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REVIEW

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Agricultural byproducts converted to biochar to enhance soil functionality through sustainable innovation

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Abstract
Agricultural by-products or residues remain in the soil and are considered a burden unless properly managed. Traditionally, agricultural by-products and agro-food industry-derived waste streams are managed through composting or incineration, but these methods fail to unlock the wastes full potential. Thus, a promising yet unexplored research area for sustainable management of agricultural waste needs to be investigated. Under these circumstances, this review paper positions the conversion of these wastes into biochar (BC). It provides a comprehensive analysis of recent advances and critical limitations in the application of BC, particularly derived from agricultural by-products, for sustainable use in agricultural soils. BC, a carbon-rich product obtained from the pyrolysis of organic materials, has gained significant attention due to its potential to improve enhance soil health by improving soil fertility while, simultaneously sequestering carbon, thereby contributing to sustainable agriculture and climate change mitigation. However, the widespread adoption of BC has notable challenges. This paper elaborates current research on the production of BC from various agricultural residues, examining its physicochemical properties (e.g., surface area, porosity, pH, etc.) and influencing soil amendment processes. The focus is on how effective BC is in enhancing soil fertility, water retention, and microbial activity, along with its role in reducing soil acidity and heavy metal and organic contamination. A critical evaluation of the limitations in current research, including variability in BC characteristics, uncertainties in long-term effects, and challenges in large-scale application, is presented. The paper also explores the economic and environmental aspects of BC application in agriculture, addressing the balance between cost-effectiveness and environmental sustainability. Additionally, the paper discusses the policy and regulatory framework surrounding BC application, highlighting the need for standardized guidelines to maximize its benefits. This review emphasizes the necessity for multidisciplinary research approaches to optimize BC use in agricultural soils, ensuring both agricultural productivity and environmental sustainability.

Keywords Agricultural byproducts, Biochar, Circular economy, Nutrient cycling, Soil remediation, Sustainable agriculture

1 Introduction

Global agricultural waste management has emerged as a pressing challenge due to the massive generation of crop residues, food processing by-products, and other organic wastes worldwide [1, 2]. Improper disposal of these wastes contributes to environmental pollution, greenhouse gas emissions, and resource inefficiency [3]. Transforming these wastes into value-added products is critical for sustainable agriculture and circular economy goals. Biochar (BC), a carbon-rich material produced through pyrolysis of biomass, offers a promising solution by converting agricultural residues into a stable soil amendment [4]. BC not only addresses waste valorization but also enhances soil health, improves nutrient retention, and mitigates climate change impacts [1, 5]. In addition, BC application can help manage residual agrochemicals and restore soil functionality, making it a multifunctional tool for sustainable farming systems [6].

The feedstocks for BC production are diverse, encompassing agricultural waste such as crop residues (e.g., straw, husk, and stalks), wood chips, sawdust, and other organic materials that would otherwise be considered waste [7, 8]. The preparation of BC from a variety of feedstocks involves a sustainable and innovative process that turns waste materials into a valuable resource. BC is produced through pyrolysis, the thermal decomposition of organic material under oxygen-free or limited oxygen conditions [9]. BC is not a single product but a class of materials whose properties are engineered through specific pyrolysis parameters. The nature of the feedstock and the pyrolysis conditions, such as temperature, heating rate, and residence time, significantly influence the properties of the resulting BC, and its chemical structure [10]. These properties, as detailed by Brassard et al. [11], include high surface area, porosity, and a rich in carbon content, which are crucial in determining its effectiveness as a soil amendment [11]. The pyrolysis process can be conducted at various temperatures, typically ranging from 300 to 900 °C, depending on the desired properties of the BC [12, 13]. At lower temperatures (300–500 °C), the thermal decomposition is incomplete. This preserves a high density of oxygen-containing functional groups, i.e., carboxyl (COOH), and hydroxyl (OH). These polar groups are crucial for cation exchange and surface complexation, making low-temperature biochar dominant in binding positively charged heavy metal cations (Cd^{2+}, Pb^{2+}) through electrostatic and chemical bonds [14]. Higher temperatures (600–900 °C) drive complete carbonization, increasing the biochar's aromaticity (graphitic structure) and surface area [15]. Prior to pyrolysis, the biomass is often dried and sometimes ground to ensure uniformity in size and moisture content, which aids in the efficiency of the conversion process [14].

BC's contribution to soil health is profound. Its porous structure and large surface area facilitate water retention in the soil, which is particularly beneficial in arid regions where water scarcity can limit agricultural productivity [16]. By retaining moisture, BC helps plants withstand drought conditions, reducing the need for frequent irrigation and conserving water resources [17]. Moreover, BC acts as a soil amendment that enhances soil fertility [6]. It does so by improving soil structure, increasing nutrient retention, and providing a habitat for beneficial soil microbes [18]. These microbes play a crucial role in nutrient cycling, enhancing the availability of nitrogen, phosphorus, and other essential elements to plants [19]. This increased nutrient retention capacity reduces the leaching of fertilizers into groundwater, thereby minimizing the environmental impact of agricultural runoff.

BC's role in pollution reclamation is equally significant. The adsorptive properties of BC enable it to bind contaminants such as heavy metals, pesticides, and other organic pollutants, preventing them from entering waterways or being taken up by plants [1, 20, 21]. This characteristic is particularly valuable in remediating polluted soils and water bodies, making BC an effective tool in environmental cleanup efforts. In urban and industrial settings, BC can be used to treat wastewater by adsorbing harmful pollutants, thus improving water quality before it is discharged back into the environment [22]. Additionally, when applied to landfills or contaminated sites, BC can reduce soil toxicity and facilitate the reclamation of these areas for agricultural or recreational use.

The sustainable agriculture movement benefits immensely from the incorporation of BC [23]. By enhancing soil health and fertility, BC supports increased crop yields and resilience to climate change [6]. BC's role in reducing the need for chemical fertilizers is another aspect of its contribution to sustainable agriculture [24]. By making soils more nutrient-rich and enhancing their ability to hold onto these nutrients, BC can lead to a decrease in the use of synthetic fertilizers. This not only cuts down on agricultural expenses but also reduces the environmental pollution associated with fertilizer production and use.

The carbon sequestration capability of BC is a vital aspect of its contribution to sustainable agriculture [25]. By converting agricultural waste into a stable form of carbon, BC aids in reducing greenhouse gas emissions from soils and the atmosphere [25]. This characteristic aligns with global efforts to mitigate climate change through carbon management. The economic feasibility and scalability of BC production and application in agriculture are also crucial. The cost of BC production, logistics of application, and market acceptance are significant factors that influence its practical utility [6].

However, the application of BC in agriculture is not without its challenges. Variability in BC characteristics, influenced by feedstock type and pyrolysis conditions, can lead to inconsistent effects on soil and plant growth [26]. Economic and logistical hurdles, such as production costs and the scalability of application methods, also present significant barriers to widespread adoption [6]. Additionally, concerns regarding the potential of contaminants leaching and the long-term effects of BC on soil health and biodiversity remain areas of active research [27]. Furthermore, there is an ongoing need for long-term studies to fully understand BC's impact on soil ecosystems and its potential environmental trade-offs. Addressing these limitations through targeted research and development is crucial for leveraging BC's full potential in sustainable agricultural practices.

