



Agricultural waste-derived biochar in a circular bioeconomy: Implications for food security, climate mitigation, and sustainable development goals

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ABSTRACT

The energy-intensive contemporary agricultural production system contributes ~20–25% of greenhouse gas (GHG) emissions to the environment. Therefore, global agricultural production systems must transition toward waste-free system to achieve the Sustainable Development Goals (SDGs). SDGs are a roadmap for a comprehensive action plan aimed at achieving global prosperity and environmental sustainability. Hence, it is imperative to develop alternative sustainable green materials, viz., biochar, to improve soil health and environmental quality in line with the United Nations SDGs. Biochar is a renewable and valuable carbonaceous product mainly prepared from biomass and has the potential to contribute to food security and environmental sustainability. Biochar can have positive impacts on environmental quality through soil improvement, waste treatment, and GHG emissions reduction, though its effects vary depending on feedstocks, biochar properties, soil and climatic conditions, and application methods. The production and use of biochar are proposed as an innovative technology to fuelled the SDGs, such as no poverty, zero hunger, safe drinking water and sanitation, affordable and clean energy, and climate protection. However, the impacts of biochar on food production, climate change mitigation, soil and water remediation, and livelihoods need to be critically assessed, which will help researchers and policy planners to set research priorities and policies for cleaner and sustainable agricultural production to achieve the SDGs. Therefore, the present study was planned to assess and synthesize the findings on the impact of biochar uses on agricultural production, environmental quality, and in achieving the SDGs.

1. Introduction

The Sustainable Development Goals (SDGs) were envisioned by the United Nations (UN) in 2015. The SDGs recognize that poverty alleviation must coexist alongside policies promoting economic growth and address a wide array of social needs, including education, health, social security, and employment opportunities, while also fighting against climate change and safeguarding the environment [1]. Furthermore, the SDGs recognize that achieving food security, climate mitigation, and environmental preservation are not mutually incompatible goals, but rather are intertwined. It also recognizes that worldwide and linked challenging problems require international and interconnected

solutions. As the world's population grows, agri-food production must rise sustainably, improving the global supply network, reducing food waste, and providing access to nourishment for those suffering from hunger and malnutrition [2]. Agricultural systems throughout the world must become more resilient, productive, and waste-free to achieve the SDGs. The contemporary agricultural production system is energy-intensive and accounts for 20–30% of energy consumption and contributes to 20–25% GHG emissions [3]. The buildup of lignocellulosic wastes is caused by rising agricultural demand as the population expands. The practice of burning agricultural residue has several negative repercussions, including smoke emissions, loss of soil microbial diversity, air pollution, and detrimental impacts on human health [4]. It

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was estimated that “116.3Tg (Tera gram) of crop residue burning in India releases about 176.1 Tg of CO₂, 10 Tg of CO, 313.9 Gg of CH₄, 8.14 Gg of N₂O, 151.14 Gg of NH₃, 813.8 Gg of NMVOC, 453.4 Gg of PM_{2.5}, and 935.9 Gg of PM₁₀” [5]. Crop residue management solutions that are both environmentally sustainable and economically beneficial are, therefore, critical for agricultural development. In terms of environmental efficiency, the use of wastes recycling and chemical recovery via thermochemical conversion procedures is a potential option [6]. The issue now is: how can agriculture contribute to the attainment of the SDGs? Among the 17 aspirational SDGs with 169 objectives, the goals with direct relation to agriculture are: “No Poverty”, “Zero Hunger”, and “Climate Action”, in addition to the one connected to “Life on Land”. In this paper, the potential of agricultural waste-derived biochar from the perspective of yield improvement, soil restoration, and climate mitigation has been reviewed. Restoration of degraded land through biochar application not only increases yields but also reduces the pressure on natural resources, viz., land, water, and forest [7]. Biochar can be produced through various thermochemical conversion processes, with slow pyrolysis, fast pyrolysis, and gasification being the most common methods, each yielding biochar with distinct physicochemical properties. Slow pyrolysis, conducted at temperatures of 300–700°C with long residence times (hours to days) and low heating rates, produces biochar with high carbon content (>60%), large surface area (50–300 m²g⁻¹), and well-developed pore structure, making it particularly suitable for soil amendment and carbon sequestration [8]. Fast pyrolysis operates at higher temperatures (400–700°C) with very short residence times (seconds) and rapid heating rates, primarily targeting bio-oil production with biochar as a co-product; this biochar typically has lower stability and different surface characteristics [9]. Gasification occurs at even higher temperatures (700–1200°C) with controlled oxygen supply, producing syngas as the main product with biochar as a byproduct characterized by high ash content (>20%), elevated pH (9–12), and high alkalinity [10]. These production method differences significantly influence biochar’s agronomic effectiveness, pollutant adsorption capacity, carbon stability, and suitability for specific applications, necessitating consideration of production parameters when evaluating biochar for particular purposes. Biochar derived from agricultural waste biomass has demonstrated potential to improve crop productivity and soil health, offset carbon emissions, and contribute to environmental quality, though the magnitude of these effects depends on feedstock type, pyrolysis conditions, soil properties, and climatic factors [11,12]. The biofuels and syn gas generated by biochar might be a sustainable supply of biofuels in the future [13], fueled in achieving the SDGs. Reducing the quantity of bulky solid agricultural waste by synthesizing it into biochar and biofuels is an effective way of biochar utilization and various product development [14]. The global biochar market increases day by day and would reach ~ 4.54 billion US\$ by 2030. Growing awareness about biochar benefits is a major driver of increasing biochar demand [15]. Biochar has a variety of uses, such as soil amendments, water filtration, livestock feed additives, pharmaceuticals, and energy generation [16]. The porous quality of biochar aids in entrapping contaminants, resulting in clean water [17,18]. Biochar as a soil conditioner reduces GHG emissions and increases soil nutrient availability, which improves plant growth and ultimately enhances farm productivity [19]. Biochar acts as a soil conditioner that can aid in the achievement of sustainable agricultural and environmental goals [20,21]. Biochar has the potential to remove pollutants due to its distinct properties, including high cation exchange capacity (CEC), large surface area, and non-carbonized fraction combined with surface oxygen-rich functional groups, though removal efficiency varies with biochar characteristics and pollutant types [22]. Biochar is also an effective carbon-sequestration material for fighting against global warming. Biochar is incredibly resilient and remains for an extended period in the soil while slowly releasing plant nutrients. Biochar has drawn attention to the bioeconomy, which is concerned with the transformation of raw materials into value-added products and green energy [23,24].

