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Review article

An extensive analysis and environmental sustainability applications of multifunctional biochar developments: Current trends and technological advances

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ABSTRACT

This review highlights the multifunctional applications, recent trends, and technological advancements of biochar (BC), a carbon-rich material produced through biomass pyrolysis. BC has emerged as a promising solution to environmental and agricultural challenges. The manuscript examines key production methods, such as slow pyrolysis, fast pyrolysis, and gasification, and their effects on BC's physical, chemical, and structural properties. It explores BC's applications in soil improvement, water treatment, waste management, and renewable energy. Recent innovations, including nano-BC, BC composites, advanced pyrolysis techniques, and feedstock diversification, are discussed alongside the importance of quality and safety standards. This review emphasizes BC's versatility and potential to drive sustainable solutions, offering insights for future research and development.

1. Introduction

Biochar (BC), a carbon-rich product derived from the pyrolysis of biomass under limited oxygen, has gained attention for its potential to address global environmental and agricultural challenges [1,2]. Its high carbon content and stability allow for long-term carbon sequestration, contributing to climate change mitigation. BC enhances soil fertility, structure, and water retention, making it a valuable tool in sustainable agriculture [3,4]. It also exhibits remarkable pollutant adsorption capacity, supports microbial activity, and offers applications in water treatment, energy storage, and ecological restoration [5]. The concept of utilizing post-combustion technology-based carbon capture was motivated by the exceptional refractoriness of BC and its potential for carbon sequestration. Due to its inherent ability to efficiently sequester carbon, it possesses the capacity to function as a highly beneficial instrument in the domain of climate change mitigation. BC exhibits promising potential in enhancing agricultural productivity in acidic soils by encouraging fertility indicators. BC in the soil has been found to strengthen aerated soils, the availability of nutrients, and water filtration [6,7]. A variety of techniques have been devised for BC, including soil enrichment, moisture retention, the slash-and-burn carbonization method, concrete additives, and incorporation into animal supplement feed. Furthermore, BC is recognized for its ability to adsorb pollutants and improve soil microbial activity, contributing to healthier and more resilient ecosystems. BC is well recognized as an environmentally friendly soil additive with a positive reputation, offering diverse applications that support sustainable agricultural practices and environmental restoration [8,9].

However, challenges such as potential soil pH alterations and contamination from feedstock-derived heavy metals necessitate comprehensive studies to ensure safe and effective BC applications [10,11]. Innovations in production techniques, such as functionalization and structural optimization, are advancing BC's efficacy for diverse applications, including hydroponic systems and remediation of contaminated sites [12,13]. This study uniquely focuses on recent advancements in BC production, including nano-BC and composites, and their impact on application-specific performance. By emphasizing regulatory frameworks and quality standards, this work provides critical insights into BC's role as a sustainable solution for addressing environmental and agricultural challenges. This manuscript aims to bridge gaps in current knowledge, highlighting BC's transformative potential in promoting environmental sustainability and tackling global issues.

Pyrolysis is a critical thermal decomposition process used extensively in the production of BC, syngas, bio-oil, and biogas from biomass [14,15]. The importance of the pyrolysis procedure can be attributed

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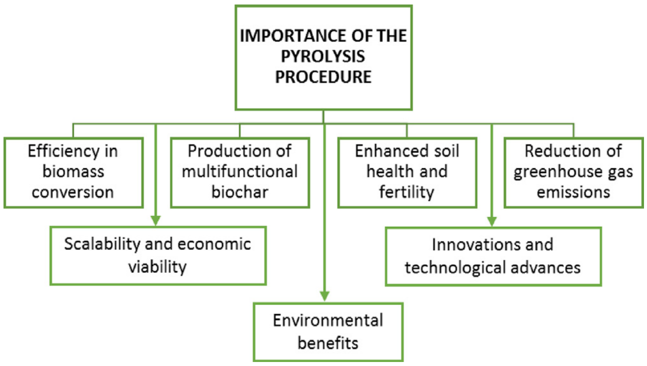

Fig. 1. The transformative role of pyrolysis in converting biomass into high-value products.

to several key factors (Fig. 1). Its efficiency, adaptability, and environmental benefits make it a key technology in advancing sustainability and addressing global environmental challenges.

In recent years, BC has garnered significant attention from the agricultural and environmental sustainability sectors due to its multifaceted applications in ecological restoration, mitigation of environmental harm, energy storage, and remediation of polluted sites [11]. The environmental efficacy of BC in carbon sequestration has been demonstrated due to its capacity to securely retain carbon dioxide, hence mitigating the release of greenhouse gases. Adding this material in the soil helps to improve plant growth by improving soil structure, water-holding capacity, and nutrient mineralization. BC may also help maintain groundwater quality by decreasing the intensity of toxins deposited into it via precipitation and irrigation [16]. Recently, a significant advancement in It reported that they are now continuing to perfect the production procedures so that it is able to produce more and bigger grades of high-quality BC. The effectiveness of BC in various circumstances is influenced by its morphology or structure [13]. Presently, scholars are working to improve BC production techniques to achieve the desired morphological features for certain applications [12]. BC serves as a valuable soil amendment by enhancing nutrient accessibility, reducing the requirement for fertilizers, and improving microbial activity within agricultural environments. Their porous nature aids in nitrogen cycling and soil organisms [16]. Furthermore, BC is already used as a substrate for some hydroponic plant cultivation systems locking potential in both soil-based and soilless operations.

BC has become a subject of considerable interest within the agriculture and sustainable development fields in the latest times, primarily due to its diverse uses in areas such as ecological restoration, mitigation of environmental damage, energy storage, and remediation of contaminated sites [17]. The holistic application of BC is illustrated in Fig. 2. The proven environmental effectiveness of BC in carbon sequestration is attributed to its ability to hold carbon dioxide firmly, hence limiting the emission of greenhouse gases. Incorporating this substance into the soil facilitates the proliferation of vegetation and ameliorates soil erosion by strengthening soil fertility, improving water retention, and preserving nutrients. The potential of BC to mitigate the impact on groundwater quality by reducing the leaching rate of contaminants during precipitation and irrigation events is worth considering. In recent decades, a notable improvement in BC production has been optimizing production techniques to ensure constant grades of high-quality BC. The impact of BC's form or structure on its efficacy in different scenarios is significant [12]. Current research endeavours are focused on enhancing BC production techniques to attain specific morphological characteristics suitable for applications [18,19]. BC functions as a soil amendment that effectively improves the accessibility of nutrients, diminishes the need for fertilizers, and promotes the proliferation of microbial growth in agriculture environments [20]. The material's structure is characterized by its porous nature, which supports the nitrogen cycling process and offers a suitable environment for vital soil organisms. BC was additionally employed as a growth medium in hydroponic plant cultivation systems, with encouraging outcomes in both scenarios.

This manuscript addresses critical gaps in existing BC research by providing a comprehensive review of its multifunctional applications and recent technological advancements. While prior studies have explored BC's utility in specific areas such as soil amendment or water treatment, this work uniquely integrates insights across diverse applications, including emerging trends in nano-BC, BC composites, and scalable production technologies. It also emphasizes the impact of production methods on BC's physicochemical properties, a crucial factor often overlooked in holistic analyses.

2. Sustainable bioenergy production with BC

The multifaceted applications and inherent benefits of BC within the bioenergy sector position it as a significant contributor to the industry's sustained viability. There are several crucial considerations to be taken into thought:

The topic of discussion pertains to the generation of renewable energy and the process of carbon sequestration. The method of biomass pyrolysis yields BC, a material abundant in carbon and characterized by its enduring stability over extended periods. BC can effectively mitigate greenhouse gas emissions due to its capacity to sequester carbon. Carbon dioxide emission during biomass combustion for energy production is of particular significance within the domain of bioenergy [20]. BC exhibits promising promise as a valuable resource for generating bioenergy through various procedures. The potential use of this technology lies in its use as a co-firing alternative with biomass in power plants. This application can provide an environmentally favourable and sustainable energy source for producing heat and electricity. In addition, BC exhibits promising potential as an important resource within gasification or pyrolysis systems since it can be effectively employed as a bio-oil fuel source for syngas production [13]. These products can be further converted into biofuels and therefore have the capability of becoming a sustainable energy source.

BC offers a viable approach to addressing organic waste through its potential to facilitate nutrient cycles, trash disposal and handling, and biodiversity remediation. BC can be generated by pyrolysis, which involves the thermal decomposition/breakdown of various materials such as agricultural by-products, biomass remnants, and municipal organic waste [21,22]. This process significantly reduces the volume of waste directed to landfills, contributing to more sustainable waste management practices. Appropriately, it takes trash and gives added value while turning waste in to an asset that can be used for power or better soil quality. Adding BC to agricultural soils has enhanced crop yields by improving nitrogen cycling and facilitating environmental restoration [23]. The integration of BC as a consistent carbon source enhances soil structure and promotes the presence of beneficial bacteria. This process enhances the soil's capacity to hold moisture and mitigates the loss of nutrients through leaching.

BC in the context of climate change adaptation, resource consumption, and the bioeconomy is a topic of significant academic interest. The best part is that BC has the ability to be produced alongside biofuel and other forms of SEP. The production of BC increases the value and sequestration opportunities with biomass feedstock [24]. Thus, this complete holistic bioenergy process is highly efficient and sustainable in long run. The BC production through the use of unwanted residues, potentially recoverable for energy and/or soil amendment destination synchronizes very well with the basic goals of a bioeconomy. The approach described by [25] demonstrates a self-sustaining technique that effectively reduces emissions, optimizes efficiency, and mitigates the reliance on fossil fuels. This makes it possible to find synergies in the context of bioenergy production and BC application and this is an opportunity for minimizing greenhouse gas emissions, so that from all

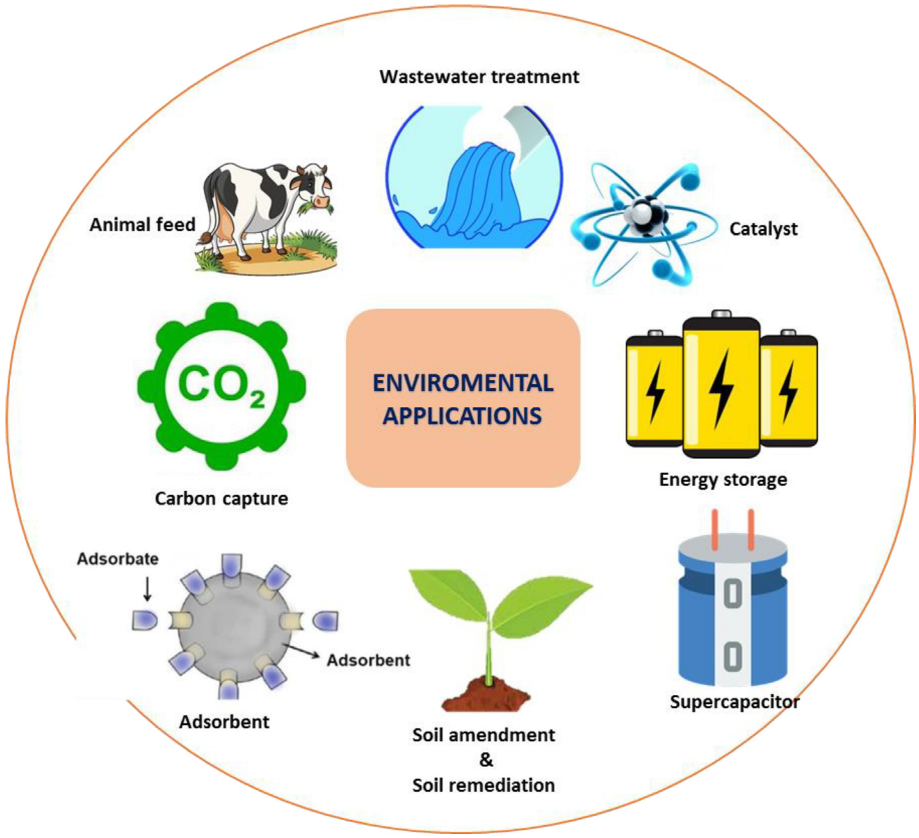

Fig. 2. Sustainable applications of BC in environmental remediation.