Numerous reviews have delved into various facets of BC, ranging from its production, activation [28], and engineering techniques of BC [29, 30], utilization of BC for remediation purposes [31, 32] such as phosphate removal and recovery [33] and rich immobilization of heavy metals in soils [34], evaluating its potential beneficial effects [35]. However, these reviews often focus on singular aspects, lacking a comprehensive discussion that encompasses multiple dimensions. Consequently, the broad scope of BC utilization remains unpredictable. Notably absent from these reviews are considerations of sustainability in BC production and utilization, strategies to address concerns in their long-term utilization, performance under varied and complicated environmental scenarios, and the necessity for tailored application approaches based on soil type and climatic conditions. Incorporating these perspectives could provide valuable insights into the barriers hindering widespread BC adoption. Furthermore, the economic viability and social acceptability of implementing BC into real-time applications have been overlooked, highlighting the need for a more holistic assessment of its potential impact and feasibility.

This review paper aims to provide a comprehensive update on the research surrounding the sustainable application of BC in agricultural soils, encompassing its benefits, recent developments, and the critical limitations that challenge its practical application. The key points of the current study are summarized in Fig. 1. The primary goals of this review are outlined as follows: (1) This study showcases the cutting-edge transformation of agricultural wastes into BC, emphasizing its dual benefits of waste management and soil enhancement, marking a significant stride in sustainable agriculture practices. (2) The article presents a thorough update on the multifaceted applications of BC in agricultural soils, spanning from nutrient retention to enhancement in water-holding capacity, establishing BC as a cornerstone in the pursuit of agricultural sustainability. (3) Uniquely, this research identifies and discusses the critical limitations facing the widespread application of BC in agriculture, including economic feasibility, scalability challenges, and the need for tailored application strategies based on soil type and climatic conditions. (4) This study provides an in-depth analysis of BC's role in mitigating climate change by sequestering carbon, alongside a critical examination of its life cycle and potential environmental trade-offs, contributing valuable insights to the discourse on eco-friendly agricultural innovations. (5) By highlighting the gaps in current knowledge and suggesting future research directions, this article paves the way for novel investigations into BC's formulation, application methods, and long-term effects on soil health, aiming to optimize its benefits for sustainable agriculture. (6) The research integrates findings from agronomy, soil science, and environmental engineering to offer a holistic view of BC's potential, underscoring the importance of cross-disciplinary approaches in addressing complex agricultural challenges. (7) Beyond its agricultural implications, the study delves into the economic viability and social acceptability of adopting BC, providing a nuanced understanding of the barriers to and opportunities for its integration into mainstream agricultural practices.

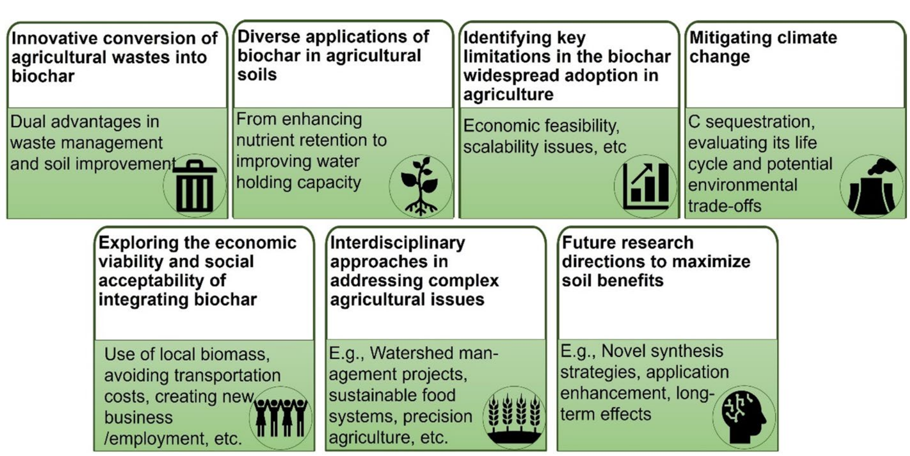

Fig. 1 Key insights for sustainable agriculture practices using biochar

2 Review methodology and search strategy

Previous studies have investigated BC derived from a variety of feedstocks and its potential applications in agriculture, environmental remediation, and waste management. BC studies cover a wide range of research topics, so we narrowed the focus of this current study to agricultural waste-derived BC and the application of that pristine and low-tech BC in agricultural soils for improved soil health, pollution reduction, and holistic development of sustainable agriculture. The review aimed to gather data on various aspects related to biochar, agricultural waste, pollution remediation, and research gaps in previously published articles from reputable sources such as Scopus, Web of Science, and Google Scholar. Furthermore, the biochar produced from agricultural waste and its potential use in agriculture was not restricted to a certain time-derived database. Consequently, our original database accumulated a substantial amount of information. However, thorough screening, selective reading, and critical analysis work together to examine the most important ones for this goal. The keywords included, but were not limited to, "biochar in agriculture", "soil amendment", "agricultural waste management", "the prospect of biochar in agricultural soil", "biochar chemistry in rhizosphere", and "biochar limitation". As a result, the search-derived publications, which included both original and review articles, were sorted without being too bulky.

3 Preparation of biochar from agricultural by-products

Agricultural wastes including horticulture waste, food processing waste, and post-harvest waste are pressing pressure on the atmosphere due to poor management of those perishable wastes [36]. As a result, agro-food waste despite its potential for recycling and valorization considered a burden for the clean environment [37, 38]. The dumping of agricultural waste and traditional composting is the common strategy for agricultural waste management practiced in developing countries [37, 39]. In contrast, biochar preparation by the low-tech approach has emerged as a sustainable option for converting all agricultural waste-derived biomass into black carbon [40]. There are several technologies employed for biochar preparation including pyrolysis, torrefaction, and gasification [41]. Amongst the biochar preparation strategies, pyrolysis is gaining popularity due to technological simplicity and easiness. The temperature range for producing biochar is between 300 °C and 800 °C [12, 13]. The prospective application of biochar for environmental clean-up and tackling global climate change has been documented in earlier studies [30, 42].

There are various agricultural biomass used as feedstocks of biochar including agricultural residues (e.g., rice straw, wheat straw, rice husk, stems, stalks, and foliage), wood chips and forestry timbers, agricultural manures, farmyard manures, cover crops residue derived from legumes, nutshell residue (e.g., coconut shell, and almond shell), and mixed compost pit [43–45]. The specific properties of biochar are mainly dependent on the feedstock biomass properties and pyrolysis process applied during the preparation of biochar. The agro-food waste-derived biochar was considered cheap and low-tech options for soil fertility amendment and stress management [46, 47]. The properties of pristine biochar can be modified through surface activation and by preparation of innovative biochar composites for extended use in environmental applications [48, 49]. The prime mechanisms of biochar during agricultural and environmental applications comprise adsorption and catalysis [6, 43]. Despite the prime application of biochar confined for improvement and organic matter amendment, the recent application of biochar was evident in the fight against soil and water contaminations by the adsorption mechanism of biochar [50–52]. The prospective applications of biochar prepared by agricultural feedstock can increase the soil carbon sink, overall nutrient dynamics, ionic balance in the vascular system, growth and development of plants, and combating against abiotic stressors [53, 54]. The orthodox biochar has a critical research pitfall that hinders the extensive application of biochar for improved soil health and restoration. Thus, the activation of biochar surface and preparation of nano-biochar and biochar composites has emerged as the new technology for addressing the prevailing limitations [55]. However, the cost-effectiveness of the technology and its sustainability as compared to previous methods are still in research infancy. These processes are considered the waste-to-resource approach for sustainable agricultural waste management [20, 56]. Proper utilization of cheap feedstock is possible through nano-biochar preparation, but the initial cost of pyrolysis setup and related obstacles has been reported by previous studies [55]. The selected studies using various feedstock and preparation processes for biochar derived from agricultural waste are available in Table 1. Further, the basic properties of biochar and promising applications of agricultural waste-derived biochar are illustrated in Fig. 2. According to Fig. 2, the porous structure, and high surface are the key features of pristine biochar and the broad application of biochar in agricultural fields for soil health conditioning and addressing abiotic stress sustainably.

