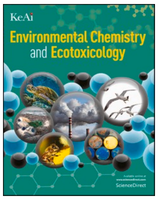
Environmental Chemistry and Ecotoxicology 7 (2025) 286–304

Contents lists available at ScienceDirect

Environmental Chemistry and Ecotoxicology

journal homepage: www.keaipublishing.com/en/journals/environmental-chemistry-and-ecotoxicology/



The multifaceted power of biochar: A review on its role in pollution control, sustainable agriculture, and circular economy

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ARTICLE INFO

Keywords:
Biochar
Adsorption
Ion-exchange
Soil carbon
Soil nitrogen
Plant growth

ABSTRACT

The key challenges of the 21st century include global warming, soil health management, wastewater treatment, and adopting sustainable green technologies. Biochar offers significant potential in addressing these issues, positioning itself as a vital tool in advancing sustainable development goals. Recent biochar research has expanded significantly beyond its traditional focus in agricultural and environmental sciences. These characteristics position biochar as an increasingly valuable material for improving soil health, enhancing agricultural productivity, and capturing atmospheric carbon dioxide, contributing to efforts to mitigate global warming. The “circular economy” concept is rapidly gaining attraction, driven by its central goal of waste elimination through meticulous planning. Recently, biochar has emerged as a significant contributor in the environmental community due to its versatility in reducing waste and enhancing the efficacy of the circular economy. This review delves into advancements in the production, modification, and treatment methods of biochar, as well as its elemental and nutrient composition. It highlights the advantages, challenges, and diverse applications of biochar while critically examining current challenges and research gaps in its potential to mitigate greenhouse gas emissions, enhance soil carbon sequestration, and improve wastewater treatment processes.The potential of biochar to reduce greenhouse gas emissions and sequester carbon in soils, along with its applications in wastewater treatment, are thoroughly covered in this article. The challenges it faces and its prospects are also discussed in detail. This review identifies the key issues that must be addressed for the sustainable utilization of biochar. It explores the development of a circular economy-based environmental management paradigm, leveraging waste conversion into biochar and its diverse applications across regions, thus effectively closing the loop and exemplifying a truly circular economy in action.

1. Introduction

For over 60 years, agricultural waste has become the subject of intensive research due to its potential to be repurposed into valuable resources [1].In pace with agricultural productivity, this waste stream keeps growing. This has detrimental repercussions on both human and ecological health [2]. Although 21 % of worldwide greenhouse gas emissions come from agriculture, the quest for zero agricultural solid waste is ongoing globally. The utilization of agricultural residues includes their use as livestock feed and for fertilizing farmland, as well as transforming agricultural waste into biochar, pulp and paper, and a fuel source. Moreover, generating renewable energy from agricultural by-products (biofuels) is a viable option [3]. Making biochar from agricultural solid waste is a viable way to lessen the bulk apart from value addition [4]. Biochar is a byproduct from the thermochemical conversion of biomass material rich in carbon produced in oxygen deficiency [5]. Biochar is generally created using different thermochemical procedures such as low, fast pyrolysis with varying process variables [6].

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https://doi.org/10.1016/j.enceco.2025.01.004
Received 25 October 2024; Received in revised form 11 January 2025; Accepted 13 January 2025

The creation and utilization of biochar have dramatically increased recently. Biochar has sparked substantial interest concerning agriculture, climate, energy, and overall improvement of the environment. The surface chemistry, the size structure, and the pore volume of biochar all contribute crucially to the capacity for adsorption [7]. Due to its inherent qualities, such as functional groups present on its surface, high thermal resistance, capacity to exchange cations, heat capacity, specific surface area, permeability, conductivity, high fixed carbon content, volatility, and ionic strength, humans have utilized biochar for various purposes over the years [8]. In recent years, the advancement of agronomic practices, carbon capture, and sustainable farming has been closely associated with biochar. This is partly due to the increasing focus on environmental safety standards, greenhouse gas emissions, and food shortages [9]. Biochar is distinct in that it has a significant cation exchange capability, a non-carbonized portion, a substantial surface area, and oxygen-containing functional groups on the surface and is efficient in removing both organic and inorganic pollutants [10]. To accomplish and safeguard soil, water, and air sustainably throughout vast-scale agricultural operations and significant industrial activity, biochar, a carbonaceous can be utilized as a byproduct of the pyrolysis process [11]. Biochar is well known for its capacity to remove contaminants, contribute significantly to the cause of combating climate change, and produce bioenergy [12].

. According to the United Nations Department of Economics and Social Affairs (UNDESA), 9.8 billion people will inhabit the planet by the year 2050, which will pose a growing danger to the global agricultural system. As a result, technology presently plays a significant role in farming and chemical supplies to meet the demand for organic produce and cereals while feeding the growing population. Some regions of the world have been able to meet their food needs, thanks to more advanced farming system technologies. These agricultural practices are categorized as agroecology, organic farming, sustainable agriculture, and agroforestry [13]. To accomplish environmentally and agriculturally sustainable practices, all of these advances in agricultural techniques aim to minimize waste and increase crop output. One of the results of scientific research is biochar, which is crucial for establishing environmentally and agriculturally sustainable practices. In addition to being a possible soil conditioner, a type of charcoal called biochar produced by a feedstock's combustion with little to no oxygen present is an effective way to sequester carbon to combat worldwide warming as well as climate change [14].

When incorporated into the soil, it is extremely long-lasting, and they can survive there for decades or centuries [15]. In the context of bioactive firms, which depend on transforming feed into various chemicals as well as energy with added value, biochar has gained public attention. The integration of physical, chemical, biological, ecological, and socioeconomic processes is the essence of what is meant by "sustainable agriculture." a thorough approach in creating new, environmentally friendly, and secure farming methods [16].

By conserving and upholding all of its natural resources, such as preserving the soil's fertility, and safeguarding surfaces and subsurface supplies, agro-farming can sustain itself over a lengthy period, finding ways to improve farming practices and creating sustainable energy sources to address climate change [17]. Additionally, biochar is being investigated for environmental rehabilitation, lowering the mobility of pollutants in polluted soils, and reducing the exposure of agronomic crops to harmful contaminants [18,19]. Typically, waste leftovers such as animal manure, agricultural residues, and forestry wastes are used to make biochar [20]. These feedstocks are important because they can turn waste into biochar, which is a beneficial and significant product [21]. Its effects on soil include improved crop output, better plant growth, and improved soil quality. The production method of biochar, the characteristics of the soil where it is applied, the crop type being cultivated, and various other factors significantly influence biochar's behavior and effectiveness [22]. In line with biochar's significance, numerous researchers have investigated how biochar might be adapted to enhance soil and environmental health. Biochar holds tremendous potential in mitigating the adverse impacts of climate change and paving the way for a circular economy [23]. A sustainable route to achieving circularity involves converting waste into biochar. Unlike incineration, which depletes organic nutrients, pyrolysis preserves most of these nutrients in the biochar. Approximately 50 % of the input carbon is retained through pyrolysis, with its byproducts offering opportunities for sustainable energy generation [15]. The diverse attributes of biochar, including its ability to harbor beneficial microbes, enhance aeration, gas exchange, water holding capacity (WHC), mitigate pollutants, prevent desiccation, and retain nutrients, actively support a productive circular economy [24]. Fig. 1 depicts biochar integration in circular economy environmental management, pioneering sustainability. This review examines advancements in biochar production, modification, and treatment methods, along with its elemental and nutrient composition. It highlights the advantages, challenges, and diverse applications of biochar, while critically addressing current challenges and research gaps in its potential to mitigate greenhouse gas emissions, enhance soil carbon sequestration, and support wastewater treatment. Additionally, it outlines future research goals emphasizing the significance of biochar-based applications across various fields. The review aims to provide an updated perspective on recent advances in the use of biochar and its modifications, particularly as an enhanced adsorbent for a wide range of applications.

2. Methodology

A search for the term "biochar" in Scopus reveals a substantial increase in research publications, review papers, and book chapters on the topic over the past 20 years. The number of articles on biochar has grown significantly between 2006 and 2024. This search was conducted using keywords such as "biochar," "biochar applications," "sustainable agriculture," "biochar effect on plant growth," and "biochar role in climate change." These documents were sourced from reliable, peer-reviewed platforms including Google Scholar, ScienceDirect, PubMed, and the Web of Science. Notably, a Web of Science and PubMed, search highlighted a marked rise in papers exploring biochar and its diverse applications, reflecting the expanding body of research in this field (Fig. 2).

The potential of biochar as a tool for pollution control, sustainable agriculture, and the circular economy was explored through a comprehensive literature review. A keyword search for "biochar and its application" was conducted on ScienceDirect, filtering research publications that provided detailed insights into biochar's benefits in these areas Table 1. summarizes the number of research and review papers referenced in the preparation of this review. Additionally, a graph was generated using Origin software to visualize the data gathered from the ScienceDirect database. This graph effectively illustrates the trends and findings related to biochar's diverse applications.

3. Biochar production from agricultural waste

Biochar can be formed from the bulk of agricultural solid waste, and there are several ways to do it from agricultural waste [25,26]. These include gasification, hydrothermal carbonization, and pyrolysis. Pyrolysis, however, is the method used most often to produce biochar [27,28]. This occurs when organic materials thermally degrade irreversibly at elevated temperatures in oxygen-deficient environments. Pyrolysis-produced biochar can be utilized as a fuel source and to better the state of the soil [29]. A circular economy in agriculture can be achieved by transforming agricultural waste into biochar and integrating it back into the farming system. Pyrolysis can also result in volatile liquid production, classified as slow, quick, flash, or intermediate pyrolysis [10]. Low temperatures (below 450 °C) and air pressure are used for slow pyrolysis, which normally takes a long time to complete [30]. The key product of slow pyrolysis is char [31]. For slow

