Biochar

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Expanding the frontiers of nanobiochar and biochar nanocomposites as versatile biomaterials for sustainable development

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Abstract

Mounting global crisis including environmental degradation, resource depletion, and health threats, necessitates the exploration of various transformative, novel, and multifunctional materials with practical applications. Nanobiochar, a nanoscale biochar produced through pyrolysis and post-pyrolysis modifications, has emerged as a versatile and sustainable carbon-based nanomaterial with numerous applications. Biochar nanocomposites, engineered hybrid materials developed from biochar and nanomaterials, have further amplified the applications of biochar. Although the environmental applications of nanobiochar and biochar nanocomposites have been extensively studied, their potential applications in other critical sectors are less explored and not well understood. This review explores the potential applications of nanobiochar and biochar nanocomposites in the medical, energy, construction, polymer, and agriculture sectors. The unique properties of nanobiochar and biochar nanocomposites make them a promising candidate for healthcare applications, aligned with the One Health approach. In times of resource depletion and climate change, such composite materials show promise as a valuable resource for alternative energy storage solutions, sustainable construction, and climate-smart agriculture. However, further research is needed on the biocompatibility and extended ecotoxicity of these hybrid materials. The integration of nanobiochar and biochar nanocomposites in various domains and broadening their scope of application into underexplored sectors will address knowledge gaps and expand the use of emerging technologies for a sustainable and low-carbon future. This review underscores the need for more interdisciplinary research to fully leverage the potential of these composite resources and facilitate the transition to a more resilient and resource-efficient future.

Highlights

- Biochar-based nanomaterials are multifunctional and critical to support sustainable growth and development
- Nanobiochar has great potential in climate-smart construction and agriculture
- Biochar nanocomposites for targeted drug delivery and biosensors are promising applications for One Health
- The environmental safety and biocompatibility of biochar nanomaterials should be further studied

Keywords Battery, Construction, Drug delivery, Energy storage, Sustainable architecture, Supercapacitors, Nanomaterials

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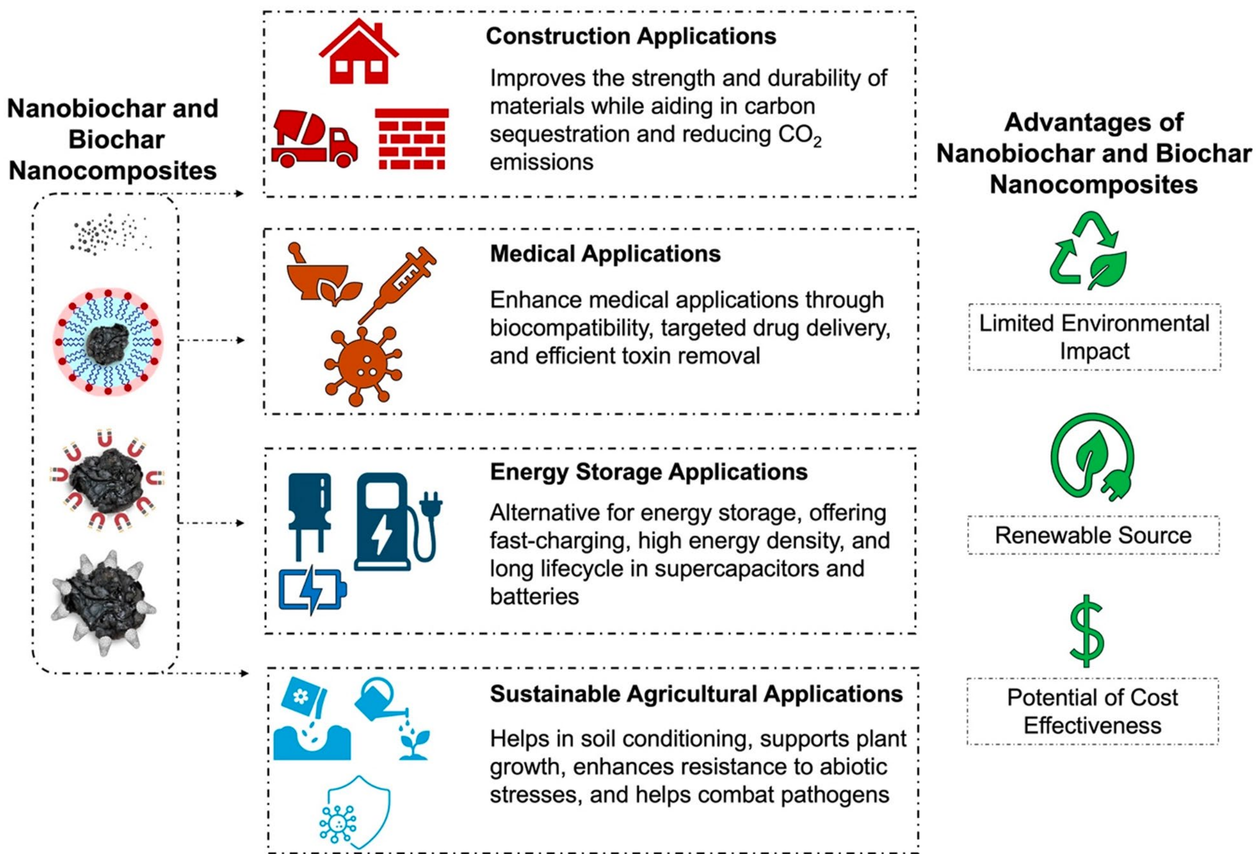
Graphical Abstract



1 Introduction

Biochar is a carbon-rich solid material produced from various types of biomass through a thermochemical carbonization process (Neves et al. 2011). Agricultural waste such as sugar cane bagasse, rice husk, peanut shell, rice straw, oil cake, soybean stover, and garden waste, as well as forest litter have been widely used for producing biochar, primarily because of their availability, low cost, and high hemicellulose, cellulose, and lignin content (Oleszczuk et al. 2016). Biochar can be produced through various thermochemical methods, including pyrolysis, gasification, torrefaction, and hydrothermal carbonization. However, slow pyrolysis is the most commonly and widely used method for biochar production (Amalina et al. 2022). During pyrolysis, the hemicellulose component of the feedstock breaks down and is converted into gas and vapor, which increases the porosity of the biochar. Similarly, the breakdown of cellulose equips biochar with various surface functional groups. Lignin is relatively difficult to break down, but it contributes primarily to the stability and structural integrity of the biochar. Hence, the composition of biomass plays a critical role in determining the properties of the resulting biochar and its subsequent applications. Biochar production and application in soil has emerged as a scalable and effective carbon capture technology for managing various types of lignocellulosic waste and organic biomass, as well as for reducing greenhouse gas emissions (Luo et al. 2023a). Due to their unique attributes and diverse application potential, biochar has been recognized as a promising material for combating climate change and addressing multiple United Nations Sustainable Development Goals (SDGs), particularly SDGs 7, 8, 11, and 13. The impact of biochar application on SDGs stems from its potential for land reclamation, mitigation of soil pollution, soil carbon storage, energy storage, sustainable waste management, and entrepreneurship development (Mazarji et al. 2021; Mishra & Mohanty 2023; Sivaranjanee et al. 2023).

The diverse applications of biochar are attributed to its versatile surface properties, varied porosity, and high cation exchange capacity. Biochar has diverse oxygen-containing functional groups, including carboxyl (-COOH), hydroxyl (-OH), carbonyl (-C=O), and phenolic (-OH) groups, which influence biochar's chemical reactivity and wettability. The highly porous structure of biochar is characterized by the presence of mesopores (pore diameter 2–50 nm) and micropores (pore diameter less than 2 nm). These pores and diverse surface functional groups impart unique physicochemical properties to the biochar. Bulk biochars (0.04–20 mm) are normally suited for agricultural and environmental applications. Reducing biochar size to the nanoscale (100 nm and below) yields nanobiochar, characterized by higher surface energy, a greater abundance of functional groups, and enhanced thermal stability (Naghdi et al. 2017; Sharma et al. 2021; Chaubey et al. 2024). Decreasing the biochar particle size increases its surface-to-volume ratio and the abundance of functional groups per unit mass. The increased surface area and functional groups in nanobiochar enhance its adsorption potential relative to the parent bulk biochar, enhancing its functionality. Therefore, nanobiochar is increasingly gaining the interest of various researchers and practitioners, particularly for environmental remediation (Elbehiry et al. 2022).

Incorporation of other potential organic or inorganic materials with nanobiochar results in the formation of composites that are referred to as biochar nanocomposites. These fortified carbon materials possess added features and attributes that broaden their potential applications, primarily as adsorbents and energy storage materials (Noreen & Abd-Elsalam 2021). Nanocomposites have a smaller hydrodynamic radius, a higher negative zeta potential, and a greater abundance of oxygen-containing functional groups, which can lead to the formation of carbon defects (Oleszczuk et al. 2016). These properties enable them to produce reactive organic species, such as free radicals and phenolics, resulting in enhanced reactivity and performance relative to bulk biochar. Most biochar nanocomposites are chemically active due to the carbon defects within their structure, which have a topological or edge effect, enhancing their reactivity and impacting the physicochemical properties of the material. These defects reduce the formation energy and accelerate electron transfer by filling the material's edges with large quantities of unpaired π electrons (Greco et al. 2019). These features enable the nanocomposites to act as key catalysts in the oxygen reduction process. Biochar and its nanocomposites have emerged as a new-age carbon material with diverse functions. Large surface area, low production cost, abundant availability of raw materials, high microporosity, and outstanding sorption capacities enable nanobiochar and biochar nanocomposites to be used for adsorbing a wide variety of contaminants.