Table 1
BC-based sustainable bioenergy production.

Bioenergy's properties	Explanation of bioenergy properties	Reference
Carbon sequestration process	The application of BC effectively mitigates carbon dioxide and other greenhouse gases due to its ability to sequester carbon sustainably.	[12]
Sustainable energy generation	BC can be employed in the firing or co-combustion process of plant materials to generate heat or power, as well as serve as a fuel source in the production of biofuels.	[13]
Systematic waste materials	BC can be derived from organic waste, offering a twofold advantage of reducing the amount of garbage deposited in landfills while simultaneously generating a valuable resource.	[27]
Nutrient cycling and environment restoration	The practical application of BC enhances various aspects of the ecological restoration of farmland, including water and nutrient retention improvements.	[28]
BC collaborative production	The efficient use of BC enhances the value and efficiency of biomass feedstock.	[29]
Implementation of the circular economy paradigm.	BC plays a crucial role in a closed-loop system by enhancing operational efficiency and mitigating environmental consequences.	[30,31]
Mitigation of climate change	The deployment of bioenergy generation effectively traps carbon and mitigates emissions.	[32]

measures mitigating global warming at least the following conclusion may be drawn out. BC is generated through the carbonization of biomass feedstocks, serving as an energy source that can effectively sequester carbon and mitigate the release of greenhouse gases. This action aligns with the overarching objective of reducing atmospheric carbon dioxide levels, as highlighted by [26]. This paper sheds light on the possibility of using BC in bioenergy applications, arguing why it is a sustainable and long-term alternative. The components are as described in Table 1.

A multitude of research studies have demonstrated the potential benefits of BC in addressing a range of concerns, encompassing environmental rehabilitation, carbon capture and storage, management of organic waste, generation of sustainable energy, and the advancement of a bioeconomy [33,34]). This technology has a far wider range of potential applications in bioenergy, making it highly promising for addressing climate change and developing eco-friendly energy resources.

2.1. *Restoring the environment with cutting-edge BC techniques for sustainability*

To achieve green remediation with progressive BC techniques, it is imperative to adopt a comprehensive approach encompassing many phases of BC synthesis procedure, characterization, and application. Biomass feedstocks were selected carefully, prioritizing renewable alternatives such as food waste, agricultural by-products, and scrap wood

[35,36]. [37] assert that implementing these methods ensures that the environmental impact of BC production is minimized and aligns with the concepts of the circular economy. Similarly, BC can be the best potential composition of properties utilizing powerful pyrolysis techniques. Using these techniques, the porosity, surface area and nutritional composition of BCs may be controlled effectively to meet certain requirements. According to [38], the pyrolysis technique can be adjusted to produce BC in an environment that facilitates the attainment of targeted enhancements in soil quality.

The effectiveness of BC is enhanced with the implementation of activation techniques. According to [11], applying chemical or steam-based activation procedures enhances the material's nutrient retention and uptake, crop growth and productivity, and microbial activities. This is where the full potential of BC in augmenting plant growth, soil health, fertility management and nutrient cycling can be unleashed. BC with environmentally sustainable soil management strategies is imperative to maximize long-term benefits. Environmental restoration can be enhanced through the comprehensive use of BC in conjunction with other systems, such as cover crops into diverse crop rotations, and organic amendments [39]. All these strategies are synergistic with increased soil-closing quality, intra season water availability (holding capacity) and microbial nutrient supply this enhances agricultural productivity and sustainability Continual monitoring and questioning are required for the development of BC strategies.

The optimization of BC application rates and methods can be achieved through continuous assessment of soil properties parameters, crop growth, and soil nutrient dynamics. BC's benefits on sustainability rehabilitation, carbon capture, and agricultural production may be quantified, permitting agriculturalists and specialists to be well informed. The enhancement and optimization of BC techniques can be further advanced by continuous study and the exchange of information. In summary, it is imperative to adopt a comprehensive approach encompassing many strategies to achieve sustainable environmental restoration through implementing advanced BC mechanisms [40,41]. The optimization of BC's efficacy in enhancing ecological restoration and food security can be achieved by meticulous consideration of biomass sources, specific pyrolysis techniques, activation procedures, integrated land-management strategies, and continuous assessment. By employing state-of-the-art techniques, BC might be harnessed to mitigate climate change, enhance soil organic carbon, and establish supplementary robust and productive crop cultivation structures. Table 2 provides an overview of sustainable BC-based strategies designed to enhance environmental rehabilitation.

The systematic use of BC solutions has been found to boost various aspects, such as soil structure, nitrogen accessibility, water preservation, and greenhouse gas mitigation. According to [54], this review has shown that particular agricultural practices can improve food sustainability and crop yield, but also reduce the environmental impacts of agriculture.

2.2. *The mechanisms of contaminant adsorption and rapid oxidation in sludge BC*

BC derived from sewage sludge exhibits promising environmental remediation capabilities due to its notable capacity for adsorbing pollutants and efficient oxidation mechanisms. Sludge BC's extensively developed porous structures and surface area provide a suitable adsorbent for many pollutants. Physical adsorption, electrostatic interaction, ion exchange, surface complexation, and precipitation empower pollutants like heavy metals (HMs), biodegradable compounds, and nutrients are susceptible to being adsorbed onto the surface of the adsorbent made up of BC [55]. The inclusion of functional groups enhances the adsorption mechanism including carboxyl, phenolic hydroxyl, and alcoholic hydroxyl, which serve as binding sites for contaminant molecules. The chemical adsorption process facilitated by sludge BC has the potential to effectively immobilize pollutants by forming robust linkages. The process of ion exchange occurs when the functional groups on the surface of BC interact with heavy metal ions, potentially leading to the displacement of these metal ions to other bivalent cations [56,57]. As a result of this immobilization process, the mobility and bioavailability of pollutants are diminished, hence mitigating their potential environmental impact. The porous structure of sludge BC tanks allows for the physical adsorption of contaminants. The entrapment of pollutant molecules within the porous structure of BC has the potential to reduce their concentration in the surrounding environment substantially [58]. The physical adsorption method exhibits a high affinity for organic compounds and nonpolar pollutants.

The oxidative properties of sludge BC have the potential to facilitate the degradation of specific pollutants, therefore expediting the process of oxidation [59]. The facilitation of oxidation processes can be attributed to oxygen-containing surface functional groups and quinones. The mechanisms described involve the transfer of electrons from contaminants to the surface properties of BC, leading to the decomposition or conversion of toxins into safer and smaller hazardous states. The remediation potential of sludge BC, particularly for persistent organic pollutants, is enhanced due to its accelerated oxidation process [60]. Sludge BC has emerged as a promising approach for environmental restoration owing to its capacity to absorb contaminants and accelerate oxidation kinetics [61]. This study advocates for implementing strategies aimed at reducing water, air and soil pollution through adsorption, immobilization, and contaminants degradation. Using sludge BC in treatment processes can contribute to sustainable waste management and pollution control, promoting environmental cleanliness and improved public health.

3. The synthesis of BC and its positive effects on the environment

Exploration and development for BC along with associated environmental benefits in the last decade have generated a significant interest due to its capability of addressing sustainability challenges. BC are a type of carbon with high mass from pyrolysis, the thermal decomposition of biomass under oxygen-free conditions [41,62]. This carbon-negative approach consists of carbon sequestration and offers numerous environmental advantages. The meticulous assessment of BC feedstock is of utmost importance. Various biomass sources, including agricultural and forest residues, organic and biodegradable biomass, and urban wood waste, can be utilized for multiple purposes. The selection of feedstock significantly impacts the characteristics and usefulness of BC. According to [38], the maximization of environmental benefits can be achieved by optimizing feedstock combinations. Evaluating BC's life cycle facilitates the comprehension of its ecological ramifications. It considers the environmental footprints of raw materials, production processes and application phases in its life cycle assessment. Life cycle analysis is crucial in selecting environmentally sustainable BC production processes.

Various factors influence BC's characteristics and stability, including temperature, residence time, and heating rate throughout the pyrolysis process (Table 3). Each method of BC preparation offers unique advantages and trade-offs. Slow pyrolysis is ideal for producing stable BC for soil amendment and carbon sequestration. Fast pyrolysis is more suitable for applications requiring higher bio-oil yields, while gasification primarily produces syngas but also generates BC that can be utilized depending on its properties. The selection of the preparation method should be guided by the intended application and desired BC properties.

These identified properties can potentially optimize the function of carbon sequestration and modify the properties of BC to meet certain environmental objectives. BC's efficacy in ecological restoration depends on its chemical composition [9]. The pore's structured and functional surface groups encourage adsorption and ion exchange, offering it a proficient sorbent for organic contaminants and HMs. The development and production of BC have the potential to enhance soil

Table 2
Ecosystem restoration through sustainable BC-based methods.

Methods to enhance ecological rehabilitation	Explanation of a BC-based sustainable systems	Advantages of sustainable methods utilizing BC	Reference
Material acquisition	The implementation of sustainability criteria in the selection of biomass feedstocks involves considering several factors, including sawdust, wood powder, rice husks, peanut hulls, cotton stalks, as well as naturally occurring such as garbage and animal dung.	The reduction of pollution, assistance with recycling, and promotion of reuse are all crucial factors.	[42,43]
Processes involving pyrolysis	Various advanced pyrolysis techniques, such as slow and rapid pyrolysis and gasification processes, are employed to adjust the specific surface area, porosity, and nutrient composition of BC.	Enables customization of BC characteristics to address specific requirements of environmental restoration effectively.	[44]
Activation of BC	Activation techniques such as steam or chemical activation are employed to enhance the adsorption capabilities, nutrient uptake and retention, and microbial growth of BC.	The combination of charcoal and other organic materials significantly enhances soil fertility and nutrient cycling compared to the use of charcoal individually.	[45]
Soil integration management	The effective use of BC and different environmentally friendly soil management strategies, including crop rotation, cover cropping, and organic amendments, can significantly enhance environmental restoration efforts.	Simultaneously enhances soil quality, complements nutrient accessibility, and mitigates soil erosion.	[46]
Investigating and monitoring	The optimization of BC application rates and tactics involves the continuous assessment of soil characteristics, crop growth, and nutritional dynamics. The continuous examination and distribution of research outcomes.	The facilitation of innovation in sustainable soil management, the attainment of desired outcomes through BC, and the enhancement of efficiency are all observed.	[47]
Carbon capture and storage	The potential of BC to mitigate global warming arises from its capacity to sequester carbon in subterranean environments for an extended duration.	Assisting in the reduction of greenhouse gas emissions, hence mitigating the pace of global warming.	[48]
Retention and availability of nutrients	BC possesses a notable cation exchange capacity, enabling it to effectively retain and subsequently release nutrients over time, facilitating plant uptake.	Enhances plant development by the augmentation of nutrient accessibility and reduction of nutrient loss via leaching.	[49,50])
Soil moisture control	The consumption of BC has been found to boost soil water availability through its capacity to increase water retention and reduce runoff.	The advantages encompass heightened resilience to arid conditions, reduced reliance on irrigation, and improved management of water resources.	[51]
Microbial activity augmentation	The intentional use of BC has been found to enhance soil biodiversity and nitrogen cycling through the provision of suitable habitat for beneficial microorganisms.	This intervention can enhance interactions between plants and microorganisms, reducing plant disease occurrence and promoting soil fertility.	[52,53])
Climate resilience	Soils that have undergone BC treatment have enhanced resilience against the impacts of climate change, including extreme events such as droughts and floods.	Enhances crop resilience to the impacts of global warming by enhancing the soil's composition, augmenting water retention capacity, and increasing nitrogen accessibility.	[28,46]

Table 3
Differences in steps involved in BCpreparation (Olugbenga et al. 2024; [63]).