Energy gasification facilities support novel techniques of biomass processing and electricity generation, which is connected with SDG 9 (Innovation and infrastructure). SDG-15, which focuses on “Life on Land,” has vowed that the nations would take immediate measures to halt the loss of natural habitat and biodiversity. Biodiversity is under threat because of several natural and anthropogenic factors [25]. Biochar can also help to preserve biodiversity and minimize reliance on expensive resources [26]. Furthermore, biochar is seen as a green alternative to fossil fuels, addressing SDG 13, which promotes “climate action”. Biochar typically produces less smoke than charcoal or coal when combusted, as volatile components are largely removed during the pyrolysis production process [21]. Due to the large surface area and porosity, biochar absorbs and retains much water when applied to the soil [27]. In line with SDG 2, which supports zero hunger, biochar has the potential to enhance agricultural productivity by improving degraded soils and increasing crop yields under appropriate conditions, thereby contributing to food security. Therefore, applying biochar improves soil quality, agroecosystems functioning, and adaptation to a changing climate, thereby increasing agricultural productivity. Biofuel and biochar-derived gases are important sources of green energy [12]. However, the beneficial potential of biochar to convert agroecosystems and produce a sustainable environment necessitates logical study in addition to economic and social research. While several reviews have examined biochar’s role in individual applications such as soil improvement, carbon sequestration, or pollution control, this review provides a unique and comprehensive synthesis by systematically integrating biochar applications across multiple interconnected SDGs within a circular bioeconomy framework. Our specific contributions include: (1) comprehensive integration of agricultural waste-derived biochar applications across five major SDGs (poverty alleviation, zero hunger, clean water, affordable energy, and climate action) with explicit discussion of synergies and trade-offs; (2) critical assessment of biochar effectiveness across diverse soil types, climatic conditions, and production methods; (3) synthesis of recent evidences on emerging applications including removal of new pollutants such as microplastics, PFAS, and pharmaceuticals; (4) integration of biochar technology into the circular bioeconomy concept, demonstrating how agricultural waste transformation creates value chains that simultaneously address waste management, energy generation, and sustainable development; and (5) identification of critical knowledge gaps and context-specific recommendations for biochar application. This integrated framework provides researchers, policymakers, and practitioners with a comprehensive roadmap for leveraging biochar technology to achieve multiple SDGs synergistically rather than in isolation.

The present review describes the state of the current application of biochar for achieving the maximum attainable SDGs. This study will provide a unique opportunity for policy planners, agricultural researchers, and environmentalists to formulate agricultural planning to achieve the related SDGs by 2030. So far, studies are in lacking a comprehensive review of the role of biochar in controlling adverse climatic conditions, securing food, and achieving the SDGs through biochar used in agriculture. Hence, the current study was conducted to screen the published documents about the effect of biochar on environmental quality, soil health, agricultural crop productivity, and human livelihood security to provide a realistic and comprehensive view of the production and use of biochar in agricultural production systems, resource conservation and generation, and overall environmental health. Furthermore, this study summarizes important information on biochar production and its marketing strategies, the multitude of implications of biochar in the agricultural sector, clean water and pollution control, environmental health and sustainability, etc., which will provide significant information for future biochar research and policy planning.

2. Biochar and sustainable development goals interface

2.1. Biochar for zero hunger and poverty alleviation (SDG 1 and SDG 2)

In 2015, the United Nations (UN) established 17 SDGs to be achieved by 2030 to ensure a sustainable future [28]. These SDGs created a global action plan to achieve peace and socio-economic and environmental justice. About 736 million people are still living on < \$1.90 a day; many don't have access to food, clean water, and sanitary facilities until 2015 [1]. Fast economic growth has lifted millions of people out of poverty in countries like China and India, but progress has been uneven. Although many developing countries that were previously plagued by scarcity and hunger are now able to fulfill their nutritional needs. However, unfortunately, extreme hunger and malnutrition remain the main issues in many countries. In 2017, an estimated 821 million people were chronically malnourished, in addition to environmental decline and biodiversity loss. The SDGs aim to eliminate all forms of poverty and hunger by 2030 by promoting sustainable agriculture, assisting small-scale growers, and ensuring equal access to land and technology.

The various forms of biochar may be produced depending upon the feedstock type and pyrolysis conditions. When utilized as a soil amendment, biochar can significantly affect soil quality by modifying the physical, chemical, and biological properties of the soil, though the extent and direction of these effects vary with soil type, climate, application rate, and biochar characteristics [29]. Its soil application can promote plant development and potentially increase yields, and it may also assist in the reclamation of salt-affected soils [30,31]. Biochar is a natural and financially reasonable method for mine spoil reclamation, which improves soil properties and further advances agricultural production in mine soil [32]. Biochar application increases soil water holding capacity (WHC), porosity, and soil microbial growth while decreasing GHG emissions [33]. Biochar can help to manage biomass, promote renewable energy, increase crop productivity, and improve quality besides mitigate the effects of climate change. Biochar supports SDG Target 2.3, which aims to "enhanced the agricultural productivity and incomes of small-scale food producers" by 2030. It contributes to

SDG Target 2.4, which focuses on "ensuring sustainable food production systems and implementing resilient agricultural practices that increase productivity", through enhanced soil health, reduced input requirements, and improved environmental sustainability. For poverty alleviation, biochar contributes to SDG Target 1.1 by creating economic opportunities through pyrolysis enterprises, biochar marketing, and improved farm incomes from enhanced productivity. Additionally, it addresses Target 1.4 (by enabling productive use of previously degraded or abandoned lands, thereby expanding the resource base available to smallholder farmers and rural communities. The following subsections present evidence for these contributions with reference to measurable impacts and documented case studies.

2.1.1. Biochar for the yield improvements of crops

To meet the food demand of a rapidly growing population, agricultural production must be enhanced more than the pace of population growth [34]. Many studies have shown that a sustainable farming system can produce more food without compromising the soil or water quality [34]. Biochar can be used to improve the land available for farming, resulting in increased yields and reduced need for land expansion [11,35,36]. Agricultural waste-derived biochar enables sustainable waste management, creates wealth by fuelling a circular economy, remediates soil, and increases yield (Fig. 1). The addition of biochar significantly increases plant development and soil nutritional status, as well as nutrient use efficiency (NUE) [37]. Biochar application increases the yields of different crops. For example, maize yield increased by 90–150%, while water use efficiency (WUE) increased by 90–140% [38]. The yield of groundnut increased by 23–24% and of wheat by 9–10% when the biochar compost was used [39]. Biochar improves the availability of plant nutrients, increases microbial diversity, and reduces the exchangeable aluminum [40,41]. Long-term (10 years) application of biochar at the rate of 50 Mg ha⁻¹ increases maize yield by 1.2 tonnes ha⁻¹ over control [42]. This indicates that biochar has a sustainable, beneficial impact on crop yields and soil fertility. The yield of maize, cowpea, and groundnut was increased due to the application of charred bark of *Acacia mangium* with fertilizer to the tune of