The use of biochar nanocomposites for the adsorption and removal of environmental pollutants from soil and wastewater is one of the most widely studied applications (Hosney et al. 2022; Burbano et al. 2023; Luo et al. 2023b). A chitosan-coated biochar-nanosilver (C–Ag) antibacterial composite, for example, was developed through high-temperature carbonization (Hu et al. 2019). The coating of chitosan and integration with silver nanoparticles enhanced the antimicrobial activity of the biochar nanocomposite, establishing its potential for use in wastewater treatment systems. In another study, Ag nanoparticle-tagged biochar-sodium alginate beads showed a strong inhibitory effect on both Gram-positive and Gram-negative bacteria, including *Escherichia coli*, *Pseudomonas aeruginosa*, and *Staphylococcus aureus*. These beads emerged as promising candidates for use in wastewater treatment plants (Xie et al. 2023). Various other biochar-derived nanocomposites are being explored for their antimicrobial properties, underscoring their promising applications in wastewater treatment systems (Ates et al. 2024; Lopresti et al. 2024; Min et al. 2025). In contrast to laccase alone, the laccase enzyme-incorporated chitosan-nanobiochar was more effective against both Gram-positive and Gram-negative bacteria (Naghdi et al. 2019). Biochar-based nanomaterials also play a crucial role in capturing environmental carbon. Improved surface area and pore structure, along with enhanced functional chemistry, enable biochar nanocomposites and nanobiochar to capture CO_2 effectively (Wang et al. 2024a). These materials, engineered from waste biomass, are altered through activation and nitrogen doping to incorporate reactive nitrogen groups and increase microporosity, thereby enhancing CO_2 physisorption and chemisorption (Wang et al. 2024b).

In the last several years, research on nanobiochar and biochar nanocomposites has witnessed heightened global activity. A significant amount of contributions has came from countries such as China, India, and the United States, as evidenced by their extensive collaborative networks and high total link strength in our recent VOSviewer analysis (Fig. 1).

In recent years (2021–2023), China and India have shown a significant increase in publication output and research connectivity. This underscores growing international collaborations and a shift towards these regions as key hubs for advancing the synthesis, application, and environmental impact of nanobiochar and biochar nanocomposites. There have been multiple recent review articles on the applications of biochar nanocomposites for pollutant remediation (Amusat et al. 2021; Chausali et al.

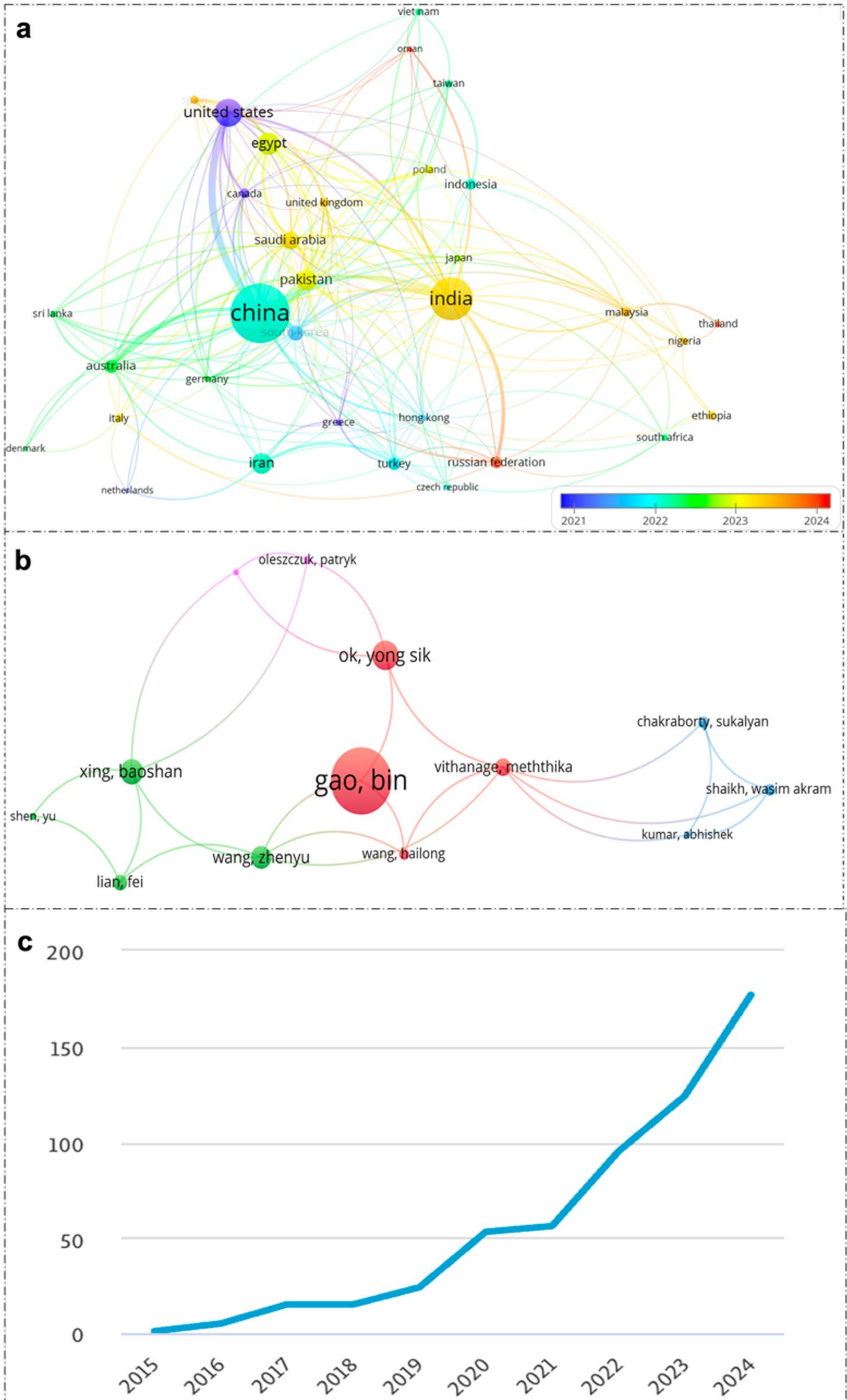


Fig. 1 **a** Network visualization of collaborations in nanobiochar and biochar nanocomposite research across countries; **b** Co-authorship network of key researchers in the field, both generated using VOSviewer software based on the Scopus database; **c** Annual publication trends (2015–2024) in nanobiochar and biochar nanocomposite research, obtained from the results analysis section of Scopus query search

2021; Mazarji et al. 2023; Chaubey et al. 2024). There are multiple reports on the use of nanobiochar and biochar nanocomposites in biosensors for detecting pollutants (Dong et al. 2018; Liu et al. 2021a, b). However, there is a paucity of literature on different types of nanobiochar and biochar nanocomposites, as well as their application potential in various other promising, yet unexplored, sectors that are equally vital to achieving sustainable development goals, promoting resource conservation, and attaining One Health objectives.

This paper provides an extensive review of the applications of nanobiochar and biochar nanocomposites, with a specific focus on unconventional and lesser-explored application potentials in the fields of energy storage, industrial additives, construction, and healthcare. The use of nanobiochar and biochar nanocomposites can promote a circular economy and accelerate sustainability efforts, making them invaluable tools for addressing climate change and resource scarcity. A detailed analysis of new, underexplored applications will open doors for enhancing the commercial viability of biochar-based materials in various sectors and easing their adoption in new markets and industries.

2 Production of nanobiochar

Nanobiochar, with enhanced structural and functional features as compared to biochar, expands the applications of biochar and thus holds promise for significantly improving the economic potential of the biochar. Multiple centrifugation processes are easy to adopt and are therefore widely employed as a simple strategy for nanobiochar production. Differences in the intrinsic properties of various biochars, including the size, density, and shape, cause varied sedimentation velocities, allowing the sedimentation of nano-sized biochar particles upon multiple rounds of centrifugation (Xu and Colfen 2021). There are various top-down techniques, including ball milling, sonication, and acid digestion, as well as more sophisticated bottom-up approaches such as hydrothermal synthesis and microwave pyrolysis, that have shown promising results (Genovese et al. 2015; Pathak et al. 2024).

The various prominent methods for nanobiochar production are presented in Fig. 2.