Aspect	Slow pyrolysis	Fast pyrolysis	Gasification
Temperature	300–600 °C	400–600 °C	800–1000 °C
Heating Rate	Low (0.1–1 °C/s)	High (>10 °C/s)	High
Residence time	Long (hours)	Short (seconds)	Short to moderate
BC yield	High	Moderate to low	Low
Bio-oil yield	Moderate	High	Low
Syngas yield	Low	Moderate	High
Applications	Soil amendment, carbon sequestration	Bio-oil production, energy generation	Energy generation, soil amendment (specific cases)
Stability	High	Moderate to low	Low to moderate
Surface area	Moderate	High after activation	Variable can be high
Porosity	Moderate to high	High after activation	High

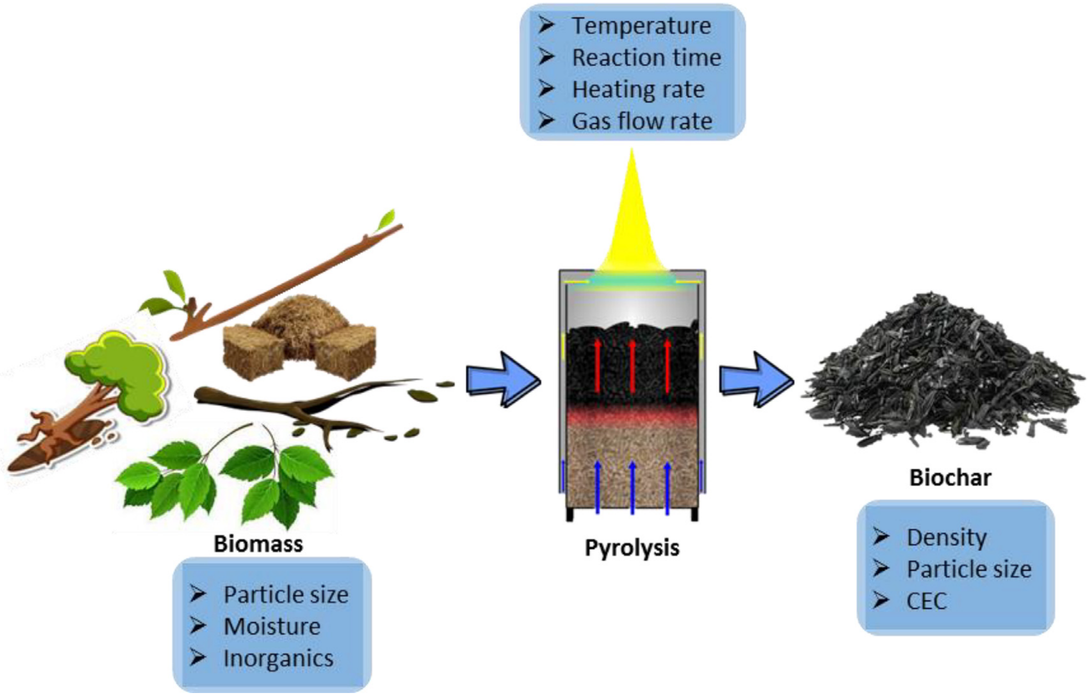

Fig. 3. Key process factors and production characteristics in BC preparation.

fertility and increase agricultural productivity through the addition of nutrients. The TEA assesses the LC system and its economic feasibility, as well as environmental benefits due to BC production According to [64], gaining a comprehensive understanding of the expenses associated with BC production, the energy requirements, and the many sources of income is crucial in developing economically viable systems. BC processing can potentially mitigate atmospheric carbon dioxide, recover soil conditions, and remediate pollutants. BC has the potential to contribute significantly towards sustainable development by optimizing raw material selection, life cycle impacts, operational variables and chemical composition. TEA is giving it a leg up in the world of energy standards as renewable green technologies, supporting a more environmentally friendly and brighter future. Integrating BC into many industries can contribute to environmental goals and promote ecological equilibrium, enhancing societal sustainability and resilience to climate change. Fig. 3 presents a visual depiction of the developing properties of BC, together with its associated process parameters.

3.1. BC synthesis with a wide variety of source materials

The production of BC using diverse feedstocks has the potential to address environmental challenges while encouraging sustainable resource management practices. BC is a carbonaceous material derived from the pyrolysis of organic matter, with multiple applications and economic advantages [65]. Using diverse materials enhances BC production [14,66]. BC can be derived from several sources, such as agricultural and forestry, animal, industrial, and municipal solid wastes. These different sources allow the recycling of many materials, and they are then turned into valuable products: decreasing landfills deposits wastes, in order to waste management being an option effectively carried out. Choice of feedstock favourably impacts properties and functionality of BC. The chemical form of the biomass affects the porous structure, surface area, and chemical stability of BC. According to [67], BC contributes to its versatility in modifying its applications in soil improvement, soil carbon storage, and environmental revitalization and remediation owing to the different types of feedstock. The commercial use of BC derived from diverse feedstocks has the potential to address both regional and global environmental challenges. BC is an environmentally friendly waste management solution that enhances the quality and productivity of soil in regions abundant with agricultural residues. BC formation has healed degraded soils and boosted reforestation efforts in areas much in forestry waste.

Diverse feedstocks for BC production have been found to trap carbon and effectively contribute to climate change mitigation. BC is an effective method for long-term carbon sequestration, as it involves the thermal decomposition of organic waste through a process known as pyrolysis [68]. This process not only aids in reducing greenhouse gas emissions but also serves as a means of mitigating climate change. The generation of BC and the precise land management practices contribute to the establishment of a circular system. Following the pyrolysis process, the resulting BC ash contains various minerals and nutrients, providing a highly beneficial soil amendment. Applying BC ash in a closed-loop system reduces fertilizer consumption and enhances soil productivity by closing the nutrient cycle. Diverse feedstocks for BC production have been identified as a significant solution to address environmental challenges and promote sustainability [26,69]. Biomass sources offer the potential to reduce waste generation, enhance effective waste management procedures, and offer specific environmental solutions. BC synthesis is a bipartite solution that allows carbon sequestration, which mitigates climate change. It also helps in sustainable agriculture by improving soil fertility with the organic nutrients from bio-degradable-meta-waste. This multifunctional and valuable product has the potential to bring about a paradigm shift in environmental management customs, thereby establishing the realization of a more ecologically conscious and sustainable for the next generations.

3.2. Assess the BC's quality

Ensuring the quality of BC requires a thorough evaluation encompassing various aspects, including feedstock selection, pyrolysis conditions, and the assessment of its physical, chemical, structural, and functional properties. Additionally, adherence to regulatory standards is crucial. Fig. 4 outlines specific measures and criteria essential for maintaining and verifying BC quality.

By focusing on these aspects and employing rigorous testing and quality control measures, the quality of BC can be ensured, making them suitable and effective for their intended applications.

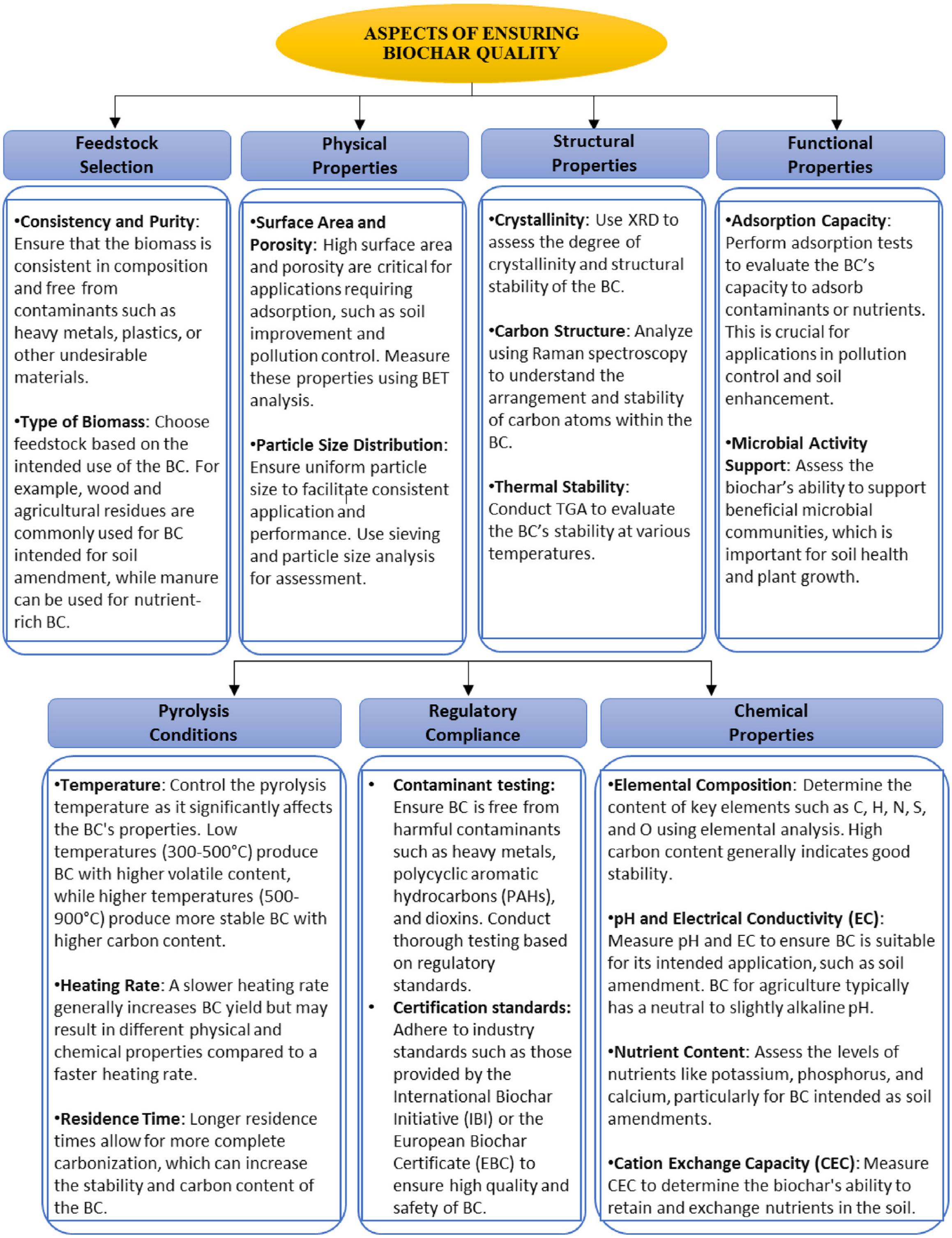

Fig. 4. Detailed breakdown of BC's quality aspects.