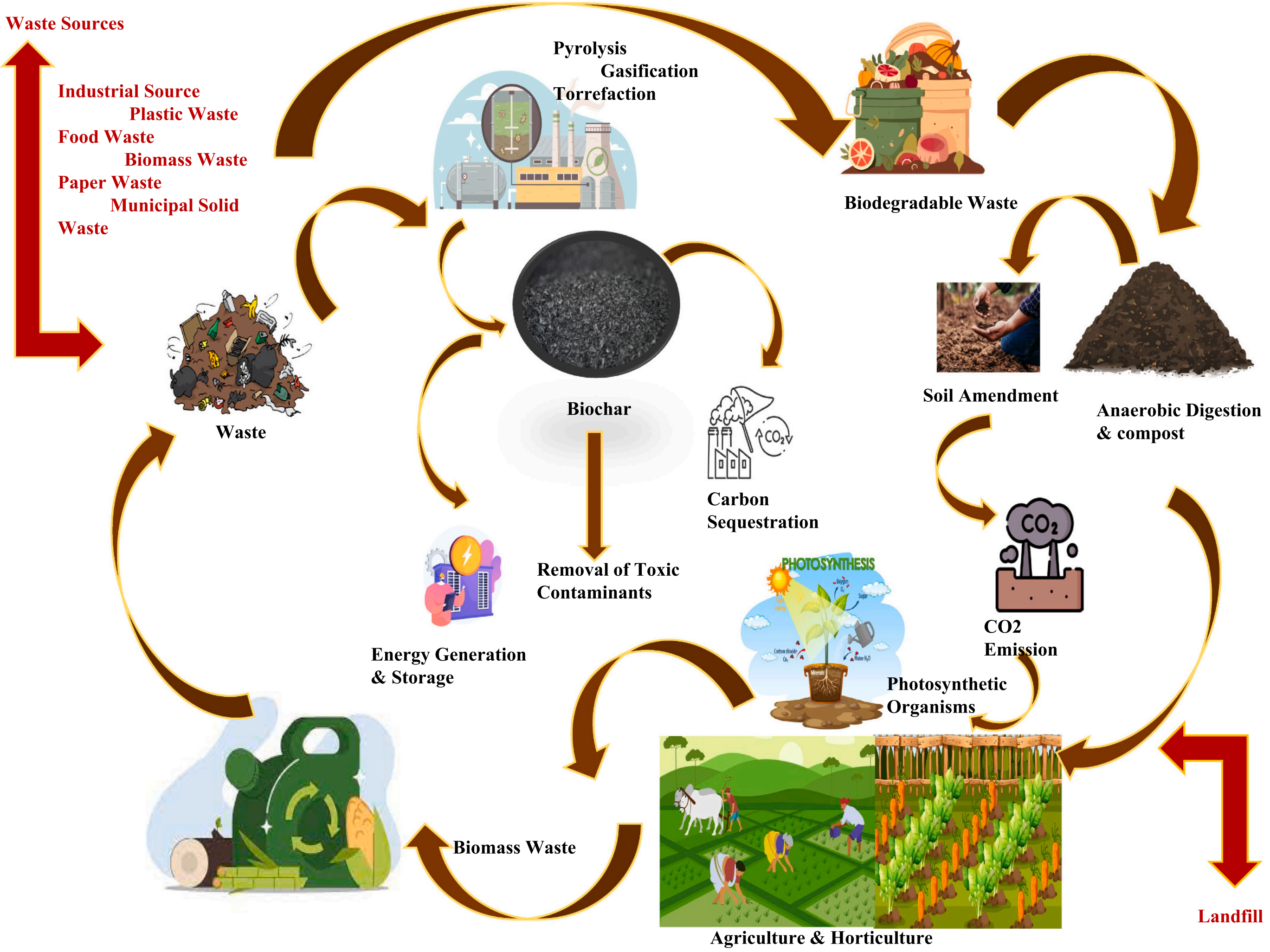

Fig. 1. Biochar integration in circular economy environmental management, pioneering sustainability.

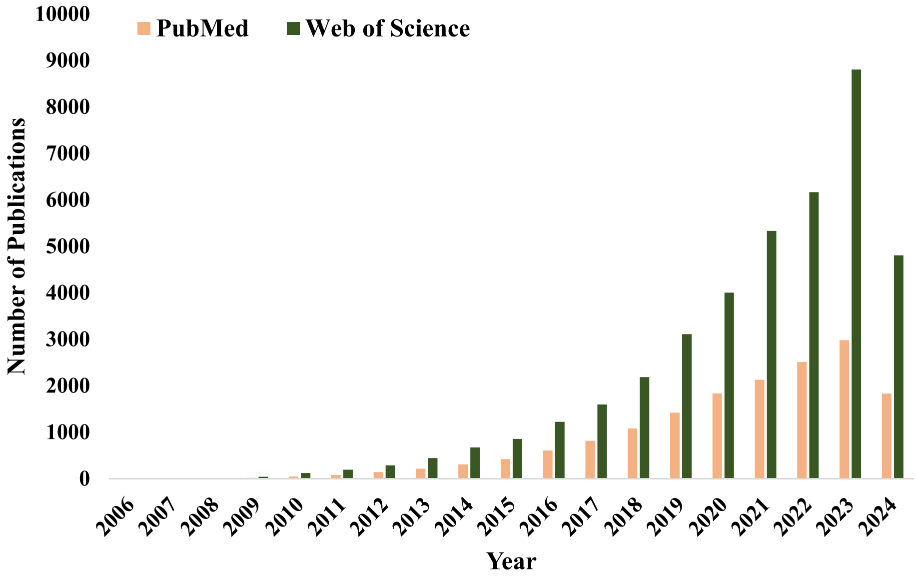

Fig. 2. Number of publications on Biochar from the year 2010 to 2024 (topic keywords “Biochar” searched from Web of Science and PubMed).

Table 1
Summary of the number of referenced research and review papers.

Year	Research articles	Review articles	Total articles
2009	1	2	3
2010	–	–	–
2011	–	2	2
2012	3	–	3
2013	3	4	7
2014	5	3	8
2015	9	1	10
2016	5	7	12
2017	5	7	12
2018	8	3	11
2019	2	11	13
2020	11	10	21
2021	6	12	18
2022	12	15	27
2023	3	9	12
2024	5	9	14

pyrolysis, conventional kilns and unique reactors (such as the Elsa barrel pyrolyzer) are utilized. The yields of slow and fast pyrolysis methods primarily differ from each other. In the latter case, more bio-oil is produced, whereas the former results in higher charcoal yields [32]. Gasification is responsible for the increased surface area and porosity observed in charcoal derived from biomass. This process predominantly converts biomass into a gaseous state, known as syngas, by subjecting it to high temperatures (≥700 °C) in the presence of a minimal amount of oxidizing agent [8].In the production of biochar, one of the primary products of interest is the carbonaceous solid, which undergoes an increase in fixed carbon content due to the evaporation of water and the release of volatile components [33,34]. Fig. 3 depicts different processes of biochar formation. The source of the raw materials used to make biochar can further be considered as it impacts the safety of the environment. Therefore, it is best to steer clear of feedstocks like wastewater sludge and municipal and industrial solid waste that may include harmful pollutants like PCBs, PAHs, and heavy metals [35]. Therefore, biochar generated from these feedstocks may act as secondary pollutants and need additional processing before use.

3.1. Biochar treatment methods: Advantages, challenges, and key insights

Biochar production utilizes various thermochemical processes, including gasification, pyrolysis, torrefaction, and hydrothermal carbonization, each offering distinct advantages and properties to the final product [36].Pyrolysis is a thermochemical process that transforms biomass into biochar, bio-oil, and syngas by heating it without oxygen. Categorized into two types: fast pyrolysis, which occurs at higher temperatures (400–600 °C) with shorter residence times, yielding less biochar but more bio-oil, and slow pyrolysis, which operates at lower temperatures (300–700 °C) with longer residence times, producing a higher biochar yield [37]. The primary benefit of pyrolysis is the synthesis of stable biochar with specialized properties, making it ideal for applications such as carbon sequestration, pollution control, and soil enhancement [38]. However, the process's high energy demand and its dependence on the quality of the feedstock influence both the production efficiency and the quality of the biochar. Moreover, pyrolysis systems can be costly to establish and operate, limiting their widespread adoption [39].

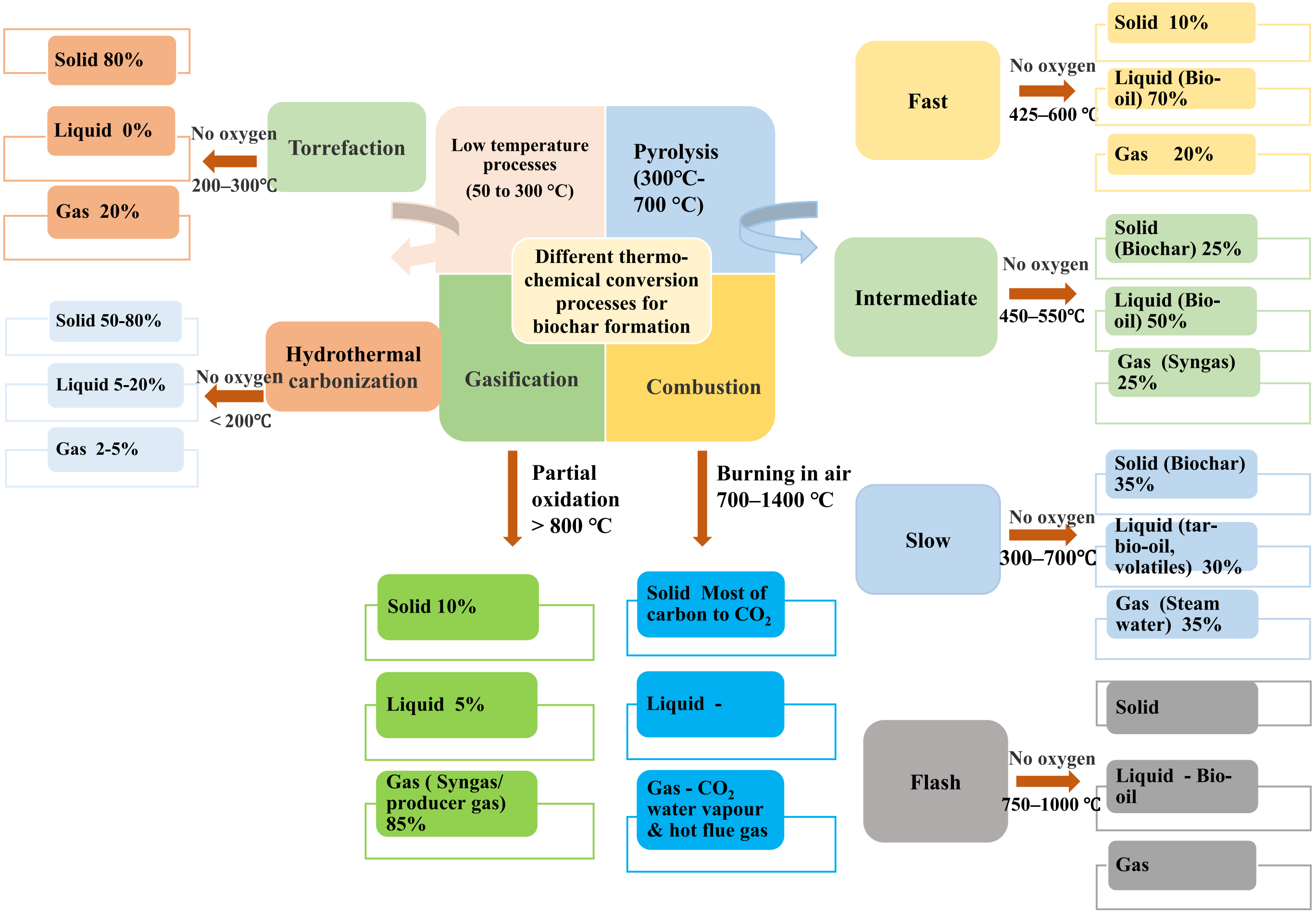

Fig. 3. Different processes of biochar formation.

In contrast, gasification involves the partial oxidation of biomass at temperatures between 700 and 1200 °C in an oxygen-limited environment. This process produces porous biochar and syngas, which can be harnessed as a renewable energy source. The key advantage of gasification is its ability to generate both biochar and energy; however, the biochar yield is lower compared to pyrolysis, and efficient operation requires advanced technology and precise process control [37]. Gasification, operating at temperatures above 700 °C, utilizes various gasifying agents such as air, oxygen, steam, and carbon dioxide to convert diverse waste materials or carbon sources into a mixture of gases, including hydrogen (H_2), carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), and other hydrocarbons. The primary output of gasification is syngas a mixture of CO and H_2 while pyrolysis primarily yields biofuels as its main byproducts [40].

Similarly, hydrothermal carbonization (HTC) transforms wet biomass, such as sewage sludge, into biochar by applying pressure to water at moderate temperatures (180–250 °C). This method is particularly well-suited for processing high-moisture feedstocks, but it comes with limitations such as lower thermal stability of the biochar and high equipment costs [41]. This approach is particularly advantageous for

Table 2
Different biochar nutrient content at various pyrolysis temperatures.