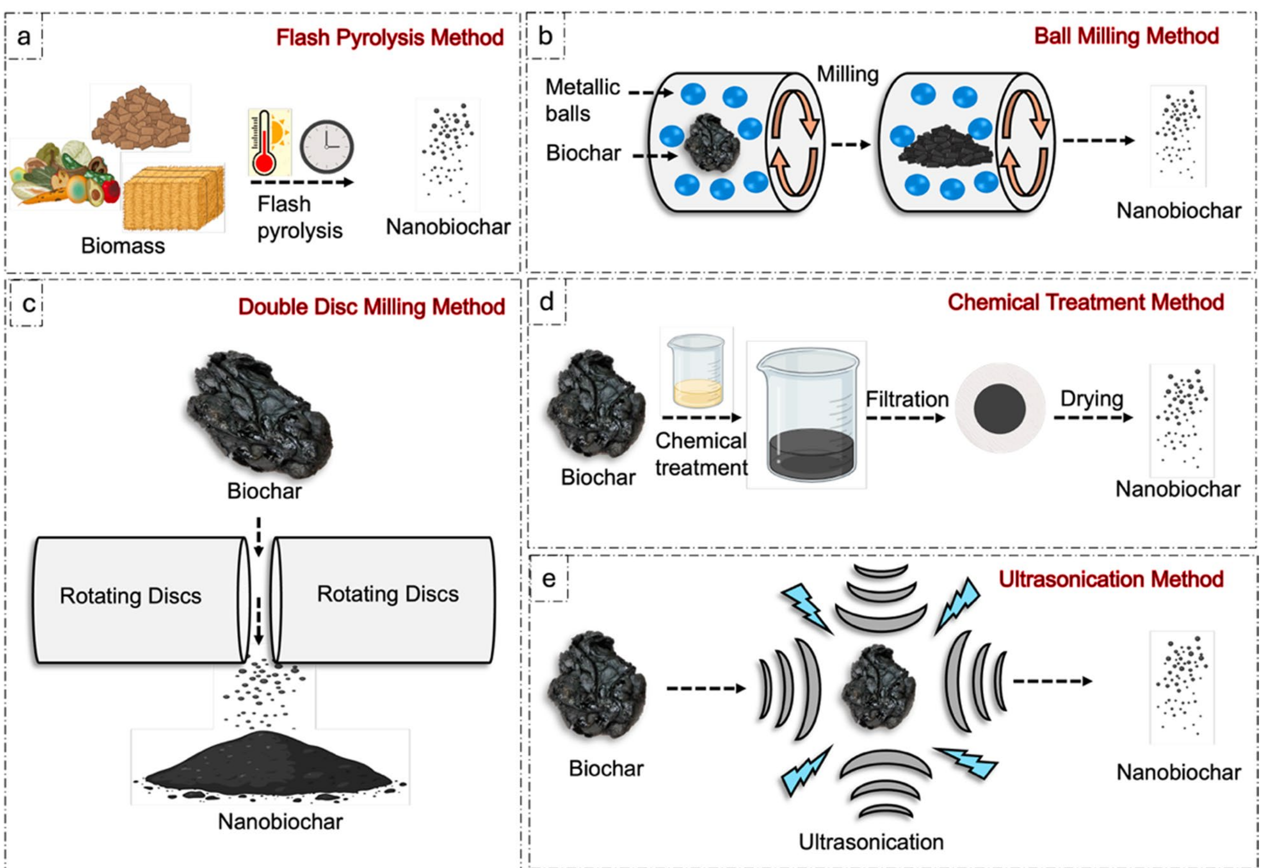


Fig. 2 Various methods of producing nanobiochar: **a** flash pyrolysis; **b** ball milling; **c** double disc milling; **d** chemical treatment; **e** ultrasonication

2.1 Ball milling

Ball milling can be used to mechanically reduce the biochar particle size to the nanoscale. The ball milling method has been widely studied due to its low cost and low energy requirements for producing nanobiochar on a large scale (Li et al. 2017a). The movement and collision of the milling medium and biochar, facilitated by milling balls, generate kinetic energy that causes charge transfers and the rupture of chemical bonds. Ball milling conditions, including the balls-to-biochar ratio, milling speed, milling duration, and ball diameter or weight, are crucial in producing biochar of a desirable nanoscale size (Shah et al. 2015). Rotation speeds of 300–600 rpm and processing times ranging from 1.6 to 12 h have been most successful (Chaubey et al. 2024). Although wet milling has shown promise in increasing the dispersion of small particles and surface functional groups, dry milling is preferred, especially for materials that are difficult to filter. Both processes yield nanobiochar with distinct structural properties (Yuan et al. 2020). Enhanced adsorption capacities for pollutants and various dyes have been reported for nanobiochars produced through ball milling (Lyu et al. 2018; Qin et al. 2020). A variety of biomass types, including agrowastes such as bamboo residue, coconut shell, corn straw, pine wood, sugarcane bagasse, wood sawdust, and wheat straw, have been converted to biochar and ball-milled to produce nanobiochar (Chaubey et al. 2024).

2.2 Sonication

Ultrasound irradiation on biochar unclogs pores and exfoliates fine particles, leading to the production of nanobiochar. High-frequency ultrasound waves (20 kHz–1 MHz) induce acoustic cavitation, resulting in the disintegration of large biochar aggregates into nanoscale particles (Fan et al. 2016). After repeated sonication cycles, larger particles remaining in the suspension can be removed by gravity settling, filtration, or centrifugation to obtain a supernatant containing biochar nanoparticles, also known as nanobiochar, with an enhanced carbon structure exfoliation, increased microporosity, and a larger microporous area. Exfoliation also exposes mineral matter at the biochar surface, leading to improved sorption efficacy. Sonication also leads to modification of surface properties, resulting in defects and increased functionalization. However, sonication time, temperature, and power all play a crucial role in determining the yield and properties of the nanobiochar produced (Oleszczuk et al. 2016).

2.3 Hydrothermal digestion

Acid treatment of biochar, followed by hydrothermal digestion, causes oxidative hydrolysis and typically yields small-sized biochar, including nanobiochar and biochar nanodots, with sizes as small as 3–6 nm (Chaubey et al. 2024). Digestion of biochar with strong acids, such as sulfuric and nitric acid, under high pressure, followed by filtration through a 0.22 µm membrane, also resulted in the production of biochar nanodots with a size of 4–5 nm (Guo et al. 2020). The yield of nanobiochar obtained through hydrothermal digestion was reported to be 10 times higher, with a more uniform particle size, a higher surface area, and a greater number of functional groups, compared to sonication or centrifugation. Modulation of duration, temperature, and the strength of acids used for hydrothermal digestion causes variations in the shape and size of the nanobiochar obtained. The potential to yield uniform-sized nanobiochar makes this process attractive. However, dependency on high pressure and long processing time remains a challenge.

2.4 Other promising methods

Other methods for producing nanobiochar, such as thermal flash pyrolysis and microwave pyrolysis, are increasingly favored due to their capacity to streamline the production process and yield a more uniform product (Ramanayaka et al. 2020). When carbon undergoes oxidation and is subsequently subjected to high temperatures, it can generate nanosheets without requiring additional mechanical grinding (Genovese et al. 2015). Microwave pyrolysis involves the direct production of nanobiochar through the heating of biomass using a microwave absorber (Song et al. 2022). However, process parameters, including microwave frequency, temperature, and residence time, play a crucial role in nanobiochar production, and appropriate post-treatment, such as ball milling and ultrasonication, may be additionally required to ensure the formation of nanobiochar. Nevertheless, recent studies indicate an increasing preference for advanced methods such as thermal flash pyrolysis and microwave pyrolysis, as they can effectively produce nanobiochar in a reduced time.

2.5 Limitations and process determinants

The two main determinants of nanobiochar production efficiency are feedstock type and preparation methods. Similar to regular biochar production, the feedstock type plays a vital role in determining the properties of nanobiochar. Agricultural residues contain a high composition of hemicellulose, whereas lignin is dominant in woody biomass. Due to the increased grindability of biomass with a high hemicellulose content relative to biomass with a high lignin content, ball milling is a more suitable option for producing nanobiochar from agricultural wastes (Agar and Wihersaari 2012; Ramanayaka et al. 2020). Biochar produced from algae and manure, on the other hand, yields a finer biochar with more nanoscale properties. The type of feedstock also determines the shape and size of the ball used for nanobiochar production. Softer biomass, such as pinewood, requires less impact force, making lighter stainless steel balls (30–45 g) sufficient for milling. Harder biomass, such as bamboo and hickory wood, requires heavier agate balls (180 g) to generate enough force for effective milling. In addition, biochar produced at a lower temperature range (300–400 °C) exhibits greater grindability and a broader particle-size distribution.

Ball milling offers advantages over conventional grinding and disc milling, as ball milling is faster and more efficient. Additionally, the particles formed after ball milling are smaller and more uniform. Therefore ball milling is one of the most widely adopted techniques for nanobiochar production. Although simple and effective, aggregation of particles and uneven particle size, relative to other advanced processes, is still often observed in ball milling (Dutta and Bhattacharya 2020). While ball milling is simple and less resource-intensive, post-treatment is compulsory to obtain the desired nanobiochar size. Nanobiochar produced by microwave pyrolysis will also require an additional ball milling step to ensure the production of appropriately sized nanobiochar. A comparative study of different processes confirmed the effect of production process on the structural properties of resultant nanobiochar (Behnam and Ferouzi 2023). While centrifugation yielded nanobiochar with varying particle sizes, sonicated and acid-treated biochar samples gave particles with sizes of 92–173 nm and 90–153 nm, respectively (Chaubey et al. 2024). Although sonication for nanobiochar formation is simple, eco-friendly, and effective, it is energy-intensive, can generate heat during prolonged processes, and may affect the nanobiochar structure and morphology, leading to structural degradation. Nanobiochar produced from sonication or centrifugation had the lowest surface area (19.1–34.3 $m^2\ g^{-1}$), while those made from hydrothermal methods had the highest surface area (51.2–167.7 $m^2\ g^{-1}$). Thermal flash heating and hydrothermal carbonization are energy-intensive but yield nanobiochar of nearly uniform size (Chaubey et al. 2024). Hence, hydrothermal methods have emerged as the most superior among the commonly used processes for nanobiochar production.

3 Biochar nanocomposites

Biochar nanocomposites are a type of engineered biochar formed by integrating biochar with various functional materials, such as magnetic or non-magnetic nanoparticles or nanostructures, metal oxides, and carbon-based nanomaterials (Ramadam and Abd-Elsalam 2020). Nanocomposites combine the properties of biochar and other nanomaterials for a wider array of applications with enhanced performance. Based on the type of nanomaterials used in the synthesis process, biochar nanocomposites can be categorized into metal oxide/hydroxide nanocomposites, functional nanoparticle-coated hybrid nanobiochar, and magnetic biochar nanocomposites (Fig. 3).