4 Biochar and sustainable agriculture- an updated appraisal

The use of biochar (a carbon-based solid material derived from biomass pyrolysis) in agricultural soils increases soil organic matter, which improves plant development and influences soil microbial growth, potentially modifying agricultural contexts and soil physicochemical qualities [65]. BC is a long-term carbon sink, sequestering carbon over hundreds or thousands of years, lowering greenhouse gas (GHG) emissions, and mitigating climate change through carbon neutrality [66]. It is estimated that 1 ton of BC adsorbs 1 GT (Gigaton) of GHG per year [67]. BC, particularly from agricultural biomass, is a long-term solution for handling organic waste resources that might otherwise end up in landfills or incinerated. The initial purpose of applying BC to the soil is to improve the organic matter status of poorly structured soils. However, longer usage of BC may be a preferable option for green environmental remediation, completing the processes in a circular economy manner [6].

Soil depletion and degradation may have a significant impact on global soil health as a result of global climate change and poor pesticide management [37]. As a result, soil erosion and nutrient depletion were observed in tropical soils under harsh circumstances. BC's higher surface area (even in a pristine state) makes it a good adsorbent for soil organic carbon and a habitat for rhizosphere microorganisms [6]. Furthermore, BC has multidimensional qualities such as good water-holding capacity, soil aggregate property, and carbon sequestration, all of which contribute to its value as a soil conditioner in agricultural soils [68, 69]. Recent research has found that BC amendment can enhance soil fertility, crop production, and biochemical nutrient cycling, leading to improved soil health and sustainable agriculture [20, 70]. The high surface area of BC contributes to its adsorption capabilities, making it advantageous for the removal of both legacy pollutants and emerging environmental contaminants as a cost-effective

Table 1 Biochar Preparation from affordable agricultural byproducts, production technology, and prospective applications

Agricultural byproducts	Biochar production technology	Unique feature of biochar	Pyrolysis temp and conditions	Major application	Mechanism of action	References
Rice straw	Pyrolysis	High surface area, and micropore for adsorption	450 °C, slow pyrolysis	Remediation of pesticides and metabolites from soils	Adsorption and catalysis	[43]
Wheat straw	Pyrolysis and torrefaction	Porosity, and high CEC capacity	500 °C	Adsorption of heavy metals (Cd, Cr, etc.)	Adsorption π-π interaction	[57]
Rice husk	Pyrolysis	Significantly reduce the uptake of polychlorinated biphenyls (PCBs) by earthworms and polyethylene passive samplers	700 °C	Polychlorinated biphenyls (PCBs) uptake by earthworms and turnips in a biochar-amended soil	Hydrophobic interaction	[58]
Sugar cane	Pyrolysis	Moisture, volatile matter, ash content, surface area and porosity, using elemental analysis, Fourier transform infrared spectroscopy, and scanning electron microscopy	380 °C	Removal of Thiamethoxam Pesticide in Wastewater	π–π interactions, hydrogen bonding, dipole– dipole interactions	[59]
Wheat straw	Pyrolysis	Largest specific Surface area and Micropore volume	600 °C 700 °C 800 °C	Porous magnetic biochar as an efficient amendment for cadmium in water and soil	Precipitation, surface complexation, ion exchange, physical adsorption	[60]
Corn straw	Pyrolysis	Specific surface area	500 °C	Removal of chromium (VI) and naphthalene from water	Electrostatic attraction, complexation, ion exchange, reduction	[61]
Rice husk	Pyrolysis	High pH and surface functional groups to dominate the immobilization process	500 °C	Cadmium, lead, and zinc immobilization in soil by rice husk biochar	Surface complexation	[62]
Peanut shell	Pyrolysis	Surface area	350 °C	Removal of antibiotics from water using peanut shells	Electrostatic attraction and ion exchange	[63]

Table 1 (continued)

Agricultural byproducts	Biochar production technology	Unique feature of biochar	Pyrolysis temp and conditions	Major application	Mechanism of action	References
Maize straw	Pyrolysis	Significant negative (antagonistic) interaction with phosphorus (P) fertilization on plant biomass production and P concentration in saline sodic soil	500 °C	Phosphorus (P) fertilization on plant growth and P uptake	Precipitation of the soluble phosphate ions, forming insoluble calcium-phosphate compounds	[64]

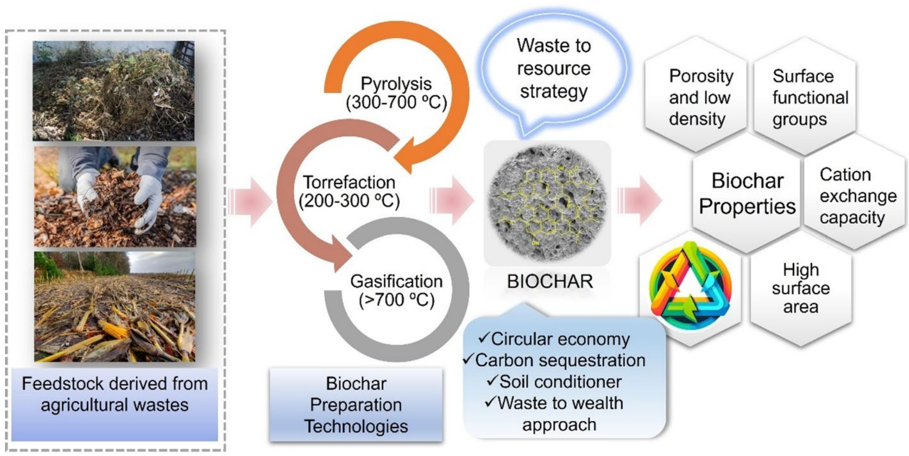

Fig. 2 Biochar derived from agricultural wastes, preparation technology and major applications

and sustainable remediation approach [6, 71]. Improving soil health and fertility by the amendment of biochar (BC) is influenced by soil types, initial organic carbon levels, and clay characteristics of soils [72]. For instance, sandy soils with coarse-textured qualities benefit more, whereas sandy soils are more responsive [69]. Earlier studies demonstrated that BC amendment influences water retention capacity, increasing it up to field capacity (40–60% water holding capacity) for better micropore chemistry [73].

Previous research has indicated that BC can be used to combat drought-stress circumstances due to its high-water retention capacity [74]. Furthermore, BC amendment was reported to regulate soil salinity by modulating electrical conductivity and soil pH conditions via catalysis and buffering of soil fluids [75]. Thus, BC amendment can address the soil attributes in dry and semi-arid regions by improving soil structure and water retention capacity. Agricultural feedstock and slow pyrolysis-derived BC are regarded as low-cost and sustainable options for balancing the water budget and nutrient retention capacity of modified soils [73, 76]. The careful change of minerals from feedstock, in particular, can aid the process of carbon sequestration, boosting sustainable agriculture and repairing salty and drought-prone arable land. BC's hydraulic characteristics and nutrient retention capability are dependent on the biomass feedstock used. For example, wood chip-derived biochar was thought to be a great water adsorbent due to its large surface area. In comparison, dairy manure-derived biochar has a low porous structure and surface area. The study by Gul et al. [77] indicated that adding biochar was beneficial in stimulating biochemical macronutrient cycles. BC amendment may impact the transport and transformation of micronutrients in soil, which is influenced by factors like as soil clay mineralogy and vadose zone chemistry [78].