S. no.	Biochar content	Temp. (°C)	pH	Total C%	Total N%	Total H%	Ash %	References
1.	Conocarpus waste	200	7.37	64.19	0.69	3.96	4.53 ± 0.07	
		400	9.67	76.83	0.87	2.83	5.27 ± 0.04	[154]
		600	12.21	82.93	0.71	1.28	8.56 ± 0.02	
		800	12.38	84.97	0.90	0.62	8.64 ± 0.01	
2.	Poultry litter	300	8.46	55.06	4.26	0.22	47.76	
		400	10.06	65.21	2.82	0.12	47.55	[155]
		500	10.51	80.05	2.54	0.08	49.93	
		600	10.80	85.34	0.92	0.09	51.89	
3.	Palm fiber waste	300	7.17	54.21	0.92	1.06	25.11	[155]
		400	8.59	61.70	0.18	0.30	28.65	
		500	8.81	71.72	0.00	0.06	31.40	
		600	10.06	91.44	0.43	0.02	39.69	
4.	Peanut hull	0	–	50.7	1.7	6.1	3.3	[156]
		400	7.9	74.8	2.7	4.5	8.2	
		500	8.6	81.8	2.7	2.9	9.3	
5.	Sugarcane bagasse	300	–	69.5	1.6	4.1	0.3	[27]
		700	–	81.8	1.5	1.6	2.0	
6.	Pine needle	300	–	68.9	1.1	4.3	1.9	[27]
		700	–	86.5	1.1	1.3	2.2	
7.	Giant reed biochar	400	0.20	72.25	0.69	4.09	8.45	[157]
		500	0.13	73.12	0.63	3.01	10.70	
		600	0.11	78.61	0.55	2.22	11.27	
8.	Groundnut biochar	350	9.94	58.13	1.37	–	–	[158]
		700	10.23	63.47	0.73	–	–	
9.	Sheanut biochar	350	9.42	58.72	0.74	–	–	[158]
		700	9.94	70.23	0.45	–	–	
10.	Peanut shell	300	7.8	68.3	–	–	1.2	[10]
		700	10.6	83.8	–	–	8.9	
11.	Sugarcane bagasse	350	7.2	74.7	–	–	1.9	[10]
		450	8.8	81.6	–	–	2.1	
		750	9.7	90.5	–	–	2.2	
12.	Miscatanthus	400	8.7	81.20	0.42	4.09	7.85–12	[159]
		500	9.5	86.66	0.40	3.20	10.06–13.5	
		600	10	90.71	0.33	2.26	9.4–13.8	
13.	Switchgrass	400	6.7		–	–	14.40	[159]
		500	6.6	39.4	0.7	1.30	18.40	
		600	7.4–9.8	68.2	1.9	2.21	3–26.3	
14.	Soybean stover	300	7.27	68.81	1.88	24.99	–	[102]
		700	11.32	81.98	1.30	15.45	–	
15.	Palm kernel shell	350	7.84	62.78	0.77	4.28	11.27	[160]
		450	8.72	66.75	0.80	3.46	12.87	
		550	8.93	74.92	0.88	3.15	13.88	
16.	Almond shell	673		82.07	1.76	5.68	15.86	[118]
		773		82.85	1.70	5.49	11.00	
		873		85.50	1.70	5.28	8.86	
17	Nut shell	673	–	78.15	1.04	6.60	3.36	[118]
		773	–	79.09	1.05	6.48	1.94	
		873	–	81.13	1.20	6.11	2.12	
18.	Hickory wood	300	–	69.13	0.39	4.85	–	[161]
		450	–	83.62	0.17	3.24	–	
		600	–	81.81	0.73	2.17	–	
19.	Wheat straw	300		63.29	4.40	0.52	–	[60]
		450		70.20	4.28	0.47	–	
		600		77.79	3.08	0.42	–	
20.	Rice straw-derived biochar	300	8.24	59.8	0.932	4.12	13.4	[162]
		500	9.72	54.0	0.807	2.08	28.4	
		700	9.98	51.0	0.567	1.32	34.2	
21.	Rice-husk	300	5.89	51.7	0.640	3.85	20.0	[163]
		600	8.90	51.8	0.56	2.05	35.2	
22.	Wood chips	300	5.79	55.7	0.0500	5.73	1.42	[163]
		600	7.27	85.6	0.0900	2.84	1.64	

processing high-moisture feedstocks, as it eliminates the need for drying. However, the scalability of hydrothermal carbonization (HTC) is constrained by the high cost of the specialized equipment required and the tendency of the biochar produced to have lower thermal stability. Torrefaction, which involves heating biomass at low temperatures (200–300 °C) in an inert atmosphere, results in a more energy-dense and transportable material. While this process improves the biomass's properties, its long-term applications are limited due to the production of biochar with lower stability compared to that from pyrolysis [42].

3.2. Elemental and nutrient makeup of biochar

A substance's properties and application in the field are influenced by its structure and composition. According to published research, C, H, O, N, S, P, K, Ca, Mg, Na, and Si are among the elements that make up the composition of biochar [43]. Carbon makes up more than 65 % of the biochar's composition [44]. Mineral components constitute the majority of the ash [45]. Biochar contains aromatic carbon, which is arranged in unstable stacks or piles. Additionally, it likely contains various types of carbon molecules such as fatty acids, esters, phenolic compounds, humic acid, fulvic acid, alcohols, and phenols [46]. Table 2 represents different biochar nutrient content at various pyrolysis temperatures. The minerals magnesium, calcium, potassium, and phosphorus in biochar can serve as a direct supply of mineral nutrients, boosting the features of plant growth, and anions such CO_3^{2-}, OH^-, SO_4^{2-}, and PO_4^{3-} leached from biochar are highly relevant in removing harmful metals by creating metal precipitates [47].

The nutritional composition of biochar depends on the biomass type and pyrolytic temperature. Animal derivative biochar wouldn't necessarily contain more nutrients than plant-derivative biochar if both types of biochar were pyrolyzed at the same temperature [48]. The available P concentration was 0.64 mg/kg, the available Ca was 5880 mg/kg, the available Mg was 1010 mg/kg, and the available Na was 1145 mg/kg in *Lantana camara* biochar formed at 300 °C [49–51].

As pyrolytic temperature increases, the nitrogen (N) content of biochar decreases due to the conversion of certain amino acids into pyridine-N and pyrrolic-N, with NH_4^+-N being lost as NH_3 through volatilization. In contrast, phosphorus (P) and potassium (K) levels rise with higher temperatures, which is linked to the "concentration effect" caused by the reduced biochar yield (Fig. 4). Thus, while P and K content positively correlates with temperature, N content declines during the pyrolysis process.

When pyrolyzed slowly (300–750 °C), it was shown that biochar made from dried swine dung was rich in soil micro-nutrients and micronutrients, comprising calcium, magnesium, sodium, iron, manganese, copper, zinc, nitrogen, phosphorus, and potassium [52]. When biochar made from poultry manure was pyrolyzed at 400 °Cand 600 °C, silt loam, and sandy soils' total N contents dramatically increased, whereas the same soils' total N contents were unaffected by biochar made from swine manure at the same temperatures or by wood chip biochar at 1000 °C [53]. Fig. 5 summarizes carbon sequestration and its utilization for the management of agriculture and environmental sustainability.

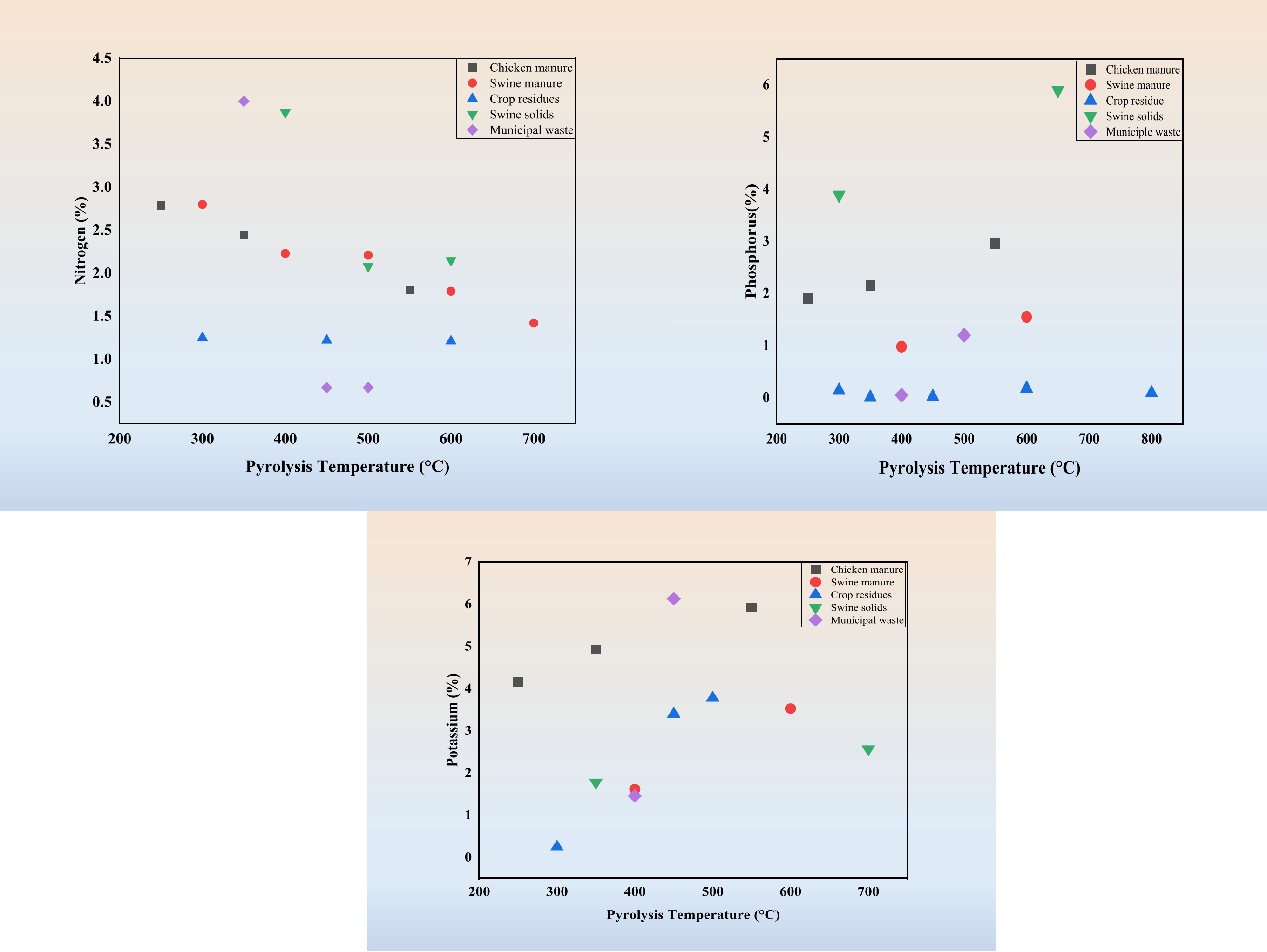

Fig. 4. Effect of feedstock type and pyrolytic temperature on the NPK composition of biochar.

