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The evolving role of biochar: recent advances and future directions - a review

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ABSTRACT

Biochar is expected to play a crucial role in advancing sustainability and conservation of planetary resources. This is necessary for the drive and fostering of a circular bio-economy. The burden of climate change and carbon footprint uncovers new potentials for biochar in soil health enhancement, reduction in greenhouse gas emissions, and carbon capture. Its integration with bioenergy production and potential to support regenerative agriculture make it an attractive organic solution. The growing importance of biochar has attracted interest across multiple industries and driven innovation in its production techniques. Advanced preparation methods for biochar, such as co-pyrolysis and microwave-assisted pyrolysis, are modern approaches to improving and enhancing the properties of biochar for several environmental and energy applications. In this work, the evolving roles of biochar in agriculture, construction, pharmaceuticals, and water management were extensively discussed. Challenges and future direction in the commercialization of biochar as a global elixir were also highlighted with emphasis on biomass stock, feedstock type, production techniques, properties of biochar, and the embrace of computational analysis in driving more effective processes.

1. Introduction

1.1. Brief overview of biochar and its historical use

Human health, animal health, and the environment, interlinked in One Health, are affected by five major threats, including food safety and security, biodiversity loss, urbanization, zoonotic diseases, and environmental pollution [1,2]. Biochar directly intersects these One Health challenges because its physicochemical and biological functionalities, ranging from contaminant immobilization to pathogen suppression and carbon stabilization, enable integrated mitigation across human, animal, and environmental domains. Several studies highlight the intensification of practices such as soil degradation, construction, pharmaceuticals and health care, and water management as the driving force of these major threats [3–6]. To protect populations and ecosystems (environment and human health), multidisciplinary research from expertise in human medicine, public health, veterinary medicine, urban planning, and environmental sciences ought to explore sustainable approaches. Before these One Health threats intensified, biochar had already been used for environmental remediation [7].

Production of biochar in this manner enhances its stability for hundreds of years, which is valuable for carbon sequestration and improved soil health [8]. Biochar use can be traced as far back as thousands of years ago in the Amazon basin for intentional and sustainable land management practices [9], as it is low-tech, climate resilient, and effective in poor soils enhancement [10]. It has historically been used to generate heat; for fuel to generate electricity and for cooking; in soil amendment for balancing soil pH, water retention and for cation exchange [11]; for filtration and adsorption of gas, liquid, or solid spilled in water; and it has been used during contamination of some feedstocks such as metal and plastic in the kitchen. Biochar is often sourced from several feedstocks, such as biomass energy crops, bioenergy residues

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[11], compost, kitchen waste, sewage sludge, and agricultural waste such as invasive alien plants if they are removed from farmland and are cleared from irrigation channels to restore productivity [12].

Invasive alien plant species are globally known for their negative impact on ecosystem functioning, biodiversity, human health, water quality, including soil health [13]. These species comprise trees and shrubs, grasses and reeds, climbers, terrestrial herbs, and aquatics [14] and continue to spread, become dominant, and cause growing threats to new environments [15,16]. Although eradication and management of IAPs is obligatory globally, management strategies can be expensive and are often ineffective due to non-target effects associated with herbicidal control and inconsistency of funding for sustainable methods like biological control [17]. Ceriani et al. [12] pointed out that since eradicated IAPs provide large biomass considered a waste during manual clearing, this biomass may be used as sustainable feedstock for biochar. Evidently, there is a growing number of studies demonstrating the efficacy of biochar from IAPs on sustainable environmental management [15,18,19]. In this study, we provide a comprehensive examination of the potential of biochar to enhance management practices across agriculture, construction, pharmaceuticals, healthcare, and water systems. In addition, we evaluate biochar feedstock selection, emerging application pathways, constraints to large-scale commercialization, and prospective research trajectories.

2. Recent advances in biochar research

2.1. Biochar in agriculture

Biochar (charcoal) is increasingly used in livestock farming because it can improve productivity, animal health, and environmental sustainability [7]. The use of biochar in animal husbandry is primarily attributed to its high carbon content, porosity, and strong sorption capacity, which enable it to adsorb toxins, regulate moisture, and influence gut and environmental microbial populations [20]. Biochar supplementation has been shown to enhance growth performance, improve blood profiles or full blood count (FBC), increase egg yield, strengthen disease resistance by suppressing pathogenic gut bacteria, and reduce enteric methane emissions in ruminants [21,22]. Beyond direct dietary applications, biochar also contributes to improved farm hygiene through its ability to bind contaminants and harmful compounds in manure and housing environments [23]. Historically, agricultural communities incorporated biochar into manure pits and composting piles to enhance nutrient retention and reduce odors, while its use as bedding material provided insulation, moisture absorption, and odor control [24]. Recent advances, including pH modification and feedstock-specific engineering, have further optimized biochar for bedding, manure treatment, and feed additive applications [25].

In addition to its benefits in animal systems, biochar application to agricultural soils improves soil physical structure, increases water retention; particularly in coarse-textured soils, and enhances soil organic carbon and microbial biomass. These effects are most consistent in acidic, sandy, or low organic soil environments. Meta-analyses and recent reviews show measurable increases in plant available water and soil carbon, with crop-yield responses depending on feedstock type, pyrolysis temperature, application rate (commonly 5–40 t ha^{-1}), and soil characteristics. Mechanistically, biochar increases porosity, provides functional groups that retain nutrients, and modulates microbial communities that regulate nutrient cycling. However, its performance varies widely with production methods and site conditions; long-term field stability remains uncertain. Therefore, pilot-scale evaluations using locally available feedstocks, supported by life-cycle assessment (LCA), are recommended before broad adoption [26,27]. A related study by Fayyaz et al. [28] reported on the use of biochar (from various feedstocks) to manage root-knot nematodes in tomato plants. The authors utilized different biochars in pot experiments and found that especially biochar from sugarcane bagasse produced at 300 °C improved tomato growth and reduced nematode development. Collectively, these studies demonstrate that the integration of biochar into animal husbandry and associated soil systems supports manure management, odor control, soil health improvement, pathogen suppression, climate mitigation, filtration, and heat-stress reduction [29,30].