3.3. Analysis of environmental advantages and life cycle assessment

Benefits and applications of BC are studied through an environmental sustainability lens while the focus on conservation and natural resource management is to investigate its implications throughout the life cycle. BC, derived through biomass pyrolytic, has numerous ecological advantages. The process of carbon sequestration assisted by BC contributes positively to ecological preservation. BC serves as a means of carbon stabilization resulting from the pyrolysis of organic biomass, thereby mitigating the release of greenhouse gases. The carbon sequestration of BC makes it important for global climate change mitigation and achieving zero net CO_2 emissions. Otherwise, BC is known to have a positive effect on soil quality. The porous structure and substantial surface area of BC contribute to the enhancement of soil water retention through soil aeration that influences the availability of many nutrients, hence fostering cultivation growth and improving crop productivity [70]. BC has been found to enhance soil nitrogen-cycling microbial communities and organic transformation and accumulation. The use of BC has proved beneficial in reducing the pollutants and enhancing environmental attributes. The substance can assimilate HMs, biological contaminants, and pesticides. BC can potentially mitigate the adverse effects of pollution on ecosystems through soil and water remediation [71].

To comprehend the environmental impact of BC, an extensive analysis of its life cycle is necessary. This study aimed to investigate the life cycle of BC from more perspectives throughout all stages (raw material extraction, manufacturing/production application and end-of-life disposal) than has been done in previous studies. Thus, life cycle assessments are essential for researchers and policymakers to detect environmental hotspots in BC production processes and optimize its sustainability. The study by [72] involved the application of life cycle assessment methodology to compare BC with other procedures to identify the most environmentally sustainable and economically viable options. The identification of enhancement opportunities and alternatives across the life cycle aids in the reduction of environmental impact. BC provides numerous environmental benefits. BC plays a crucial role in environmental conservation through its ability to absorb carbon, enhance soil fertility, and mitigate pollutants. BC has been suggested as a potential means to improve agricultural productivity, sequester carbon, and remediate contaminated soils and water, hence playing a crucial role in promoting ecological equilibrium and mitigating the effects of greenhouse gas emissions [20]. An efficient production and utilization of BC should be optimized, with special emphasis on the environmental sustainability by life cycle analysis.

3.4. Assessment of operational conditions, chemical compositions, and techno-economic analysis

Systematic understanding of the BC production and its environmental benefits require comprehensive consideration on operational conditions, chemical compositions, and TEA. The considerations mentioned above demonstrate BC's efficacy, efficiency, and economic viability as a viability and sustainability option.

3.4.1. Operational conditions

The preparation conditions of BC, including the type of feedstock, pyrolysis temperature, and heating rate, significantly influence its properties and effectiveness. Table 4 summarizes these conditions and their impacts.

The preparation conditions of BC profoundly affect its physical and chemical properties, which in turn dictate its effectiveness for various applications. Optimal conditions must be selected based on the intended use to harness the full potential of BC. The chemical and physical characteristics of BC are reliant upon the temperature at which pyrolysis occurs [2]. BC generated at low temperatures exhibits a notable increase in surface area and adsorption capacity. In contrast, BC produced at higher temperatures demonstrates enhanced carbon content, hence encouraging long-term storage of carbon. The residence time and heating rate influence the BC production and carbonization process. Gradual heating rates and prolonged heating time have been seen to enhance BC production and elevate its carbon content. Consequently, this offers BC a valuable soil supplement and an effective means of carbon sequestration. Feedstock selection is of utmost importance due to the diverse chemical compositions and properties exhibited by different biomass sources [17]. The thoughtful choice of feedstocks for specific applications is of paramount priority because of the significant impact that feedstock attributes have on BC's functionality, porosity, and stability.

BC synthesis is a multi-step process that includes pre and main pyrolysis, followed by the development of carbonaceous soil products. The initial phase of the process, which consists of the transition from the surrounding temperature to 200 °C, can be attributed to the evaporation of moisture and light volatiles. Moisture evaporation induces bond cleavage, forming hydroperoxide, –COOH, and –CO moieties. During the second stage, which occurred within the temperature range of 200 to 500 °C, there was a rapid devolatilization and degradation of hemicelluloses and cellulose [45]. The thermal decomposition of lignin and other organic substances characterized by more robust chemical bonds is observed to transpire at elevated temperatures, typically exceeding 500 °C. Based on the findings of much research, it is evident that the physicochemical characteristics of BC were significantly influenced by the temperature at which pyrolysis occurred [77]. The surface area, pH and functional groups are important features with respect to BCs reactivity as a soil amendment. The study results indicate a rise in surface area, carbonized fractions, pH, and volatile matter with an increase in pyrolysis temperature. Conversely, there was a decrease in cation exchange capacity and surface functional group content. BC's carbon and ash content exhibits an upward trend with increasing pyrolysis temperature. BC possesses a substantial carbon content, indicating the presence of residual organic plant matter, such as cellulose.

3.4.2. Chemical compositions

The sorption, nutritional value, and stability of BC are determined by its chemical composition. Based on the raw material, BC may also contain oxygen, carbon, hydrogen, nitrogen, etc, and trace elements (or mineral nutrients) [16]. BC's reactivity and adsorption are influenced by functional groups, including carboxyl, phenolic hydroxyl, and lactone [78]. These functional groups permit ion exchange and contamination adsorption, which makes BC an effective water and soil rehabilitate. The chemical composition of BC regulates soil structure with nutrient retention and uptake. BC with a substantial amount of ash upgrades the availability of nutrients and crop production.

3.4.3. Techno-economic analysis

This TEA evaluates the potential for BC manufacturing and utilization on substantial scale. The present investigation focuses on evaluating many factors, such as feedstock, pyrolysis equipment, energy consumption, and additional expenditures. The economic viability of BC production is determined by the successful commercialization of BC, as well as the generation of different revenue streams through the sale of high-value products such as bio-oil or syngas [79]. According to TEA reports, a bioeconomy can be established with the help of BC preparation along with present corporations or destruction systems. BC for sustainability objectives necessitates thoroughly investigating operational conditions, chemical compositions, and TEA [17]. Comprehending the chemical elements and precise adjustment of operational parameters leads to synthesizing BC in accordance with environmental requirements. The TEA supports BC processing's economic viability and fosters environmental practices. By incorporating these attributes, BC becomes a more efficient and extensively utilized instrument for addressing environmental concerns and promoting sustainability.

4. Adsorption mechanisms

The adsorption mechanisms between heavy metals (HMs) and BC include several interactions such as surface sorption, ion exchange, electrostatic contact, and precipitation complexation. These interactions depend on the specific properties of the BC prepared [80].

Surface sorption occurs when metal ions bind to the BC surface, typically through chemical bonds formed in the pores of the BC. The efficiency of this mechanism depends on factors like the BC's porosity, surface area, and pore volume, which are influenced by the temperature used during BC preparation. Higher carbonization temperatures tend to increase the surface area and pore volume, enhancing the adsorption capacity [81]. However, the effectiveness of surface sorption also varies based on the metal's affinity for the BC surface.

Ion exchange involves the swapping of cations (positively charged ions) on the BC surface with metal ions from the solution [82]. This process is influenced by the size of the pollutants, the functional groups on the BC, and factors like ionic charge differences and bonding

Table 4
Influence of preparation conditions on BC properties.

Preparation conditions	Explanation	Influences	Reference
Feedstock types	• Agricultural waste Commonly used due to availability and low cost (crop residues, wood chips). • Manure Contains higher nutrient levels (poultry litter, cow dung). • Forestry residues • Often used for their high lignin content, leading to BC with stable carbon structures.	• Nutrient content Manure-based BC is rich in nutrients (nitrogen, phosphorus, and potassium). • Carbon content Woody biomass results in BC with higher carbon content and stability. • Porosity and surface area • Varies significantly with feedstock; affects water retention and microbial activity in soils.	[73,74]
Pyrolysis temperature	• Low temperature (300–400 °C) Produces BC with higher volatile content and more functional groups (oxygen, hydrogen). • Medium temperature (400–600 °C) Balance between carbonization and retention of functional groups. • High temperature (600–900 °C) Yields BC with high carbon content, low volatile matter, and high surface area.	• Surface area and porosity Increases with higher temperatures, enhancing adsorption capacities. • Stability Higher temperatures produce more stable BC with greater resistance to decomposition. • Nutrient retention Lower temperatures preserve more nutrients, while higher temperatures can lead to losses.	[38,75]
Heating rate	• Slow heating Allows thorough decomposition of biomass, resulting in more uniform BC properties. • Fast heating Can produce BC quickly but may lead to incomplete pyrolysis and heterogeneous products.	• Structural integrity Slow heating typically results in BC with better structural integrity and stability. • Chemical composition Fast heating might retain more volatile compounds but can also produce more tars and condensates.	[30,76]

behaviour [83]. BC's ability to adsorb metals through ion exchange is closely related to its cation exchange capacity [84].

Electrostatic interactions occur when the charged BC surface attracts metal ions, restricting their movement. This process is strongly influenced by the pH of the solution and the BC's point of zero charge [85].

Precipitation is another mechanism where metal pollutants are removed from the solution by forming solid complexes on the BC surface. This works best with BC produced from alkaline feedstocks, pyrolysed at temperatures above 300 °C, which break down the biomass into simpler components [86]. Precipitation is particularly effective for metals like cadmium, chromium, and lead.

Complexation involves the binding of metals to functional groups on the BC surface, such as carboxylic and phenolic groups, especially when BC is produced under low temperatures and has high oxygen content. Higher oxygen levels enhance metal complexation, improving the adsorption of heavy metals. BC from vegetable feedstocks, for example, tends to show a greater ability to bind metals like copper, cadmium, nickel, and lead compared to BC from animal feedstocks [87].

5. Ammonium adsorption and recycling in agricultural field

The adsorbability and recycling ability of BC in agricultural soils on ammonium make this method one of the most attractive ways to ensure sustainable *N* control without polluting environment. This ability of BC to adsorb onto its porous structure also means that BC has a good potential in removal of ammonium from soils. This will facilitate the recycling of nutrients within plant systems. According to [88] research, producing BC is an effective approach for separating ammonium from soil. In the soil, BC acts as a sorbent, attracting and retaining ammonium ions for later use. The combination of adsorption on the surface, ion exchange, electrostatic interaction, precipitation, and complexation can prevent ammonium from leaching or volatilizing in water environment. Specification of feedstock used in BC-synthesis procedure, impacts the ammonium separation efficacy from soil by BC. According to [89], the distinctive physicochemical properties of different feedstocks impact the degree to which they attract ammonium ions. The various BC applications in agricultural soils are outlined in Table 5, including ammonium adsorption, recycling, and separation. It is common for BC made from manure or sewage sludge. Carbon and nitrogen-rich materials typically have a greater ammonium adsorption capacity than other sources.