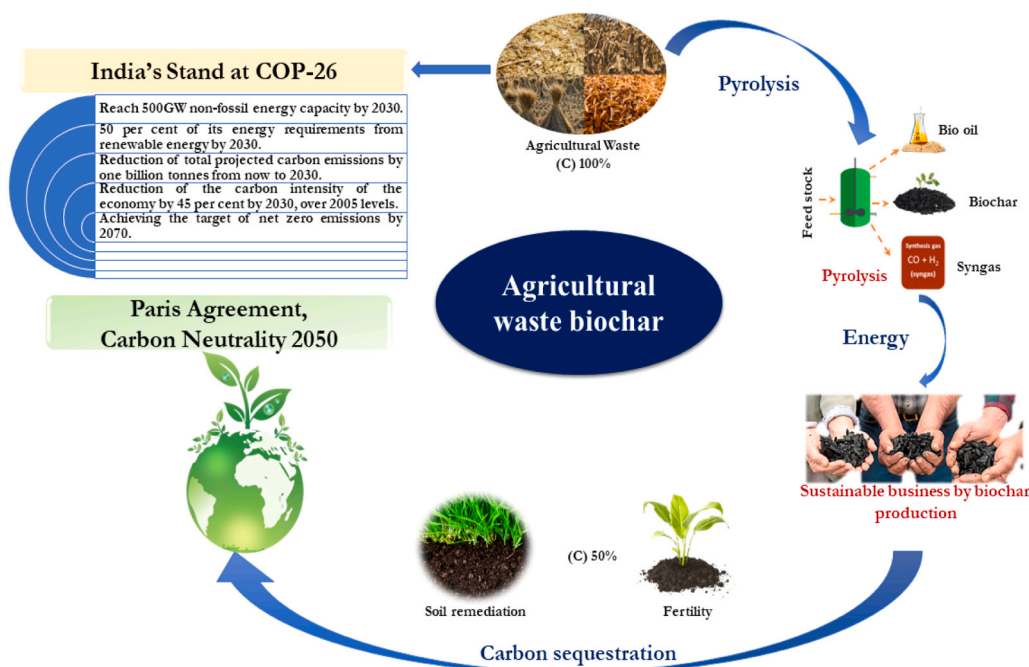


Fig. 1. Circular economic pathways of agricultural waste biochar. The schematic shows the conversion of agricultural residues and agro-wastes into biochar via pyrolysis and its major application routes, including soil amendment, water treatment, carbon sequestration, renewable energy generation, and development of value-added products. Circular flows highlight the closed-loop system that enhances agricultural productivity, resource efficiency, and sustainability within a bioeconomy framework.

200% in less fertile soil due to an increase in the availability of nitrogen and phosphorus, mycorrhizal fungi colonization, and reduction of exchangeable aluminum [40]. Biochar made from rice husks increased maize yield by 68% over control when combined with lime [43]. The biochar used in this study was produced through slow pyrolysis at 450°C, which resulted in a moderate surface area and good nutrient retention capacity suitable for acidic soil amendment. Biochar compost enhanced crop yields by increasing the supply of nutrients, modifying soil pH, enhancing NUE, increasing the soil CEC and improving soil WHC [44,45]. The instant effects of applied biochar on soil nutritional status are mainly due to the faster release of macro- and micro-nutrients in the soil system [46]. Rice yields in temperate and subtropical countries were enhanced by biochar amendments, mainly due to a decrease in soil pH [47]. Furthermore, when biochar was applied at 10 Mg ha⁻¹ along with 100 N ha⁻¹, 60 P ha⁻¹, and 60 K ha⁻¹, the yields of maize, okra, and cassava were substantially increased [48]. The average yield increment in barley was 257% with the application of biochar + compost compared to the control [41]. Under deficit irrigation conditions, the growth and yield of tomatoes increased with biochar application [49]. However, it is important to note that biochar effects on crop yields are not universally positive and vary considerably across different contexts. Several studies have reported neutral or minimal effects of biochar application on crop productivity, particularly in fertile soils with adequate organic matter content. A meta-analysis has shown that biochar effectiveness is highly context-dependent, with the greatest yield benefits observed in acidic soils (pH < 5), coarse-textured soils, and in tropical regions, while effects are often negligible in neutral to alkaline soils or well-managed agricultural systems [50]. The variability in crop response depends on multiple interacting factors, including soil type, initial soil fertility status, biochar feedstock and pyrolysis temperature, application rate, crop species, and climatic conditions. Additionally, some studies have reported that excessively high biochar application rates (>40 Mg ha⁻¹) can lead to nutrient immobilization, particularly nitrogen, potentially reducing yields in the short term [51]. These variable results highlight the need for context-specific biochar recommendations and careful matching of biochar properties to soil conditions and crop requirements.

2.1.2. Biochar for restoration of degraded lands

Biochar is gaining research attention due to its potential to improve soil fertility, store carbon, contribute to energy generation, and adsorb organic and inorganic pollutants, though effectiveness varies across applications [52,53]. Biochar can potentially improve soil pH, CEC, soil structure, water holding capacity (WHC), and surface area under abiotic stress conditions while reducing soil bulk density (ρ_b) [54,55]. The carboxylic, phenolic, and lactones were removed by biochar application derived from pine needles, while basic functional groups such as ketones, pyrones, and chrome were accumulated [39]. Biochar represents a potentially viable and cost-effective option for removing toxins and pollutants from soils and water through sorption mechanisms [53]. Biochar alleviates salinity stress through sodium (Na) removals, reducing Na adsorption ratio, and electrical conductivity (EC) [56]. In rhizospheric soils under maize cultivation, the combined application of biochar and poultry manure compost with pyrolytic solution increases microbial biomass carbon (MBC), urease, invertase, and phosphatase activities [57]. In saline soils, furfural biochar decreased pH while increasing SOC, CEC, and available phosphorus [58].

The goals of SDG 12 (responsible consumption and production) can be accomplished through biochar-based soil restoration and mitigation. Biochar-based eco-restoration of coal mines can improve soil health and WHC while increasing carbon storage [32]. Biochar can remove oxygen-rich volatile substances such as phenols and ketones from the environment. When biochar was used in newly recovered coal mine debris, Liu et al. [59] found a 97%, 66%, and 90% increase in N, K, and P levels, respectively. Furthermore, biochar amendment reduced the bioavailability of toxic metals and increased the immobilization of

heavy metals [60]. Likewise, the application of macroalgae biochar reduced Zn, Ni, and Cr concentrations by 55%, 2%, and 49%, respectively [61]. Biochar applications may also have significant potential for improving soil WHC and reclaiming degraded landscapes and soils [41]. The yak dung biochar applications had a positive impact on the restoration of degraded grasslands in the Tibetan Plateau [33]. Recent studies have also highlighted the variable effectiveness of biochar in land restoration depending on soil type and biochar characteristics. Research on wood gasification biochar application in sub-alkaline Mediterranean soil conditions demonstrated inconsistent or negligible effects on soil properties and plant growth under certain circumstances. Specifically, studies showed that gasification biochar, characterized by high ash content and alkalinity, may not provide expected benefits in already alkaline soils and can even reduce nutrient availability in some cases [62,63]. These studies emphasize that biochar produced through different thermochemical processes, such as gasification versus slow pyrolysis, can have substantially different physicochemical properties, leading to variable outcomes in different soil environments. The alkalinity, ash content, surface area, and functional groups of biochar vary significantly based on feedstock and production process, which in turn affects its performance. This underscores the importance of matching biochar characteristics to specific soil conditions and restoration objectives rather than assuming universal applicability.