Metal oxides/hydroxides are a common class of biochar nanocomposites produced by either pyrolysis of biomass with bioaccumulated metals, pyrolysis of biomass pre-treated with nanometal salts, or post-treatment of biochar with nanometals. Some of the commonly used metal oxides for production are titanium dioxide (TiO_2), zinc oxide (ZnO), silver (Ag), and gold (Au). Aluminium hydroxide ($Al(OH)_3$) and iron oxide ($Fe(OH)_3$) are commonly used hydroxides for the production of these hybrid materials (Tan et al. 2016; Wei et al. 2020). Coating biochar with nanomaterials, such as carbon nanotubes, graphene, graphene oxide, nanoclays, chitosan, zinc sulfide (ZnS) nanocrystals, and layered double hydroxides, yields functional nanoparticle-coated biochar, a new class of biochar nanocomposites (Chausali et al. 2021). These nanoparticles can be incorporated onto the biochar surface either pre- or post-pyrolysis, with the post-pyrolysis method being most commonly employed. The third category of nanocomposites is magnetic biochar nanocomposites. This category of nanocomposites was introduced to address the challenges of separating fine suspended particles and pollutants in water, which are often difficult to remove through simple filtration. Modifications during pre-pyrolysis or post-pyrolysis can be introduced to produce magnetic nanocomposites. Some of the commonly used chemicals for coating the biochar surface include cobalt ferrite ($CoFe_2O_4$), ferric oxide (Fe_3O_4), ferrous oxide (Fe_2O_3), and nickel chloride (Reddy et al. 2014; Baig et al. 2014; Yao et al. 2020). Magnetic nanocomposites offer the added advantage of recyclability for multiple adsorption cycles, thereby promoting sustainability in the remediation process, and making them one of the most preferred nanomaterials for use in environmental and catalysis sectors.

Due to the synergistic interactions between biochar and nanomaterials, novel functional materials with improved properties and greater stability than either biochar or nanomaterials alone are created when biochar nanocomposites are produced (Tan et al. 2016). The association of biochar with metals and other nanomaterials alters the surface properties of carbon composites, imparting new properties to the material developed (Zhang et al. 2012; Yan et al. 2015). Hence, biochar nanocomposites exhibit enhanced properties, including higher catalytic activity, improved electrical conductivity, greater adsorbent capacity, and increased antimicrobial activity. This work

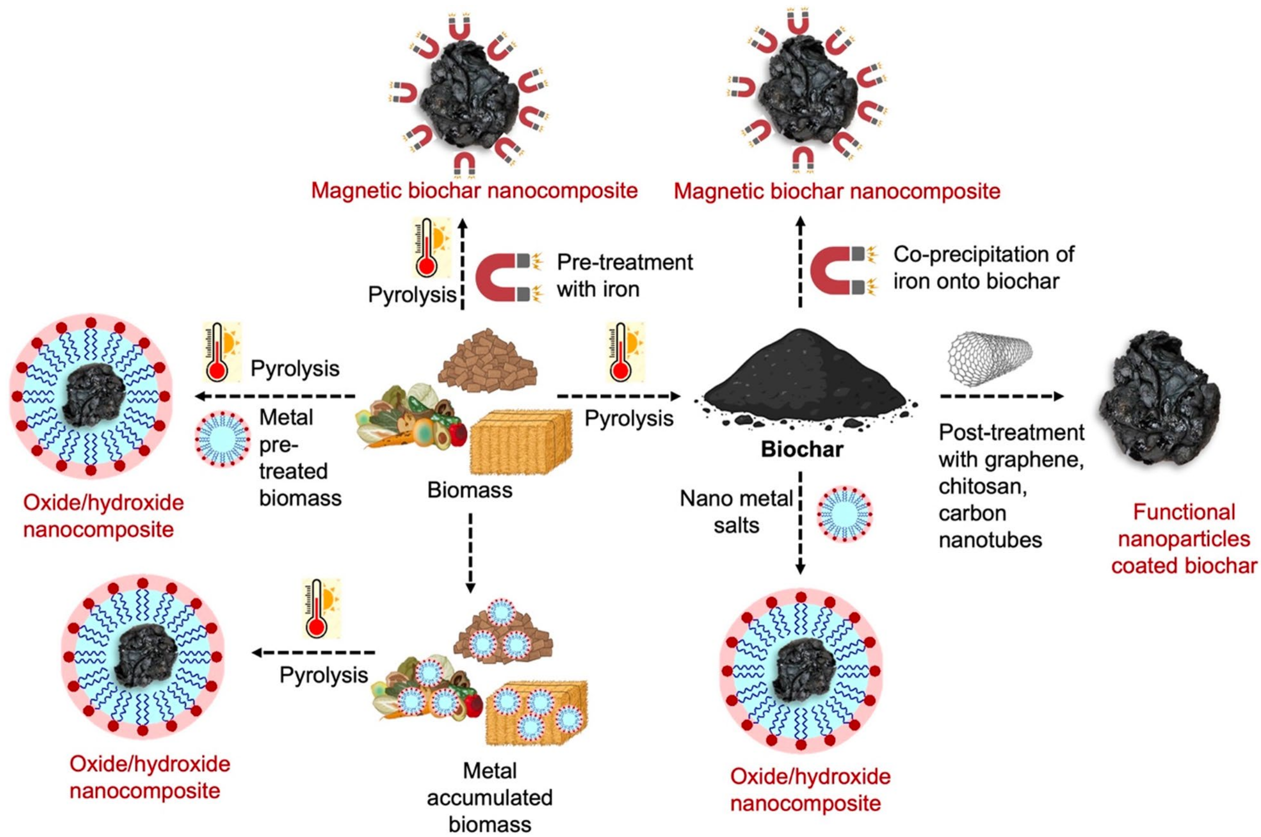


Fig. 3 Overview of various biochar nanocomposite production methods and processes

discusses several lesser-explored, yet promising, applications of nanobiochar and biochar nanocomposites.

4 Nanobiochar and biochar nanocomposites for healthcare applications

The use of activated carbon in medicine for toxin removal and decontamination of poison or drug overdoses has a long history, and is one potential area in which biochar composites can replace traditional activated carbon in the medical field (Jandosov et al. 2022). Production of toxins, such as deoxynivalenol, by many species of *Fusarium* in stored grains has cytotoxic and genotoxic effects on humans and poultry. Normalization of biochemical parameters, reduction in cytotoxicity of the bone marrow, and alleviation of hepatic genotoxicity were observed in the co-treatment of deoxynivalenol and activated carbon (Abdel-Wahhab et al. 2015). Biochar nanocomposites with additional nutritive fortifications can be effective substitutes for activated carbon in preventing and reducing this toxicity, thereby making them a promising strategy for removing fungal toxins in poultry feed. With natural raw materials as primary sources, biochar nanocomposites exhibit promising biocompatibility potential for various biological tissues, including those of humans and animals. The tunable nature of nanobiochar and biochar nanocomposites makes it easier to introduce features such as hydrophilicity, specific markers to target specific cells, or specific functionalizations to make them target specific. Thus, biochar nanocomposites are being actively pursued for use in the biomedical sector, including applications such as antimicrobial therapy, wound healing, drug delivery, anticancer therapy, and diagnostics.

4.1 Antimicrobial therapy

With increasing antimicrobial resistance in microbial populations and the widespread occurrence of multidrug-resistant microbial strains, there is a pressing need to develop new-age antimicrobials with novel structures and unique mechanisms of action. This is especially critical as the medical community faces growing threats from antimicrobial-resistant superbugs (Algammal et al. 2023). The use of biochar nanocomposites for therapeutic applications holds considerable promise. Free radical-mediated inhibition of antimicrobial genes was observed in aqueous environments using nanobiochar. This highlights the potential of nanobiochar for antimicrobial therapy and in combating the spread of antimicrobial resistance (Lian et al. 2020). Nanoparticles exhibit effective antimicrobial activity against both Gram-positive and Gram-negative bacteria and are being proposed, among other applications, for use in wastewater treatment technology. This will help limit the spread of waste-associated microbial populations, including those of antibiotic-resistant microorganisms that are difficult to address (Zeng et al. 2019; Hosny et al. 2022). The presence of biochar enhances the efficacy of the composite material; hence, nanoparticle biochar nanocomposites, due to their unique structures and numerous functional groups, have emerged as a new-generation antimicrobial agent (Xie et al. 2023).

The use of silver (Ag) nanoparticle-tagged nanobiochar is especially promising. The effective antibacterial activity of the Ag–Cu-biochar composite was observed against the Gram-negative bacteria *Escherichia coli* and *Klebsiella pneumoniae*. This composite, synthesized from *Atriplex halimus* extract and biomass, with silver and copper nanoparticles attached to the biochar surface, exhibited both antimicrobial and antioxidant activity (Hosny et al. 2022). *Chenopodium ambrosioides* leaf extract and biomass were used for the synthesis of a silver biochar composite that exhibited broad-spectrum antibacterial activity against *Pseudomonas aeruginosa, Klebsiella pneumoniae, Bacillus subtilis,* and *Candida albicans* (Eltaweil et al. 2022). Proximity and association with biochar increased the efficacy of nanoparticles against pathogenic bacteria, as seen with Ag-nanoparticle-tagged biochar against both Gram-negative and Gram-positive bacteria (Alqaraleh et al. 2023) and Cu_2O nanoparticle-tagged biochar prepared from distillery grains against *Escherichia coli* (Yang et al. 2019).

The 3-dimensional porous structure, enriched with numerous functional groups, enables the design of diverse materials with high adsorptive properties, including the ability to carry antimicrobial peptides. In one study, antimicrobial peptide-attached nanocomposites were designed using human defensins and cathelicidin, along with acid-modified biochar (Gao et al. 2020). The presence of antimicrobial proteins with differing modes of action broadened the action spectrum, making it effective against both Gram-negative and Gram-positive superbugs. Carbodiimide coupling chemistry was used to couple carboxyl (-COOH)-functionalized activated biochar with an amine (-NH_2)- rich protein host defense antimicrobial agent. The capture of bacteria by the nanobiochar, followed by the binding of defensins to the bacterial surface, resulted in cell membrane stress and eventually led to cell death. This antimicrobial nanocomposite effectively filtered drug-resistant bacteria from water samples, demonstrating its potential for application in the medical field and in wastewater treatment systems. In another study, melittin (an antimicrobial peptide) attached to multifunctional biochar inhibited to multidrug-resistant *Staphylococcus aureus* by forming pores on the microbial cell membrane (Gao et al. 2017).