2.1.1. Feed additives and animal health

The use of biochar (Fig. 1a) in animal feed is an emerging trend, and this is due to its unique features or properties such as high porosity, surface area, stability, carbon content, and nutrient retention. Studies have demonstrated that introducing biochar into animal feed can improve nutrient absorption, resulting in enhanced growth performance and feed efficiency [7]. One of the key reasons for using biochar in animal feed is its capacity to adsorb toxins and mycotoxins due to its porous granular solid structure; biochar has a large specific surface area, with rich pores (Fig. 1b) and rich surface functional groups (Fig. 2), the toxic substances are produced by fungi and molds present in feed ingredients [31].

By binding to these toxins, biochar can reduce the harmful effects on animal health and performance. As reported by Lao and Mbega [33], biochar inclusion at 1–3 % of the dry matter of animal feed rations improved health conditions and performance of farm animals, such as weight gain, immunity response, feed intake, feed conversion rates, and carcass characteristics. Additionally, biochar has been proven to promote nutrient use and digestion in animals, resulting in increased feed efficiency and growth rates [21]. Furthermore, biochar can operate as a prebiotic, encouraging the growth of beneficial microbes in the gut microbiome of animals [29]. Specifically, animal physiology, metabolism, and immunology have been linked to gut microbe-host interaction [34,35]. Early-life microbial succession in newborn offspring is critical for immune system development and gut maturity, and it may also be a major factor in the animals' later-life resistance to infections [36]. Biochar addition in animal feed has also been shown in studies to minimize greenhouse gas emissions from enteric fermentation, hence increasing the sustainability of livestock production systems [37,38]. However, more study is needed to maximize its use, such as finding the most effective dosage levels, particle sizes, and production techniques for various animal species and production systems. The effect that different feedstock types, pyrolysis settings (i.e., for the production of biochar/charcoal), and also the impact(s) of post-processing treatments may have on the characteristics of biochar raises questions about how safe and effective it is as a supplement to feed [38,39].

Biochar as a feed supplement for nutrient digestibility and growth performance of *Catla catla* (*C. catla*) fingerlings is well documented, though outcomes depend strongly on the biochar source. In the foundational study on *C. catla* fed a *Moringa oleifera* seed meal (MOSM)–based diet, adding 2 mg/kg biochar derived from various materials (parthenium, farmyard manure, poultry waste, vegetable waste, corncob waste) markedly enhanced growth: fish receiving poultry-waste biochar achieved a weight-gain of ~256.6 % and an efficient feed

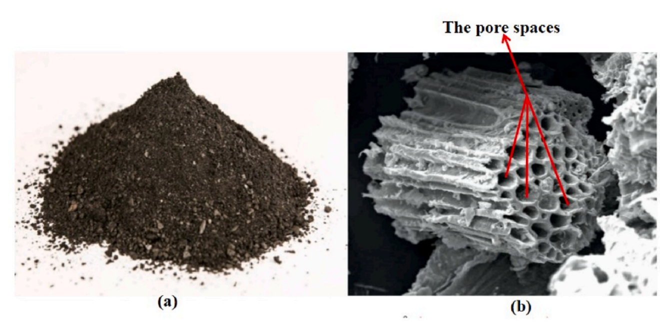

Fig. 1. (a) Raw biochar (b) Surface morphology of the porous structure of biochar showing the rich pores (adapted from Gąsior, D. and Tic, W. J. [32]).

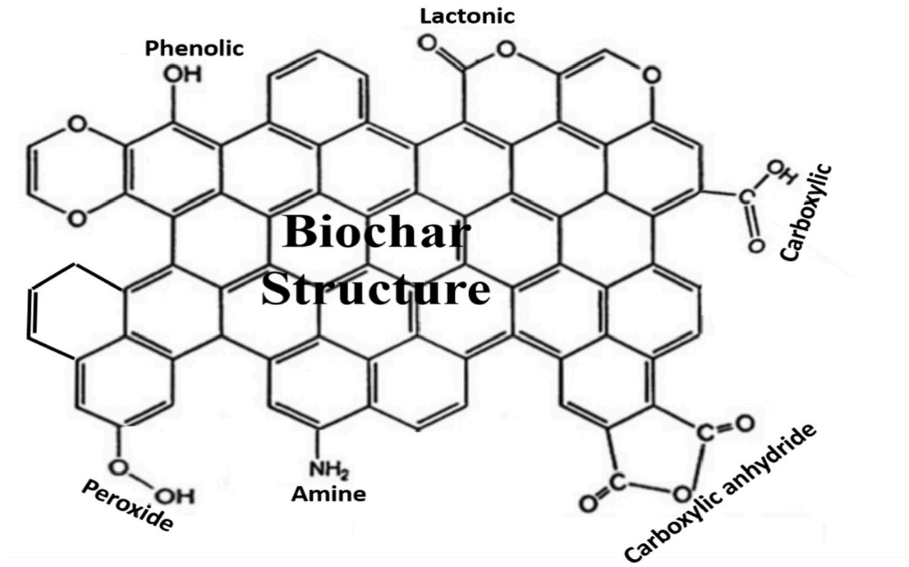

Fig. 2. Functional groups commonly found on biochar surfaces.

conversion ratio (FCR ≈ 1.19), significantly outperforming control and other biochar types. Alongside growth, apparent digestibility coefficients for protein (~75.9 %), fat (~81.9 %), and gross energy (~74.84 kcal/g) were highest in the poultry-waste biochar treatment [21]. The positive effect of biochar supplementation appears not limited to *C. catla* but extends across other aquaculture species, supporting its broader potential. For instance, a recent 60 day feeding trial with *Ctenopharyngodon idella* (grass carp) fingerlings showed that 2 % inclusion of corncob biochar (CCBC) in a sunflower-meal based diet significantly improved growth, nutrient digestibility, body composition, hematological parameters, and mineral absorption compared to control or other biochar types; in contrast, biochar from household waste had adverse effects [40]. Similarly, experiments with other species such as *Labeo rohita* (rohu) demonstrated that poultry-waste biochar added to plant-meal-based diets markedly enhanced growth, crude-protein and energy digestibility, carcass composition, hematology, and mineral uptake (Ca, P, Fe, Zn, etc.) compared to control feeds or other biochar sources [41]. These cross-species results lend credence to the hypothesis that biochar, when properly sourced and processed, can boost the digestion and growth of *C. catla* fingerlings. Its porous structure helps improve nutrient absorption and feed efficiency. However, poor-quality biochar may harm performance, so choosing safe, well-processed sources is essential for healthier fish and better plant-based diets.