2.1.3. Employment generation via the pyrolysis industry and biochar marketing

Bioeconomy refers to the exploration and utilization of biological resources and the use of biotechnology to develop new commercial bioproducts [64,65]. The raw material, in this case, is biomass, and the bioproduct is biochar, which is an important feature of the bioeconomy. Essentially, production, marketing, awareness campaigns, and commercialization are necessary for the sustainability of the bioeconomy. Large-scale biochar production brings agronomic and economic benefits. For example, the economic equilibrium is determined by the yield of the crops to which the biochar is applied and the profit from multiple harvests. Recently, biomass has been converted into biochar due to its economic benefits, sustainability benefits, and ever-increasing demand from environmental and energy industries [66]. Economic acceptance results for biochar production in Selangor were \$532.00 per year, with total revenue of \$8012.00 per year from biochar sales [67]. With cheaper raw materials and promising processing technology, the net margin of biochar production can be improved [35]. The development of the pyrolysis industry can generate additional income for farmers through the collection and sale of otherwise unused agricultural residues. Apart from this, the use of locally available feedstock reduces dependence on fossil fuels, and since biochar can be used as fertilizer, dependence on purchased/imported fertilizers can be reduced, which can also help developing countries reduce their budget deficits. Biochar derived from crop residues has an estimated market value of ~US\$500 billion in India. Its applications in the cosmetic, pharmaceutical, and chemical industries provide market and employment opportunities [68].

2.2. Biochar for clean water and sanitation (SDG 6)

Biochar applications in water treatment directly address multiple specific targets under SDG 6 (Clean Water and Sanitation). Target 6.3 aims to "improve water quality by reducing pollution, eliminating dumping of hazardous chemicals and materials, and substantially increasing recycling and safe reuse globally" by 2030, measured by Indicator 6.3.1 (proportion of wastewater safely treated) and Indicator 6.3.2 (proportion of bodies of water with good ambient water quality). Biochar contributes through efficient removal of heavy metals (46–95% removal rates), organic pollutants (pesticides, dyes, pharmaceuticals), and emerging contaminants from various wastewater streams as documented in Table 1 and discussed in subsections below. Target 6.6 focuses on "protecting and restoring water-related ecosystems, including

Table 1
Heavy metals, organic contaminants, and nutrients removal using biochar.

Agricultural waste/ Feedstock	Pollutants	Adsorption capacity (mg g^{-1})	Mechanism of removal	Ref.
Paper millsludge	Arsenic (As^{5+})	34.1	Chemisorption	[69]
Green waste	Cadmium (Cd^{2+})	6.72	Chemisorption	[70]
Banana peels	Lead (Pb^{2+})	359	Ion exchange	[71]
Switchgrass	Metribuzin herbicide	39.6	Electrostatic attraction and H-bonding	[72]
Gliricidia	Crystal violet dye	-	Chemisorption	[73]
Bagasse	Pb^{2+}	12.7	Ion exchange& Surface complexation	[74]
Rice straw	Imidacloprid& Atrazine	High	Pore volume and pH value	[75]
Soybean & corn straw	Atrazine	High	Pore volume and pH value	[76]
Wood dust	Bisphenol A	high adsorption efficiency	High specific surface area	[77]
Wheat straw	Nitrate (NO_3^-)	24.8	Adsorption and surface precipitation	[78]
Walnut shells	Cu, Zn, and Cd	60, 54, and 46%, respectively	-	[79]
Rice straw	Tetracycline	98.33	-	[80]
Bagasse biochar	Sulfamethoxazole&Sulfapyridine	1.6	-	[81]
Peanut shell	Trichloroethylene	4.6	Hydrophobic partitioning	[82]
Corn straw	Polystyrene microplastics	> 95%Removal efficiency	Entangling and trapping	[83]

mountains, forests, wetlands, rivers, aquifers, and lakes," measured by Indicator 6.6.1 (change in extent of water-related ecosystems over time). Biochar-based filtration systems for stormwater and agricultural runoff reduce pollutant loads (nutrients, sediments, toxins) entering surface waters and groundwater, thereby protecting aquatic ecosystems. Target 6.1, which aims for "universal and equitable access to safe and affordable drinking water," is supported through biochar's capability to remove waterborne contaminants at relatively low cost, particularly relevant for decentralized water treatment in rural and underserved communities where conventional treatment infrastructure is limited. The adsorption capacities, removal efficiencies, regeneration potential, and practical applications detailed below demonstrate biochar's role in achieving these specific water-related SDG targets with measurable environmental and health outcomes.

To achieve SDG 6 (Clean water and sanitation), biochar derived from agricultural waste biomass will be useful in wastewater treatment and bioremediation (Fig. 2). Wastewater is a source of pathogens, heavy metals, and organic micro-contaminants, and therefore their bio-transfer through the food chain [84]. It causes progressive and permanent contamination of soil, surface water, and groundwater. Thus, in this sense, the scientific community is currently focusing on the development of efficient, environmentally friendly, economically viable, and socially acceptable sustainable materials for large-scale environmental applications [85]. Biochar has the potential to be a useful agent in wastewater treatment and bioremediation. Indeed, biochar has been widely used as an adsorbent in wastewater treatment to remove pollutants [86]. Biochar has a higher surface area, adsorption capacity, and functional groups, making it an effective wastewater treatment agent [87]. However, these adsorption properties vary significantly depending on the production method; slow pyrolysis biochar typically exhibits superior adsorption capacity for organic pollutants compared to gasification biochar due to its more developed pore structure, while gasification biochar may be more effective for certain heavy metal removal applications due to its higher ash content and alkalinity [88]. Biochar has been reported as an economical and environmentally robust technology for wastewater treatment ([68]). Biochar is a renewable bio-sorbent that removes chemical, biological, and physical contaminants while preserving the organoleptic properties of water [84,89]. Biochar is used as an adsorbent and catalyst for a wide range of pollutants, and reduces the carbon footprint [90]. It has been reported that biochar produced from paper mill sludge can be used to remove arsenic (As) from wastewater [69]. Biochar obtained from sugar cane straw and banana peels has been found to remove heavy metals Cd^{2+} and Pb^{2+} from aqueous solutions ([71,91]). It has also been studied for the removal of antibiotics (sulfonamides and tetracyclines) and herbicides (metribuzin) from aqueous solutions [56]. A biochar-based filtration medium was studied to remove Cu (85%) and Zn (95%) from stormwater runoff [92].