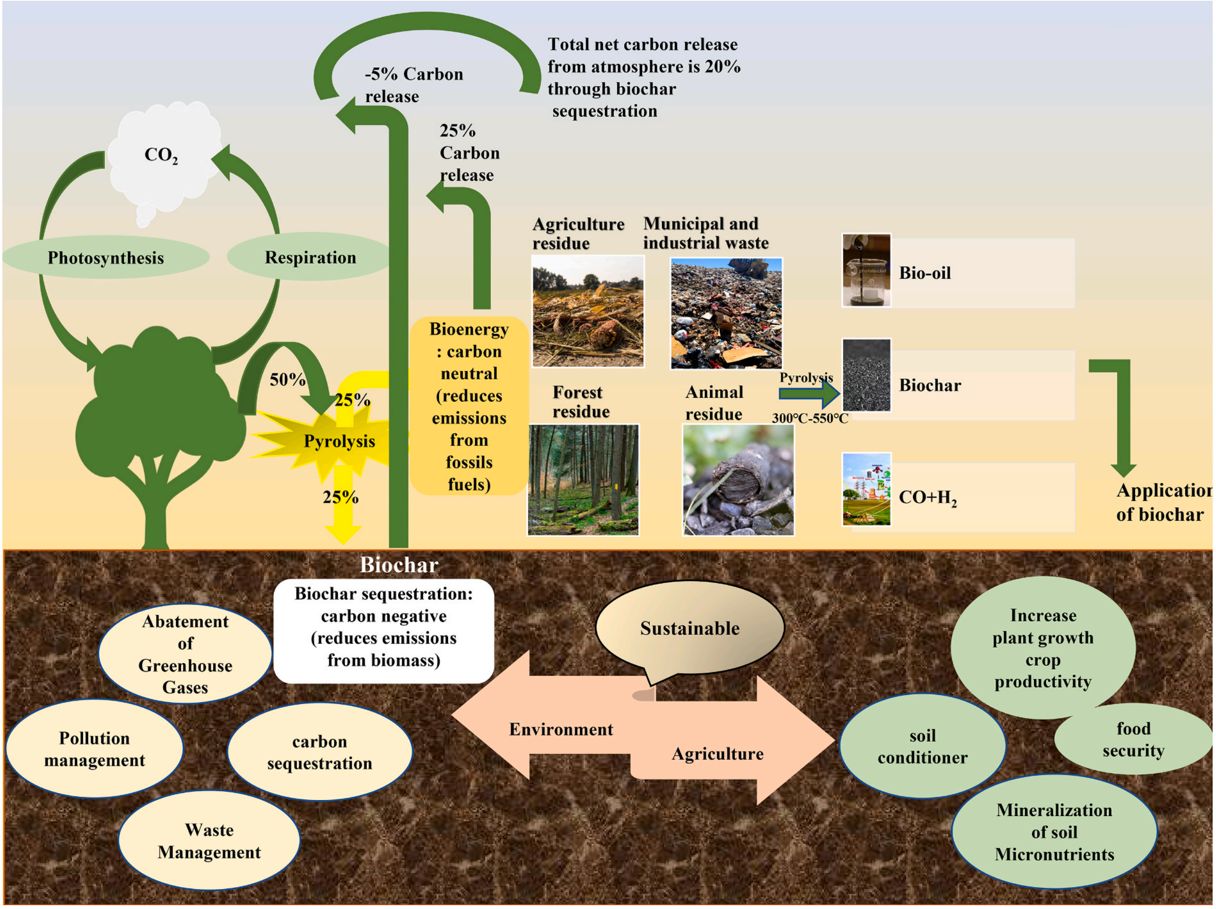

Fig. 5. Biochar-induced carbon sequestration and its utilization for the management of agriculture and the environment sustainably.

Similar to freshly prepared biochar, which may release a significant amount of nutrients (N and P) between 23 and 635 mg/kg and 46 and 1664 mg/kg respectively, biochar prepared freshly is a rich source of instantly available nutrients [49,54]. These illustrations suggest that biochar may have the ability to influence the nutritional content of soil [52]. To ensure that plants can access biochar's long-term nutritional value, nevertheless, it is crucial to make the appropriate choice. Further research is being done on the consequences of adding biochar to organic matter and humic compounds on soil fertility and agricultural productivity [55]. After being heated to 600 and 500 °C, respectively, soil pH increased and dissolved organic material was liberated by biochar produced from cocoa and rice husks [53]. The decomposition of organic waste was expedited, and soil nutrients were enriched when biochar, produced from straw, was heated to temperatures between 500 and 600 °C [56]. Biochar influences the dynamics of composting, which enhances the efficacy of the composting process and the humification process by accelerating the decomposition of organic waste and enhancing soil porosity [57,58]. To increase the carbon content of both fulvic and humic acids, 10 % of biochar generated from cow and chicken manure was added to a composting mixture.

3.3. Modification of biochar

Biochar's inherent properties can be fine-tuned to enhance its efficiency, enabling its adaptation for a wide range of applications. Research in the field of biochar modification has primarily focused on developing tailored biochars optimized for the sorption of various pollutants and nutrients [59].Physical modification techniques are often favored for biochar production due to their simplicity and cost-effectiveness, though they tend to be less effective compared to chemical modification methods. One common approach, steam activation, involves a two-stage process: first, pyrolysis at moderate temperatures (400–800 °C) in an oxygen-free environment, followed by a second stage where the produced biochar undergoes partial gasification with steam. This enhances the biochar's properties for specific applications [60]. By chemically altering biochar's hydrophilicity and surface binding groups, it becomes possible to tailor its ability to remove specific contaminants from wastewater and serve as a soil additive for contaminated areas at a controlled rate [61]. Changes to the binding sites on the biochar surface can significantly enhance its sorption capacity. It is well-established that groups such as amine, carboxyl, phosphonate, hydroxyl, and phenolic can effectively bind to a variety of metals and dyes, boosting biochar's effectiveness in contaminant removal [61]. At low temperatures, chemical oxidation using a combination of $KMnO_4$, H_3PO_4, HNO_3, and H_2O_2 can introduce acidic functional groups, such as phenolic, carbonyl, carboxylic, and lactonic sites, onto the surface of biochar [62]. Xue et al. demonstrated that modifying peanut hull-derived biochar with H_2O_2 significantly enhanced the oxygen-containing functional groups, especially carboxyl groups, on the biochar surface. This modification resulted in a more than 20-fold increase in the lead sorption capacity compared to untreated biochar [63].

4. Biochar for a greener future: Bridging environmental conservation and sustainable agriculture

Today, biochar finds application in a wide range of sectors, mostly in environmental sciences. Biochar has garnered a lot of interest in the removal of toxic metals since it is environmentally benign, inexpensive to replenish, and useful on a wide scale when compared to polymeric and commercial adsorbents. To target particular pollutants, their electroactive components can be adjusted. Because of this, biochar is an effective and multipurpose technique for environmental cleanup. Biochar's substantial surface area, surface functional groups, and microporous structure make it a superior adsorbent for eliminating heavy metal pollutants [64]. Heavy metals can be effectively removed from wastewater through biochar-based adsorption, a highly efficient, versatile, and eco-friendly alternative to conventional techniques. Over the past decade, significant advancements have been made in exploring biochar as a green adsorbent for water remediation. This approach has demonstrated exceptional potential as an affordable solution, offering superior removal efficiency and enhanced sustainability compared to traditional methods [65]. Biochar is emerging as a more affordable and increasingly popular option for wastewater treatment, particularly for the removal of pharmaceutical residues. Its advantages include cost-effectiveness, suitability for large-scale applications, environmental benefits, and highly effective absorption capacities [66,67]. It is increasingly recognized as a cost-effective adsorbent for pollution control. Recent studies indicate that laboratory-produced biochar matches the efficiency of commercial activated carbon in adsorbing organic dye pollutants. Furthermore, biochar and its modified composites offer an innovative wastewater treatment approach that is both economical and environmentally sustainable [68].It has been found that biochar can reduce the prevalence and consequences of these problems both through direct and indirect means [69]. It has a variety of uses, such as the removal of both organic as well as inorganic contaminants from wastewater [70,71].It is also utilized in removing antibiotics from wastewater [72,73]. Table 3 and Table 4 show the removal of heavy metals and antibiotics from water and wastewater using biochar. Due to its capacity to filter out contaminants including pathogens and particulate matter, biochar can be used to replace or improve sand filters in wastewater treatment facilities [74,75].Furthermore, it has been employed in a treatment process, achieving a range of 18 % to 74 % effectiveness in Chemical Oxygen Demand (COD) reduction [28,76]. Carbon-containing compounds have long been used as sorbents to remove organic and inorganic pollutants from soil and water [77,78]. Biochar's adsorption capacity varies greatly depending on the feedstock and production techniques used, leading to notable changes in its surface chemistry and chemical properties [79,80].Due to its versatility, biochar can serve as a sorbent to remove organic and inorganic pollutants from water [28,81]. The efficiency of pollution removal is significantly affected by factors such as pH and adsorbent dosage [82]. Extensive research has explored the potential of modified biochar in removing organic compounds and heavy metals from contaminated environments [83,84]. Biochar is being extensively modified in numerous studies to enhance its adsorption capabilities. Compared to pristine biochar, biochar composites often demonstrate superior physicochemical properties, including an abundance of functional groups, larger surface area, more reactive sites, and remarkable magnetic properties. Fig. 6 illustrates various biochar modification methods lead to enhanced properties that greatly elevate its overall performance. These modifications optimize biochar's structure, reactivity, and functionality, making it more effective for a wide range of applications. Due to their toxicity and accumulative qualities, organic pollutants such as pesticides, herbicides, aromatic hydrocarbons, pigments, and drugs have been a major problem [5,78]. Biochar has been employed for heavy metal sequestration in the soil medium. In this procedure, metals are immobilized rather than eliminated and may be changed into precipitates of hydroxide, carbonate, and phosphate [85,86]. Pesticide sequestration from contaminated soils and carbon storage (a tactic to combat climate change) have been achieved in soil treated with biochar [87]. The ability of biochar to effectively adsorb organic pollutants depends on several factors, including the degree of aromatization, the composition of the elements, the pH, the size of the pores, and the surface qualities [20,88]. Biochar hence reduces atmospheric CO_2 emissions. Conserving the natural environment is challenging due to unchecked resource use and the growing environmental damage caused by human activity. Table 5. Represent different types of biochar's capacity to absorb carbon dioxide. Biochar is also utilized to neutralize acidic soil conditions due to its magnesium and calcium carbonate concentration and potential to elevate pH levels [89,90]. Nevertheless, lower acidity may negatively impact fungi and worms that prefer low-pH soil environments. In addition, biochar can be used to speed up the breakdown of organic contaminants because it includes nutrients like N, P, and K and has surfaces that encourage microbial adhesion [91,92].As

Table 4
The antibiotic adsorption capacities of various adsorbents.

S. no.	Adsorbents	Adsorbate	q_m (mg/g)	References
1.	Activated carbon from macadamia nut shell	tetracycline	455.33	[168]
2.	Rice-husk	levofloxacin	4.99	[163]
3.	Woods chips	levofloxacin	7.72	[163]
4,	Used tea leaves biochar	ciprofloxacin	238.10	[169]
5.	Iron modified *syzygiumcumini* l. wood biochar	ciprofloxacin	4.25	[81]
6.	Iron modified *syzygiumcumini* l. Wood biochar	doxycycline	4.32	[81]
7.	*Tectona grandis* Linn. F. biochar	tetracycline		[72]
8.	Ball milled biochar	sulfamethoxazole	100.3	[170]
9.	Ball milled biochar	sulphapyridine	57.9	[170]
10.	Soap nut seeds	ciprofloxacin	33.4	[171]
11.	Bamboo biochar	ciprofloxacin	50.76	[172]

Table 3
The removal of heavy metals from water and wastewater using biochar.