The overall specific mechanism of nanoparticle-tagged nanocomposites' antibacterial action is poorly understood. However, the few mechanisms that have been proposed include cell death due to the disruption of cell membrane proteins, nutrient uptake imbalance, and oxidative stress resulting from the generation of reactive oxygen species (Min et al. 2025). Disruption of the fungal cell wall, DNA fragmentation, nuclear condensation during cell death, and inhibition of the respiratory chain are among the other mechanisms proposed for the antifungal activity of nanoparticles and nanoparticle-tagged nanobiochar, leading to fungal cell apoptosis (Eltaweil et al. 2022). The antibacterial properties of nanocomposites can emerge when biochar is utilized as an adsorbent for removing metals from aqueous solutions and wastewater. The coupling of metals on the biochar surface imparts antimicrobial properties to the composite. Zerovalent iron (ZVI) loaded biochar was used for the sorption of silver from an aqueous solution. The resultant silver-sorbed ZVI-biochar nanocomposite exhibited new properties and effective antibacterial activity against *Escherichia coli*. The outcome established a new antibacterial material and underscored the concept of waste valorization and sustainable research goals (Zhou et al. 2014). This process offers a dual advantage, wherein the nanobiochar not only removes heavy metals from the solution through adsorption but also transforms into a new nanocomposite with enhanced functionalities, thereby ensuring circularity in the process. Considering the increasing antimicrobial resistance in pathogenic microorganisms and the emergence of new human pathogens, these antibacterial nanocomposites introduce a new dimension to antimicrobial therapies, successfully expanding the use of antimicrobials in other domains, such as wastewater treatment and drug delivery.

4.2 Biochar nanocomposites in regenerative medicine

Biochar nanocomposites have emerged as promising candidates for application in regenerative medicine. Various neurological lesions and disorders can be addressed by the transplantation of human embryonic stem cells encased in biomaterial scaffolds. Activated carbon-based biocomposites have been successful in supporting the attachment and differentiation of stem cells. The concentration of growth factors and cell adhesion proteins by carbon composites can further promote attachment and differentiation of human embryonic stem cells (Chen et al. 2012a). Novel and tissue-compatible three-dimensional bioscaffolds can be derived from biochar-based nanocomposites, which will aid in stem cell therapy and circumvent the often-observed nanotoxicity effects of activated carbon-based scaffolds on many healthy cell lines. These scaffolds provide structural support for cell growth and can be functionalized to facilitate the slow release of molecules, such as growth factors, thereby accelerating tissue proliferation and wound healing.

Similar applications of biochar nanocomposites can be found in wound dressings or as coatings in medical devices to prevent infections. Biochar alone does not possess any wound-healing properties. However, when combined with nanoparticles, it has been shown to be effective in the wound-healing process, with added antimicrobial properties. Silver nanoparticles (AgNP) derived from the fungus *Emericella dentata*, when applied in combination with date seed biochar, exhibited enhanced antibacterial efficacy against *Listeria monocytogenes*, *Staphylococcus epidermidis*, *Staphylococcus aureus*, *Escherichia coli*, and *Pseudomonas aeruginosa*. The combined material reduced the expression of anti-apoptotic genes and pro-inflammatory cytokines, thereby triggering apoptosis in lung cancer cells and demonstrating potential for anticancer treatment. Biochar has been proposed to play a role in AgNP adsorption and controlled release, thereby enhancing its selectivity for lung cells and reducing the release of AgNPs and associated toxicity (Abu-Hajleh et al. 2023). Biochar-incorporated hydrogels, enriched with nanoparticles such as Ag-NP, can also be used in dressings for wound healing. This will be especially beneficial for diabetic wound healing that is impaired and delayed due to microbial infections, impaired angiogenesis, and chronic inflammation (Wang et al. 2023). The network-like structure of hydrogel and biochar facilitates the translocation of Ag-NPs to the active site, supporting wound closure through a nano-bridge effect. Photo-responsive hydrogels are equally effective and advantageous for wound healing applications. An innovative nanocomposite comprising biochar embedded in an iodine-containing polyvinyl alcohol/polyvinyl pyrrolidone hydrogel was designed and studied for its antimicrobial action and wound-healing properties. In the presence of biochar, irradiation by visible light triggered the generation of reactive oxygen species from the hydrogel. Reactive oxygen species reacted with iodine under near-infrared light to form reactive iodine. The photothermal performance of biochar, coupled with the regulated release of reactive iodine from the hydrogel, inhibited ampicillin-resistant *Escherichia coli* and methicillin-resistant *Staphylococcus aureus*, exhibiting low toxicity towards mammalian cells. Along with bacterial infection resistance, epithelial regeneration was observed, leading to healthy wound healing facilitated by visible and near-infrared light irradiation (Borjihan et al. 2023). When incorporated with antimicrobial agents and/or biomaterials, the resultant biochar nanocomposite-based dressings exhibit a higher potential for bactericidal effect, biocompatibility, and non-cytotoxicity, as well as enhanced tissue growth, compared to commercial dressings (Balasubramanian and Selvam 2023). *N*-halamine hydrogel, developed from biochar derived from cow dung, exhibited antimicrobial activity and enhanced wound healing (Chu et al. 2024). The wound dressing thus developed not only resisted bacterial infection but also promoted epithelial regeneration and the healing process.

4.3 Drug delivery and anticancer therapy

Due to their small size and high surface-to-volume ratio, nanomaterials are being extensively explored for use in drug delivery, particularly for targeting cancer cells (Liu et al. 2021a, b). Several mechanisms of action are being explored. The alkaline nature of biochar can inhibit tumor growth by disrupting the acidic environment in cancer cells. Biochar and functionalized molecules can generate reactive oxygen species in cancer cells, resulting in cell death (Rahman et al. 2024). Three key attributes serve as a foundation for understanding the potential contribution of nanobiochar in cancer therapy. These include the enhancement of drug delivery systems, targeted drug delivery, and modulation of cell signaling (Min et al. 2025). With their highly adsorptive properties, biochar has shown promise as a vehicle for targeted drug delivery. Similar to activated carbon, the high surface area and porosity of nanobiochar and biochar nanocomposites offer an enhanced and efficient drug loading capacity, as well as controlled release of drugs. The slow release of biomolecules from biochar can also reduce the drug toxicity typically associated with nanoparticles or drugs due to their strong inhibitory effect (Liu et al. 2024). Activated carbon-enriched polycaprolactone scaffold was found to be biocompatible with human gingival fibroblasts and umbilical vein cells and exhibited potential to be used for the controlled delivery of immunosuppressant sirolimus (Nazarkina et al. 2023).

Functionalized biochar nanocomposites can be used for targeted drug delivery in chemotherapy, thereby minimizing damage to healthy cells, associated side effects, and systemic toxicity associated with conventional chemotherapy. Nanobiochar derived from orange peel was studied for its ability and compatibility in specifically targeting a human alveolar cancer cell line. Biotin (vitamin B7), hyaluronic acid, folic acid (vitamin B9), and riboflavin (vitamin B2) were used as targeted ligands and DHF cancer drug (5,5-dimethyl-6a-phenyl-3-(trimethylsilyl)-6,6a-dihydrofuro[3,2-*b*]furan-2(5H)-one) was used as the target therapeutic agent.

Nanobiochar carrying DHF, and functionalized with biotin, was found to be the most efficient in being internalized and caused more cancer cell death than DHF alone (Iannazzo et al. 2022). Drug-loaded nanobiochar can be further applied in phototherapy to kill cancer cells using heat from stored infrared light. Maize-derived biochar-ZnO nanocomposite, prepared using the ball-milling method, exhibited antioxidant, anti-inflammatory, and antiparasitic activity with high biocompatibility to red blood cells (Kamal et al. 2022). An Ag–Cu-ZrO_2 functionalized biochar nanocomposite, derived from *Mangifera indica* bark, resulted in a 74% reduction in the death rate of cancerous cells in neuronal cells, highlighting the potential of biochar nanocomposites for targeted treatment of neuroblastoma (Pathania et al. 2024).

However, although effective, as with other cancer therapies, a major limitation of this therapy is the potential for untargeted killing of healthy cells, thereby necessitating further studies and improvements in using biochar nanocomposites in phototherapy and targeted drug delivery for cancer treatment. In a recent study, a butyrate-glycerides-biochar nanocomposite was found to significantly interfere with the proliferation of colorectal cancer cells. A marked metabolic shift from glycolytic metabolism to mitochondrial respiration caused a 22% increase in anticancer effect compared to the control. The targeted and successful biochar-mediated delivery of bioactive compounds, specifically butyrate-glycerides, selectively interferes with the Warburg effect in aggressive cancer cells, opening translational opportunities for an effective anti-colorectal cancer strategy (Fei et al. 2025). This highlights the potential of biochar as an adjunct to precision medicine, enhancing the therapeutic efficacy of anticancer bioactive compounds and contributing to significant improvements in colorectal cancer treatment outcomes.