2.1.2. Manure management

Manure management is a key part of sustainable agriculture because incorrect handling of manure may result in environmental degradation, greenhouse gas emissions, and nutrient runoff [42,43]. Biochar, a carbon-rich material, is a promising tool for reducing the environmental impact of manure management while also giving agricultural benefits [26]. Biochar has been used in odor control; one of the biggest issues with manure management is the generation of bad odors, which can be a nuisance to adjacent residents [44]. Biochar can successfully absorb and neutralize odorous chemicals, minimizing odor releases from stored or applied manure. Studies have demonstrated that integrating biochar into manure storage facilities or applying charcoal-amended manure to fields can greatly reduce odor issues [45]. This is possible because of its porous nature and large surface area. Biochar can absorb odorous substances such as sulfides, volatile fatty acids, and ammonia released by manure; these odorous gases are absorbed and held inside the biochar structure (Fig. 1b), limiting their discharge into the atmosphere [46,47]. For example, Nguyen et al. [47] reported that incorporating biochar into food-waste co-composting reduced ammonia emissions by approximately **32**–**58 %** and decreased key odorous volatile fatty acids by **28**–**47 %**, while Dougherty [46] documented measurable reductions in lagoon-emitted odors and associated gases when biochar was used as a surface cover. Apart from its adsorption function in odor management, several emerging mechanisms explain biochar's broader odor-mitigation potential. Firstly, chemical transformation processes occur when biochar supports surface or catalytic reactions that convert malodorous compounds into less or non-odorous forms, thereby improving air quality around livestock operations [48,49]. Secondly, microbial modulation arises as biochar alters microbial community structure, promoting beneficial taxa while suppressing odor-producing microorganisms and consequently reducing emissions [50]. Thirdly, long-term odor control is achieved because biochar maintains adsorption capacity and reactive functionality well beyond the short-term effects observed with materials such as zeolite [51], continuing to adsorb and transform odorous substances long after application [52]. However, the effectiveness of these mechanisms can vary with biochar dose, pyrolysis temperature, feedstock type, and the physicochemical characteristics of the manure or composting matrix, necessitating careful optimization for practical deployment. Applied studies revealed that co-application of biochar with manure during storage or composting reduces ammonia volatilization and can reduce odors and greenhouse gas emissions (N_2O, CH_4) depending on application rate, particle size, and the biochar's surface chemistry. Biochar can also act as a carrier for microbial inoculants in composting and for nutrient capture in manure lagoons; however, effect sizes vary, and high application rates are sometimes required for robust mitigation. For on-farm adoption, advise: (1) trialing small pilot batches (manure piles or lagoon dosing), (2) monitoring ammonia and GHG fluxes, and (3) assessing the end-product quality for land application [53].

2.1.3. Slow-release nutrients and nutrient retention

Some of the vital nutrients necessary for plant growth that are found in manure are nitrogen, phosphate, and potassium (NPK). When manure is applied to a field, some of these nutrients can be lost by leaching or volatilization, which may result in water body contamination and nutrient unavailability for crops. Research has shown that adding biochar to manure or applying biochar-amended manure to soils can improve nitrogen retention and support more sustainable nutrient management techniques [54,55]. Again, this is possible due to its rich porous structure (Fig. 1b). The porous nature allows for nutrients to be trapped, preventing them from leaching away by erosion [56]. Biochar has a very good ion exchange capacity, which has been reported to have a strong influence on nutrient retention. This made it possible for it to attract and hold some of the positively charged ions, like ammonium (NH_4^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}), serving as a nutrient reservoir, thereby allowing plants to access them over an extended period of time. Singh et al. [57] conducted a meta-analysis of 59 studies on biochar application, demonstrating the positive impact of biochar on soil CEC (cation exchange capacity) and nutrient retention. However, they highlight the need for long-term field studies on its aging and re-application.

2.1.4. Greenhouse gas (GHG) mitigation

During the manure management, a considerable amount of greenhouse gases, mostly methane (CH_4) and nitrous oxide (N_2O), are usually emitted into the environment, contributing to climate change [43]. By serving as a stable carbon sink, biochar can help to mitigate the emissions of GHGs, thereby effectively sequestering carbon from the atmosphere [58]. Also, biochar has been proposed by Cayuela et al. [59] as an "electron shuttle" that facilitates the transfer of electrons to soil denitrifying microbes, which, together with its liming effect, would subsequently cause reduction of N_2O to N_2. The work of Rittl et al. [60] showed that *Miscanthusgiganteus* biochar applied at high rates suppresses the typical warming-induced stimulation of N_2O emissions, thereby showing high mitigation potential of N_2O in tropical soils. Green energy for a sustainable environment sparks interest in the synergies between biochar and renewable energy production, where the heat produced during pyrolysis can be collected and utilized to generate electricity or heat, thereby replacing fossil fuel-based energy sources, and further reducing GHG emissions. A typical work in this regard was that of Leme et al. [61], where they demonstrated electricity generation from pyrolysis gas produced during charcoal production.