S.N.		Feedstock	Temp. (K)	Applied dose (g/L)	Q_{max} (mg/g)	Removal efficiency	References
1.	Cr (VI)	Eucalyptus bark biochar	303	2	21.3		[164]
2.	Pb (II)	Oil palm (*Elaeis guineensis*) fibers	300	2–10	38.75	16.67	[165]
3.	Cu (II)	Oil palm (*Elaeis guineensis*) fibers	300	2–10	51.54	16.59	[165]
4.	Fe (II)	Oil palm (*Elaeis guineensis*) fibers	300	2–10	75.47	16.65	[165]
5.	Zn (II)	Oil palm (*Elaeis guineensis)* fibers	300	2–10	0.6414	16.54	[165]
6.	As (V)	Rice husk	303	8	NF	25	[166]
7.	Cr (III)	Rice husk	303	2	NF	14	[166]
8.	Cr (VI)	Rice husk	303	16	NF	18	[166]
9.	As(V)	Organic fraction of municipal solid wastes	303	16	NF	55	[166]
10.	Cr (III)	Organic fraction of municipal solid wastes	303	2	NF	>99	[166]
11.	Cr (VI)	Organic fraction of municipal solid wastes	303	16	44.05	44	[166]
12.	As (V)	Sewage sludge	303	16	13.42	53	[166]
13.	Cr (III)	Sewage sludge	303	12	94.34	>99	[166]
14.	Cr (VI)	Sewage sludge	303	12	64.10	89	[166]
15.	Cr (VI)	***Neolamarckia cadamba*** wood biochar	300	0.1	86.95	94	[28]
16	Cr (VI)	Groundnut husk	303	0.5	93.80	97.5	[167]

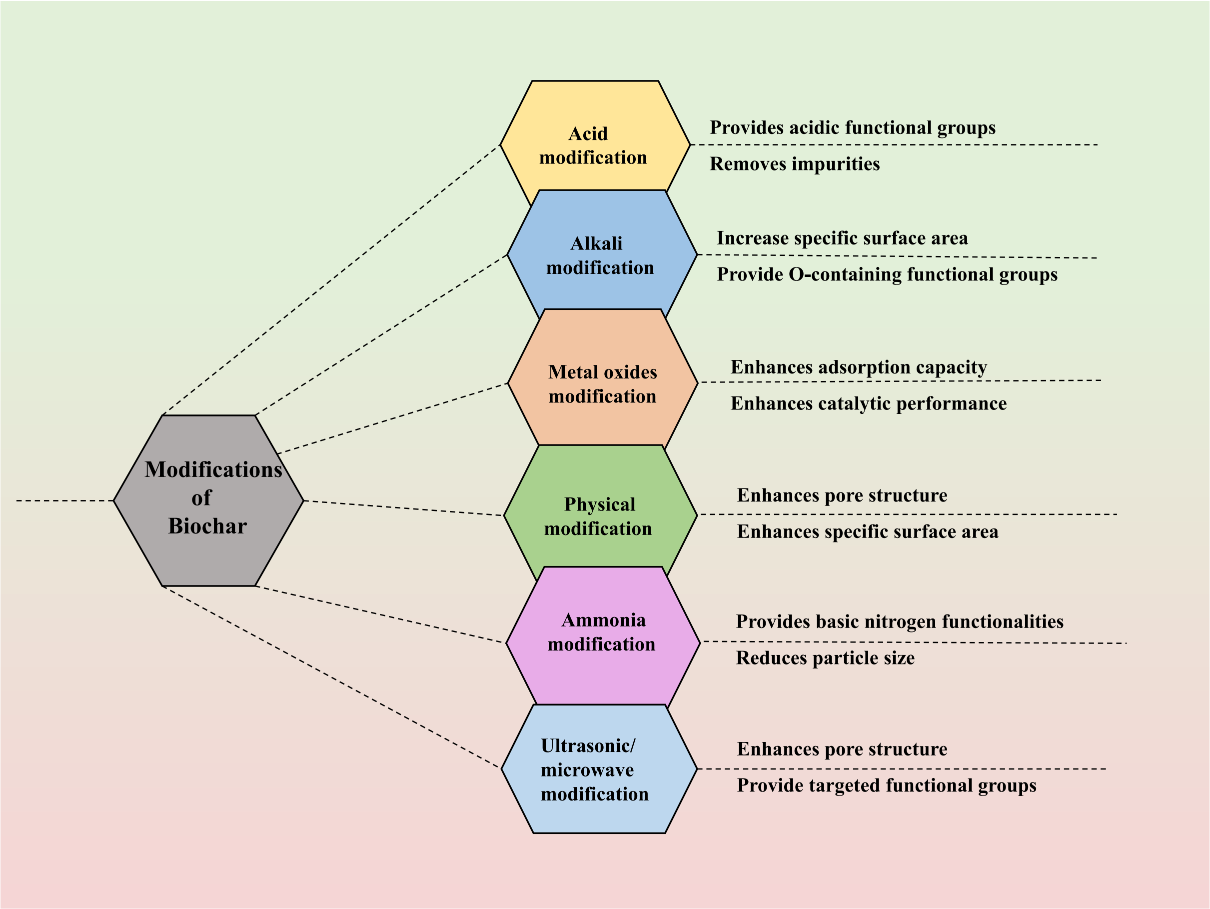

Fig. 6. Different biochar modification techniques yield enhanced properties, greatly boosting its performance and efficiency.

buffering agents in these digesters, biochar has been employed in anaerobic digesters to reduce the impact of NH^{4+}. Many studies have shown that biochar is quite efficient in eliminating both inorganic and organic pollutants The type of contaminant, pH, and surface characteristics of the biochar are often all factors that affect how well inorganic pollutants are absorbed by it [93]. Relatively high pH values reduce the capacity of charcoal to absorb phosphate. Because the adsorbed P is still available, fertilizers can be made that release P gradually. Agricultural soil with biochar added can have its phosphorus leaching reduced by 89.25 % while having its surface phosphorus availability increased about 3.5 times when relative to soil deprived of biochar [94]. In addition to inorganic impurities, biochar can also remove harmful organic chemicals such as dyes, drugs, pesticides, oils, polyphenolic compounds, polycyclic aromatics, and POPs [82,95]. According to the type of contaminant and the characteristics of the biochar surface, the process for entrapping organic material can be divided into pore-filling, p-p interaction, electrostatic interactions, cation exchange, hydrophobic interactions, complex adsorption [96,97]. Engineered biochar has been extensively utilized to eliminate organic pollutants. The proposed mechanisms of pollutant adsorption (organic and inorganic contaminants) are illustrated in Figs. 7 and 8 respectively. With tailored biochar, organic pollutants have been successfully eliminated. The development of biochar loaded with cerium trichloride for the enhancement of levofloxacin elimination is one such example [98,99]. Engineered biochar is also effective at removing biological impurities from water. For instance, the surface area of the biochar increases when wood is treated with H_2SO_4, and *Escherichia coli* retention from stormwater is enhanced. Recently, raw biochar produced from pseudostem of banana biomass pyrolyzed at 600 °C was considerably enhanced by Fe_3O_4 loading. The modified biochar was utilized to remove the antibiotic furazolidone from wastewater effectively and showed superparamagnetic characteristics with a large surface area [100]. Engineering biochar improves its ability to remove pesticides. A field experiment employing almond shell biochar that had been steam activated at 800 °C for 45 min and then gradually pyrolyzed at 650 °C for 1 h under N_2 gas successfully tested the removal of dibromo chloropropane from well fluids [71,101]. The removal of solvents from water is another application of biochar. For example, biochar derived from soybean stover has successfully removed trichloroethylene from water [71,102].Through the development of hybrid approaches like permeable reactive barriers, biochar-based membrane filtration, and biochar-augmented biofilters, biochar can be effectively incorporated into water purification processes [103].In general, bioengineering can be accomplished through hybridization approaches to significantly increase or improve biochar’ removal ability.

Biochar contributes to enhanced plant health and increased agricultural productivity through four significant pathways. The initial mechanism is linked to biochar’s capacity to enhance beneficial bacteria within the root system [104,105].By fostering microbial populations and other microorganisms, biochar facilitates plant growth through heightened micronutrient accessibility and its role as a reservoir of reduced carbon compounds [49].Secondly, biochar’s exceptional water retention capacity enhances the soil’s moisture dynamics, a particularly valuable trait in regions with sandy soil [106,107]. By mitigating moisture loss through reduced leaching, biochar curbs water scarcity, while also averting waterlogging issues in clay-heavy areas by promoting efficient drainage [108].

Furthermore, the third advantage stems from biochar’s remarkable capability to sequester and counteract phytotoxic organic compounds, encompassing synthetic, xenobiotic, and naturally occurring

Table 5
Different types of biochar's (adsorbent) capacity to absorb carbon dioxide (adsorbate).

S. no.	Adsorbents	Modification	q_m(mgCO_2/g adsorbent)	References
1.	Sawdust 450°	Monoethanolamine (MEA)	Temp.30 °CRaw: 19.7, MEA: 19.1 Temperature 70 °CRaw: 13.5, MEA: 12.1	[173]
	Sawdust 750°	Monoethanolamine (MEA)	Temp. 30 °CRaw: 45.2, MEA: 39.7 Temp.70 °CRaw: 25.4, MEA: 22.6	[173]
	Sawdust 850°	Monoethanolamine (MEA)	Temp. 30 °CRaw: 47.5, MEA:44.8 Temp 70 °CRaw: 28.8, MEA: 25.2	[173]
2.	Spent coffee grounds 400 °C	–	0.7(mmol/ g) Temp. 30 °C	
	Spent coffee grounds 500 °C	–	1.3 (mmol/ g) Temp. 30 °C	[174]
	Spent coffee grounds 600 °C	–	2.8 (mmol/ g) Temp. 30 °C	
3.	Walnut shell 500	–	–	[175]
	Walnut shell 900	–	72.6; Temp. 25 °C 30.07; Temp 70 °C	
	Walnut shell 900	Mg loaded	82.04; Temp.25 °C 43.76; Temp. 70 °C	[175]
4.	Pomegranate peels	–	6.89; Temp. 273 K 4.00 Temp. 298 K	[137]
5.	Carrot peels	–	4.18 (mmol/ g) Temp.298 K 5.64 (mmol/ g) Temp. 273 K	[176]
6.	Fern leaves	–	4.12 (mmol/ g) Temp.298 K 4.52 (mmol/ g) Temp. 273 K	[176]
7.	Sugarcane bagasse 600 °C	–	73.6; Temp.25 °C	[161]
8.	Hickory wood 600 °C	–	61; Temp.25 °C	[161]

allelopathic substances. This detoxifying capacity is intricately linked to the substantial increase in surface area during the pyrolysis process [5].

Enhancing the soil's pH, as the fourth technique suggests, brings about a marked and beneficial influence on acidic soil conditions [47].

4.1. Effect of biochar on soil organic matter, microbes and plant growth

The two main methods by which biochar treatment promotes soil fertility are nutrient uptake from different source materials, including the nutrients provided by the soil itself, and elements (such as K, P, and numerous micronutrients) [109]. Because biochar absorbs fertilizers and releases them gradually, it boosts the accessibility of nutrients such as carbon, nitrogen, calcium, and magnesium which benefits overall crop development. Following biochar treatment, soil with a higher CEC binds cations to keep nutrients in the humus, the clay, and the surface of the biochar instead of allowing them to leach out and become less easily available for plant uptake [110].