In addition to increasing the amount of organic carbon in the soil, BC amendments alter the soil's porosity, cation exchange capacity, and redox potential. On the contrary, research has demonstrated that the introduction of BC can enhance both soil biochemistry and plant physiology in the presence of abiotic stressors [79]. Previous studies have found that the addition of coconut husk BC (5% BC, w/w) can modify the physiology of halophytes (such as sesbania and seashore mallow), including root-foliage development and vascular exchange, as well as yield parameters (such as sucrose content and biomass yield in sugarcane plants and maize biomass production, respectively) [63, 80, 81]. In contrast, alkaline BC has the potential to enhance root biomass. Along with initiating nutrient dynamics and modulating soil physicochemical properties, the addition of BC benefits the habitat of numerous soil-beneficial bacteria [82, 83]. BC can serve as a habitat for a variety of soil microorganisms, including plant growth-promoting bacteria and mycorrhiza, as well as a primary trigger for soil microbial population and dynamics [54]. Traditional BC is cost-effective and environmentally friendly for improving soil health and for removing leftover pesticides from treated fields due to the use of inexpensive and readily available feedstock [1, 56, 71]. It is utilized for soil health, and organic matter management, and can serve as an in-situ remediation approach. The efficacy of BC-facilitated pesticide recovery relies on variables such as pyrolysis method, temperature, and the interplay between pesticide and BC. BC-amended soil can reduce pesticide absorption and retain organic carbon and contaminants in stable forms [56].

BC is increasingly being employed in sustainable agriculture to counteract abiotic stress situations such as water stress and organic pollutants due to its multifunctional sustainable technology performance [17, 84]. The promising use of BC for carbon sequestration and soil health restoration has been reviewed [85, 86]. However, pristine BC may not perform well due to the poor nutritional effect of cheap feedstock biomass; thus, modifying or activating the BC surfaces can result in improved performance for soil conditioning and control of pollutants [87, 88]. Nano-BC and biochar composites are new tactics that could lead to advancements in biochar application, as suggested by Chausali et al. [48], Issaka et al. [50], and Rajput et al. [55]. Studies have demonstrated that BC additions can improve soil quality. However, the conventional pyrolysis method has drawbacks such as inefficiency, pollution from raw materials, and issues with soil-plant-nutrient interactions [6]. The global application of BC derived from diverse feedstock biomass is listed in Table 2.

5 Critical evaluation of biochar studies: scale and temporal variability

The presented synthesis, particularly the data compiled in Table 2, necessitates a critical evaluation of the methodologies employed across the cited literature. The reported effects of biochar on soil parameters and plant yield exhibit considerable variability, which is frequently attributable to discrepancies in the scale and temporal resolution of the studies. Therefore, differentiating findings based on experimental type (pot,

Table 2 Selected studies focusing on Biochar application in global agriculture, including feedstock properties and application rates

Type of feedstock or biochar	Biochar application (rate)	Plant/crop	Country	Application in agriculture	References
Wood residues (e.g., teak and rose wood)	Up to 16 t ha^{-1}	Rice	Laos	Higher yield, improved saturated hydraulic conductivity of top soil	[89]
Peanut hull residues	0-200 t ha^{-1}	Quinoa	Germany	Increased growth, crop production & drought tolerance	[90]
Wheat straw	0–40 t ha^{-1}	Maize	China	Increased yield by 15.8% and 7.3% without N fertilization	[91]
Olive stone, almond shell, wheat straw, pine wood chips, and olive-tree pruning	0.5–7.5% (w/w)	sunflower	Spain	Effects on seed germination, improved soil properties and crop production	[92]
Poultry waste	0–1% (w/w)	Brassica campestris	Pakistan.	Reduced metals (Pb and Cd) uptake, improved growth promoter, and soil properties	[93]
Coconut shells	0–15% (w/w)	willow	Czech Republic	Decreased leaching Cd and Zn from the soil	[94]
Hardwood and softwood	0–15% (w/w)	Potato	Denmark.	Ameliorate salinity stress by adsorbing Na+	[95]
Stems of Lantana plants	1–5% (w/w)	Okra	Pakistan	Promote plant growth	[96]
Maize straw	0–30 t ha^{-1}	Maize	China	Crop yield increased	[97]
Cotton stalk	5 t ha^{-1}	Cotton	India	Higher leaf water content (RLWC), chlorophyll stability index (CSI) and seed cotton yield	[98]
Rice husk	20 ha^{-1}	Rice	China	6% economic yield enhancement	[99]
Straw BC	20 t ha^{-1}	Maize	Indonesia	Cacao shell BC recorded an 8.6 times higher yield	[100]
Rice husk and sorghum	2 t ha^{-1}		Ghana	Increment in grain (27%) and shoot biomass yield (16%)	[101]
Corn cob feedstock	5 t ha^{-1}	Cowpea	Ghana	Increased seed yield by 36%	[102]
Acacia spp. wood BC	100 t ha^{-1}	Soybean	Kenya	Increased seed yield by 0.43 t ha – 1	[103]
Sugarcane bagasse BC (SBBC)	4.5 g kg^{-1}	Green gram	India	Enhanced pod yield by 15% over 50% RDF alone	[104]
Willow wood BC	10 t ha^{-1}	Groundnut	Australia	Increased seed yield by 21% over fertilizer alone	[105]
Poultry litter BC	13 t ha^{-1}	Cucumber	Australia	Increased cucumber yield by 300%	[106]
Wheat straw BC	37.18 g kg^{-1}	Wheat	Pakistan	Increasing water use efficiency by 19.30%	[107]
Eucalyptus BC	12 t ha^{-1}	Teff	Ethiopia	Reduced the negative effects of soil acidity on plants	[108]
Pinus roxburghii needle and Lantana BC	2.0 t ha^{-1}	Wheat	Indonesia	Increased nitrogen and phosphorus uptake in loamy soil, increased yield	[109]
Betula spp. wood	20 t ha^{-1}	Barley	Canada	Above 6% yield increased	[110]
Coppiced woodland	0 and 30 t ha^{-1}	Wheat	Italy	Yield increased by up to 30% compared to control.	[111]
Maize con	2 t ha^{-1}	Maize	USA	Positive response in yield	[82]

Reported application rates use different units (t ha^{-1}, % w/w, g kg^{-1}) based on the original studies short-term field, and long-term field trials) is paramount for achieving a nuanced understanding of biochar efficacy.

5.1 Pot and incubation studies

Pot and laboratory incubation studies are characterized by highly controlled environments, utilizing a restricted volume of soil and often high biochar application rates for optimal homogenization. While these conditions facilitate the precise observation of immediate chemical and biological reactions (e.g., rapid pH increase, initial heavy metal sorption), they inherently introduce a "pot effect." This artificial confinement typically leads to an overestimation of biochar's potential in a natural system. Factors such as nutrient dynamics, water flow, and root growth are constrained, meaning the maximal beneficial effects observed in these settings may not be replicated under field conditions. Consequently, results from such studies must be interpreted as demonstrating the mechanistic potential rather than guaranteed field performance.

5.2 Short-term field trials

Short-term field trials, typically spanning one or two growing seasons, offer a more realistic environment by including uncontrolled climatic and soil heterogeneity. These trials are essential for validating initial observations and quantifying immediate, site-specific impacts on crop yield and contaminant mobility. However, the limited temporal scale fails to capture the gradual aging and long-term stabilization processes that govern biochar's ultimate efficacy. As biochar ages, its surface becomes oxidized, altering its functional groups and potentially changing its sorption capacity and nutrient retention over years. A reliance on short-term data risks underestimating the long-term changes in soil structure and soil organic carbon (SOC) that are crucial for sustainable soil management.