4.4 Imaging and diagnostics

The tunable nature, conductive properties, and high surface area of biochar nanocomposites make them excellent candidates for developing sensors to detect and monitor various biomolecules (Min et al. 2025). However, research on biochar nanocomposite-based biosensors for diagnostic applications is limited. Glucose is one of the most prominent biomolecules explored for biosensor development and holds much significance in diabetes management. A glucose oxidase and biochar-based sensor, tagged with Prussian Blue, was successfully used to detect glucose in real samples, including human saliva and blood, making it a promising sensor for real-time monitoring in diabetic patients (Kalinke et al. 2024). A Cu-biochar hybrid-coated biosensor for glucose monitoring exhibited high sensitivity (6214.4 $\mu A\ mM^{-1}\ cm^{-2}$) and a low limit of detection (0.8 μM) (Larsati et al. 2023). Human–computer interaction sensors based on triboelectric nanogenerators have emerged as a promising advancement in the field of imaging, diagnostics, and real-time monitoring. Hydrogels, with good tensile properties, biocompatibility, and super self-healing ability, offer advantages over other conventional materials as effective components of triboelectric nanogenerators and are good candidates for use in human sensors, such as wearable skin sensors. Biochar-incorporated conductive polypyrrole hydrogels have shown promising results as a conductive material, making the sensors more sensitive and highly conductive under altering physiological conditions. The addition of biochar also enhances the reusability of the sensors, as self-healing accelerates, facilitated by the formation of hydrogen bonds between functional groups in biochar and polypyrrole (Wang et al. 2024c). Incorporating a highly conductive material, such as biochar nanocomposites, into the hydrogel enhances its conductive properties, expanding its usability and applications. Hence, although there is a wide scope of nanobiochar and biochar nanocomposites in the healthcare sector, there are disadvantages that limit their widespread use (Table 1).

Despite limitations, the application potential of biochar-based composites in healthcare is high. Further research is needed on continuous monitoring of health conditions and diverse biomolecules to fully leverage biochar nanocomposites for diagnostic applications and real-time health monitoring. Additional in-depth studies are required to clarify long-term stability, immunogenicity, degradation mechanisms, immune responses, and regulatory hurdles associated with biochar-based systems.

5 Biochar nanocomposites as new-age energy storage materials

Using biochar as a carbon material for energy storage has emerged as one of the most promising applications of biochar. Batteries and supercapacitors are two such energy storage options. Supercapacitors, also known as ultracapacitors or electrochemical capacitors, are fast-charging energy storage devices used in machines that require quick charging, such as electric vehicles, and in some commonly used electronic equipment, including flashlights, voltage stabilizers, and portable speakers (Sahin et al. 2022). The long lifecycle, high energy density, and higher reversibility make them ideal for use in energy storage functions. The electrode materials used in supercapacitors are usually porous carbon compounds with high specific surface area and fine pore structures. Batteries are energy storage devices that store energy chemically, utilizing chemical bonds in carbon-based materials to store energy, which is then converted into an

Table 1 The scope and limitations in the use of biochar and biochar nanocomposites for health care applications

Application	Advantage	Limitation	Reference
Drug delivery and anticancer therapy	Enhanced surface area, targeted drug delivery, surface modifiability, and sustainable synthesis	Low reproducibility, aggregation and dispersion challenges, heterogeneity in structure, lack of in vivo studies	Iannazzo et al. 2022
Imaging and diagnostics	Low cost and sustainable	Sensitivity, susceptibility to biofouling, biocompatibility issues, lack of in vivo studies	Larsati et al. 2023
Antimicrobial therapy	Broad spectrum activity, biofilm disruption, and toxin adsorption	Unintended cytotoxicity and immunogenicity probability	Gao et al. 2017; Eltaweil et al. 2022
Regenerative medicine	Promotes cell attachment and differentiation in scaffolds, wound healing applications, and controlled drug release	Limited studies on long-term effects, potential toxicity to mammalian cells	Chen et al. 2012a, Wang et al. 2023

electric current through chemical reactions (e.g., redox reactions). Compared to supercapacitors, batteries have a higher energy density but exhibit several undesirable properties, including a shorter shelf life, slower charge and discharge cycles, a narrow operating temperature range, and lower power density (Noori et al. 2019). Graphene, carbon nanotubes, graphite nanoparticles, and activated carbon are among the conventional carbon materials used in the development of supercapacitors and batteries (Aval et al. 2018; Li et al. 2018).

The conventional porous carbon compounds, although effective, have low conductivity, high ion transport resistance, and insufficient ionic diffusion in the inner pores. Traditional carbon materials, including graphene and graphite, are typically produced from coal or petrochemical sources, which involve energy-intensive and often harsh synthetic processes. Graphite has a relatively low theoretical specific capacity of 372 mA h g^{-1}, which limits its wider applications (Zhou et al. 2019). Despite their widespread use, the production of these conventional materials is expensive and environmentally unsustainable. There is a need to explore sustainable alternatives to these carbon compounds, derived from renewable resources with minimal environmental impacts. The search for efficient, low-cost, and eco-friendly porous materials for supercapacitors and batteries, hence, remains a pressing priority.

5.1 3D carbon materials for electrochemical devices

Biochar offers a promising substitute to conventional carbon materials for incorporation into supercapacitors and batteries. Surface chemistry and the ability to be easily tuned for porosity offer an advantage over traditional carbon materials, making biochar and biochar-derived nanocomposites a versatile platform for developing electrochemical devices. The abundant functional groups on the surface of nanobiochar play a pivotal role in the phase transition processes during energy storage and conversion (Liu et al. 2019). Biochar is especially rich in oxygen-containing functional groups, such as hydroxy (-OH), carbonyl (-C=O), and carboxyl (-COOH) groups, which limit further oxidation and modification of the carbon matrix, thereby enhancing the cyclic stability of the electrode material. High conductivity and microporosity are key features of an efficient capacitor material. However, limited porosity, surface area, or the presence of functional groups that impart increased resistance to electrolyte diffusion can lead to a decrease in conductivity of the developed material. Hence, modifications of biochar to develop a 3D layered structure with high porosity and surface area by various activation techniques are key to developing a carbon material with high electrochemical performance. 3D porous carbon material with a unique hierarchical porous structure offers lower diffusion resistance to ion transport and has emerged as a promising candidate for energy storage.

5.2 Enhancing energy storage with biochar nanocomposite-based supercapacitors

To date, multiple studies have investigated the potential of biochar-based supercapacitors, yielding promising results. A high specific gravimetric capacitance of 397 F g^{-1} and excellent long-term cycling stability were demonstrated by the activated biochar obtained from coconut shells (Wang et al. 2022). Treatment of biomass by subjecting it to freezing before pyrolysis resulted in biochar with increased pore volume and smaller pore sizes, as indicated by surface Brunauer–Emmett–Teller (BET) analysis. Mesopores are critical to rapid ion transport and, hence, important for high capacitance. Larger mesopores facilitate ion transfer and diffusion, while smaller micropores are thought to hinder the transfer and diffusion of ions, thereby decreasing the capacitance of the carbon material. Hence, the textural properties of the material must be tuned through various activation processes, yielding controlled levels of micro- and mesopores that significantly influence the capacitive performance of the material (Wang et al. 2013; Liu et al. 2019).

Carbon materials obtained from sargassum, tea saponin, water hyacinth, and wheat husk have demonstrated effective capacitance, with gravimetric capacitances of 314, 278, 273, and 269 F g^{-1}, respectively (Wu et al. 2016; Guo et al. 2019; Baig & Gul 2021; Ma et al. 2021). Multiple studies have worked towards improving the specific capacitance of biochar using primarily chemical or physical activation methods. Such activation increases the surface area and functionalizes the surface of macro biochar, thus enhancing its specific capacitance. Specific capacitance ranging from 115 to 418 F g^{-1} has been reported from activated biochar derived from various biomass (Table 2).

As indicated in Table 2, strong alkalis and acids are two of the most widely studied activating agents for increasing the hierarchical porosity in carbon materials. Potassium hydroxide (KOH), one of the most widely explored activating agents, selectively reacts with carbon atoms in the biochar to form multiple pores. Chemical activations with nitric acid (HNO_3) combined with KOH and zinc chloride ($ZnCl_2$) have also enhanced the specific capacitance of biochar (Jiang et al. 2013; Lu et al. 2020). CO_2 is another promising activating agent, where activation with CO_2 results in the transition of micro to meso and macropores. However, limited information is available on the exact mechanisms involved, and hence, the extensive use of CO_2 activation to alter electrochemical performance requires further exploration (Zhou et al. 2019).

Biochar nanocomposites have emerged as a promising alternative to traditional activated biochar or other carbon materials. Simple chemical activation can quench electrical conductivity in biomass-derived biochar. Incorporation of heteroatoms into the carbon matrix enables the formation of a stable and optimal pore structure, along with good thermal conductivity, and significantly enhances the capacitance performance of the biochar. Sulfur, phosphorus, and nitrogen have been successfully doped into biochar to enhance its specific capacitance (Nazir et al. 2022; Xia et al. 2022). Nitrogen is a widely studied element for biochar nanocomposite production. N-doped 3D carbon exhibits excellent double-layer capacitive performance considerably higher than that of pristine carbon materials and is a forerunner for use in energy storage devices. The N_2-doped biochar has demonstrated specific capacitances ranging from 330 to 380 F g^{-1} (Sun et al. 2020; Zhang et al. 2020; Jiao et al. 2022). Doping procedures are carried out using an external nitrogen source, such as nitrogen gas (N_2) or ammonia (NH_3), or with a N_2-rich biomass as the precursor. Li et al. (2021) produced N_2-doped biochar using N_2 first and then switched to NH_3 gas during pyrolysis. The N_2 doping enhanced the biochar's surface wettability, resulting in improved interaction between the electrode and electrolyte, as well as enhanced redox reactions of the nitrogen and oxygen functionalities in the carbon material (Liu et al. 2019). The presence of inherent nitrogen and other elements in the algae-derived biochar makes it conducive for self nitrogen doping (Norouzi et al. 2021 2011). Maximum specific capacitances of 158, 296, and 445 F g^{-1} were obtained from raw algal biomass, 3D interconnected functional biochar with a mesopores network, and tile-like microstructure containing cobalt oxides, respectively.