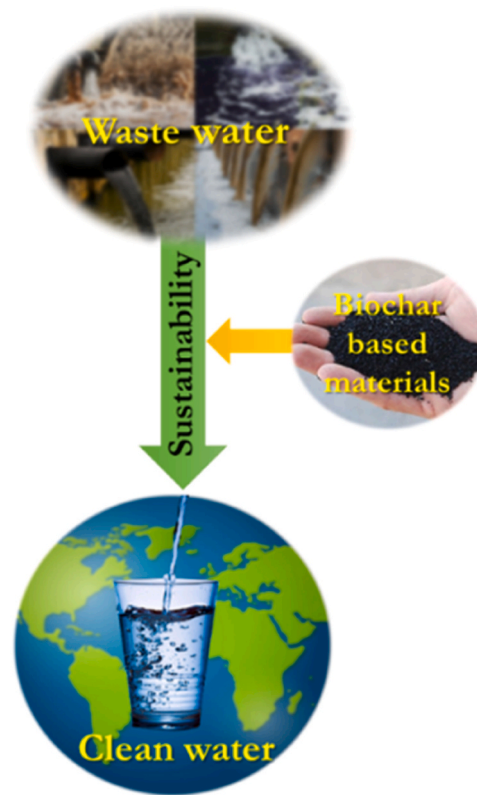


Fig. 2. Biochar applications for clean water and sanitation (SDG 6) The diagram summarizes how biochar's high surface area, porous structure, and functional groups enable the removal of heavy metals, organic pollutants, nutrients, and emerging contaminants from water through adsorption, ion exchange, and surface complexation. Applications span industrial effluents, municipal wastewater, agricultural runoff, and stormwater systems, supporting SDG 6 targets for improved water quality and safe sanitation.

2.2.1. Biochar for decontamination of polluted water

Biochar has excellent adsorption properties, making it ideal for wastewater decontamination [79]. Biochar demonstrates significant adsorption capacity for removing various pollutants from contaminated water systems [93]. Systematic water quality evaluation frameworks employing multivariate statistical approaches such as principal component analysis (PCA), entropy-weighted water quality indices, and sensitivity analysis provide robust methodologies for assessing pollutant sources and health risks in contaminated water systems [94,95], approaches that can be adapted for evaluating biochar effectiveness in

water treatment applications across diverse contexts. Wastewater, which is a byproduct of domestic, manufacturing, or agricultural activities, has already been a global problem. Biochar has great potential for wastewater treatment. Fig. 3 shows the role of biochar in the remediation of polluted waters. Industrial wastewater from various sectors contains a high concentration of organic and inorganic pollutants. Hussain et al. [96] found that the combination of biochar and chitosan affected the uptake of Cu, Pb, As, Cd, and other heavy metals in industrial wastewater. *Gliricidia* biochar has been reported to remove dye (purple crystal) from dye-based industrial wastewater [73,97]. Application of bagasse biochar removed lead from industrial effluents [74] [36]. For wastewater treatment, biochar can be used alone or in conjunction with biofilters due to its highly porous surface [98]. NH_4^+ , NO_3^- and PO_4^{3-} adsorbed on biochar could be used as slow-release fertilizer [99]. Agricultural pollution is becoming increasingly severe because of the excessive use of agrochemicals [100]. Several studies have examined biochar and modified biochar materials for treating agricultural wastewater. Mandal and Singh [75] reported that the phosphoric acid-treated rice straw biochar removed 8.84mg/10L of atrazine pollutant in single adsorption from waste water. Biochar has also been evaluated for its adsorption capacity to remove various pesticides from agricultural wastewater. The adsorption behavior of biochar to pesticides is mainly determined by the biochar raw material and the target pollutants [101]. As cities grow, urban stormwater runoff has become a major concern, contributing significantly to the degradation of natural water quality due to the increased concentration of organic and inorganic pollutants [77]. Biochar has proven to be an effective treatment for various heavy metals and other pollutants (Table 1) [102,103]. Critical comparison of biochar adsorbents reveals significant variations in performance across different pollutant types and application conditions. Heavy metal removal efficiencies vary considerably: while some studies report > 90% removal for Pb^{2+} and Cu^{2+} , others show only 46–60% removal for Cd^{2+} and Cr^{3+} , depending on biochar feedstock, pyrolysis temperature, solution pH, and initial metal concentration (Table 1). For organic pollutants, adsorption capacity ranges from 1.6 mg/g for antibiotics like sulfamethoxazole to 98.33 mg g⁻¹ for tetracycline with modified biochar [80,81]. However, most reported

efficiencies are from laboratory batch experiments under optimal controlled conditions with single pollutants. Field-scale applications and studies with real wastewater containing multiple competing ions typically show 20–40% lower removal rates [68]. Regeneration capacity also varies considerably: while activated biochar's can maintain > 70% efficiency after 3–5 regeneration cycles using thermal or chemical treatments, unmodified biochar's often show rapid performance degradation after 2–3 cycles [36]. Furthermore, economic analysis indicates treatment costs ranging from \$2 to 8 per kg biochar, depending on feedstock and production method, which translates to \$0.50–5.00 per m³ of wastewater treated, potentially limiting large-scale application in resource-constrained settings [85]. These practical considerations underscore the need for continued research on cost-effective biochar production, modification techniques to enhance performance, and regeneration methods to improve economic viability.

2.2.2. Biochar for the removal of new emerging pollutants from soil and water

About 3.2 billion people (40% of the world's population) are currently affected by land degradation [104]. Soil and water contamination have a negative impact on food security as it reduces crop yields and affects the quality of agricultural products through their toxic levels that are unsafe for consumption. Recently, various environmentally friendly materials have been tested in water treatment with good results [97]. Nanomaterials like doped titanium oxide (Co/TiO₂) were used for the photodegradation of amido black dye in water with good results [17]. A low-cost sorbent based on the Ajwa date was tested to remove Cu (II) ions from aqueous media. This indicates that sorbents made from Ajwa date are an economical and environmentally friendly alternative for Cu (II) ion removal [103]. A mesoporous amide citric anhydride [AMCA-MIL-53(Al)] organometallic framework (MOF) is an excellent adsorbent for the efficient and rapid removal and recovery of Pb (II) from wastewater [91]. The activities of industrial enterprises and the agricultural sector generate large amounts of waste every year [84]. Producing eco-friendly materials such as biochar from waste will reduce agricultural pollution and also remediate contaminated soil environments.

In recent years, biochar has grown in popularity for various environmental benefits. In recent decades, new emerging pollutants such as bisphenol A, carbamazepine, polybrominated biphenyls (PBBs), per- and polyfluoroalkyl compounds (PFAS), pharmaceuticals, personal care products, microplastics, and various antibiotics, etc. are causing serious problem to the environment. Emerging pollutants are a class of pollutants that, even in trace amounts, can have a lethal impact on humans and wildlife. Conventional treatments are unable to remove these pollutants from the environment [105,106]. Biochar has the potential as a sustainable carbon-neutral material. This is mainly due to biomass emissions, with carbon emissions during conversion and use equal to the amount consumed in photosynthesis [107]. The main advantages of biochar-based materials are high porosity, high surface area, excellent ion exchange capacity, and a large number of functional groups. Biochar's physico-chemical properties, such as its three-dimensional network and pore structure, may serve as a permanent storage solution for carbon while adsorbing and degrading contaminants. Several researchers have published results on the physicochemical properties of biochar and its potential applications in environmental remediation. Biochar can be made from green waste, mainly agricultural biomass and solid waste such as wood chips, straw, husks, bagasse, and manure. Xu et al. [108] compared different complex formation mechanisms for mercury adsorption on bagasse and hickory chip biochar. X-ray photoelectron spectroscopy (XPS) showed that the formation of (-COO)2Hg and (-O)2Hg was mainly due to Hg adsorption on bagasse biochar. Similarly, He et al. [109] found that PSB/Fe3O4/biochar composites are promising materials for bioremediation of wastewater. Rice husk and soybean biochar (600–700°C) facilitate the removal of non-polar carbofuran (a pesticide) and trichloroethylene (VOC) from contaminated