2.1.5. Pathogen reduction

Manures can harbor dangerous bacteria like *E. coli* and *Salmonella* [62]. Applying manure to agricultural lands can expose people to these dangerous bacteria, which can compromise food safety and human health. It has been documented that biochar exhibits anti-bacterial properties, capable of adsorbing and immobilizing microorganisms, making them fairly inert, thereby limiting their survival and transmission in the environment [63]. Lehmann et al. [64] reported that incorporating biochar into manure or applying biochar-amended manure to soils can significantly reduce pathogen levels and reduce risks associated with pathogen contamination. Microbial competition and predation approach, where biochar amendments in manure can alter the microbial community makeup and dynamics, encouraging the growth of beneficial microbes that compete with and prey on pathogenic bacteria, has been used in the reduction of pathogens in manure, thereby mitigating the risks of pathogen transmission to humans, animals, and the environment [65]. A study by Chung et al. [66] on the impact of biochar amendment on compost quality, gaseous emissions, and pathogen reduction during in-vessel composting of chicken manure revealed that 10 % addition of biochar showed a reduction of ammonia and GHG emissions and pathogens in the chicken manure.

2.2. Biochar in construction materials

Biochars are utilized in construction materials mostly because they exhibit properties such as chemical stability, high porosity, and enhanced thermal capacity, less environmental impact, mechanical strength improvement, enhanced soil properties, and are applicable with sustainable practices. Today, different approaches have emerged for more efficient manure management using biochar. These include; (1) The customized biochar production (CBP) which involves the manipulation of biochar production techniques to tailor their properties for specific manure management purposes. This may involve the adjustment of pyrolysis conditions such as residence time, temperature, and feedstock composition to produce biochar with better nutrient retention, pathogen reduction, and odor control properties [67]. (2) The biochar composite materials (BCM) approach, in which organic or inorganic compounds are combined strategically to have synergistic effects in manure management or other construction purposes. For example, biochar-based composites integrating components like zeolites, metal oxides, or clay minerals have shown potential for boosting nutrient retention, lowering ammonia emissions, and increasing soil fertility [68]. (3) Precision application technologies (PAT) involves targeted application of biochar-amended manure through specialized strategies such as variable rate application, global positioning system, sensor-based systems, manure management software, injection and incorporation equipment, and remote sensing [69]. (4) The life cycle assessment (LCA) studies, which are largely concerned with the environmental sustainability practices, involves a holistic life cycle assessment to evaluate the environmental impacts of biochar-based construction materials management systems. LCA studies should include energy consumption, carbon sequestration, greenhouse gas emissions, and land use changes evaluation to provide insights into the overall sustainability performance of biochar utilization. This is pivotal in decision and policy making [70]. However, while performance gains are evident, durability considerations require further attention. Some studies have noted potential leaching of trace metals from biochar derived from sewage sludge or industrial residues, as well as uncertainties about the long-term stability of biochar-cement matrices under cyclic moisture or mechanical loading [71,72]. Incorporating durability and leachability testing into future work will be essential to ensure environmental safety and regulatory acceptability.

2.2.1. Concrete and cement products

The incorporation of biochar in concrete and cement is an emerging trend, and further research is ongoing in the practice. It's been documented that well-engineered that incorporation of biochar enhanced the mechanical properties, including flexural strength, compressive strength, and durability of concrete [73]. Zhao et al. [74] studies showed that biochar derived from plant-based feedstocks (excluding rice and hardwood) increased the 28 days compressive strength of Portland cement composites by 3–13 %. Biochar produced at pyrolysis temperatures of more than 450 °C, with a heating rate of approximately 10 °C min^{-1}, significantly boosted the 28 days compressive strength. Furthermore, the addition of biochar with tiny particle sizes raised the compressive strength of Portland cement composites by 2–7 % over those without biochar [74].

2.2.2. Asphalt mixtures

The porous structure, high surface area, and surface functional groups of biochar have been found to improve the moisture resistance, rheological properties, and reduce rutting in asphalt when blended. Biochar addition can modify the rheological properties of asphalt binders, influencing their viscosity, rigidity, and temperature sensitivity, thereby enhancing resistance to deformation under traffic loads and temperature fluctuations [75,76]. Emerging literature from laboratory and limited field trials shows that biochar, when used as a bitumen modifier or filler (typical dosages 1–5 % by binder mass or as partial filler replacement), can further improve high temperature rutting resistance. In asphalt mixtures, its porous structure (Fig. 1b) absorbs and retains moisture, preventing penetration that can cause damage and significantly slows the ageing process [77]. Critical considerations for application include uniform particle size, compatibility with the binder matrix, effects on low-temperature cracking, and long-term durability and moisture sensitivity. Recommended next steps include multi-season field trials in the target climate, standardized pre-treatment such as sieving or activation, and life cycle assessment (LCA) comparing conventional filler versus biochar scenarios [78,79].

2.2.3. Bricks and blocks

The effect of biochar in bricks and blocks is almost the same as that on concretes and cement, as discussed in section 2.2.1. In addition, biochar in brick/block production helps boosts their insulation properties, reduce weight, and improves fire resistance. This is because biochar is sustainable, renewable, and helps to reduce the environmental impact of bricks and blocks [80,81]. This is basically in the area of minimizing carbon footprint by locking carbon away in the material for potentially hundreds to thousands of years, depending on the stability of the material (carbon sequestration) [82,83] and ultimately preventing greenhouse gas emission. Traditional brick and block production involves firing clay in kilns, which produces considerable volumes of greenhouse gases. By substituting some of the clay with biochar, the overall carbon footprint of these building materials can be lowered, resulting in lower greenhouse gas emissions [84]. Biochar offers insulating characteristics that can help improve the thermal performance of bricks and blocks [80]. This may be due to the inertness of elemental carbon, which is the basic composition of biochar. Carbon is insoluble in water, diluted acids, and bases, as well as organic solvents. At high temperatures, it binds with oxygen to form carbon monoxide or carbon dioxide [85]. |In the work of Praneeth et al. [71], it was discovered that substituting 10 % of the sand in concrete bricks with biochar can greatly increase insulating performance, such that the thermal conductivity of the bricks was reduced from 0.64 W/(m·K) to 0.47 W/(m·K).