5.3 Long-term field trials

Long-term field trials (multi-year) are considered the gold standard for assessing the utility of biochar as a sustainable soil amendment. These trials integrate all temporal and environmental variables, allowing for the accurate monitoring of biochar's persistent and evolving effects. The data generated from these studies provide the most reliable basis for establishing practical and economically viable application rates. It is through these long-term studies that the true mechanism of action transitions from simple, acute chemical reactions (e.g., immediate liming effect) to complex, chronic ecological changes (e.g., stable SOC sequestration and modified microbial communities). Moving forward, the scientific discourse requires a greater weighting of evidence from these extended trials to bridge the existing gap between laboratory optimism and agricultural reality.

6 Biochar-modulating soil features

6.1 Biochar modulating soil physical features

The application of BC to soil is a practice with ancient roots, recently revisited for its potential to address contemporary agricultural and environmental challenges. BC's impact on soil's physical properties is multifaceted, influencing water retention, aeration, and structure [112]. BC's porous structure significantly increases soil's water-holding capacity, mitigating drought stress and reducing irrigation needs. Jeffery et al. [113]

found that BC amendment improved the water retention capabilities of sandy soils, demonstrating its potential to enhance drought resilience. BC decreases soil bulk density (SBD), enhances soil porosity, and augments soil nutrient availability. SBD is strongly correlated with soil compaction and significant aspects of soil physical characteristics [114]. The application of BC in the soil leads to a considerable reduction in SBD compared to soil without BC treatment [25]. When 25 gm kg^{-1} of BC was applied to silty soil, the bulk density reduced from 1.52 to 1.33 gm cm^{-3}. Similar findings were observed in the study conducted by Ahmad Bhat et al. [114].

Soil pores offer ample space and necessary oxygen for soil microorganisms, facilitating their involvement in water transformation, storage, and utilization processes [115]. BC improves the porosity of soil, thereby expanding its surface area. A larger surface area boosts the population of soil microorganisms and activates microbial activities, thereby supporting the development of plant roots in the soil [116]. BC has a high surface area and cation exchange capacity, which enables it to retain nutrients that would otherwise be leached from the soil. Lehmann et al. [117] highlighted BC's potential to act as a nutrient reservoir, slowly releasing nutrients for plant uptake. Following the incorporation of BC into the soil, a significant improvement in soil porosity was observed, particularly in the 5–10 and 25 μm ranges [118]. Wang et al. [119] reported increased wheat yield and root biomass in BC-amended soils, underscoring the direct benefits to plant productivity. BC-amended soils can enhance plants' resistance to biotic and abiotic stresses, such as pests, diseases, and drought. The improved soil conditions and nutrient availability support healthier and more resilient plant growth.

6.2 Biochar modulating on soil chemical properties

BC's interaction with agricultural soil, particularly its modulation of soil chemical features, has garnered significant attention due to its potential to enhance soil quality, fertility, and plant growth. BC can be alkaline, increasing the pH of acidic soils, which is advantageous for plant development in areas where soil acidity constrains the availability of nutrients. For example, a study by Zhang et al. [120] demonstrated that mineral-rich BC application significantly increased soil pH, enhancing nutrient availability and potentially reducing the need for chemical lime amendments. The pH of BC typically ranges between 4 and 12, and its alkaline characteristics can affect the soil's pH upon application [121]. The addition of BC to temperate and tropical zones resulted in a 25% increase in yield in the latter due to low soil acidity and nutrient levels; temperate zones had no effect on crop yield [122]. Alkaline soils were unaffected by the progressive increase in pH that occurred with the BC application rate [123]. Consequently, BC has a good impact on alkaline crops and acidic soils when added to the soil.

BC's porous structure and large surface area contribute to its high cation exchange capacity (CEC), which improves the soil's ability to retain nutrients, such as potassium (K), magnesium (Mg), and calcium (Ca) [25]. This retention prevents nutrient leaching, especially in nutrient deficient environments like rain-fed agricultural systems, making nutrients more available to plants over time. Atkinson et al. [124] found that BC amendments increased the retention of essential nutrients in the soil, promoting sustained nutrient availability for crop uptake.

BC can also reduce the bioavailability of heavy metals in contaminated soils, mitigating the risk of heavy metal uptake by plants and minimizing potential health risks associated with heavy metal accumulation in the food chain [125]. The adsorptive properties of BC can immobilize heavy metals, reducing their mobility and bioavailability. Beesley et al. [126] reported that BC application to contaminated soils decreased the bioavailability of heavy metals, such as lead and cadmium, thereby reducing their uptake by plants.

BC contributes to the stabilization and increase of soil organic matter (SOM) content. Its addition to soil can protect organic carbon from microbial decomposition, leading to an overall increase in SOM [127]. This enhancement of SOM not only improves soil structure and fertility but also contributes to carbon sequestration, mitigating greenhouse gas emissions. Lehmann et al. [82] highlighted the role of BC in enhancing soil organic carbon pools, emphasizing its potential for long-term carbon storage. According to Güereña et al. [128], adding BC to soil changes the nitrogen's circulation, conversion, and retention, which increases the nitrogen's availability and decreases its leaching. Ammonium nitrate is absorbed by BC, which enhances nitrogen use and minimizes nitrogen loss. Chen et al. [129] demonstrated through sand culture studies that BC had potent adsorption effects on NH_3 and NH_4^+, hence mitigating the loss of nitrogen gaseous ammonia in the soil.

6.3 Biochar effects on biological properties and soil microbes

BC's influence on soil extends beyond its physical and chemical properties, significantly impacting the biological aspects of soil health, particularly soil microbial communities (Fig. 3). BC provides a porous habitat that can harbor diverse microbial populations, thereby enhancing both microbial activity and diversity [130]. Its large surface area and unique chemical composition create a conducive environment for microbial colonization and growth. This effect is crucial for nutrient cycling, as microbes play a key role in the decomposition of organic matter and the transformation of nutrients into forms accessible to plants. A study by Lehmann et al. [82] highlights how BC amendment leads to increased microbial biomass and diversity, which can contribute to improved soil fertility and plant health. Moreover, biochar is frequently enriched or combined with beneficial microbes to enhance soil functionality. Its porous structure enables retention of nutrients and microbial cells, allowing it to act as both a nutrient source and a carrier for microbes, as demonstrated in previous studies [131–134].

Biochar amendments selectively alter the soil's microbial community structure, shifting the balance between different functional groups of microorganisms [135]. A particular significant biological interaction is the effect of biochar on mycorrhizal fungi, which form symbiotic association with plant roots. Biochar application has been shown to enhance arbuscular mycorrhizal fungi (AMF) colonization by providing protective microsites and facilitating hyphal network expansion. These mycorrhizal associations improve plant nutrient uptake, particularly phosphorus, and enhance plant resilience to environmental stresses [136]. Furthermore, the synergistic relationship between biochar and mycorrhizae can lead to improved soil aggregation and carbon sequestration, as fungal hyphae bind soil particles together while utilizing biochar as a stable substrate for colonization. However, these advantages of soil amendments on microbial community are dependent on the applied biochar nature as well as the applied quantity and frequency [7].