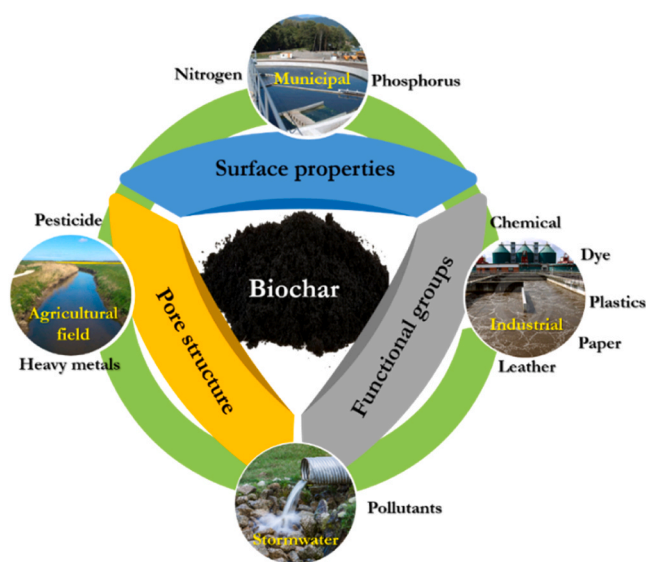


Fig. 3. Biochar-mediated remediation mechanisms for polluted waters. This figure depicts major pollution sources (industrial effluents, agricultural runoff, and urban stormwater) and corresponding biochar treatment mechanisms, including adsorption, ion exchange, complexation, and precipitation. It highlights the physicochemical properties of biochar, enabling contaminant removal and the progression from laboratory research to field-scale applications for restoring water quality.

water [110]. Experimental results indicated excellent target heavy metal scavenging properties of the material. Biochar has become a viable option for soil remediation and wastewater treatment [111]. Wang et al. [83] reported in a column study that 90% of microplastics (10 µm) were removed by corn straw biochar. Activated biochar was found to reduce 86% of perfluorinated and polyfluorinated alkylated substances (PFAS) in leachate concentrations [112]. Biochar has been shown to remove the antibiotics sulfamethoxazole and sulfa pyridine from commonly used aqueous solutions for animals and humans [81]. Some studies have examined that biochar can also eliminate widely used antibiotics such as tetracycline and florfenicol [113]. Biochar has been used in conjunction with biofilters to remove bisphenol A (BPA) from rainwater [77]. Organic micropollutants present in wastewater, such as benzotriazole, sulfamethoxazole, carbamazepine, and diclofenac, were assessed. Activated biochar has been found to have a sorption efficiency of 45% from wastewater [114]. A test was performed to investigate the adsorption behavior of biochar upon disposal of pharmaceutical and personal care products. Acid-modified biochar has been found to remove over 75% of target contaminants [115].

2.3. Biomass-to-biochar conversion for affordable and clean energy (SDG 7)

The world is being pushed to drastically reduce greenhouse gas emissions, but the gap is widening day by day. When crop residues are burned in the open, CO₂ and other dangerous pollutants are produced [116]. Storing carbon in plants and soil has long been part of the earth's natural balance. But the problem is that we have upset this balance. The rapid depletion of precious coal reserves, along with the detrimental environmental impacts of fossil fuels, necessitate the development of renewable and alternative clean energy sources [117]. Among the various energy sources available, plant residues can be a carbon-neutral alternative energy source [118]. In addition to all these interconnected qualities, biomass must be converted into a form that can be used for several production purposes, including energy generation and climate change mitigation [119]. Crop waste, organic fertilizers, bioenergy crops, fruit peels, agro-industrial waste, and herbs are all used to produce sustainable biochar. Biomass is a renewable carbon source that can be used to generate low sulfur and nitrogen biochar [120]. To convert biomass into biochar, pyrolysis is applied, i.e., the overheating and thermal transformation of biological waste at higher temperatures (350–700°C) on a specially constructed surface that absorbs all the pollutants produced. The biochar production process through pyrolysis simultaneously generates renewable energy products, thereby contributing to SDG 7 (Affordable and Clean Energy) and its specific targets. Target 7.2 aims to "substantially increase the share of renewable energy in the global energy mix" by 2030, measured by Indicator 7.2.1 (renewable energy share in total final energy consumption). Thermochemical conversion of agricultural biomass through pyrolysis typically yields approximately 25–35% biochar, 30–40% bio-oil, and 20–30% syngas by mass [8], with the liquid and gaseous fractions providing immediate energy value for heat and power generation while biochar offers long-term carbon storage and soil benefits. The bio-oil can substitute for heating oil or be upgraded to transportation fuels, while syngas can replace natural gas in engines or turbines, representing renewable alternatives to fossil fuels derived from agricultural waste that would otherwise be burned or decompose. Target 7.a promotes "enhanced international cooperation to facilitate access to clean energy research and technology" and "promote investment in energy infrastructure and clean energy technology"; agricultural waste-to-biochar-and-energy systems represent accessible, scalable technology particularly suitable for rural and developing regions where agricultural residues are abundant but often unutilized [118]. This distributed energy generation model can enhance energy security and independence in agricultural communities while reducing dependence on imported fossil fuels, decreasing energy costs for farmers, and

contributing to local economic development through the creation of bioenergy enterprises. The combustion or expulsion of oxygen, methane, carbon monoxide, and other flammable gases in the biomass leaves behind carbon-rich biochar. Biomass pyrolysis has received a lot of attention due to its most effective and excellent ecological properties. Agricultural biomass, forest, and household waste can also be successfully converted into green energy sources through pyrolysis. Traditional cogeneration ovens, on the other hand, burn biomass but only produce ash, with consequent smoke and greenhouse gas emissions. Biochar is used for a variety of purposes, including carbon enhancement, soil quality construction, environmental sustainability, wastewater treatment, and thermal and metallurgical applications. In addition, with its long-lasting, clean, and low-cost production process, biochar has the potential to significantly reduce greenhouse gas emissions and play a key role in the global carbon market. The pyrolysis process also converts all pollutants produced by the combustion of biomass into liquid fuels, such as biogas (synthetic gas), bio-oil, and industrial chemicals. The bio-oil produced can be used for heating and power generation in the same way as a low-grade fuel. Syngas, a byproduct of pyrolysis, can be used as natural gas or catalyzed into ethanol and other petroleum-based chemicals. These by-products can be sold in the market, stored for future use, or used on-site in the power generation process [121]. It is much easier to generate energy from bio-oil and syngas than from ethanol from fermentation. Miscanthus grass can produce more bio-oil per hectare, while corn after fermentation, can produce less ethanol per hectare. The fermentation process uses energy and converts it to fuel only in a 35% efficient way [122]. Thus, by transforming plant biomass into biochar, soil carbon sequestration can be improved, agricultural waste reduced, and fossil fuel inputs replaced with a renewable energy source.