2.2.4. Soil stabilization

Soil stabilization entails all chemical, physical, biological, mechanical, or combined techniques geared towards maintaining and improving the stability of weak soil in order to achieve a construction goal [86]. Biochar is utilized in soil stabilization to improve soil quality and support sustainable construction practices. Biochar addition to soil can improve structural stability by enhancing aggregate stability and decreasing soil compaction. This improves load-bearing capacity, lowering the danger of soil erosion and structural failures in construction projects [80]. A study by Wang et al. [87] found that highly aromatic carbon structure in biochar may promote aggregation by aiding in the binding of natural SOM (soil organic matter), increasing soil aggregates' resistance to water, and making aggregates more tolerant to physical disturbance (e.g., wet-dry cycles). Biochar incorporation has also been reported to enhance soil water retention and drainage, which helps to prevent or control soil erosion, reduce water-logging, and keep soil moisture levels appropriate for plant growth, as well as in building projects that require landscaping [88,89].

Other emerging applications of biochar in construction materials are in green roofs and geopolymer materials. Green roofs are layers of vegetation planted on top of a structure. They can be installed on both flat and sloping roofs to help manage stormwater. In green roof construction, biochar can be used as a component of growing media to enhance soil quality, water retention, and plant growth [90]. The findings of Chen et al. [91] revealed that sludge biochar addition considerably enhanced substrate moisture, regulated substrate temperature, altered microbial community structure, and boosted plant development. The application rate of 10–15 % sludge biochar on the green roof had the greatest impact on both microbial and plant biomass by 63.9–89.6 % and 54.0–54.2 %, respectively. A typical, green-roofed complex is shown in Fig. 3.

Fig. 3. A green roofed complex. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Biochar is rapidly being investigated as a sustainable additive in geopolymer materials due to its ability to improve mechanical qualities, reduce environmental impact, and trap carbon [92,93].

2.3. Biochar in pharmaceuticals and health care

Biochar has found several applications in the pharmaceuticals, basically due to its unique characteristics such as the adsorption property, ease of functionalization, low toxicity, etc. The latest advancements in this field are in drug delivery systems, wound healing and tissue regeneration, toxicity management and biocompatibility level, biochar-based therapeutics, etc.

2.3.1. Adsorption properties and drug delivery systems

The highly porous feature of biochar (Fig. 1b) provides a high surface area for the adsorption of pharmaceutical entities. It has been shown that it can adsorb a wide range of pharmacological chemicals like antibiotics, heavy metals, and organic contaminants, from aqueous solutions [94,95]. In drug delivery systems, biochar may effectively absorb and release pharmaceuticals in a controlled manner, making it a promising component in drug delivery systems [96]. In the study of Maged et al. [97], coffee bean waste (CBW) was utilized to synthesize pristine ($\boldsymbol{CBW_{550}}$) and activated ($\boldsymbol{CBW_{550}^{HPO}}$) biochars for the elimination of diclofenac (DF) and levofloxacin (LEV) from water. The continuous flow mode studies confirmed that $\boldsymbol{CBW_{550}^{HPO}}$ can be successfully utilized in large-scale treatment applications. More recent research have investigated the integration of biochar into several drug delivery platforms; such as hydrogels, nanoparticles, and scaffolds, to improve their drug loading capacity and release kinetics. Incorporating biochar into hydrogels can improve their ability to remove pollutants. Hydrogels are materials that may capture hazardous pollutants from water; they have unique physical and chemical properties, making them valuable for drug administration [98]. Nano-biochar has a large surface-to-volume ratio, which boosts its surface energy, adsorption capacity, and biological efficiency [99]. Chausali et al. [99] reported that nano-biochar, as compared to biochar, has an excellent ability to adsorb pollutants, nutrients, and toxins while also being mobile in soil, making it a suitable waste management option. Because of its rich porous structure as well as strength, biochar is well utilized as a scaffold in drug delivery. Scaffold drug delivery is the use of implants or injections to introduce medications, cells, and genes into the body. In the work of Ateş et al. [100], boron-doped biochar was investigated for various applications, including drug delivery, biosensing, biological scaffolds, and biological imaging, and also as an adsorbent in the removal of pollutants and a catalyst in oxidation and electrochemical reactions.

2.3.2. Removal of pharmaceutical contaminants

Alarm has been raised about some organic emerging pollutants termed pharmaceuticals and personal care products (PPCPs) found in water bodies, endangering human, and environmental health [101,102]. Biochar can effectively remove these PPCPs pollutants from aqueous solutions via mechanisms like π-π interactions and hydrogen bonding [103]. A recent study by Maleki and Mao [104] used biochar-based adsorbents in bio-filtration systems to remove nutrients, pathogens, and pharmaceutical and personal care products from wastewater. Removal of pharmaceutical contaminants utilizing biochar may involve consideration of some critical parameters like adsorption mechanism, pore volume and size, surface area, surface modification, and environmental sustainability. The various roles of biochar in PPCPs removal are described in Fig. 4.

A study examined the adsorption of several pharmaceuticals on biochar, and the underlying mechanisms were elucidated using spectroscopic techniques. This study found that the adsorption mechanism and absorption capacity are determined by the feedstock type and production process of biochar [97]. When biochar is functionalized, carbonyl groups, carboxyl groups, hydroxyl groups, ketone groups, endo-lipid groups, and mineral crystals are all active adsorption sites in biochar, technically boosting further its adsorption capacity. Most of these locations have oxygen-containing or basic functional groups [105]. A study by Mojiri et al. [106] on the removal efficiency of PPCPs using a microalgae (*Chaetocerosmuelleri)* and that of a microalgae blend with biochar, the second case (blend with biochar) showed a better performance in removing PPCPs. Research has shown that modified biochar has a higher surface area and more functional groups, perhaps improving its ability to absorb contaminants. Sayin et al. [107] modified biochar with H_3PO_4 for the removal of ciprofloxacin (CFX) from a polluted aquatic environment and found an amazing result where the blend was nearly 100 % efficient in removing CFX. Because biochar is readily available, sustainable, cost-effective, and harmless to the environment, it is an acceptable alternative to traditional wastewater treatment methods for the removal of pharmaceutical pollutants [108, 109].