The ammonium adsorption capacity of BC may be influenced by the pyrolysis process employed in its production. The chemical composition, porosity, and residence time all impact the adsorption capacity of BC, which is subsequently determined by the pyrolysis temperature, heating rate, and residence time. To enhance the ammonium removal and retention capabilities of BC, it is imperative to optimize the pyrolysis parameters [90]. Therefore, the practical application of BC as a senior soil amendment for ammonium removal and adsorption from agricultural soils by dynamic adsorptions may only be feasible after taking into account effective scaling. To facilitate effective implementation across diverse soil types and environmental conditions, assessing BC's kinetics and adsorption capacity is imperative. Knowledge of BC-ammonium interaction's adsorption kinetics and long-term stability is essential for sustainable nutrient management. The ammonium recycling potential of BC is comparable to that of agriculture. The capacity of BC to gradually liberate ammonium under specific conditions enables plants to obtain the nutrient. The slow-release technique reduces the probability of volatilization and nitrate leaching, thereby enhancing the efficiency of fertilizer consumption and minimizing adverse environmental impacts [91]. Soil ecosystems and plant life gain substantially: BC's application in agricultural soils for ammonium removal,

Table 5
BC's role in ammonium removal, uptake, and reusability in agricultural soils.

Implementation	Explanation	Causes and effects	Advantages
Adsorption/binding of ammonium ions	BC can potentially eliminate surplus ammonium from soil solutions through the process of ion adsorption.	Surface chemistry and distribution of pore size are two characteristics of BC. The soil's characteristics, such as its pH and organic matter content The local climate and humidity levels;- The soil's composition.	The reduction in ammonium leaching has increased the accessibility of nutrients. Fertilizer loss was diminished.
Ammonium retention in soil	The application of BC to agricultural soils has the potential to hold ammonium, thereby reducing the probability of nutrient loss.	The impact of BC's cation exchange capacity (CEC) on the structure and texture of soil. - Conditions of water passage and drainage.	Reduced nutrient loss through discharge; enhanced efficiency in nutrient utilization; Reduced damage to the natural environment.
Nutrient recycling	Ammonium is among several nutrients that exhibit enhanced recyclability in soils undergoing BC modification.	Composting; the rate of BC modifications and microbiological processes; root absorption, exudation, and plant assimilation.	Enhanced nutrient accessibility; Long-term improvements in soil fertility; Responsible application of fertilizers.
Enhanced efficacy of fertilizers	The effectiveness of nitrogen fertilizers is enhanced through the incorporation of BC.	The BC application ratio rate When and what to fertilize depends on the soil's moisture and temperature.	Fertilizer loss decreased, resulting in improved assimilation of vital nutrients and decreased fertilizer requirements.
Controlled release fertilizers	As a fertilizer carrier, BC can be utilized to control the rate of ammonium release.	The quantity of fertilizer added to BC, the thickness of the layer. The environmental conditions and the nutritional needs of plants.	Precise delivery of nutrients reduces the necessity for daily application. Reduced or prevented discharge of nutrients.
BC recovery of ammonium	A nutrient recovery process utilizing ammonium-saturated BC.	Environmental concerns regarding treatment techniques involving BC, extraction or leaching processes, and reprocessing decisions.	A closed-loop system for nutrient recycling and conservation of natural resources; The application of supplemental fertilizers has been reduced.

adsorption, and upcycling benefits plant development, soil formation, litter decomposition, nutrient cycling, and biotic regulation [92]. Environmental restoration and production benefit from BC-ammonium interactions since they enhance fertility, nutrient and carbon availability, microbial abundance, and water retention. BC can remove and retain ammonium, retaining more nutrients, reducing leaching losses of nutrients for green, renewable agricultural methods, relying upon adopting appropriate energy sources, pyrolysis environment, and scaling-up protocols.

Studies indicating the application of BC to agricultural soils for removal, adsorption, and upcycling along with potential ammonia mitigation in environmental as well nutrient management are discussed. To reduce ammonia leaching and improve N use efficiency in agriculture, the absorption of NH_4^+ ions within different BC types as well as their retention are being studied. These studies demonstrate that BC has the potential to provide sustainable and cost-effective solutions for mitigating environmental pollutants and nutritional imbalances caused by ammonium. Existing research voids include the following: first, to comprehend ammonium adsorption and discharge under diverse soil conditions and agricultural systems, longer-term experimentation is required. To maximize the efficiency of BC, it is crucial to understand how functional groups, surface properties, and porosity influence ammonium uptake reactions. BC development for ammonium separation and recycling must be scalable and effective. BC's practicality and cost-effectiveness in industrial crops require being evaluated to attain widespread adoption. Further research is needed to determine how BC-ammonium reactions affect microbial and plant communities for the development and stability of soil ecological functions. To preserve the health of ecosystems, it is necessary to perceive the negative effects of BC [82]. Present research indicates promising outcomes regarding the utilization of BC in the processes of ammonium separation, adsorption, and recycling. Nevertheless, there remain areas of research that require attention and challenges that need resolution. BC's efficacy could be enhanced by tackling these constraints and issues, and its feasible application in agriculture nutrition management and ecological preservation could be advanced.

5.1. Biomass char production, feedstock selection, pyrolysis conditions and sorption for soil ammonia removal

BC synthesis is an effective means of removing soil ammonia, resulting in a reduction of nitrogen loss and an improvement in soil quality. The mechanism is influenced by many critical aspects, including the biomass source selection, the pyrolysis technique employed, the potential for scalability, and the phenomenon of adsorption. The effectiveness of BC in the degradation of ammonia in soil is heavily determined by the specific material employed during its production [93]. Ammonia is sensitive to the type and properties of sources (wood, forestry residues, crops, or municipal organic waste). The removal ability of ammonia is frequently elevated in materials that contain both carbon and nitrogen, especially crop or green manure residues. BC is produced by the pyrolysis technique, wherein feedstocks undergo thermal degradation in an oxygen-depleted environment. The characteristics of BC and its ability to adsorb ammonia are influenced by various factors throughout the pyrolysis process, including temperature, heating rate, and residence time [45]. Elevated pyrolysis temperatures frequently lead to the production of BC with enhanced carbon content and heightened capacity for ammonia uptake. The successful use of BC-based ammonia treatment in cropping areas is determined by its ability to be scaled up effectively. The evaluation of efficiency and effectiveness on a larger scale is necessary. To ensure BC's sustained effectiveness in removing ammonia, it is imperative to consider many parameters, such as feedstock availability, logistical aspects of BC production, and appropriate application rates in the field.

The capacity of BC to eliminate ammonia is attributed to a phenomenon known as adsorption, whereby ammonia ions are attached to and retained on the surface of BC. The adsorption capacity of BC can be attributed to its inherent porosity and extensive surface area [94]. Adsorption can manifest through various mechanisms, including electrostatic interaction, ion exchange, and surface mineral adsorption. To optimize the efficiency of ammonia extraction from soil, it is imperative to possess a comprehensive understanding of the equilibrium adsorption, adsorption/desorption kinetics and long-term stability of the reactions between ammonia and BC [13,16]. BC development that includes the ammonia uptake from the soil has various positive aspects, particularly reducing nutrient losses by volatilization or leaching, improving soil nutrient retention, and preventing environmental contamination. The ability of BC to effectively mitigate ammonia levels in the soil is influenced by several key elements, which encompass the precise selection of appropriate feedstocks, the optimization of pyrolysis parameters, the assessment of scaling considerations, and a comprehensive understanding of adsorption dynamics.

5.2. Slow-release fertilizer, nitrogen desorption, ammonium cycling

BC plays a significant role in promoting environmentally sustainable approaches to nutrient management in agriculture through its involvement in ammonium cycling, and progressive nitrogen fertilizer sustained-release material [95]. In agriculture BC could thus substantially increase the ammonium recycling capacity of soils. This would in turn potentially provide a slow-release of ammonium ions adsorbed to the carbon surface which plants could take up [96]. Implementing slow-release mechanisms has been found to mitigate nitrogen leaching and volatilization, enhancing nutrient utilization efficiency and minimizing adverse environmental impacts. The cycling of nitrogen in the soil-plant system is a dynamic process that is influenced by the adsorption and ensuing discharge of ammonium by BC [97]. The porous nature and huge BC surface area enable it to retain nutrients such as ammonium and other fertilizers effectively. Incorporating BC into the soil is a long-lasting, slow-release fertilizer that sustains plant growth. The characteristic of slow-release assists in reducing nutrient runoff, enhances plant accessibility to nutrients, and prevents imbalances in soil nutrient levels.

BC can potentially encourage nitrogen desorption, as well as its role in ammonium recycling. According to [67], BC can function as a reservoir for surplus nitrogen in the nitrate form under suitable soil conditions. BC provides a conducive environment for bacteria nitrogen-transforming, enabling the transition of nitrate to nitrogen gas, a phenomenon referred to as denitrification. This procedure aids in the mitigation of nitrogen leaching and the reduction of its adverse environmental consequences, such as the polluting of water sources. BC offers valuable strategies for enhancing nitrogen management in agricultural systems through improving ammonium recycling, slow-release fertilizer, and nitrogen desorption [98]. These systems promote a sustainable nutrient cycle, enhance nutrient utilization productivity, and reduce biodiversity degradation caused by nitrogen loss (Fig. 5). BC in soil health management systems can strengthen nutrient accessibility, mitigate environmental impacts, and promote sustainable ecological rehabilitation and productivity.

5.3. The effects of BC on soil ecological systems, chemistry, microbial communities, organisms, and agronomy crops

The usage of BC can present many benefits with regards to soil systems, effects on microorganisms and creatures living in the system, chemistry, and crop systems as well for sustainable agriculture management. Structured soils, water retention capabilities and nutrient preservation can significantly affect ecosystems by improving BC. The porous structure of BC enhances soil aeration, leading to a reduction in soil compaction and promotion of root growth. According to [99], BC serves as a protective environment for the advantageous plant and animal life inside the soil, enhancing biodiversity and strengthening the ecological relationships within the ecosystem. BC has the potential to impact soil chemistry through various mechanisms, such as adjusting pH levels, modifying cation exchange capacity, as well as influencing the availability of important nutrients [100]. BC has the potential to influence soil properties, such as pH and nutrient retention, in an attempt to be subject to the specific feedstock utilized and the conditions under which pyrolysis occurs. The extensive surface area and ion-exchange capacity of BC enable it to effectively adsorb and store nutrients, reducing their leaching rate and prolonging their availability for plant uptake. BC has been observed to have an impact on the composition and functionality of soil microorganisms. The proliferation and flourishing of advantageous microbes that contribute to ecological recycling and the decomposition of organic material may occur as a consequence. BC has additional advantages, including enhanced nutrient availability and improved soil fertility.

The presence of fauna in BC can potentially provide soil fauna, including earthworms, insects, and microorganisms, with enhanced opportunities for habitat expansion and access to novel food resources. Microorganisms are vital in nutrient cycling, organic material decomposition, and soil structure improvement. Better resource availability via BC may promote an increased species rich community of microbes making them more resilient and stable ecosystem functionaries. BC has been found to yield advantageous effects on crops. Enhanced fertilizer availability, water retention, and root development contribute to the enhancement of plant growth, productivity, and hardness. According to [15], BC has been found to enhance nutrient uptake and retention within the root zone and reduce nutrients' leaching, leading to improved nutrient usage efficiency. BC can potentially improve the soil's capacity to retain moisture, alleviating drought's adverse impacts on plant cultivation. BC has numerous interconnected consequences for soil ecosystems, chemistry, microbes, organisms, and the cultivation of agricultural products [101]. BC plays a crucial role in supporting cropping systems, mitigating the impacts of global warming, and preserving the atmosphere through its ability to improve soil health, improve ecological recycling, and enhance crop growth. When incorporating BC into agronomic standards, it is crucial to consider specific criteria associated with the location, including the type of feedstock, application rate, soil properties, and environmental factors [58], as these factors all potentially influence the distinct effects of BC.