2.4. Biochar and climate action (SDG 13)

Anthropogenic activities are the main driver of GHG emissions, responsible for the degradation of soil quality and the environment [123,124]. An increase in greenhouse gas emissions poses a global threat to environmental sustainability [12]. Each year, agricultural, forestry, and land-use models emit about 19.9 gigatonnes (Gt) of CO₂ equivalent, accounting for nearly a quarter of total anthropogenic emissions [125]. It is a global challenge to implement a green economic model in agriculture while meeting the food needs of the growing population [126]. It forced the production of more crops per unit area and time due to the limited natural resources available [127]. Food and nutrition security and environmental sustainability have been affected globally by increasing environmental crises and resource degradation [128]. The demand for food continues to increase with the growth of the world's population. To meet these demands, the use of agrochemicals has increased. As a result, there has been a shift toward environmentally friendly substitutes that help maintain environmental sustainability to mitigate the negative impacts of chemical fertilizers and pesticides on ecosystems [129]. Researchers and policymakers in all countries face the major challenge of developing environmental sustainability in terms of water, carbon, and energy balance. Environmental sustainability becomes the primary goal for maintaining global food and nutrition security [130]. Biochar has recently gained the attention of the scientific community, and research is directed toward the development of agricultural wastes that provide both agricultural and environmental sustainability [44]. Biochar has the potential to reduce fertilizer requirements [131]. Especially in tropical regions, it can act as a soil conditioner and reduce nutrient leaching [131]. Furthermore, the use of biochar in agriculture helps in reducing the carbon footprint and improving carbon sequestration, ensuring environmental sustainability. Consequently, biochar may be a viable long-term tool to combat climate change (Fig. 4) [132]. Biochar has attracted the attention of the scientific community as a soil improver that reduces GHG emissions and improves carbon sequestration capacity ([56]) (Tables 2, 3). Biochar



Fig. 4. Biochar’s role in climate change mitigation and adaptation (SDG 13). The conceptual framework illustrates biochar’s contributions through long-term carbon sequestration, reduced greenhouse gas emissions from soils, and enhanced climate resilience via improved soil water retention, nutrient efficiency, and crop productivity. These pathways collectively support climate mitigation and adaptation targets while strengthening sustainable agriculture.

Table 2
Carbon sequestration using agricultural waste biochar.

Agricultural waste/ Feedstock	Crops	Type of soil	Soil C status/ sequestration	Ref.
Straw-derived biochar	Wheat-maize	Silty clay loam	Increase SOC	[133]
Maize & wheat straw	Rice- wheat	Anthrosol	Increase SOC	[134]
Straw	Maize-rice	Silty clay	28 % increase in SOC than control	[135]
Activated rice hull biochar	Rice	Clay loam	1.23 t ha ⁻¹ versus 0.89 ha ⁻¹ in the control	[136]
Rice husks and cottonseed hulls	Maize	Fluvisol	Increase SOC	[137]
Straw	Super rice	Gleyic luvisols	Improve C sequestration	[138]
Maize & wheat straw	Wheat-maize	Anthrosol	SOC increased by 14.4%	[139]
Acacia (<i>Acacia spp.</i>)	Barley	-	34% increase in SOC	[41]
Wood (<i>Quercus, Ulmus, and Carya spp.</i>)	Switchgrass	clay loam	Soil C increased by 36%	[140]
Eucalyptus wood	Rice	Loamy soil	C-sequestration increased by 1.87–13.37 t C ha ⁻¹	[141]
Corn straw	Wheat-maize	Fluvic Cambisol	In ten years, 62–81 % of biochar-C converted to SOC	[142]
Wheat straw	Rice	Anthrosol	In 6 years, sequestered 2.6 times C more than straw	(Liu et al., 2021)
Maize straw	Maize	Mollisol	Sequestered 4.5 times more carbon than straw	[143]

applications are directly aligned with SDG 13 (Climate Action) and its specific targets aimed at combating climate change and its impacts. Target 13.2 calls for "integrating climate change measures into national policies, strategies, and planning," with progress measured by Indicator 13.2.2 (total greenhouse gas emissions per year). Biochar contributes to this target through two primary quantifiable mechanisms: (1) stable carbon sequestration, removing atmospheric CO₂ and storing it in recalcitrant aromatic carbon form in soils for centuries to millennia,

Table 3
Effect of biochar on GHG emissions/GWP.

Agricultural waste/ Feedstock	Crops	Type of soil	Effects on GHGs/ GWP	Ref.
Rice straw	Rice	Anthrosols	Decreased the GWP by 375.6 g CO ₂ -eq m ⁻² season ⁻¹	[144]
<i>Eucalyptus</i> wood	Paddy	Loamy soil	Decrease GHGs	[141]
Maize stover	maize	brown earth soil type	N ₂ O, CO ₂ , and CH ₄ levels were reduced	[145]
Activated rice hull biochar	Rice	Clay loam	N ₂ O emission decreased, but CH ₄ has not changed significantly	[136]
Manure & wood residue biochar	Sorghum	Andisol	Soil N ₂ O decreased by 50%	[146]
Sawdust and coffee husk biochar	Incubation Study	-	Decrease GHGs by 55%	[147]
Wheat straw	Maize	Calcareous soil	N ₂ O emission reduced by 95.14%	[148]
Switchgrass and wood biochar	Incubation Study	Loamy sand and silt loam	N ₂ O emissions were reduced by 42–90 %	[149]
Modified rice-straw biochar	Incubation Study	Red acidic soil	N ₂ O emissions were reduced by 22–33%	[45]
Corn residue biochar	Maize	Sandy loam soil	Decrease CO ₂ , N ₂ O, and CH ₄ emissions	[150]
Spent mushroom substrate biochar	<i>Camellia oleifera</i>	Red soil	Under flooded conditions, N ₂ O emissions decreased while CH ₄ emissions increased	[151]

with studies showing that biochar can sequester 920 kg CO₂-equivalent per 1000 kg of crop residue converted to biochar [93]; and (2) reduction of direct greenhouse gas emissions from agricultural soils, particularly N₂O (global warming potential 265 × that of CO₂) and CH₄ (global warming potential 28 × that of CO₂), with documented reductions of 22–95% for N₂O and 15–50% for CH₄ in rice systems depending on biochar properties and soil conditions (Table 3). Target 13.1 focuses on "strengthening resilience and adaptive capacity to climate-related hazards," measured by Indicator 13.1.1 (number of countries with national and local disaster risk reduction strategies that strengthen resilience). Biochar enhances agricultural climate resilience through multiple pathways: improved water retention capacity (15–18% increase in water holding capacity) supporting crop production during drought periods, enhanced soil structure increasing resistance to erosion from extreme rainfall events, improved nutrient retention maintaining productivity under variable conditions, and increased organic matter buffering soil against temperature extremes [27,55]. Target 13.3 promotes "improving education, awareness-raising, and capacity on climate change mitigation and adaptation"; the visible, measurable benefits of biochar in agricultural systems provide a tangible demonstration of climate-smart agriculture practices that can be communicated to farming communities. The following subsections detail quantitative evidence for biochar’s contributions to carbon sequestration and GHG emission reduction, demonstrating its role as a nature-based climate solution that simultaneously provides agricultural benefits.