2.3.3. Wound healing and tissue regeneration

In wound healing and tissue regeneration, biochar possesses inherent antimicrobial properties, which make it effective against a wide range of bacteria that are typically associated with wound infections [110]. Biochar has a wide surface area, good pore structure, and an abundance of functional groups that promote microbe adhesion and proliferation [111]. Hence, biochar provides an excellent locked surface for immobilizing bacteria. Bacterial immobilization can be achieved by the adoption or embedding method, as shown in Fig. 5. Biochar-based wound dressings have been created to enhance wound healing by creating a favorable environment for tissue regeneration [112,113]. A wet environment is essential for wound healing [114]. A moist environment keeps the tissue from drying up and preserves the cell's vitality and functions for wound healing [115]. A well-engineered cow dung biochar-based polyvinyl alcohol/polyvinylpyrrolidone hydrogel (BCPP) was designed by Borjihan et al. [116] to *in situ* produce iodine on demand and regulate its release via the light-triggering strategy for the infected wound therapy.

Another intriguing area of research is biochar's potential to support angiogenesis. Angiogenesis is a process by which new capillaries grow from established blood vessels in the body. It is typically a beneficial, necessary procedure that promotes wound healing and delivers oxygen-rich blood to organs and tissues [118], and this makes their role in various pathological and physiological processes very crucial. Biochar has been shown to enhance nutrient retention and release in the area of wound healing [115], modulation of cytokine and growth factor expression, regulation of oxidative stress (biochar ameliorated the oxidative stress by increasing the activities of antioxidant enzymes-SOD, POD, and CAT) [119], microbial interactions, structural support, and scaffolding. These are all activities that are found to promote angiogenesis. The study by Alqaraleh et al. [120] examined AgNPs' (Silver nanoparticles) antibacterial and anticancer properties alone and combined with biochar. They found that the combination of AgNPs and biochar enhanced the antibacterial activity against all tested bacteria, and that AgNPs with biochar significantly reduced VEGF and proinflammatory cytokine expression levels.

2.3.4. Biochar-based therapeutics

Biochar modification and functionalization have led to the formulation of other potential medicinal agents known as biochar-derived compounds. Compounds like activated charcoal and bioactive molecules have pharmacological properties that could be used to treat a variety of conditions, including gastrointestinal disorders and poisonings [121]. Biochar (charcoal) has been mentioned in the detoxification and adsorption of toxins from the gastrointestinal tract or as a treatment for poisoning [122]. Silberman and Galuska [121] suggested that an oral suspension of activated charcoal should be considered in poisoning cases where gastrointestinal decontamination of an ingested toxin is required, and that activated charcoal/biochar is most effective when administered within 1 h of ingesting the poison. Biochar has also been explored for dental applications. Though Machla et al. [123] questioned the role of charcoal-containing dentifrices in promoting oral and dental health, some other researchers have come up with positive results. For example, a study by AlDhawi et al. [124] found that using a charcoal toothbrush dramatically reduced the quantity of bacteria in GCF, and that 96.6 % of the studied participants noticed a decrease in the amount of germs in their GCF after using a charcoal toothbrush. Furthermore, in the USA, though the Food and Drug Administration (FDA) has approved activated charcoal for a variety of health conditions, the American Dental Association (ADA) does not recommend any activated charcoal products for dental health [125].

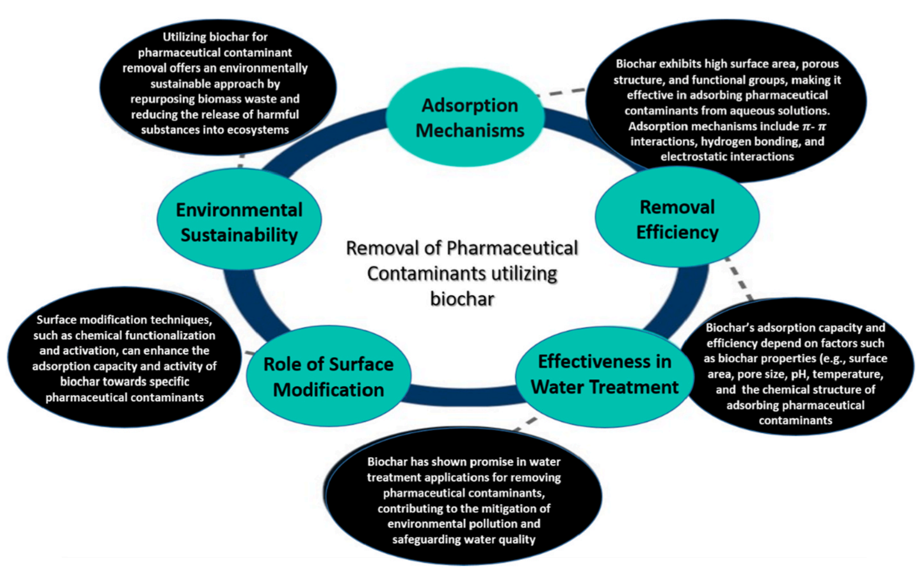

Fig. 4. Various roles of biochar in PPCPs removal.