Due to its large surface area, high porosity, and the presence of both polar and nonpolar sites, biochar significantly enhances soil nutrient retention. This improvement is particularly due to the polar sites of the biochar, where the soil's cation exchange capacity (CEC) is likely to increase. For example, biochar with a high CEC reduces nutrient loss through leaching, allowing more nutrients to remain available in the soil [47]. Additionally, biochar raises soil pH and organic matter content, further aiding nutrient retention. The biochar's CEC results from forming various functional groups, such as carboxyl and hydroxyl, during the pyrolysis process. Applying biochar to soil can modify its cation exchange capacity (CEC). As depicted in Fig. 9 biochar produced from winter grass, when applied at rates of 45, 90, 135, and 180 t ha^{-1}, significantly increased the CEC of entisol soil (initially 14.3 cmol kg^{-1}) to 17.2, 20.2, 24.3, and 27.1 cmol kg^{-1}, respectively. This suggests that biochar can substantially enhance the nutrient-holding capacity of soils, depending on the application rate [111]. Applying biochar enhances nutrient retention by increasing both the soil's pH and its organic matter content. These changes create a more favorable environment for nutrient availability and retention, ultimately improving soil fertility.

Compared with younger or intentionally aged biochar, older biochar typically showcases a more pronounced negative charge. This innate feature effectively enhances soil aggregation and the accessibility of nutrients [112]. The augmented capacity of biochar to retain plant-available water also implies a potential reduction in the necessity for frequent irrigation in agricultural fields, especially within regions grappling with water scarcity [113]. Crop fields, particularly those located in regions with limited water availability, could potentially demand less frequent irrigation due to the amplified plant-available water resulting from biochar application [114]. When juxtaposed with clay-rich soil, the reduced specific surface area and diminished microporosity in sandy soils could accentuate the significant impact of biochar in enhancing water-holding capacity (WHC).The influence of biochar extends to enzymatic activity within its vicinity, affecting both its surface and the surrounding areas, while also providing a habitat for microbial life [115]. This dual role of biochar is rooted in its exceptional porosity, which enables it to modify the soil's physical and chemical conditions. Furthermore, the introduction of charcoal into the soil ecosystem has the potential to reshape the composition and structure of the microbial community, thereby inducing changes in biomass and overall makeup. Soil bacteria encounter biochar's pores as tangible barriers, influencing their movement and interactions [116]. Biochar's aptitude for mitigating pH fluctuations plays a crucial role in upholding a stable and suitable pH environment [117]. This stability within the biochar microcosms fosters the thriving expansion of microorganisms, thereby facilitating their accelerated growth. The interplay between the physico-chemical attributes of biochar and the nature of biowaste significantly influences nutrient availability [118]. The increase in the availability of essential plant nutrients resulting from the integration of biochar is attributed to the gradual release of trace nutrients that would otherwise remain less accessible to soil microbiota [119]. Table 6 shows the effects of adding biochar to soil on plant development and crop production. Biochar enhances plant yield and productivity through diverse mechanisms, reshaping the natural growth conditions of plants. When applied to soils, biochar's distinct black hue modifies heat dynamics, fostering accelerated plant growth and development. This augmentation in environmental conditions contributes to extended periods of environmental health advancement [120]. The utilization of rice husk and sawdust biochar significantly enhanced the uptake of nitrogen, phosphorus, and potassium by maize plants. Furthermore, this application notably augmented plant height, and leaf count, as well as both the dry and fresh weights of the corn cobs [121]. Fig. 10 shows changes in the physico-chemical and biological properties of soil after the addition of biochar.

5. Biochar's role in reducing climate change

Utilizing biochar can lead to the attainment of various objectives, one of which involves enhancing crop productivity to ultimately secure global food sources security [109], enhancing soil attributes to bolster its vitality and overall quality not only counteracts land degradation but also mitigates the release of greenhouse gases, thereby curbing the progression of climate change, all while effectively adsorbing hazardous compounds onto its receptive surface [122].In the global quest to harmonize our climate's cadence, the partnership of biochar and bioenergy emerges as a formidable duet, poised to make substantial strides in rectifying the discordant notes of irregular climate change. Together,

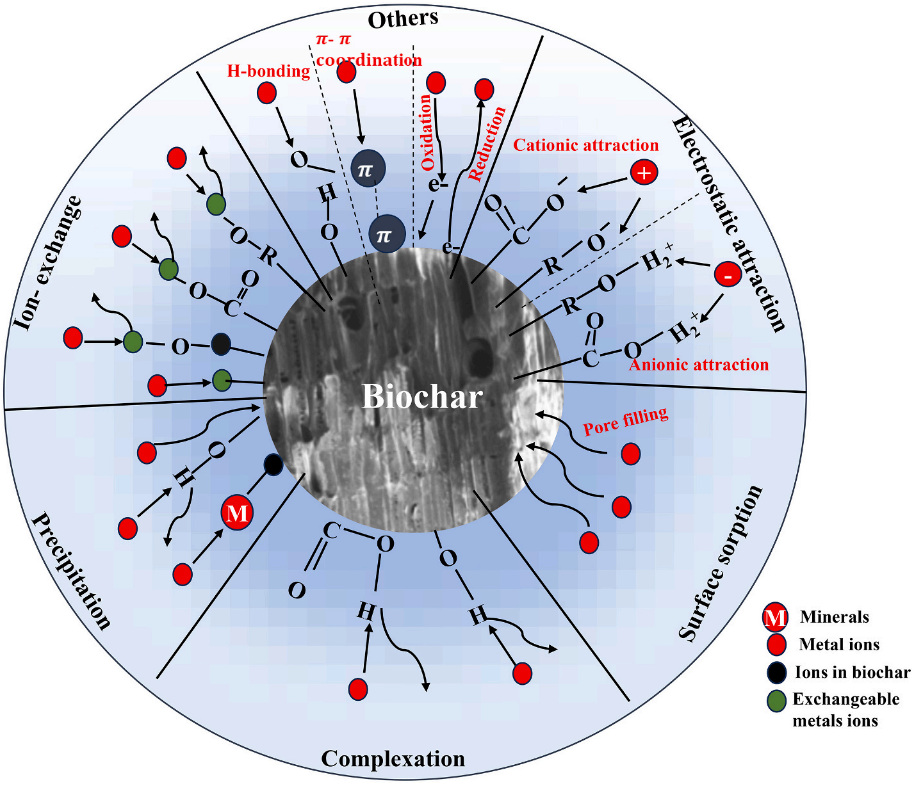

Fig. 7. Illustration of various biochar adsorption mechanisms for inorganic contaminants.

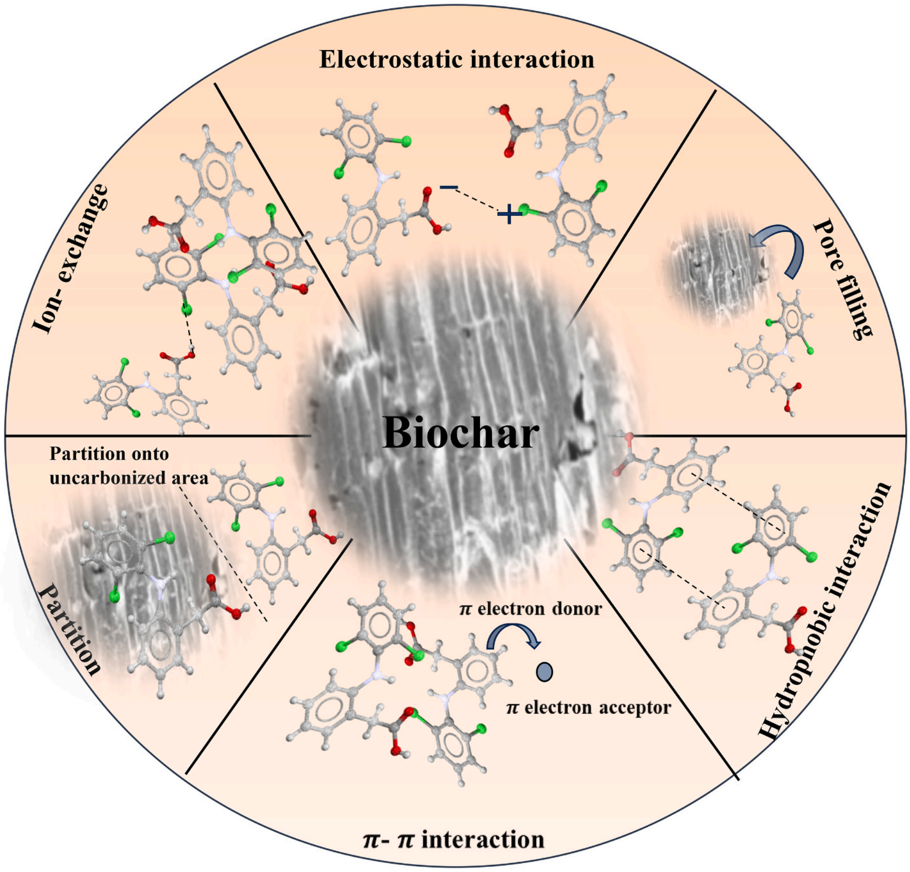

Fig. 8. Depiction of biochar's diverse adsorption mechanisms for organic contaminant removal.

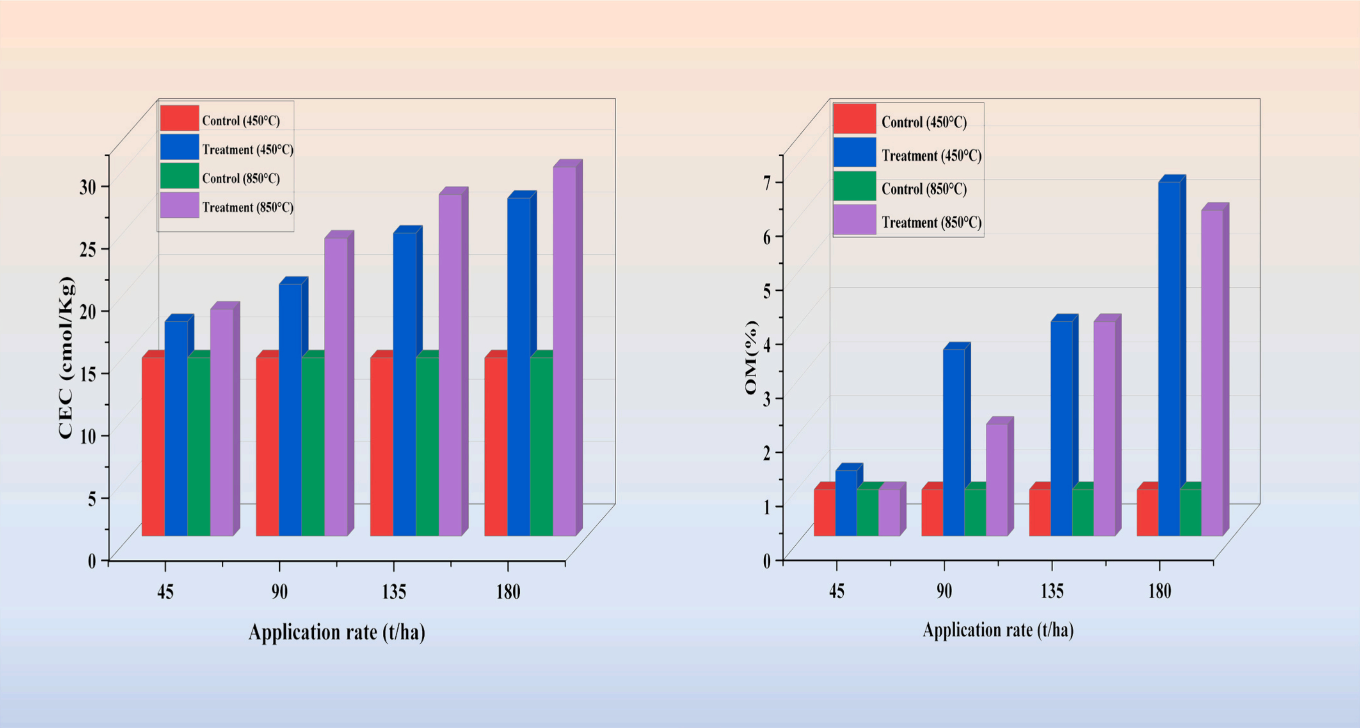

Fig. 9. Impact of biochar application on soil cation exchange capacity and organic matter content.