6. Catalytic sludge BC for wastewater treatment and energy storage

Current research efforts are focused on exploring novel approaches for remediation and containment, driven by an increasing recognition of environmental pollution and the imperative to provide sustainable energy options. Sludge BC catalysts have gained prominence as a leading contender among feasible options due to their dual functionality in remediating contaminated sites and serving as energy storage systems [102]. This research aims to examine the application of BC-based catalysts in efficiently removing wastewater and sewage sludge containing organic matter and their prospective applications in remediating contaminated soil and the co-pyrolysis technique for improving sewage sludge BC.

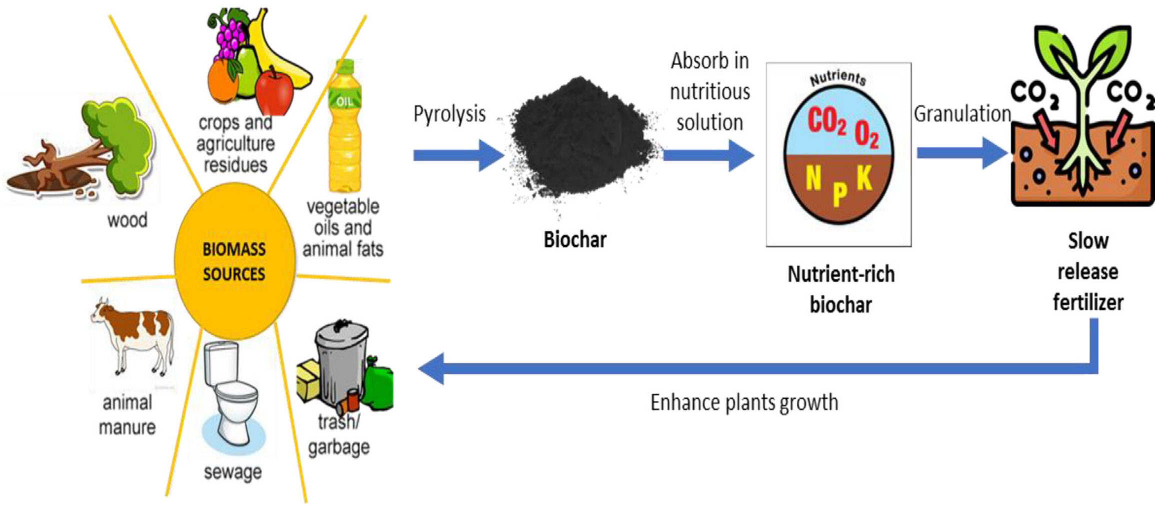

Fig. 5. BC as a tool for ammonium recycling, slow-release fertilization, and nitrogen desorption.

According to the research findings, waste-derived BC sourced from municipal, agricultural, and industrial solid waste, and domestic sewage sludge has a high degree of versatility. The waste products transform into an adsorbent resource, which possesses the capability to eliminate impurities from various water sources. The study by [103] examines several BC adsorption techniques and their efficacy in removing HMs, organic contaminants, and nutrients. The considerable BC's porous nature and surface area provide exceptional adsorption capabilities, positioning it as a promising candidate for water treatment applications. It also signifies the need to tailor the synthesis parameters of BC to improve its adsorption properties. The customization of BC properties to focus on specific water pollutants can be achieved by investigating pyrolysis reactions in temperature, heating rate, and biomass content, as demonstrated by [104]. The study also underscores the significance of waste-derived BC in the context of recycling and waste management to achieve sustainable development. BC production contributes to waste reduction, greenhouse effect mitigation, and promoting bioeconomy principles through utilizing biodegradable materials. [89] emphasize the potential applications of BC derived from waste materials in water treatment. The publication also discusses how the use of BC might contribute to the achievement of sustainable development goals. The extensive study provides necessary needs and valuable insights to effectively guide research on BC and its applications in managing water contamination and promoting green sustainability.

6.1. Soil remediation through pyrolysis

Pyrolysis is a thermal reaction wherein the decomposition of organic waste and biomass occurs in an oxygen-free environment, resulting in the production of BC [105]. BC exhibits great potential as a soil amendment due to its considerable porous nature and carbon content. BC as a sorbent for the remediation of contaminated soils has been explored. According to [60], removing HMs and organic pesticides is efficacious. BC enhances soil fertility through various mechanisms, including improved water retention capacity, increased available nutrients, and promotion of microbial communities.

6.2. Co-pyrolysis for metal removal from sewage sludge and enhanced BC production

Sewage sludge may contain elevated concentrations of HMs and biological contaminants, which can be attributed to sewage treatment [106,107]. The disposal of sewage sludge by conventional methods is an environmental hazard. The achievement of sustainable management of sewage sludge can be simplified by utilizing a process known as co-pyrolysis. This technique involves the pyrolysis of both biomass source and residual sludge simultaneously. The immobilization of HMs in the sewage system and BC production could be achieved using co-pyrolysis, as demonstrated by [108]. Due to its expanded surface area and upgraded adsorption properties, the BC derived from wastewater treatment residual is a valuable sorbent for HMs. This immobilization technique effectively mitigates the risk of HMs pollution, as illustrated in Fig. 6.

6.3. BC-based sludge catalysts

Organic material poses a challenge to the complex processes involved in sludge disposal and treatment. BC-based catalysts have demonstrated promising results in efficiently degrading organic substances in sludge. BC's catalytic activity can be enhanced by introducing substances such as transition metal oxides, enabling its use as a catalyst [41,59]. The modified charcoal catalysts have the potential to facilitate the degradation of organic pollutants via organic redox reactions. Furthermore, BC's porous nature facilitates organic molecule adsorption, enhancing its efficiency in the removal process. BC-based catalysts can potentially improve sludge treatment processes, hence mitigating the release of organic compounds and reducing associated pollutants.

Sludge BC catalysts have demonstrated potential in environmental remediation and energy storage. The pyrolysis technique effectively achieves soil remediation, carbon sequestration, and increased fertility [28,109]. Additionally, this procedure is commonly employed for the production of BC. The co-pyrolysis of sewage sludge and biomass has the potential to produce BC, a material that can effectively immobilize HMs and mitigate their biodiversity impact. Furthermore, BC-based catalysts have been shown to enhance the efficiency of organic waste removal from residual sludge. Sludge BC catalysts exhibit significant promise in addressing environmental concerns and promoting sustainable strategies as ongoing research and development efforts persist [41,110].

7. New practices for renewable organic contamination abatement using nanomaterial-based BC

The significance of growing nanotechnology in utilizing biomass waste and sustainable resources is substantial, as highlighted by [57]. In recent years, significant scholarly focus has been on integrating nanomaterials and BC within environmental remediation. Sustainable alternatives such as nanomaterials and BC successfully mitigate organic contaminants [11,111]. This part will explore the novel approach of nano-BC in agriculture and bioremediation, along with its

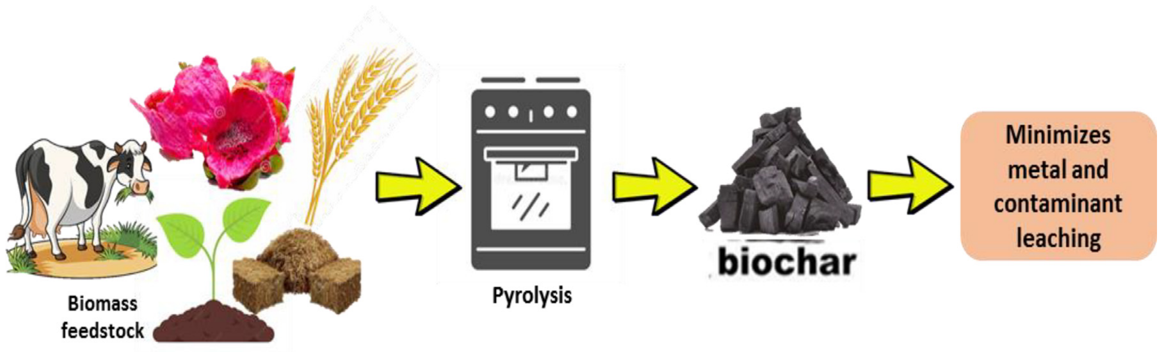

Fig. 6. Remediating soil with BC produced by pyrolysing organic waste and biomass.

diverse range of practicable applications. These applications encompass nanocomposites derived from BC utilized for wastewater treatment.

7.1. Fabrication, characterization, and potential applications of multifunctional nano-BC

Nano-BC refers to BC produced at the nano-scale level, yielding a material with multiple applications in removing organic pollutants. Nanoparticles such as zinc oxide, silicon dioxide, titanium dioxide, silver, and carbon nanotubes in the BC matrix can be referred to as the formation of nano-BC [112]. For this purpose, different methods could be applied such as hydrothermal processes, impregnation method or precipitation. Selection of nanoparticles: The selection is based on the type of pollutants and their removal. Iron oxide nanoparticles can be used for the catalytic degradation of organic pollutants and silver has antimicrobial properties. The characterization of nano-BC involves the analysis of its chemical and physical properties as well as structural [113]. The evaluation of nano-BC's crystallinity, particle morphology, particle size, specific surface area, and surface functional groups is conducted through analytical techniques such as X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), Scanning electron microscopy (SEM), Transmission electron microscopy (TEM), and Brunauer–Emmett–Teller (BET) surface area analysis [18,114]. These characterizations can provide a deeper understanding of a material's adsorption capacity and catalysis application. Characterizing BC involves various analytical methods to understand its physical, chemical, and structural properties. These methods provide insights into the quality and suitability of BC for specific applications. Table 6 describes common characterization methods.

A combination of these characterization methods is often employed to comprehensively evaluate BC properties, ensuring its suitability for specific applications, and enhancing our understanding of its functional mechanisms. Nano-BC exhibits a diverse array of potential applications. The potential application of nano-BC involves its application in water purification processes through its capacity to adsorb and sequester various organic pollutants, HMs, and emerging toxins. Due to its notable adsorption capacity, catalytic properties, and broad surface area, the substance exhibits a high degree of efficacy in the removal of contaminants. According to [124], the nano-BC in air filtration systems is attributed to its capacity to absorb volatile organic compounds and several additional air pollutants involving gases (ammonia, carbon monoxide, sulphur dioxide, nitrous oxides, methane, and chlorofluorocarbons). The potential utility of nano-BC in biomedical applications, notably medication distribution, arises from its ability to encapsulate and release medicinal chemicals. The multifaceted applications of nano-BC render it a highly significant asset in long-term environmental remediation endeavours.

7.2. Bioremediation of wastewater using BC nanocomposite

The implementation of bioremediation techniques in the treatment of wastewater plays a crucial role in the mitigation of water pollution and the preservation of the availability of safe drinking water. BC-based nanocomposites have demonstrated their efficacy in wastewater treatment due to their exceptional capabilities in removing pollutants. Combining BC and functional nanomaterials, such as nanostructured zero-valent iron and graphene oxide, is a widely employed approach for synthesizing nanocomposites [125]. The joint-utilization of BNCs and nanoparticles for wastewater bioremediation is beneficial in several ways. Firstly, BC's porosity and structural and substantial surface area offer it a proficient adsorbent for organic and inorganic substances in wastewater. Nanoparticles have been shown to enhance both the adsorption removal and nanocomposite selectivity [111,126]. One example is graphene oxide, which accelerates the organic molecules' adsorption, whilst nanosized zero-valent iron can potentially expedite the removal of HMs.