BC amendments have been shown to affect soil enzyme activities, which are indicative of soil microbial functional diversity and overall soil health. Enzymes involved in carbon,

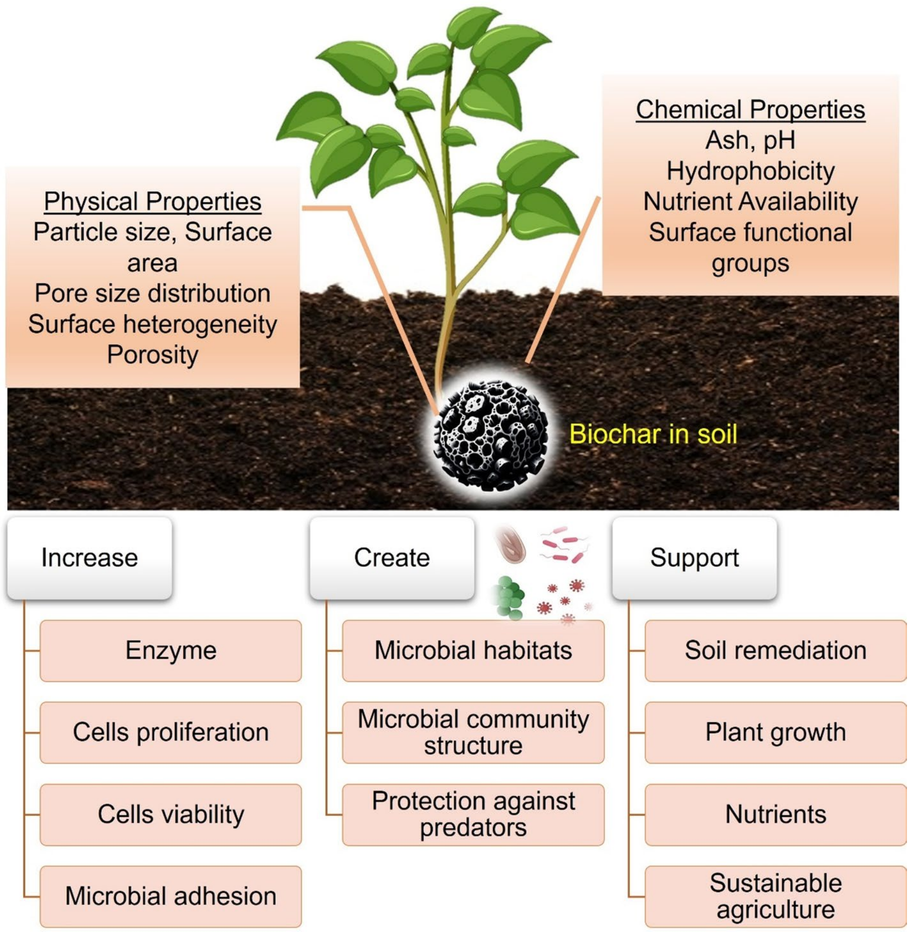

Fig. 3 Schematic illustrating the complete lifecycle of biochar from agricultural byproducts, detailing the transformation process, its application in soil, and the holistic benefits encompassing the modification of physicochemical properties, enhancement of soil microbial communities, and overall improvement of soil functionality and sustainability

nitrogen, and phosphorus cycling can be particularly affected, with BC often enhancing enzyme activities related to these nutrients' availability. For instance, research by Bailey et al. [137] demonstrates that BC application can increase the activity of enzymes like β-glucosidase, phosphatase, and urease, which are involved in the breakdown of complex molecules and nutrient cycling, facilitating improved soil fertility.

BC can modify the interactions between plants and soil microbes, often leading to enhanced plant growth and health. This is partly due to BC's ability to influence rhizosphere microbial communities, which can enhance plant nutrient uptake and provide protection against soil pathogens. The increased microbial activity and diversity in the rhizosphere can lead to more efficient nutrient use by plants and reduced disease incidence. A study by Warnock et al. [138] suggests that BC amendments can alter rhizosphere microbial communities in ways that benefit plant health, including enhanced symbiotic relationships with mycorrhizal fungi.

BC has been reported to suppress soil-borne pathogens, reducing the incidence of diseases in crops. This suppression may result from direct effects on the pathogens, such as physical adsorption or chemical alteration, or indirect effects through the modification of soil microbial communities and enhancement of beneficial microbes that compete with or inhibit pathogens. Graber et al. [139] provided evidence that BC could reduce the severity of soil-borne diseases, attributing this effect to both the direct and indirect influences of BC on soil pathogens and microbial communities.

7 Biochar for agricultural pollution remediation

7.1 Sources and types of pollutants in agricultural soil

Agricultural soil pollution is a growing concern worldwide, as it threatens the long-term sustainability of our food production systems and poses significant risks to both the environment and human health [14]. The contamination of agricultural soils with pollutants such as heavy metals, pesticides, and organic compounds has far-reaching consequences for crop yields, ecosystem health, and food safety [140]. Agricultural soil pollution can originate from various sources, including the excessive use of chemical fertilizers and pesticides, industrial runoff, sewage sludge application, and atmospheric deposition [141]. These pollutants can accumulate in the soil over time, leading to contamination. Pesticides chemicals are used to control pests, weeds, and diseases in crops [1]. Pesticides can include insecticides, herbicides, and fungicides. Residues from pesticide use can remain in the soil and may enter groundwater or be absorbed by crops [1]. Heavy metals like lead, cadmium, and mercury can contaminate agricultural soils through various sources, including irrigation with contaminated water, sewage sludge application, and atmospheric deposition [20, 141]. These metals can accumulate in crops and pose health risks to consumers. Organic contaminants, such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and persistent organic pollutants (POPs), can be introduced through the use of contaminated soil amendments, pesticides, or through the deposition of airborne pollutants [142, 143]. Agricultural activities can introduce pathogens, such as bacteria and viruses, into the environment through animal manure and contaminated water sources [6]. These pathogens can pose health risks to humans and livestock. Contaminated soil can result in the uptake of pollutants by crops, which can then enter the food chain, posing health risks to consumers. This contamination affects the safety and quality of agricultural produce. Soil pollution can disrupt soil ecosystems, affecting soil microorganisms, earthworms, and other beneficial organisms critical for soil health and nutrient cycling. This disruption can lead to reduced soil fertility and ecosystem degradation. Agricultural contamination remediation is important for protecting the environment, ensuring human health, promoting sustainable agriculture, preserving biodiversity, and complying with legal standards.

7.2 Biochar as a remediation solution

BC has gained increasing attention as a sustainable and effective tool for remediating polluted agricultural soils [14]. BC, a form of carbon material produced from biomass, particularly from available agricultural sources, plays a significant role in remediating heavy metals, pesticides, and organic contaminants in agricultural soils due to its unique properties [6]. BC is a stable, porous carbon material that can effectively remediate polluted agricultural soils through various mechanisms. The mechanism of BC in the remediation of heavy metals, pesticides, and organic contaminants in agricultural soil involves several key processes such as adsorption, ion exchanges, complexation and precipitation, modification of soil pH, enhancement of microbial activity, reduction of leaching, oxidation, and reduction reactions [6, 21] (Fig. 4).