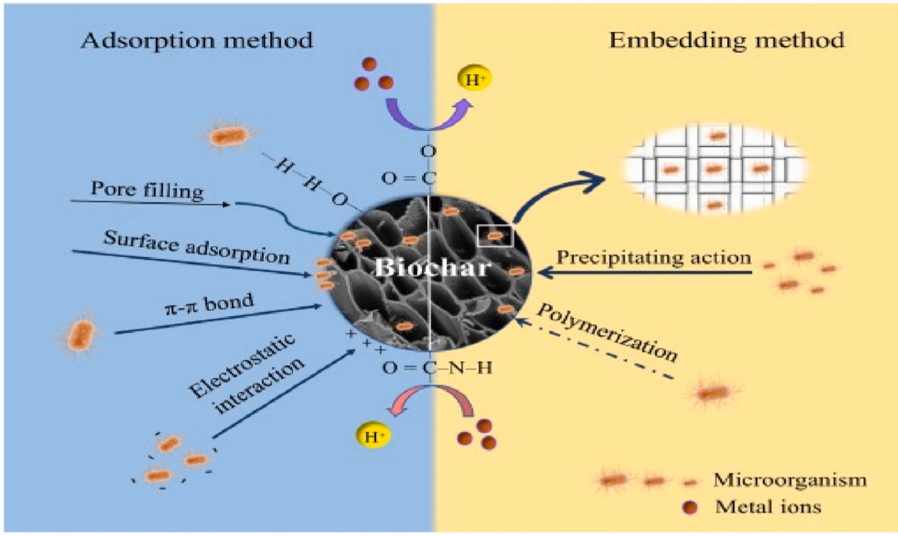

Fig. 5. Absorption and Embedding methods of Microorganisms with Biochar (Adapted from Li et al. [117]).

2.4. Biochar in water management and filtration

Biochar has rapidly gained attention for its applications in water management and filtration, basically due to its unique physicochemical properties, which include high porosity (Fig. 1b), large surface area, and tunable surface chemistry, making it a sustainable and cost-effective alternative to conventional filtration media like activated carbon [7]. Due to man's daily activities, there are emerging contaminants affecting water quality. Biochar has found application in emerging contaminants removal, drinking and wastewater treatment, and urban storm water management.

2.4.1. Biochar for emerging contaminants removal

The emerging contaminants (ECs), including pharmaceuticals, pesticides, and endocrine-disrupting compounds, are on the increase due to improper disposal of wastes containing these contaminants, posing serious environmental and public health threats [126]. Traditional treatment methods often fail to remove these trace pollutants efficiently. Biochar has shown effectiveness, especially when modified or functionalized to enhance its properties. Cheng et al. [127] utilized modified biochar for chemical, physical, or biological treatments; the result showed significantly higher adsorption capacities for ECs than pristine biochar. For example, biochar activated with water treatment residuals like iron-rich biosolids has been used to enhance the adsorption of persistent pollutants such as perfluorooctanesulfonic acid (PFOS), reaching removal efficiencies of up to 87.9 % [128]. Functionalized biochar clay composites significantly enhances pollutant-removal. For instance, a functionalized algal biochar–clay composite (FBKC) demonstrated approximately 30-fold increase in surface area compared to its precursors, and achieved maximum sorption capacities of 192.8 mg/g for the antibiotic norfloxacin and 281.2 mg/g for the dye crystal violet [129]. Mechanistic studies suggested that the enhanced removal resulted from multiple synergetic interactions involving π–π stacking, hydrogen bonding, electrostatic attraction, and pore-filling rather than simple adsorption alone. These results indicate that composite materials combining biochar with clay represent a powerful, low-cost, and scalable strategy for removing persistent aquatic pollutants.

2.4.2. Biochar in drinking water and wastewater treatment

Biochar-based systems are currently being explored as cost effective alternatives for clean water provision, especially in rural communities where resources are limited. Unlike conventional methods that primarily remove pathogens, biochar can remove a variety of contaminants, ranging from heavy metals, organics, to microbes, while preserving the taste and safety of water [130]. Fig. 6 illustrates the multi-mechanical nature of contaminants removal by biochar. The contaminated water (top box) with heavy metals (say Zn^{2+}) and organic pollutants (depicted with aromatic ring with –OH and = O attached) flows to the biochar surface (bottom box), where different mechanisms of interactions (a to d) takes place, and which also is the binding and replacement sites (K^+ replaces the Zn^{2+} in the water). Key operational parameters include specific surface area (m^2/g), point of zero charge ($pH_{p}zc$), contact time, and influent concentrations. Limitations to consider include variable removal efficiency across pollutants, potential leaching of trace contaminants from poorly produced biochar, and mechanical disintegration under hydraulic shear. Therefore, pilot designs should utilize pre-screened biochar, incorporate column tests, and assess regeneration and life-cycle aspects [53].

2.4.3. Urban storm water management

In urban environments, storm water runoff gathers all manner of contaminants, emptying them into water bodies; thus polluting ground and surface water [131]. Biochar has been integrated into geostructures and storm water channeled through them for filtration (Fig. 7). This has been shown to remove heavy metals and organic pollutants effectively, preventing them from contaminating water bodies, hence very good for maintaining the aquatic ecosystem [31]. Rizzo [132] demonstrated that passing stormwater runoff through biochar improved their quality; however, the biomass used to create biochar has an effect on its performance.

2.4.4. Biochar-assisted anaerobic digestion as a dual-valorization route

Biochar-assisted anaerobic digestion is another emerging field demonstrating dual benefits: enhanced removal of antibiotics such as tetracycline and improved biomethane yields through microbial stimulation and electron transfer pathways. A recent study by El-Qelish et al. [133] demonstrated that biochar can improve both pollutant removal and biogas production when used in anaerobic digestion (AD) systems, enabling a dual-valorization of waste streams. For example, a composite derived from coastal biowaste (biochar + $CaCO_3$) achieved a tetracycline sorption capacity of 342.3 mg/g, and when added to AD, increased methane yield: in a dual-substrate reactor (glucose + tetracycline), methane production rose from 94.5 to 153.0 mL CH_4 per batch. Similarly, in AD of waste-activated sludge, biochar supplementation improved methane yield by approximately 22.1 %, while stimulating electro-active microbial communities and enhancing electron transfer