Furthermore, the catalytic properties of BC-based nutritional nanocomposites enable the degradation and transformation of persistent organic pollutants. Advanced oxidation processes such as photocatalysis systems, photo-Fenton reactions and microwave-assisted synthesis are effective for the degradation of persistent organic compounds. These processes are effective due to nanomaterials integrated within the BC matrix, which act as catalysts for the reactions above [22,127,128]. Furthermore, BC stimulates the proliferation of bacteria and microbes that contribute to biological remediation., including organisms and fungi. The porous characteristics of BC make it very suitable for hosting microbial communities, enhancing its capacity to facilitate the degradation of contaminants. Because of the above properties, BC-based nanocomposites showed application as adsorbents in a variety of fields such as organic pollutants removal and wastewater treatment.

7.3. A new strategy for farm management and bioremediation with nano-BC

The nano-BC promises to substantially transform agriculture and biological remediation methods within the crop cultivation and ecological domains. According to [8], nano-BC in agricultural practices has demonstrated the potential to promote soil fertility and improve nutrient-holding capacity. The BC matrix is composed of nanoparticles that can enhance plant development, augment nutrient accessibility, and mitigate the transmission of soil-borne diseases. Nano-BC in the bioremediation of contaminated soils is advantageous due to its high efficiency in absorbing and degrading organic pollutants [129]. The enhancement of environmental restoration and cleanliness is attributed to the expanded surface area and enhanced responsiveness exhibited

Table 6
Analytical techniques for BC characterization.

Characterization methods	Detailed explanation of the techniques		Reference
Proximate and ultimate analysis	Proximate analysis determines moisture content, volatile matter, ash content, and fixed carbon using standardized methods.	TGA measures weight loss at different temperatures to identify moisture, volatile matter, and ash.	[115,116]
	Ultimate analysis provides elemental composition (C, H, N, S, O).	Elemental analysis combusts the sample to quantify elemental percentages.	
Surface area and porosity	BET assesses specific surface area and pore size distribution by nitrogen adsorption–desorption isotherms.	Gas adsorption techniques measure gas uptake at various pressures to determine porosity characteristics.	[117]
Structural analysis	SEM examines surface morphology and microstructure. TEM provides detailed images of internal structure at the nanoscale. XRD identifies crystalline phases and the degree of graphitization.	EDS coupled with SEM for elemental mapping.	[4]
Chemical functional groups	FTIR detects functional groups and bonds by measuring infrared absorbance. Raman spectroscopy analyses carbon structure, particularly the degree of disorder and graphitic content.		[4]
Thermal stability and decomposition	TGA measures weight change under controlled heating to study thermal stability and decomposition patterns. Differential Scanning Calorimetry (DSC) heat flow associated with thermal transitions.		[118]
Surface chemistry and charge properties	pH and Electrical Conductivity (EC) were measured in BC-water suspensions to evaluate acidity/alkalinity and ionic strength. CEC indicates the ability to retain and exchange cations, important for soil fertility.		[119,120]
Elemental composition and nutrient content	Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) measures the concentration of metals and nutrients. X-ray Fluorescence (XRF) determines elemental composition and detects heavy metals.		[121]
Sorption properties	Batch adsorption tests evaluate the capacity to adsorb pollutants (heavy metals, organic contaminants) from solutions. Column studies assess dynamic adsorption properties under flow conditions.		[122]
Molecular and spectroscopic techniques	Nuclear Magnetic Resonance (NMR) Spectroscopy provides information on molecular structure and dynamics. X-ray Photoelectron Spectroscopy (XPS) analyses surface chemical states and composition.		[123]

during the reaction of removal [17,130]. Agriculture production and ecological restoration encouraged to employ sustainable, eco-friendly nano-BCs. The synthesis conditions utilized for nano-BC entail a precisely regulated pyrolysis step conducted at elevated temperatures, commonly involving metallic nanoparticles. The customized production method yields nano-BC that exhibits a notable decrease in particle size and a corresponding increase in surface area when correlated to the original BC. The intensified characteristics exhibited by nano-BC, including its increased adsorption removal and enhanced reactivity, provide it an optimistic alternative for employment as a soil enhancement in agricultural operations and as an effective means of pollutant removal in bioremediation processes. Furthermore, nano-BC demonstrates exceptional skills in retaining nutrients and stimulating plant growth, presenting a promising sustainable approach for upgrading crop yield and soil fertility. The distinctive characteristics and adaptable uses of nano-BC allow it a good path for promoting the principles of sustainable agriculture and mitigating environmental challenges.

Nanomaterials with charcoal hold promise for the development of sustainable approaches to remove organic contaminants. The versatility and effectiveness of nano-BC in various environmental applications can be attributed to its ability to synthesize, characterize, and potentially utilize multiple functions [131]. According to [60], BC-based nanocomposites have demonstrated enhanced efficacy in removing pollutants and promoting water management sustainability in wastewater treatment. Nano-BC in agricultural farming and bioremediation practices holds considerable promise for improving soil fertility, promoting plant growth, and addressing soil pollution [132]. The advancement of sustainable environmental restoration approaches can be enhanced by conducting additional research utilizing a combination of BC and nanomaterials.

8. Agricultural BC for closed-loop economy

Green resource management is a discipline that aims to enhance resource efficiency and encourage the adoption of sustainable practices. According to [133], BC has the opportunity to foster a circular economy that yields positive outcomes for both the environment and agriculture.

8.1. Sustainable resource management

The principles of sustainable resource management incorporate the development, organization, and execution of human activities to help in optimal use and maintenance for future availability. Sustainable

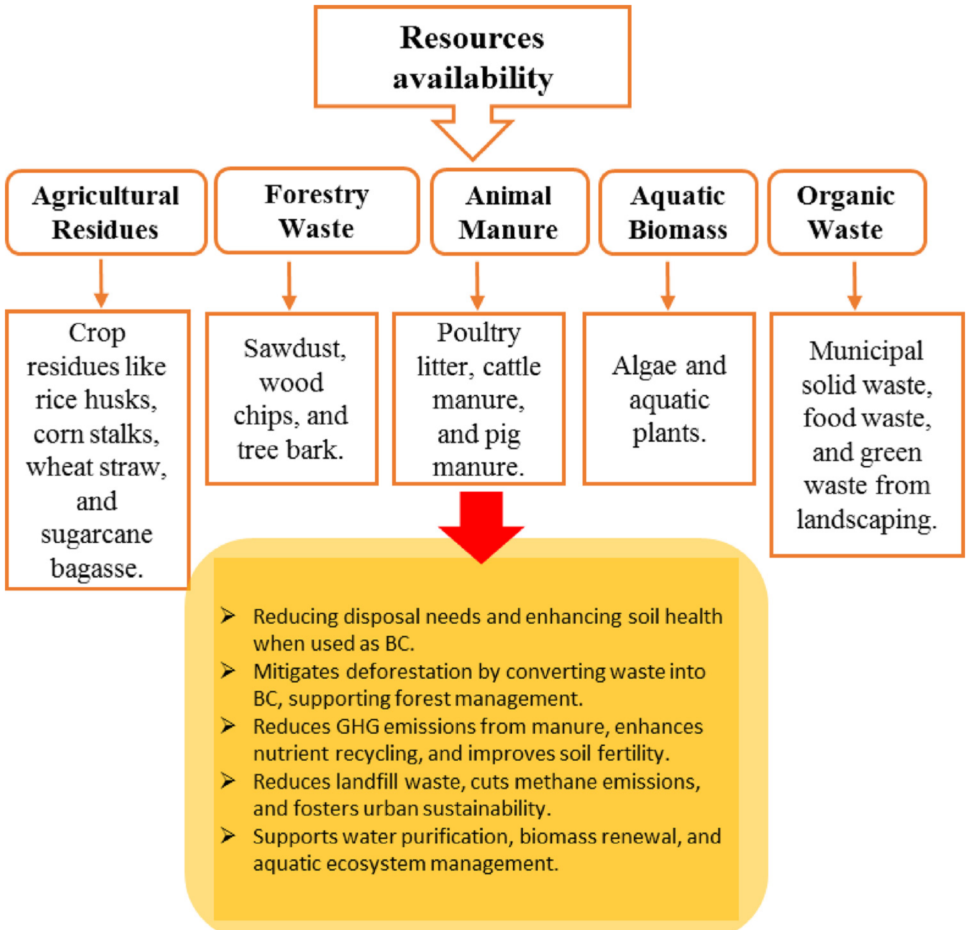

Fig. 7. Global availability of resources.

development entails systematically identifying, assessing, and mitigating environmental risks and implementing corresponding measures. BC, a carbon-rich substance, is derived from the pyrolysis of organic waste and biomass. It has been found to have multiple functionalities in environmental monitoring [6,67]. BC can effectively store carbon within the soil for an extended period, impeding its subsequent release into the environment. BC is a chemically rich carbonaceous material that has the potential to enhance soil quality in agricultural contexts or rehabilitate eroded soil. BC has also demonstrated possible advantages in increasing nutrient retention, stimulating soil fertility, and enhancing soil quality and structure [134]. According to [135], the enhancement of soil's water retention capacity reduces the runoff rate of rainwater. Amending with BC improves the availability of soil nutrients to plants and reduces nutrient leaching allowing essential minerals to bound within the BC structure satisfying limits for lost mineral-based fertilizers. BC has the potential to mitigate soil pollution through its sorption capabilities, which enable the removal of many contaminants, including HMs, natural substances, and pesticides. This improvement is derived from the existing of water sustainability by minimizing both surfaces, as well as groundwater system infiltration with pollutants. The production of BC using biomass and organic residues is a good example in this regard because it shows an ecologically advantageous waste management process that closes the carbon cycle (Fig. 7). BC production contributes to the circular systems and mitigates greenhouse gas emissions via recovering sources typically disposed of in landfills or incinerated.

8.2. BC-based agricultural economic system

Integrating BC into agriculture practices establishes a closed-system economy, optimizing resource utilization and minimizing waste generation. The procedure involves producing BC using agricultural residues and applying it in various farming practices. The method engages in manufacturing BC from agricultural wastes, and it is used for multiple agro practices. It can be manufactured by the pyrolysis of organic matter (agricultural residues such as crop waste, manure and pruning residue). In conjunction with BC, bioenergy development in syngas or bio-oil presents prospective applications in generating thermal–mechanical–electrical energy [20]. The incorporation of BC into agricultural soils has demonstrated a positive impact on both ecological rehabilitation and rural productivity. More supply of soil will have more nutrient retention, less loss and much enhancement in the recycling. This leads to increased development of crops, lower use of fertilizers and higher drought tolerance/ resistance in plants. A circular economy model that relies on agrarian BC promotes the reuse and recycling of land-based by-products [136]. BC can be produced using agricultural residues and different forms of biodegradable waste that would ordinarily be disposed of to reintroduce it into the soil. The self-sustaining system exhibits a reduced resource requirement and generates a lower volume of waste than traditional methods. Along with its application as a soil amendment, BC demonstrates aptitude as a sustainable energy source. The achievement of sustainable energy for agricultural activity is facilitated through the conversion of bioenergy generated during BC production into viable sources of heat