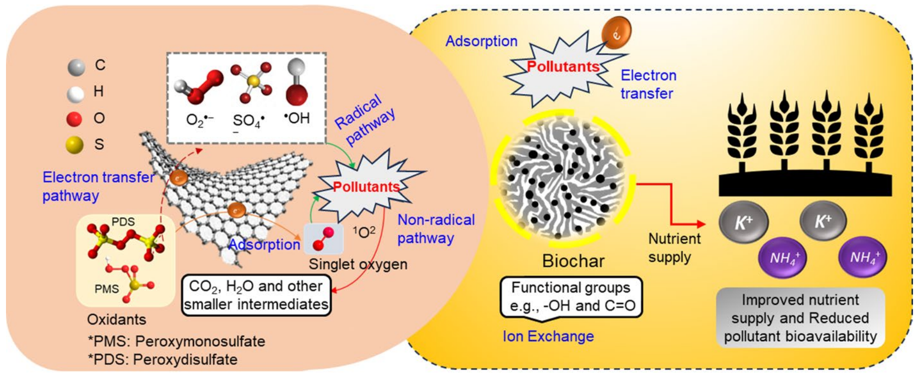

Fig. 4 Mechanistic pathways of soil remediation and enhancement of soil fertility by biochar

BC has a high surface area with a porous structure, making it extremely effective in adsorbing contaminants. The surface of BC can attract and hold onto heavy metals, pesticides, and organic contaminants, trapping them in its structure. One of the primary mechanisms is the adsorption of heavy metals onto the surface of BC [13]. Due to its high surface area and porous structure, BC effectively traps heavy metal ions [144]. This physical and chemical adsorption is facilitated by the various functional groups present on the surface of BC, such as hydroxyl, carboxyl, and phenolic groups [14]. BC can promote ion exchange processes. It contains various inorganic minerals and organic functional groups that can exchange their ions, i.e., Ca^{2+}, Mg^{2+}, and K^+ with heavy metal ions in the soil [145]. This exchange effectively reduces the concentration of heavy metals in the soil solution, thus decreasing their bioavailability to plants [146]. BC can alter the chemical forms of heavy metals in soils through complexation and precipitation reactions [147]. These reactions can transform heavy metals into less bioavailable forms, reducing their mobility and toxicity.

BC often has an alkaline nature and can raise the pH of acidic soils [132, 133]. The increase in pH can lead to the precipitation of some heavy metals as hydroxides, which are less bioavailable [148]. Higher pH can also increase the negative charge on soil particles, enhancing the cationic metal ion adsorption of positively charged metal ions. The porous structure of BC provides a habitat for soil microbes [149]. Iron-containing BC's have been shown to effectively adsorb oxyanions, such as arsenic (As), chromium (Cr), and selenium (Se), from contaminated water, making them a promising solution for environmental remediation. Some microbes are capable of degrading organic contaminants, including certain pesticides, and BC can enhance these bioremediation processes by providing a favorable environment for microbial growth [132, 133]. By improving the soil's physical properties, such as water-holding capacity and aggregate stability, BC can reduce the leaching of contaminants and nutrients. This helps in preventing the spread of contaminants to groundwater or adjacent areas.

BC can serve as a catalyst for advanced oxidation processes (AOPs) in the degradation of organic contaminants in soil, leveraging its unique properties to enhance the efficiency and effectiveness of these processes [14]. Figure 4 depicts the mechanism by which organic compounds in soil are broken down using AOPs, aided by the incorporation of BC systems. BC's role in enhancing the generation of reactive oxygen species (ROS) is a key aspect of its application in environmental remediation and soil health improvement. The high surface area and porous structure of BC provide an ideal environment for catalytic reactions that lead to the production of ROS, such as hydroxyl ($^{\bullet}OH$), sulfate ($SO_4^{\bullet -}$), superoxide ($O_2^{\bullet -}$) radicals and non-radical singlet oxygen ($^1O_2$) [150]. These reactive species are instrumental in breaking down various pollutants, including organic contaminants and potentially harmful chemicals in soil. In addition, BC can produce electron (e^-) transfer in AOPs, which plays a critical role in the degradation of organic pollutants [151]. By facilitating the generation of these powerful oxidizing agents, BC effectively contributes to the degradation of complex molecules into simpler, less toxic forms. This capability positions BC as a valuable tool in AOPs for environmental cleanup and sustainable soil management. BC can engage in redox reactions in the soil. It can alter the oxidation state of certain heavy metals, potentially transforming them into less toxic forms [152]. For example, the reduction of hexavalent chromium (Cr(VI) to trivalent chromium (Cr(III) can occur in the presence of BC [153].

BC emerges as a highly promising solution for the remediation of agricultural soils. Its unique properties, including a high surface area, porous structure, and rich functional groups, make it exceptionally effective in adsorbing and immobilizing a range of contaminants, from heavy metals to organic pollutants. The ability of BC to enhance soil fertility while simultaneously reducing the bioavailability and mobility of harmful substances addresses both environmental and agricultural productivity concerns. Moreover, its role in facilitating advanced oxidation processes and supporting microbial activity further underscores its versatility and efficiency as a remediation agent.

8 Advanced research for future Biochar in sustainable agriculture

The arena of BC research in sustainable agriculture is expanding, targeting the enhancement of soil fertility, and addressing ecological concerns [70]. BC, characterized by its stable carbon content, high porosity, and specific surface area, has demonstrated significant benefits as a soil amendment [154]. Its application has been linked to improvements in the physical, chemical, and biological properties of soil [6]. For instance, BC has shown to increase soil aggregate stability, which is particularly beneficial in sandy soils, leading to increased water retention and reduced soil compaction [155]. Moreover, the diverse agricultural byproducts used for BC production, such as crop residues, can distinctly influence its effectiveness in improving soil health (Fig. 5).

Chemically, BC interacts with soil to enhance its fertility, aiding in the retention of nutrients and agricultural chemicals, thereby reducing their loss through leaching into

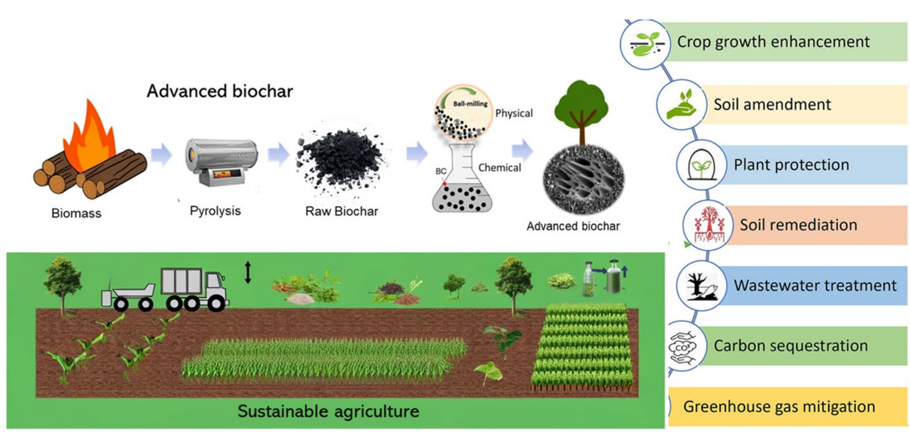

Fig. 5 Enhanced sustainable agriculture by advanced biochar derived from conventional sources

groundwater [156]. BC's structure and surface functionalities make it an efficient adsorbent, thus improving the soil's capacity for nutrient retention [14]. Over time, BC can contribute essential nutrients to the soil, further fostering soil fertility and productivity.

The longevity of BC's effects on soil quality and its role in carbon sequestration also make it a strategic tool for environmental applications. It assists in creating a long-lasting positive impact on soil health and has the potential to store carbon for thousands of years, contributing to climate change mitigation efforts [6]. Advances in research are directed towards the development of engineered BC-based composites tailored to meet specific soil and crop requirements without compromising soil functions [157].