Preparing biochar nanocomposites by introducing metals and metal nanoparticles is another way of enhancing the specific capacitance. A study by Lim et al. (2017) found that biochar-loaded metal nanocomposites showed enhanced electrochemical performance compared to unmodified biochar. Glucose-based biochar was used to

Table 2 Activated biochar derived from various feedstock and their specific capacitance

Feedstock type	Activating agent	Initial capacitance (F g^{-1})	Capacitance after activation (F g^{-1})	Reference
Camellia oleifera	$ZnCl_2$	–	374	Zhang et al. 2012
Paper mill sludge	KOH	–	180–190	Wang et al. 2013
Red Cedar wood	HNO_3	14	115	Jiang et al. 2013
Water hyacinth	KOH	108	273	Wu et al. 2016
Nanochloropsis salina	$ZnCl_2$	–	328	Zhou et al. 2017
Cladophora Glomerata	KOH	150	418	Pourhosseini et al. 2018
Sawdust and tannic acid	$Na_2S_2O_3$	–	202	Sevilla et al. 2019
Sargassum	KOH	–	316	Guo et al. 2019
Lotus leaves	KOH and HNO_3	53	478	Lu et al. 2020
Tea saponin	KOH	140	278	Ma et al. 2021

coat Fe_3O_4 nanoparticles, and the resulting nanocomposite was subjected to KOH activation. The activated nanocomposite contained uniform mesopores and a pore size considered optimal for ion diffusion and electron movement, leading to increased electrochemical performance. The specific capacitance of the biochar containing the metal nanoparticle was higher than that of biochar alone (259.3 and 204.7 F g^{-1}, respectively) (Lim et al. 2017). A Pd-Au biochar nanocomposite, prepared by carrying out pyrolysis in the presence of lead (Pb) and gold (Au), showed a high specific capacitance of 690 F g^{-1} (Latif and Khan 2024). Similarly, TiO_2 nanoparticle-modified 3D porous carbon has been shown to improve pseudocapacitance characteristics (Chen et al. 2012b). Pyrolysis of corncob and melamine yielded a nanotube@mesoporous carbon aerogel, which exhibited a specific capacitance of 538 F g^{-1}, suitable for use in electrochemical devices (Li et al. 2017b). The presence of inherent metals in corncob and melamine facilitated self-activation. The ultimate goal is to replace the current electrode materials in supercapacitors with a more environmentally friendly and cost-effective option: biochar-based composites. The establishment of the efficiency of such low-cost material paves the way for the wider acceptance and commercialization of biochar nanocomposites in energy storage applications.

5.3 Nanocomposites for use in batteries

Biochar-based materials, with a moderate surface area, unique structural characteristics, and high specific capacity, are highly sought after for lithium-ion batteries. Multiple waste biomasses have shown potential to be used as raw materials for valorization into biochar for use in battery technology (Table 3).

An investigation into the potential of biochar derived from HCl-treated tea waste as an anode material in Li-ion batteries found that HCl treatment enhanced the capacity of biochar. After 200 cycles, the demonstrated discharge capacity of 479 mAh g^{-1} was higher than what was theoretically possible using graphite (Choi et al. 2016). A much higher capacity of 728 mAh g^{-1} was shown by waste tea leaves activated with KOH (Wang et al. 2020). KOH-activated water hyacinth biochar has the potential to be used as an anode in a Li-ion battery, with a specific capacity of 697 mAh g^{-1} (Chen et al. 2021). Similarly, $ZnCl_2$-activated biochar from the same material could potentially be used as a cathode in Li–S batteries (Nurhilal et al. 2023). Doping electron-rich N atoms into the graphite carbon matrix of biochar introduces more chemically active defects, providing more active sites for Li^+ adsorption and a higher Li^+ storage capacity. It also facilitates strong electronegativity and interactions between the biochar matrix and Li^+, thereby enhancing electronic conductivity and electrochemical stability (Chen et al. 2014). Due to their high conductivity, the incorporation of metals and metal nanoparticles into the biochar matrix enhances the surface properties of carbon (Liu et al. 2019). The use of low-cost waste biomass as raw materials brings sustainability and circularity through the waste-to-wealth aspect. In addition to the high performance and cost-effectiveness of the carbon material, the scalability potential of the carbon composite material is also critical to increasing the acceptability of these biochar derivatives in energy storage devices.

6 Sustainable architecture using nanobiochar-derived materials

The cement industry is highly resource-intensive and a significant contributor to atmospheric CO_2, a greenhouse gas. The use of carbon sequestration agents in cementitious materials may compensate for some of these emissions, and hence eco-friendly building material additives are being extensively explored. Due to its structural properties and pollutant adsorptive capacity, biochar has been gaining attention as a reinforcement filler in building materials (Singhal 2023). Biochar can be mixed with

Table 3 Biomass for use as carbon material in battery manufacturing

Biomass type for biochar production	Activating agent	Battery type	Electrode type	Capacity (mAh g^{-1})	Reference
Macroalgae *Ahnfeltia tobuchiensis*	–	Li-ion	Cathode	300	Belmesov et al. 2023
Water hyacinth	KOH	Li-ion	Anode	697	Chen et al. 2021
Water hyacinth	$ZnCl_2$	Li-Sulfur	Cathode	312	Nurhilal et al. 2023
Rice husk	KOH	Li-sulfur	Cathode	1230	Chen and Xue 2017
Cladophora glomerata	HCl	Li-ion	Anode	700	Salimi et al. 2017
Tea waste	HCl	Li-ion	Anode	479	Choi et al. 2016
Waste tea leaves	KOH	Li-sulfur	Cathode	728	Wang et al. 2020
Forestry waste	$ZnCl_2$	Li-ion	Anode	370	Simões dos Reis et al. 2022
Wheat straw	–	Na- ion	–	200	Saavedra Rios et al. 2020

concrete, composite panels, and mortars to be incorporated into the construction of commercial and residential buildings without compromising the safety and durability of the structure. Biochar, along with asphalt, clay, and geopolymers, has been incorporated into building construction to enhance the mechanical properties of the materials (Marathe and Sadowski 2024). Nanobiochar and biochar nanocomposites, with their enhanced structural and functional properties, offer an added advantage for this application. In a study on nanobiochar obtained from apricot kernel shells, a 15% increase in compressive strength was observed when nanobiochar was mixed with mortar at a 0.04% weight by volume ratio, compared to the standard mortar (Sisman et al. 2023). Fracture energy for flexure also increased by 98%, relative to the standard mortar. The increased strength and fracture energy were attributed to the porous structure of the nanoscale biochar, which serves as a hydration nucleation site, promoting internal curing. However, incorporating a higher volume of nanobiochar negatively impacted mortar strength, primarily due to the formation of weak zones resulting from inadequate dispersion of the nanobiochar (Sisman et al. 2023). Incorporation of softwood biochar nanoparticles as cement additive enhanced the toughness of cement and increased the flexural strength of mortar by 20%, relative to reference mortar (Cosentino et al. 2018). Feedstock type, heating rate, pyrolysis temperature, and pressure were key determinants in the potential of biochar nanoparticles as a construction material for carbon capture and sequestration. Nevertheless, the incorporation of nanobiochar in building materials creates new opportunities for carbon capture and climate-resilient architecture.

6.1 Climate-smart architecture

Due to its lightweight nature, biochar is being increasingly incorporated into building blocks to reduce the density of building materials, thereby making them lighter. Biochar nanocomposites can effectively enhance the structural performance of building materials by increasing their strength. Agal biochar-derived zinc and calcium nanocomposites (biochar-Zn and biochar-Ca) were reported to increase the compressive strength of cement paste. This property was attributed to a nucleation effect caused by the Zn and Ca phases, as well as the internal curing effect of biochar (Chen et al. 2024). Good thermal insulating properties enable the use of biochar as an insulating material to reduce energy costs incurred in indoor temperature control. The use of biochar in combination with other organic materials, such as organic phase change materials, alters the thermal properties of the building and is being investigated for passive thermal management. Mixing biochar with an organic phase change material (encapsulation by biochar) significantly enhances the thermal conductivity while also improving the shape and structural stability of the phase change material. This addresses leakage concerns and boosts the performance for effective thermal management of the structure (Bordoloi et al. 2022).

Metallic nanoparticles incorporated into biochar-derived nanocomposites exhibit antimicrobial activity, enhancing the climate resilience of the construction material while protecting against microbial infections. Silver nanoparticle (AgNP)- tagged biochar was constructed using a facile strategy that could be utilized in filters for indoor air filtration, particularly in public places such as railway stations and subways. This material can also be used as a filler in construction materials and furniture to offer protection from bacterial action, thereby increasing the shelf life of the products (Huang et al. 2017).

6.2 Green housing

Rising pollution levels in urban areas have a detrimental impact on the health of the growing urban population. Coupled with climate change, deteriorating air quality is reducing the life expectancy of millions of people worldwide. Biochar, with its adsorptive properties, can play a significant role in reducing the levels of airborne chemicals and pollutants, thereby improving indoor air quality. The high water-retention ability of biochar makes it effective for humidity control. Once demolished, biochar-impregnated, eco-friendly, and resilient structures would also contribute carbon to the soil, making way for sustainable and greener development. Integration of biochar nanocomposites in sustainable urban development presents a promising strategy for mitigating greenhouse gas emissions. A 3D N-self-doped carbon developed from chitosan exhibited a CO_2 capture performance of 3.07–3.44 mmol g^{-1} (25 °C). The 3D material consisted of nanorods and fibre wall-interconnected porous carbon, which can be further tailored for higher gas capture capacity (Tong et al. 2016). Freeze drying followed by pyrolysis of the banana stem yielded microporous carbon monoliths and carbon fibers exhibiting a CO_2 adsorption capacity of 7.1 mmol g^{-1} (Sivadas et al. 2019). Structured 3D biochar-derived porous materials can also adsorb other harmful pollutants, such as nitric oxide and airborne particulate matter, thereby mitigating urban air pollution. The pollutant adsorption property of biochar positions it as a valuable player in urban landscaping. With enhanced performance and environmental impact, biochar nanocomposites can play a decisive role in sustainable town planning to maintain healthy and clean air quality.

