in soil and water. Coupled biochar fertilizer formulations are created by mixing biochar with organic or inorganic fertilizers, microbial inoculants, or other soil amendments to form integrated soil amendment solutions. The development of these strategies can be viewed as efforts to enhance the agronomic efficacy of biochar, to maximize nutrient use efficiency, and to further integrate biochar into sustainable, and precision agriculture system (Manikandan *et al.*, 2024) ^[71].

7.2 Integration with carbon markets

Carbon markets make biochar application financially attractive by monetizing the value of maintaining soil carbon in the long-term. Climate finance instruments, such as international funding schemes and green investments, facilitate biochar research, infrastructure implementation, and technology transfer. Furthermore, MRV-based protocols for carbon sequestration verification are crucial to properly measure carbon storage and to ensure that there is transparency and trust in carbon markets. Collectively, these processes contribute to mainstreaming biochar within formal climate mitigation options and enhancing its practical application and extension in sustainable agriculture (Frelih-Larsen *et al.*, 2022) ^[18].

7.3 Biochar in circular economy

Biochar contributes to the promotion of circular economy by turning organic waste into wealth. Waste-resource technologies transform agricultural waste, such as crop stalks, animal manure, and garden and kitchen waste, into

biochar while also protecting the environment in the process, as it is a beneficial soil amendment. Energy production can be coupled with biochar production in rural bioenergy-biochar systems, where biomass is converted to energy (heat or electricity) and the char residue is returned to soil, enhancing energy security and soil quality in rural environments. Sustainable biomass use also means that organic resources are efficiently and responsibly utilized to reduce waste and increase environmental and agronomic benefits. Collectively, these strategies facilitate resource recovery, mitigate our reliance on fossil fuel, and provide greater sustainability to the ecosystem as a whole (Pachiyappan *et al.*, 2025) ^[47].

7.4 Digital agriculture integration

Digital agriculture practices are being applied to biochar management, such as integrating biochar into soil carbon sequestration to increase the efficiency and precision of this process. Based on AI technology, soil carbon monitoring provides real-time performing of soil organic carbon dynamics by combining the data from sensors, field observations, and environmental variables. Site-specific information from precision biochar amendments informs the optimal dosage, placement, and timing of the biochar amendment to achieve greatest soil benefit with least resource wastage. Furthermore, soil organic carbon estimation by remote sensing techniques provide a means to monitor carbon fluctuations at regional and global scales through application of satellite remote sensing and geospatial modeling. These technologies and methodologies combined enable better decisions, more accurate carbon accounting, and integration to data-driven sustainable soil management systems (Pradhan *et al.*, 2026) ^[50].

7.5 Long-term field trials

There is impatience towards more cumbersome and longer-term studies to capture the effect of biochar across varying agro-ecological contexts. Multi-site evaluations are required to determine the performance of biochar in different soil types, cropping systems and management regimes applicable to the site of the study. Decade-long investigations are similarly important to investigate the long-term stability of biochar, its effects on soil C sequestration, and its persistent effects on soil quality and crop productivity through time. In addition, validation specific to the climate zone is required since temperature, rainfall, and humidity have great influence on moisture content, decomposition rate, and soil process interaction of biochar. Collectively, these related research efforts are essential to provide credible evidence, enhance recommendations, and safely enable widespread uptake of biochar as an innovative technology for sustainable agriculture and climate mitigation (Jatav *et al.*, 2025) ^[28].

8. Conclusion

Biochar is an attractive approach for sequestering soil carbon and has additional co-benefits in terms of soil health and crop productivity. It's a naturally long-lived form of carbon that resists breakdown by microbes. It also alters other soil physical properties (*e.g.* bulk density, porosity, water holding capacity) and biogeochemical (nutrient retention, cation exchange capacity, microbial communities and soil health) processes. Nevertheless, widespread application is hampered by biochar quality variability, production costs, logistical issues, insufficient long-term

field validation of its efficacy, and uncertainties in carbon accounting. Advances in engineered biochar, enhanced life cycle assessment (LCA) and monitoring, reporting, and verification (MRV) methodologies, and integration with carbon credit mechanisms are anticipated to further cement its significance in sustainable agriculture and climate mitigation. A multidisciplinary strategy of scientific development and enabling policies will be essential to realize its full potential over time.

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