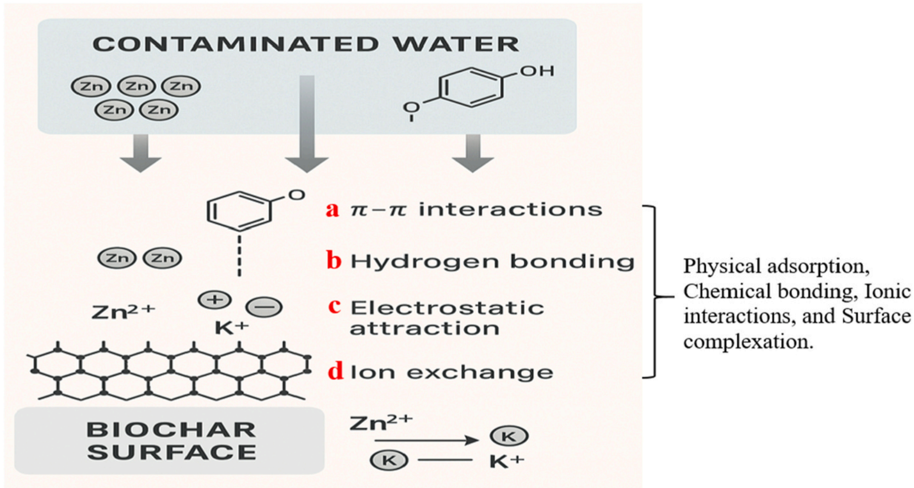

Fig. 6. multi-mechanistic nature of contaminant removal by biochar.

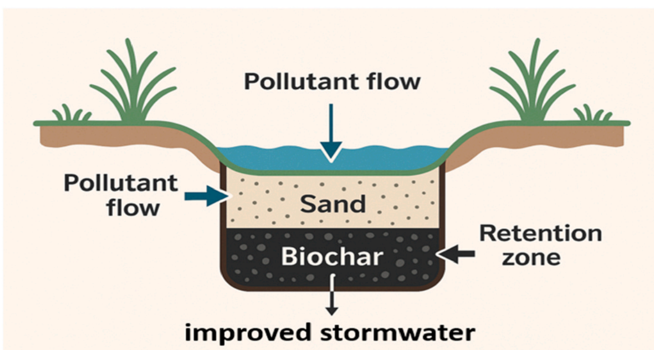

Fig. 7. Biochar geostructure for storm water filtration.

mechanisms thought to underpin improved digestion performance [134]. These findings indicate that biochar-AD systems can offer both wastewater (or waste-pollutant) remediation and renewable energy generation is a promising complement to adsorption-based treatment or construction-material applications. Given the rapid growth of this research area, we recommend including biochar-assisted AD among the key future directions for waste-to-resource conversion.

3. Challenges and future directions

Despite these promising advancements, challenges such as scalability for large-scale installations require significant amounts of biochar, which may strain production capacities, and the regeneration of spent biochar. While invasive alien plants can combat issues of large-scaling, caution is needed for harvesting and use of these species to avoid their further spread and human health risks associated with them. Similarly, the biochar properties are largely dependent on the composition of the biomass. Biomass profiling and library are thus desirable for informed decision-making during biochar preparation. Pristine biochar has a finite adsorption capacity and thus requires enhancement through chemical, thermal, or biological methods, which can be energy-intensive and expensive. Variability in feedstock performance, such as source and pyrolysis conditions during production, is responsible for the ubiquitous properties of biochar. Prior determination of the choice biomass might not be feasible until preparation and characterization. This poses a significant challenge. There are also concerns about planetary safety and conservation that might result from deforestation arising from unmonitored biomass harvest. The use of machine learning (ML) and artificial intelligence (AI) in biochar research might help to optimize design and application strategies. These approaches assist in predicting adsorption capacities utilizing feedstock properties, production parameters, and contaminant characteristics, enabling a more efficient pathway to functionalize or customize biochar for specific applications.

4. Conclusion

Biochar research has progressed from proof-of-concept studies to specific applications with demonstrable environmental and engineering benefits, although key challenges remain for large-scale implementation. Major takeaways highlighted in this study include;

- **Agricultural systems:** Biochar improves soil physical structure, nutrient retention, and microbial stability, with expanding applications in odor suppression and manure management that directly support sustainable livestock and crop production.
- **Construction materials:** Incorporation of biochar enhances mechanical strength and thermal performance in cementitious and asphalt-based materials; however, long-term durability and leachability remain critical research gaps for safe and reliable deployment.
- **Water and pharmaceutical remediation:** Functionalized and composite biochars, including biochar–clay systems, demonstrate high adsorption efficiencies for complex organic contaminants, positioning them as advanced materials for water and pharmaceutical pollution control.
- **Pathway to implementation:** Progress toward large-scale adoption requires standardized testing protocols, comprehensive techno-economic and life-cycle assessments, and enabling policy frameworks that support certification, sustainable feedstock sourcing, and commercial scale-up.

The future of biochar research is filled with potential, yet it faces some challenges. One significant area for progress is the development of regulatory frameworks and standards. Market potential and economic viability are also critical for the widespread adoption of biochar. Research is needed to explore cost-effective production methods and potential market incentives for farmers and businesses to adopt biochar. Future studies should focus on the long-term effects of biochar in various soil types and climates, as well as its interactions with different agricultural practices. These insights will enhance our understanding of how best to utilize biochar effectively.

CRediT authorship contribution statement

Kennedy I. Ogunwa: Writing – original draft, Visualization, Conceptualization. **Ebenezer C. Nnadozie:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Conceptualization. **Nontembeko Dube:** Writing – original draft, Visualization, Conceptualization. **Peter Olusakin Oladoye:** Writing – review & editing. **Kehinde Shola Obayomi:** Writing – review & editing, Project administration.

Some Abbreviations that are not described in the text

SOD	superoxide dismutase
POD	peroxidase
CAT	*catalase*
VEGF	Vascular endothelial growth factor
GCF	gingival crevicular fluid
IAPs	Invasive Alien Plants
W	Watt

Data availability

No data was used for the research described in the article.

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