While nano-biochar and biochar-based composites represent promising innovations for enhancing soil fertility and remediation efficiency, their adoption requires careful consideration of potential drawbacks. These advanced materials often involve higher production costs and increased energy inputs due to physical (e.g., ball milling) and chemical activation processes [14], which may limit their scalability and economic feasibility for large-scale agricultural use. Additionally, the long-term ecological implications of introducing engineered nanomaterials into soil ecosystems remain uncertain. Potential risks include unintended interactions with soil microbiota, disruption of nutrient cycling, and persistence of nanoparticles in the environment. Addressing these challenges through comprehensive life cycle assessments, toxicity studies, and cost-benefit analyses is essential to ensure that the sustainability benefits of nano-biochar and composites do not come at the expense of soil health or environmental safety [14, 158].

There is a focus on understanding the mechanisms of biological interactions in the soil- BC system, particularly through long-term and large-scale trials [159]. The integration of BC into poor soils has been shown to notably enhance soil fertility, leading to improved crop development and yields. Furthermore, the coupling of BC with bioremediation strategies offers a holistic approach to soil and environmental health [39]. BC can support microbial communities that are essential for bioremediation processes, aiding in the breakdown of pollutants and the restoration of contaminated sites [1].

The research is pivoting towards customizing BC applications that not only bolster soil health but also optimize nutrient and water use efficiency and play a role in contaminant retention. These efforts contribute to a broader climate adaptation strategy, marking BC as an integrative component of sustainable agricultural practices [160, 161].

The effectiveness of biochar in agricultural soils is highly dependent on site-specific characteristics such as soil texture, climate, and crop requirements. For coarse sandy soils in arid regions, biochar with high water-holding capacity and microporosity, typically produced from lignocellulosic feedstocks (e.g., wood chips) under slow pyrolysis at moderate temperatures (400–500 °C) is ideal for improving moisture retention and mitigating drought stress. In contrast, heavy clay soils in temperate regions benefit more from biochar with enhanced cation exchange capacity and surface alkalinity, often derived from manure-based feedstocks or crop residues subjected to higher pyrolysis temperatures (≥ 600 °C). These tailored strategies ensure that biochar amendments address specific soil limitations, thereby optimizing nutrient retention, water balance, and overall soil functionality under varying environmental conditions.

9 Policy and socio-economic instruments for biochar adoption

The transition of biochar from a promising research output to a mainstream agricultural and environmental tool necessitates the establishment of robust, targeted policy frameworks. While the generalized support for sustainable land management exists, specific, concrete policy instruments are required to overcome financial and regulatory barriers and accelerate adoption.

9.1 Leveraging carbon markets: specific examples

Biochar's intrinsic function as a stable carbon sink makes it uniquely suited for carbon-market integration. The policy discussion must move beyond the concept of carbon sequestration to active market participation.

- Carbon credit schemes: Biochar is already recognized within several voluntary carbon markets, notably those operating in Europe and North America (e.g., *Puro.earth*, EU-ETS compliance schemes). These frameworks provide a verifiable methodology for quantifying the tons of CO_2 permanently removed per ton of biochar applied. This financial incentive is critical, as it can offset 50% to 100% of the production and application costs, thereby shifting the economics from a loss-making endeavor to a profitable venture for producers and farmers.
- Need for standardization: To scale this, international policy must standardize the Measurement, Reporting, and Verification (MRV) protocols for biochar permanence and quality. Global initiatives, like the Intergovernmental Panel on Climate Change (IPCC), need to fully integrate biochar as a recognized negative emission technology to unlock access to larger compliance markets.

9.2 Analysis of policy and regulatory barriers

Despite its benefits, biochar adoption is constrained by identifiable policy gaps:

1. Regulatory uncertainty (Contaminants): The European Biochar Certificate (EBC) and national regulatory bodies (USEPA) still struggle to reconcile biochar with existing fertilizer and waste management laws. Biochar produced from different feedstocks must be categorized consistently to ensure low levels of PAHs (Polycyclic Aromatic Hydrocarbons) and heavy metals are guaranteed, alleviating farmer and regulatory concerns about soil contamination.
2. Lack of financial de-risking: For farmers, the initial capital investment for procurement and application, coupled with the uncertainty of long-term return on investment, represents a significant risk. Existing agricultural subsidies are rarely designed to specifically cover biochar applications.

To overcome these barriers, specific policy instruments (summarized in Table 3) should be implemented at the regional or national level.

10 Conclusion

The exploration of Biochar (BC) as a pivotal element for soil sustainability has unveiled significant insights into its potential to recycle agricultural by-products efficiently. The research presented in this article underscores BC's multifaceted role in enhancing soil health, promoting crop productivity, and contributing to the mitigation of climate change through carbon sequestration. By transforming agricultural residues into

Table 3 Concrete policy instruments for accelerating Biochar adoption

Policy instrument	Mechanism of action	Target outcome
Tax credits/subsidies	mplement direct tax incentives for farmers purchasing certified biochar or using pyrolysis equipment on-farm.	Reduces the upfront cost barrier, making biochar economically competitive with traditional soil amendments like lime or fertilizer.
Regional grant programs	Establish localized grant programs (e.g., through water quality or soil conservation districts) that financially reward biochar use in priority areas (e.g., heavy metal contaminated sites or areas prone to nutrient runoff).	Targets high-impact environmental areas and provides a mechanism for technology transfer and local data generation.
Standardized procurement	Government or municipal entities should initiate public procurement mandates requiring biochar use in public landscaping, soil remediation projects, or land reclamation efforts.	Creates a stable, predictable initial market for new biochar producers, encouraging industrial-scale investment in pyrolysis facilities.

a valuable resource, BC application presents a sustainable solution to waste management challenges while improving the agricultural ecosystem's resilience and productivity. Incorporating BC into agricultural soil also directly aligns with and supports several United Nations Sustainable Development Goals (SDGs), particularly Goal 2 (Zero Hunger), Goal 6 (Clean Water and Sanitation), Goal 12 (Responsible Consumption and Production), Goal 13 (Climate Action), and Goal 15 (Life on Land). The journey towards fully harnessing BC's potential is not without its challenges. The variability in BC's effects on different soil types, crops, and environmental conditions calls for a more nuanced understanding of its interactions within the soil-plant system. Furthermore, the development of localized BC production units highlights the need for tailored approaches that consider local soil characteristics and agricultural practices. This approach ensures that BC's benefits are maximized without unintended ecological or economic consequences.

Although long-term studies on biochar application remain limited, existing research provides valuable insights into its sustained effects on soil and water systems. Evidence suggests that nutrient-holding capacity can persist for several years, though the magnitude and stability of this effect vary with feedstock type, pyrolysis conditions, and environmental factors. Some studies also indicate potential contaminant aging, where pollutants become less bioavailable over time, yet uncertainties remain regarding the mechanisms and duration of these changes. These findings underscore the need for systematic, multi-year investigations to clarify biochar's long-term performance and environmental implications.

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Author contributions

Aniruddha Sarker: Conceptualization, methodology, writing – original draft. Md Abdullah Al Masud: Conceptualization, methodology, writing – original draft, writing – review and editing, visualization, and supervision. Mahlet M. Kebede: Writing – original draft; writing – review and editing. Hasara Samaraweera: Writing – original draft; writing – review and editing . Deen Mohammad Deepo: Writing – original draft. Kallol Das: Writing – original draft. Md. Refat Jahan Rakib: Writing – original draft. FM Jamil Uddin: Writing – review and editing. Ahmed Khairul Hasan: Writing – review and editing.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable. This manuscript is a review based exclusively on previously published literature and does not involve any new studies with human participants or animals performed by any of the authors. Not applicable. No human participants were involved in this study.

Consent for publication
Not applicable. This manuscript does not contain any individual person's data in any form.

Competing interests
The authors declare no competing interests.

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