Table 6
Effects of adding biochar to soil on plant development and crop production.

Biochar Source	Application Rate	Soil Type	Plant Type	Crop Yield	Reference
Conocarpus biochar	4–8.0% (w/w)	Sandy soil	tomato	Increased vegetative growth and yield increased 14.0–43.3 %	[43]
Wheat straw	0, 20, and 40 Mg ha^{-1}	Calcareous inceptisol	Maize	Significantly increased maize yield in both years Addition of nutrients and soil structure and moisture improvement	[43]
Willow wood (Salix spp.)	2.5 Mg ha^{-1}	Red Ferrosol	Maize	increases in grain yield between 10 and 29 %	[177]
Mature switchgrass	1–10 % (*w/w*)	Calcareous soil	Maize	increases in grain yield between 10 and 29 %	[177]
Mixed hardwood	5 % (w/w)	Sandy loam	Wheat	Increased growth and final yield	[178]
Mixture of hardwood	5 % (w/w)	Sandy loam	Potato	Increased growth and tuber yield	[178]
Wheat straw biochar	5 % (w/w)	–	wheat	Increase in wheat grain production	[179]
Sorghum	200 bushels ha^{-1}	Norfolk soil and Dunbar soil	wheat	Wheat yield increased by 31 %	[53]
Rice husks	0, 10, 25 and 50 tha^{-1}	Upland soil and paddy soil	rice and wheat	Increased rice and wheat yield by 12 % and 17 %, respectively	[53]
Maize Cobs	0, 2, and 6 t ha^{-1}	Sand and loamy sandy soil	Maize and groundnuts	Has positive effect on crop yield	[180]

they wield the power to compose a symphony of carbon removal on a planetary scale, a performance that promises to resonate throughout the atmosphere Biochar-bioenergy can significantly contribute to reducing irregular climate change on a worldwide scale in removing atmospheric carbon [15]. Through the incorporation of biochar, not only are crop yields significantly enhanced, but it also plays a pivotal role in facilitating a more cost-effective process of capturing and storing carbon from the atmosphere. With the amendment of biochar, crop yields are greatly increased while also assisting in the cheaper collection and stowage of carbon from the atmosphere [123].Roughly 62 to 66 % of carbon dioxide emissions have the potential to be taken in by biochar, making it a valuable tool in mitigating climate change by effectively sequestering a greater amount of CO_2 from the air and incorporating it into the soil [124].Not only carbon dioxide but also methane and nitrous oxide emissions, among other greenhouse gases, have reached a critical point, posing a significant threat to the ecosystem.

Three main greenhouse gases CO_2, CH_4, and N_2O are responsible for 90 % of the human-induced global warming [125]. In a concerted effort to reduce CO_2 emissions and mitigate their environmental impact, biochar has emerged as a recommended solution, serving both as a waste product repurposing and a practical soil additive for effective carbon (C) sequestration [126].

Numerous studies lend credence to the idea that biochar application leads to a significant reduction in emissions of CO_2, N_2O, and CH_4 gases. However, the path forward requires more extensive, long-term investigations. While the existing research provides a solid foundation, additional in-depth studies are imperative to comprehensively understand the potential and limitations of biochar in achieving sustainable environmental goals [127].

6. How benign is biochar's use for the environment?

The process of biochar synthesis converts easily oxidizable carbon elements present in organic remains into exceptionally stable forms,

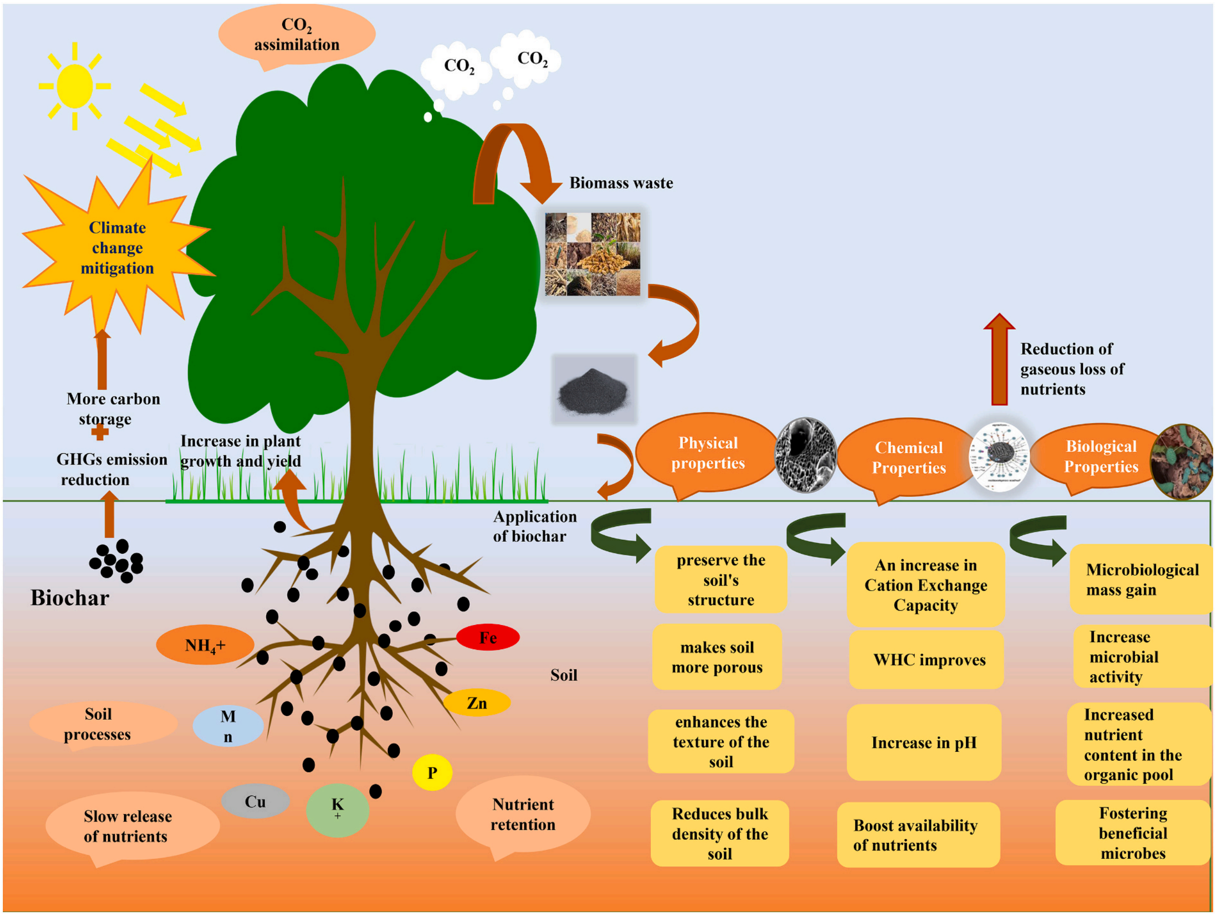

Fig. 10. Changes in physico-chemical and biological properties of soil after the addition of biochar.

capable of enduring in soils for extended durations [128]. Implementing biochar reduces the emission of greenhouse gases, positioning it as a strategy to mitigate climate fluctuations [129,130]. However, the quantities of this amendment required to enhance soil productivity over time, whether in conjunction with composting or other organic inputs, may not yield identical results. Consequently, biochar, often referred to as the "black diamond," is promoted as a promising soil conditioner carrying substantial environmental and economic benefits [131].

Nevertheless, it's essential to account for several environmental factors when implementing this modification. Foremost among these factors is production. The pyrolysis of biochar, while beneficial, does contribute to a noteworthy release of CO_2 emissions. This emission influx has the potential to elevate concentrations of atmospheric greenhouse gases [132]. The breakdown of biochar within the soil stands as the second most significant threat. When the climate is warmer, there is a heightened potential for additional greenhouse gas emissions to emanate from biochar-modified soils due to the accelerated decomposition of biochar in such conditions. A third concern involves the pyrolysis of charcoal, yielding ethylene as a secondary product. When biochar is integrated into soils, ethylene experiences a marked increase, thereby exerting substantial control over various microbial processes within the soil. Despite its capacity to modify the physical and chemical attributes of the soil, the soil biota also plays a pivotal role in enhancing overall plant health [133]. Numerous studies have emphasized the advantageous effects of incorporating biochar into the soil to enhance agricultural productivity. Despite the alkaline properties exhibited by several biochar additions, research has convincingly illustrated that introducing biochar into soil significantly amplifies the accessibility of both macro- and micronutrients [109]. Furthermore, the integration of biochar into soil mitigates the loss of nitrate (NO_3) via leaching and curtails the emission of nitrous oxide, a gaseous byproduct, both of which contribute beneficially to fostering plant growth.

Nevertheless, the outcomes of integrating biochar into soil display variability and are closely intertwined with the specific attributes of the biochar in question, encompassing factors such as particle size and pyrolysis temperature. Notably, coarse biochar particles (exceeding the size of sand) leave soil hydraulic conductivity unaffected, while fine biochar particles exhibit the capacity to lower soil hydraulic conductivity [134].

Furthermore, the temperature at which biochar undergoes pyrolysis exerts a substantial influence on various characteristics, including pH, EC, ash content, presence of functional groups, and carbon stability. As pyrolysis temperature increases, carbon stability notably augments [135]. An additional advantage of utilizing biochar as a soil conditioner lies in its potential to ameliorate the susceptibility of agricultural regions to salinization [136].

Recently, biochar has emerged as a highly effective and sustainable renewable resource with multiple applications. From enhancing product conditions by regulating pollutants to combating climate change, its versatility is unparalleled [137]. With its eco-friendly nature, biochar holds immense potential to bolster a circular economy, conserving resources for future generations while curbing greenhouse gas emissions and enhancing soil and water quality [130].

7. Biochar materials and its applications

The scalability and sustainability of biochar production enable the development of hybrid structures and a wide range of functionalized biochar materials, as explained in previous sections, providing a wide range of commercial uses. Until now, most research has focused on using biochar-centered functional materials for environmental remediation and agriculture applications. Biochar, renowned for its versatility as a catalyst across energy, agriculture, and environmental sectors, emerges as a potent and auspicious catalyst due to its distinctive attributes [70]. The abundance of functional groups concentrated near its surface emphasizes the pivotal role of its expansive surface area in facilitating catalytic processes effectively [8]. Employed in diverse applications such as biodiesel production, energy generation, tar removal, waste management, syngas generation, microbial fuel cell electrodes, chemical manufacturing, and environmental pollutant mitigation, biochar showcases its multifaceted utility as a catalyst [61,138]. Fig. 11 depicts biochar's diverse applications across multiple fields highlighting its remarkable versatility.

8. Limitations of biochar application

The increasing research trends on biochar emphasize the promising potential of utilizing biochar, it's crucial to address certain limitations. Increasing the application dosage of biochar, obtained from wheat straw (300–1100 °C) at a rate of 15 tons/ha, has revealed a notable consequence: a 200 % surge in weed production. This surge intensifies competition for soil nutrients with the main crops, posing a significant challenge [139]. When evaluating the toxicity of biochar, heavy metals (HMs) are among the most significant inorganic pollutants of concern. The chemical composition of the feedstock or any pre-existing contamination in the original material influences its presence in biochar. During pyrolysis, the partial mineralization of organic matter often leads to a concentration effect, where the levels of HMs in the resulting biochar are higher than those in the original feedstock [140].Biochar is commonly used to treat metal-contaminated soils by immobilizing pollutants. There has been a growing trend toward producing biochar from controversial sources, such as waste or sewage sludge in recent years. However, the pyrolysis process can concentrate metals present in these feedstocks, potentially posing environmental risks when such biochar is applied to soil [141].