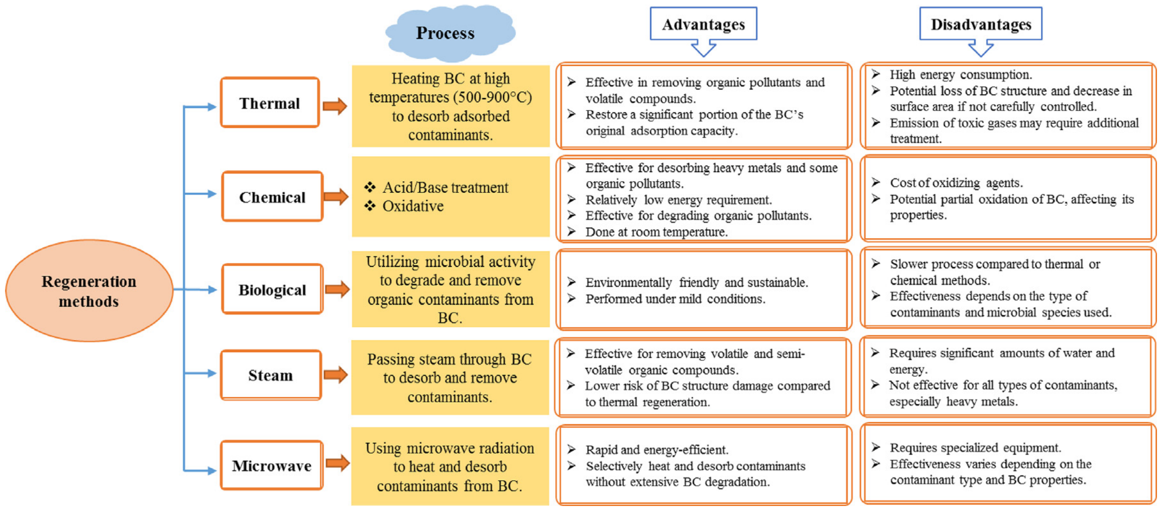

Fig. 8. Overview of regeneration methods and their effectiveness.

and electricity. The process of nutrient recovery: BC, in conjunction with other waste products such as sewage sediment or animal waste, has been proposed as a means to achieve this objective [137]. The BC materials derived from the decomposition of these waste products contain a significant amount of nutrients and can be effectively employed as fertilizers or soil amendments. To achieve sustainability, it is imperative to incorporate environmental monitoring strategies and adopt a bioeconomy model centred around utilizing agricultural BC. BC has multiple purposes, such as carbon capture from the atmosphere, and hence must be incorporated into strategies for environmental monitoring.

Integrating BC production into agricultural systems supports a circular economy by recycling waste and improving environmental sustainability. Overall, BC is a versatile and valuable tool for enhancing soil health, mitigating climate change, managing waste, and promoting sustainable agricultural practices.

8.3. Regeneration of industrial BC

Regenerating BC used in industrial applications is crucial to maintaining their effectiveness and extending their lifespan. BC is commonly used in environmental remediation, water treatment, and soil amendment [10,138]. Regeneration methods aim to restore the adsorptive capacity and reactivity of BC that have become saturated with contaminants. Here's an overview of the regeneration methods and their effectiveness. The regeneration of BC used in industry can be achieved through various methods, each with its advantages and limitations. The alternative method depends on the specific application, the type of contaminants involved, and practical considerations such as cost, environmental impact, and the preservation of BC properties (see Fig. 8).

9. Constraints and difficulties associated with the use of BC

9.1. Accessibility and development costs of raw materials

BC has demonstrated significant value in diverse environmental applications. However, major research gaps still require attention (Table 7). Obtaining appropriate raw materials for the processing of BC can be difficult. The choice and calibre of biomass employed can impact the characteristics and efficacy of the BC. Securing a constant and dependable source of feedstock can pose challenges, particularly in regions with scarce biomass resources. BC processing can be energetically demanding and may require substantial equipment and infrastructure investment. Hence, the expense associated with BC production can be a constraint, specifically for small-scale implementations or areas with restricted supplies.

10. Advancements and prospects for cutting-edge BC study

Given present trends and potential technical advancements, one might postulate various avenues for future advanced BC research. The following alternatives are presented below. According to [142], contemporary production methods offer enhanced sustainability and cost-effectiveness in BC production, making them a prominent area of investigation in future research. Incorporating BC synthesis into complementary processes, notably renewable clean energy and product generation, may necessitate consideration. This may involve exploring novel pyrolysis methods. To enhance BC use, scholars may improve its characteristics [22]. To strengthen its capacity for nutrient storage and recycling, carbon sequestration, and organic amendment, perchance imperative to modify the conditions of BC development to achieve convenient characteristics. Exploring BC formulations tailored to specific applications and environmental conditions has significant potential for future scholarly investigation. The development of BC with particular characteristics for specialized applications such as water filtration, phytoremediation or bioremediation technologies, and animal feeding operations enhancement could be achieved through the exploration of different combinations of feedstock, pyrolysis temperatures, and pre-treatment techniques [143–145]. Investigating prospective interest associated with BC in agricultural sustainability is still in its early stages. It is anticipated that ongoing ingenious research on BC will contribute to a deeper understanding of this subject matter. [146] assert that several areas warrant investigation, including soil fertility, the natural nutrient cycling in soil, water retention, and bacterial community. The potential for further analysis into BC-based fertilizers, soil amendments, and BC-compost blends is also likely to expand [98]. The importance of BC in the process of carbon sequestration is expected to be a prominent area of research in the future, given the urgent need to address the issue of climate change. Future studies may prioritize investigating the potential of BC to serve as a long-term carbon storage mechanism across diverse soil types and ecosystems [147]. There may be increased interest in exploring BC's possible applications, including its utilization in carbon-negative materials and incorporation into soil culture. The increasing global concern regarding waste management has led to a growing interest in researching the possibilities of BC in waste valorization. BC exhibits promising potential in remedying environmentally detrimental substances such as organic waste, sewage sludge, and polluted soils. Examining sustainability issues and assessing life cycle analysis studies may involve investigating BC production and utilization's environmental and economic implications [72]. By considering potential trade-offs and unanticipated consequences, incorporating these factors will facilitate the sustainable development and

Table 7
Key aspects and challenges in specified BC studies.

Area of research emphasis	Prominent characteristic	Primary obstacles	Reference
BC composites	Enhancing the efficacy of BC composite for sustainable remediation of emerging pollutants through optimization of operating conditions.	Issues such as secondary pollution, economics, and incompatibility of BC composites arise when implementing them on a wide scale in real-world situations.	[11]
BC in agricultural soils	BC is a traditional method for improving soil quality and restoring degraded soil. It is considered a cost-effective and easily implemented technology.	There is uncertainty in studies on the application of BC on a broad scale in the field and its impact on toxins and vectors.	[20,92]
BC for the elimination of air pollution	Pure and amended BC to eliminate atmospheric contaminants such as greenhouse gases and volatile organic compounds.	Efficient and enhanced BC, optimizing the process of BC production for sustainable reduction of air pollution	[12,13]
Adsorption of hazardous elements by BC	The main methods of metal sorption in BC are complexation, redox reaction, and chemisorption.	Insufficient investigation into the competitive sorption of metals by BC and a scarcity of studies on cost-effective BC for wastewater remediation.	[139]
BC for carbon neutrality and enhancing the circular economy.	Low-cost BC in soil to effectively reduce carbon dioxide emissions.	Unforeseen release of greenhouse gases and inadequate handling of biomass both prior to and during the production of BC.	[67]
BC to reduce pesticide contamination in soils	The study investigated the effects of different BC types, soil conditions, and climatic parameters on using BC for pesticide remediation.	The incompatibility between BC and mixed pesticides, as well as the uncertainties surrounding pesticide metabolites as secondary pollutants.	[60]
BC as a protective barrier for the remediation of environmental pollutants	BC is a highly effective solution for addressing environmental pollutants in many mediums, such as soil, air, and water.	The use of designed BC in the remediation of environmental pollutants is limited, and functional BC is not commonly adopted.	[140]
Functional BC, optimizing feedstock, and employing a comprehensive approach to apply BC as an effective tool against environmental contaminants.	The selection of particular feedstock, surface activation, modification of BC, and comprehensive utilization of BC for soil, water, toxic metals, pesticides, and air pollutants, along with the associated potential and difficulties.	The gap between laboratory research and real-world field applications is a worry regarding the widespread use of BC, as it can lead to secondary pollution. Additionally, there are technical challenges that need to be overcome to commercialize BC for environmental remediation purposes.	[11,141])

implementation of BC technologies. These estimates should be treated with care, however, since they are somewhat speculative and may shift if significant results come from ongoing research efforts in the future or societal goals undergo a transformation. Despite that, these results suggest some interesting future lines of BC research projected by a well-designed study.

The research highlights the environmentally friendly aspects of BC concerning ecological restoration and long-term viability. The potential of BC for environmental restoration is investigated by utilizing various feedstocks and pyrolysis parameters. In fact, a large number of factors can affect the performance of BC production, and this emphasizes that there is no 'one size fits all' when it comes to designing/ tailoring BC for specific environmental conditions. Further, the review highlights that source-specific BC products are effective in immobilizing contaminants during environmental recuperation efforts [2]. The findings, as mentioned earlier, have the potential to inform the customization of BC-based solutions to address environmental challenges that are specific to particular sites. The assessment identifies significant deficiencies in existing research despite notable promising advancements. To address potential concerns and guarantee the secure integration of BC in agricultural contexts, it is imperative to conduct a thorough examination of the impact of BC on human health. The paper also examines the potential effect of BC in agricultural practices on several aspects, including ecological restoration, ecosystem stability, physicochemical and biological properties. Following the discovery of these findings, further investigation is required to enhance the use of BC in sustainable agriculture and evaluate its enduring impacts. The efficacy of BC-based applications is substantiated by mechanistic research. This extensive analysis will be of great value to research-practice partnerships in green recovery and achieving renewable resource-friendly. Nanotechnology in BC processing presents novel research opportunities [146]. The role of BC in environmental restoration and ecological sustainability is enhanced through the identification and resolution of research deficiencies, as well as the incorporation of nanotechnology in the manufacturing procedure. The utilization of a "win-win approach" in this context yields advantages for both the preservation of environmental health and the enhancement of human well-being.

11. Conclusions

Building on the objectives outlined in the introduction, this study underscores the transformative potential of BC as a sustainable solution for addressing pressing environmental and agricultural challenges. Recent advancements in BC development, particularly enhanced processing techniques, have significantly expanded its applications. The material's porous nature and broad surface area improve plant growth, reduce nutrient leaching, and enhance soil water and nutrient retention, aligning with the goal of promoting environmental sustainability. A thorough understanding of the relationship between BC's morphology and its application-specific functionalities is essential for optimizing its effectiveness. Additionally, the integration of BC and charcoal-based sludge catalysts offers promising pathways for fostering a sustainable future. Continued research is necessary to scale up production techniques, develop cost-effective methods, and explore innovative feedstocks to enhance BC's efficiency and accessibility. Future research should focus on the development of standardized quality assessment protocols for BC, ensuring consistency and safety across applications. Investigating the long-term environmental and ecological impacts of BC in diverse settings, including its interactions with soil microbiota and water systems, is critical. Furthermore, interdisciplinary collaboration between researchers, policymakers, and industry stakeholders is vital to bridge knowledge gaps and accelerate the adoption of BC technologies. By addressing these areas, the potential of BC as a versatile, affordable, and impactful tool for global sustainability can be fully realized, paving the way for practical solutions to mitigate climate change, enhance resource management, and restore ecosystems.

CRediT authorship contribution statement

Farah Amalina: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Santhana Krishnan:** Validation, Supervision, Resources. **A.W. Zularisam:** Supervision, Project administration, Funding acquisition. **Mohd Nasrullah:** Validation, Supervision, 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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