2.4.1. Biochar and carbon sequestration

Biochar application is widely recognized as a CO₂ removal technology [125,152] and an effective strategy for sequestering CO₂ when mixed with soil [11]. Due to its versatile properties, biochar is used for a variety of applications in addition to carbon sequestration [153]. Biochar has demonstrated potential to improve soil productivity and health while reducing carbon footprint under appropriate conditions,

contributing to climate change mitigation efforts [70]. Biochar improves soil nutrient retention, organic matter, soil fertility, and carbon sequestration. Biochar-based agriculture contributes to reducing the carbon footprint [154]. Biochar obtained from agricultural waste has the potential to increase soil carbon by accelerating the rate of soil carbon mineralization. Consequently, converting agricultural waste into biochar could be a promising way to capture soil carbon [5]. Increasing the carbon sequestration capacity of agricultural fields can be a crucial part of a strategy to combat climate change. Several studies have supported the use of biochar in agricultural areas to improve carbon sequestration [66,93]. Several studies reported that combining biochar with chemical fertilizers can reduce carbon footprint, improve carbon sequestration, improve NUE, and enhance yield [93]. The use of biochar in combination with chemical fertilizers releases slowly in the soil to reduce CH₄ emissions and improve carbon sequestration ([153]). Yang et al. [145] proposed converting agricultural waste into biochar and then storing it in the soil as a potential carbon sequestration strategy. A study reported that converting 1000 kg of crop residues into biochar could sequester 920 kg of CO₂ equivalent [93]. Improving C sequestration is essential for long-term agricultural sustainability and environmental protection. Over 6 years, straw-derived biochar sequestered 2.6 times more CO₂ than straw [155].

2.4.2. Biochar and greenhouse gas (GHG) reduction

GHG emissions resulting from anthropogenic activities pose a global threat to environmental sustainability [127]. The demand for food continues to increase, putting a strain on agriculture. To meet these requirements, chemical fertilizers are increasingly used. As a result, there has been a shift toward ecological substitutes that help maintain environmental sustainability by reducing greenhouse gases, maintaining soil nutrient balance, and increasing productivity [156]. In this context, biochar has increased the interest of the scientific community as a soil improver that reduces greenhouse gas emissions. Awasthi et al. [148] found that biochar-modified soil reduced N₂O emissions by 95.14%. Compared to other soil amendment strategies, biochar is one of the most effective. Biochar, on the other hand, can prevent N₂ leaching and retain excess nitrogen, thereby reducing N₂O emissions. In addition, when there is a nitrogen deficiency in the soil, the nitrogen retained by the biochar is gradually released. It acts as a slow-release fertilizer and ultimately supports plant growth [19]. Biochar-based agriculture has sparked the interest of the scientific community in reducing the carbon footprint to achieve carbon neutrality. Agricultural waste streams must be integrated into a sustainable and profitable circular economy. The continuous increase of GHGs in the atmosphere caused by human activity, especially CO₂, has led to several serious global problems. Due to the exponential population growth, the use of biochar is not only promising in terms of its hydrophobic character, but it is also an impressive strategy for solid waste management [145]. Each year, agricultural, forestry, and land use models emit about a quarter of total anthropogenic emissions [125]. Agriculture, in particular, contributed significantly to 12% of total greenhouse gas emissions. The contribution of agriculture to total greenhouse gas emissions is estimated to increase to 50% by 2030 [125]. According to Shin et al. [136], activated rice husk biochar reduces GHG emissions by increasing C sequestration and N use efficiency, aiding sustainable agriculture. While numerous studies have reported reductions in greenhouse gas emissions following biochar application, it is essential to acknowledge that results are not uniformly positive across all conditions. Some studies have found no significant effect of biochar on N₂O emissions, particularly in well-drained soils or under optimal nitrogen management [157]. In certain cases, biochar application has been associated with increased CH₄ emissions in waterlogged rice paddy conditions, especially when biochar with high labile carbon content is used [151]. A meta-analysis revealed that while biochar reduces N₂O emissions on average by 38%, the effect is highly variable, ranging from significant reductions to slight increases depending on soil moisture, biochar properties, and nitrogen fertilizer

rates [157]. These inconsistent effects can be attributed to variations in biochar properties (particle size, surface area, pH, ash content, C/N ratio), soil characteristics (texture, organic matter, pH, microbial community structure), environmental conditions (temperature, moisture regime), and management practices. These variable outcomes emphasize the need for careful site-specific assessment and biochar selection before recommending biochar for climate change mitigation purposes.

3. Conclusions and future perspective of the study

The sustainability of agricultural ecosystems is crucial for safe food production and poverty elimination. This comprehensive review has synthesized evidence demonstrating that agricultural waste-derived biochar offers a nexus solution that simultaneously addresses multiple interconnected challenges, including food security, environmental pollution, energy needs, and climate change mitigation. Unlike previous reviews focusing on isolated applications, our integrated framework demonstrates how biochar serves as a connecting technology within a circular bioeconomy, transforming agricultural waste into multifunctional products that contribute to the achievement of multiple SDGs. Due to its amorphous nature, biochar is an economically robust waste treatment material. The use of biochar increases yield and soil fertility and reduces heavy metals and GHG emissions from agrarian food production systems. Of course, the production and application of biochar is not a panacea for all environmental, soil, and food safety problems, but it is a valuable material that needs more attention to achieve various SDGs. To fully exploit the potential of biochar technology to achieve the goal of food and energy security, soil restoration, wastewater treatment, and the reduction of GHG emissions, proper integration and a multi-disciplinary approach are therefore required. Agricultural waste biomass in the form of biochar must be incorporated into a circular, viable, and sustainable bioeconomy, which offers a great opportunity to achieve the SDGs globally.

CRedit authorship contribution statement

Sanjeev Kumar: Writing – original draft, Methodology. **Dinesh Kumar Yadav:** Writing – review & editing, Software. **Raghavendra Singh:** Writing – review & editing, Writing – original draft, Formal analysis. **Subhash Babu:** Methodology, Formal analysis, Conceptualization, Writing – original draft. **Sanjay Singh Rathore:** Writing – review & editing, Visualization. **Deviden Yadav:** Writing – review & editing, Writing – original draft, Visualization. **Veluswamy Venktramanan:** Writing – review & editing, Data curation. **Owais Ali Wani:** Writing – review & editing, Visualization, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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