Polycyclic aromatic hydrocarbons (PAHs) are among the most common pollutants found in biochar. These hydrocarbons, composed of molecules with two or more fused aromatic rings, form primarily during the pyrolysis process. Their production is driven by the carbonization and aromatization of organic materials, the addition of hydrocarbon radicals, and the synthesis of more complex aromatic compounds [142]. Adding different types of biochar to soil is generally safe and often leads to beneficial outcomes, such as increased plant biomass and enhanced microbial activity. However, these effects depend on several factors, including the type of biochar (determined by its feedstock and pyrolysis temperature), the application rate, and the characteristics of the soil to which it is applied [143]. Biochars derived from plant-based materials generally have lower levels of contaminants compared to those made from sources like animal manure or sewage sludge, making them less toxic.Due to biochar's capacity to effectively slow down soil aging, maintaining optimal nutrient cycling and aquatic conditions within the soil may require periodic infusion of fresh biochar [144]. For instance, Anyanwu's research highlights that the utilization of older rice husk-derived biochar can significantly impede the growth of earthworms and soil fungi [145]. Moreover, the application of biochar might lead to a delay in the flowering capability of plants.

Zhao's research shows that *Solanum lycopersicum* and *Oryza sativa's* root biomass are significantly reduced when aged biochar is utilized. The application of 14 t ha^{-1} of biochar to tomato crops, however, did not show the same effect on fruit yield, highlighting how the impact of

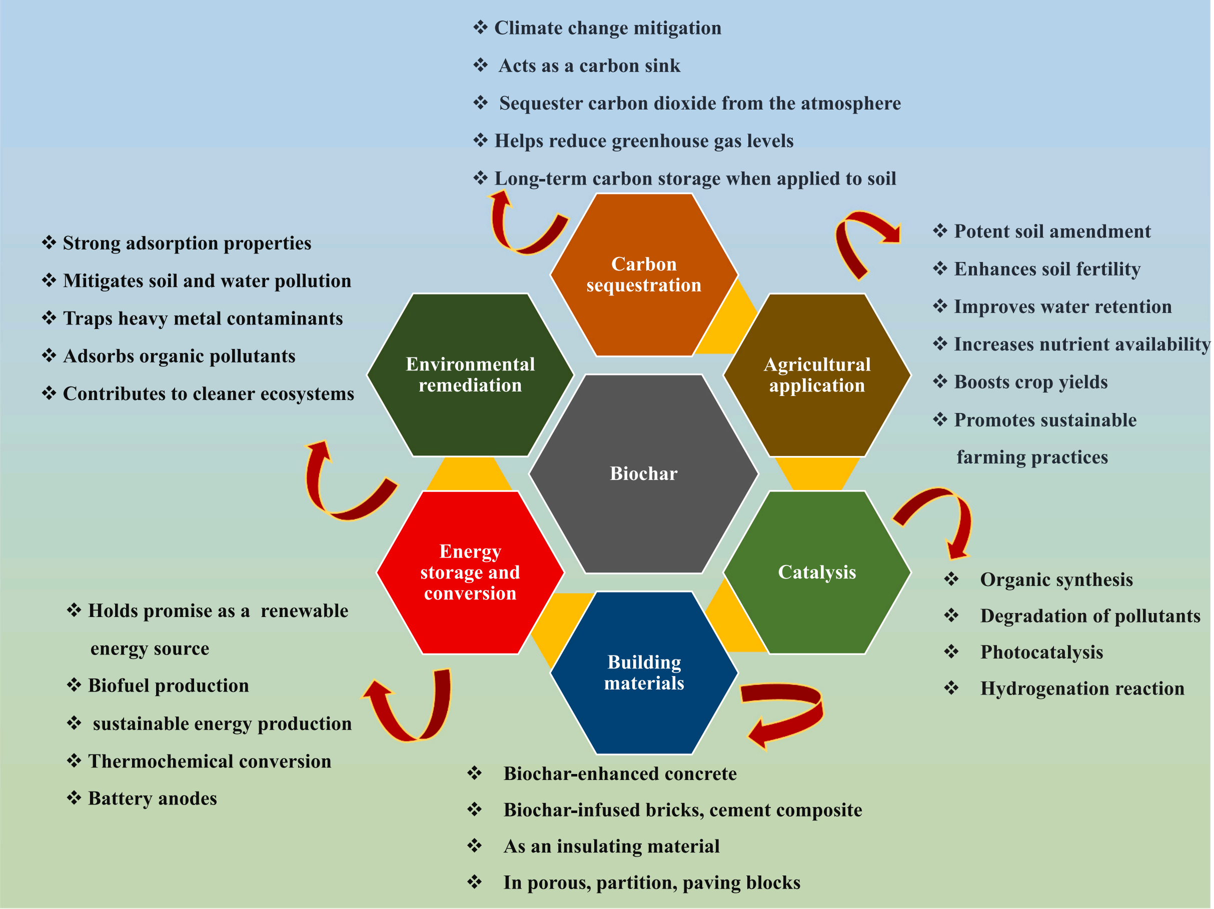

Fig. 11. Biochar's diverse applications across multiple fields highlight its remarkable versatility.

biochar on crop output varies depending on the plant species or the targeted plant part [146]. Furthermore, biochar exhibits a distinctive ability to selectively absorb contaminants [147]. It's noteworthy that the presence of charcoal within the soil doesn't appear to affect its capacity to absorb the herbicide dichlorodiphenyltrichloroethane (DDT). The increased ash content in biochar produced under high temperatures could potentially hinder plant growth [148].Furthermore, biochar's ability to absorb essential nutrients and act as a competitor may negatively affect crop yields [149]. For instance, when biochar and phosphorous fertilizers are applied to saline or sodic soil, they promote phosphate precipitation or sorption, reducing phosphorus accessibility for plants [150]. Additionally, incorporating biochar into the soil may disturb organic matter decomposition, potentially diminishing the populations of Ascomycota and Basidiomycota fungal species, thus impacting soil health [151].

9. Advancing biochar utilization: Future prospects

Advances in sustainability and environmental impact reduction present significant opportunities for the future use of biochar across various sectors. In agriculture, biochar's role as a soil amendment will be further optimized to enhance fertilizer efficiency, improve nutrient retention, and sequester carbon, promoting long-term soil health and reducing reliance on chemical inputs [152]. Given its ability to store carbon for generations, biochar is also well-positioned to contribute to climate change mitigation and could play a key role in carbon markets. In waste management, producing biochar from urban and agricultural waste not only helps address disposal challenges but also transforms waste into a valuable byproduct with multiple applications.

In recent years, biochar has gained attention as a promising catalyst for hydrogen production due to its unique structure, versatility, and widespread availability. Its application as a catalyst has shown the potential to significantly enhance both the yield and quality of hydrogen by exhibiting improved catalytic activity and thermal stability. The physiochemical properties of biochar are largely influenced by the type of feedstock used, providing flexibility in its design and application [153]. Furthermore, modifications such as the addition of alkali or acidic agents, metal ions, carbonaceous materials, oxidants, gas purging, and steam have been found to substantially boost its catalytic [40].

The use of biochar as a renewable energy source for generating heat, syngas, or bio-oil in bioenergy systems is expected to expand, particularly in integrated systems. Additionally, biochar's potential as an adsorbent for soil remediation and water filtration is being explored, with advancements focused on its ability to remove pollutants and toxins. Its applications are also extending to innovative materials, including construction composites and energy storage devices such as supercapacitors. As biochar technology progresses, its integration into smart agricultural systems could lead to more precise, data-driven applications that optimize both environmental sustainability and economic benefits.

10. Future prospects of biochar research

To address global issues like mitigating climate change, biochar has emerged as a crucial and affordable material that reduces net greenhouse gas emissions and global warming. Concurrently, it can improve soil production and quality, which will support efforts to promote food security.

With its great potential, biochar can be used in both agricultural and environmental contexts. It is an economical and effective way to improve soil fertility, quality, remediation, storage of carbon dioxide, and greenhouse gas mitigation. An extensive body of knowledge remains regarding several aspects of biochar in agroecosystems: its long-term persistence; the best application rates for a range of biochar-soil-crop-environmental conditions; interactions with soil carbon stocks; particular mechanisms affecting the biotic properties of the soil.

Further exploration is needed to advance the prediction of nutrient dynamics in biochar-amended soils by refining existing kinetics models, both in laboratory and field environments. A comprehensive understanding of the mechanisms governing soil fertility and nutrient availability is paramount for grasping nutrient dynamics.

11. Conclusion

Despite extensive literature reviews highlighting the potential of biochar and its modified composites for sustainable applications across various fields, several knowledge gaps persist. Biochar produced from different biomass feedstocks and methods typically demonstrates enhanced surface areas, increasing active sites and improving adsorption efficiency for removing toxic heavy metals from wastewater. Critical factors such as pyrolysis temperature, heating rate, and biomass type significantly influence biochar properties, including pore distribution, specific surface area, pore size, surface functional groups, carbon content, and ash content. While biochar is increasingly employed in adsorption-based wastewater remediation, as well as in catalytic synthesis, soil enhancement, and energy storage, key unresolved questions must still be addressed to ensure its effective and optimized use in these applications.

The review article examined the viability of utilizing biochar derived from agricultural waste as an eco-friendly alternative to conventional methods for mitigating environmental contaminants, improving soil health, and implementing prolonged biochar applications in a given ecosystem. Biochar, derived from agricultural waste, holds the potential to significantly enhance environmental sustainability and safety. The optimization of biomass composition and quantities is essential for harnessing its positive environmental impact, as the attributes of biochar are intricately tied to its mineral composition. Beyond its role in curbing greenhouse gas emissions and mitigating soil nutrient loss, biochar exhibits a multifaceted influence on soil productivity, atmospheric carbon sequestration, mitigation of environmental pollutants, and reduction of greenhouse gas discharges.

Deliberate and thoughtful consideration of biochar's type, application rate, and compatibility with agricultural systems is imperative before implementation. By integrating biochar usage, it becomes possible to preserve the environment while maintaining crop yield through the controlled release of nutrients. This necessitates a blend of informed scientific investigation and socio-economic analysis to fully harness the considerable potential of biochar in bolstering agroecosystems and fostering an ecologically balanced sustainable environment. The strategic incorporation of biochar holds the capacity to elevate soil quality, amplify agroecosystem resilience, and fortify agroforestry practices, enabling them to better cope with evolving climatic conditions. It's important to note, however, that the effects of biochar can exhibit variability based on geographical factors. While biochar is not a universal solution for all agroecosystem challenges, it stands as a valuable tool to contemplate for future agroecosystem development.

While this study delves into numerous benefits, complexities, and implications of biochar, a more comprehensive understanding of the intricate processes driving biochar and its intricate interactions with plant life, soil composition, and broader ecosystems requires further investigation.

Funding

This study did not receive any specific grant from funding agencies.

Author's contribution statement

Amreen Bano, Mohd Kashif Aziz: Literature collection, Validation, Formal analysis. **Bablu Prasad, Rajesh Ravi, Pollyanna Vanessa dos Santos Lins:** Conceptualisation, Interpretation. **Maulin P Shah, Lucas Meili, Kumar Suranjit Prasad:** Writing, Visualisation, Supervision.

Declaration of competing interest

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

Data availability

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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