7 Nanobiochar as fuel and polymer additives

Several additives are added to combustion fuel to reduce particulate matter and NO_2 emissions (Safieddin et al. 2020). Waste-derived fusel oil (fuselol) and various nanometals, such as aluminum, boron, and copper, are commonly used additives. However, the use of metals poses an added risk of environmental contamination and health hazards. Nanobiochar has gained recognition as a sustainable alternative to conventional fuel additives. Nanobiochar blended with fusel oil was used as an additive to ethanol biodiesel blends, resulting in increased viscosity and reduced emission of unburnt particles, thereby lowering nitric oxide (NO_2) emissions. The addition of nanobiochar also lowers the combustion temperature and increases the heat transfer rate, thereby enhancing fuel efficiency (Mirbagheri et al. 2020). The polymer and rubber industry also uses synthetic additives or fillers to improve product stability and quality. Among the most common additives are carbon black and silica, which are used in tyres to reduce abrasion and improve wet skid resistance (Xue et al. 2019). Nanobiochar presents a sustainable alternative. Rice husk nanobiochar, added as a filler to natural rubber, improved tensile strength, modulus, and tear strength by 44%, 18%, and 9%, respectively (Xue et al. 2019). Biochar obtained from *Digitalis purpurea*, and ball-milled to nanobiochar, was used as a filler in polyurethane. The polyurethane film was used in mulching to reduce weed growth and reduce photosynthetically active radiation in plants. Improved light transmission reduction, enhanced surface color, superior barrier properties, increased contact angle, optimized porosity, and increased tensile strength, tear strength, and oxygen transmission rates were observed in the nanobiochar additive-enhanced polyurethane mulch film (Mayakrishnan et al. 2023). Considering the changing climatic conditions, the properties of nanobiochar make it beneficial for use in climate-smart agriculture and eco-friendly polymers.

8 Nanobiochar and biochar nanocomposites for sustainable agriculture

Due to their enhanced surface area and improved pore structure, nanobiochar and biochar nanocomposites have successfully found applications in sustainable agriculture, including soil conditioning, enhancing plant growth, suppressing pathogens, and mitigating abiotic stress (Deepshikaa et al. 2024; Xu et al. 2024). Considering the extensive body of literature available in this field, the current work includes only a brief discussion on specific agricultural applications of nanobiochar and biochar nanocomposites (Fig. 4).

Enhanced surface functional groups on biochar-based nanomaterials improve soil properties by increasing cation exchange capacity and facilitating the adsorption and slow release of essential ions, such as K^+ and Ca^{2+} (Lateef et al. 2019). The micropores and nanopores in biochar-based nanomaterials trap water molecules, improving soil water-holding capacity. The carbon-rich matrix of these materials enhances soil organic matter, while the surface chemistry improves soil buffer capacity, also providing a suitable habitat for microbial growth and nutrient recycling (Pavlicevic et al. 2022). Biochar-based nanomaterials improve a plants' ability to take up nutrients, photosynthetic efficiency, and resistance

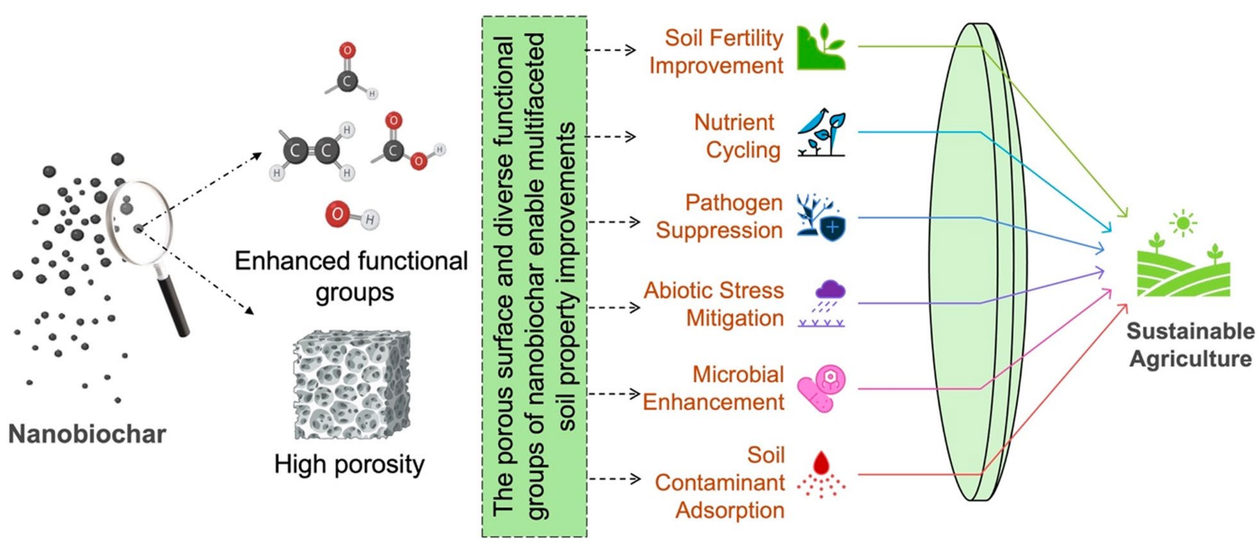


Fig. 4 A schematic representation of the multifaceted role of nanobiochar in agriculture, highlighting its contributions to soil fertility, plant growth enhancement, nutrient cycling, pathogen suppression, abiotic stress mitigation, microbial enhancement, and soil contaminant adsorption

to oxidative stress, leading to enhanced plant growth (Shani et al. 2024; Sashidhar et al. 2025). The application of biochar nanomaterials to soil has led to improved soil properties, such as aeration and water availability, which support root development and consequently enhance chlorophyll content. Biochar nanomaterials help stimulate microbial activity, thereby improving the ability of plants to recycle nutrients and combat diseases.

Biochar-based nanomaterials also suppress plant pathogens. The high surface area and enhanced surface functional groups present on biochar nanomaterials adsorb phytotoxic compounds and pathogen secretions, thereby reducing their virulence (Aftab et al. 2022). The amendment of biochar nanomaterials led to an enhanced pathogen-resilient rhizosphere, fostering the growth of beneficial microorganisms that outcompete the pathogens. The surface properties of biochar nanomaterials help alleviate a range of abiotic stresses. The drought stress tolerance of plants was improved by biochar through enhanced soil water retention and plant water uptake (Rasheed et al. 2024). The highly porous structure of nanobiochar helps trap water molecules in the soil, while the hydrophilic functional groups facilitate stabilizing the plant membrane integrity and improving soil water availability. Biochar amendment is suggested to reduce the reactive oxygen species by boosting antioxidant enzyme activity and maintaining nutrient homeostasis under water scarcity (Ghassemi-Golezani et al. 2021). Owing to its high surface area and cation exchange capacity, biochar nanocomposites effectively adsorb excessive sodium ions commonly present during high saline conditions, thereby reducing soil salinity and osmotic stress on plants (Khan 2025). They can enhance root hydraulic conductivity and nutrient uptake, helping to maintain plant physiological balance. Similar to salinity stress, biochar nanocomposites can reduce the stress caused by heavy metals through adsorption and immobilization of the contaminants in the soil (Mazarji et al. 2023). The nanoscale surface functional groups bind with heavy metals such as lead and cadmium, reducing their bioavailability and phytotoxicity. This leads to soil remediation and prevents metal leaching, supporting safer plant growth.

9 Perspectives, challenges, and future directions

Increasing the economic viability of biochar nanocomposites primarily requires lowering their production costs, standardizing large-scale production processes, and establishing clear guidelines and regulations for their production and use. Environmental safety assessment, economic viability analysis, batch consistency, and application-specific research are some of the pressing challenges hindering the widespread adoption of nanobiochar and biochar nanocomposites in various commercial sectors and hence those are promising future scopes of work required to advance the use and adaptability of these materials for varied commercial applications (Fig. 5). More specifically, we propose the following research needs:

- Assessing the long-term impact of biochar nanocomposites on the environment and human health. The small size of nanobiochar makes it easy to travel deep and far in soil and air. For example, the potential airborne dispersion of small-sized nanobiochar during farm applications raises concerns regarding its agricultural use. There are limited studies on the health and environmental impact of nanobiochar and biochar nanocomposites (Li et al. 2023). This includes studies on their cytotoxic effects, if any. The retention, distribution, and bioavailability of nanobiochar relative to bulk biochar have not been well documented. There are reports on the toxicity of biochar nanoparticles to aquatic plants, primarily due to oxidative stress (Huang et al. 2021). However, most studies point to the long-term impact of chronic exposure rather than short-term intermittent exposure. The impact of the aging process of nanobiochar and nanocomposites on the long-term performance and repeatability of the materials developed requires further investigation.
- In vitro studies on the interactions of biochar nanocomposites with tissues need to be conducted. Further research on the biocompatibility, with the use of biochar composites in tissue regeneration and wound healing, is required to establish a successful and safe product for medical applications.
- Cost and quality control guidelines for nanobiochar and biochar nanocomposites need to be established. Currently, there is no robust techno-economic analysis available for nanobiochar and biochar nanocomposites. Process optimizations are necessary to reduce heterogeneities in the final product, thereby establishing replicability and enabling large-scale production. An integrated economic and life cycle assessment, covering the production and application of nanobiochar and nanocomposites, is hence required.
- Complex nanocomposite synthesis should be explored for biomedical applications. Further research on bioactive biochar-based nano- and microspheres, loaded with antimicrobial agents, growth factors, and angiogenic factors, could enhance wound healing and offer a promising solution to address the challenge of irregularly shaped infected wounds and infections.

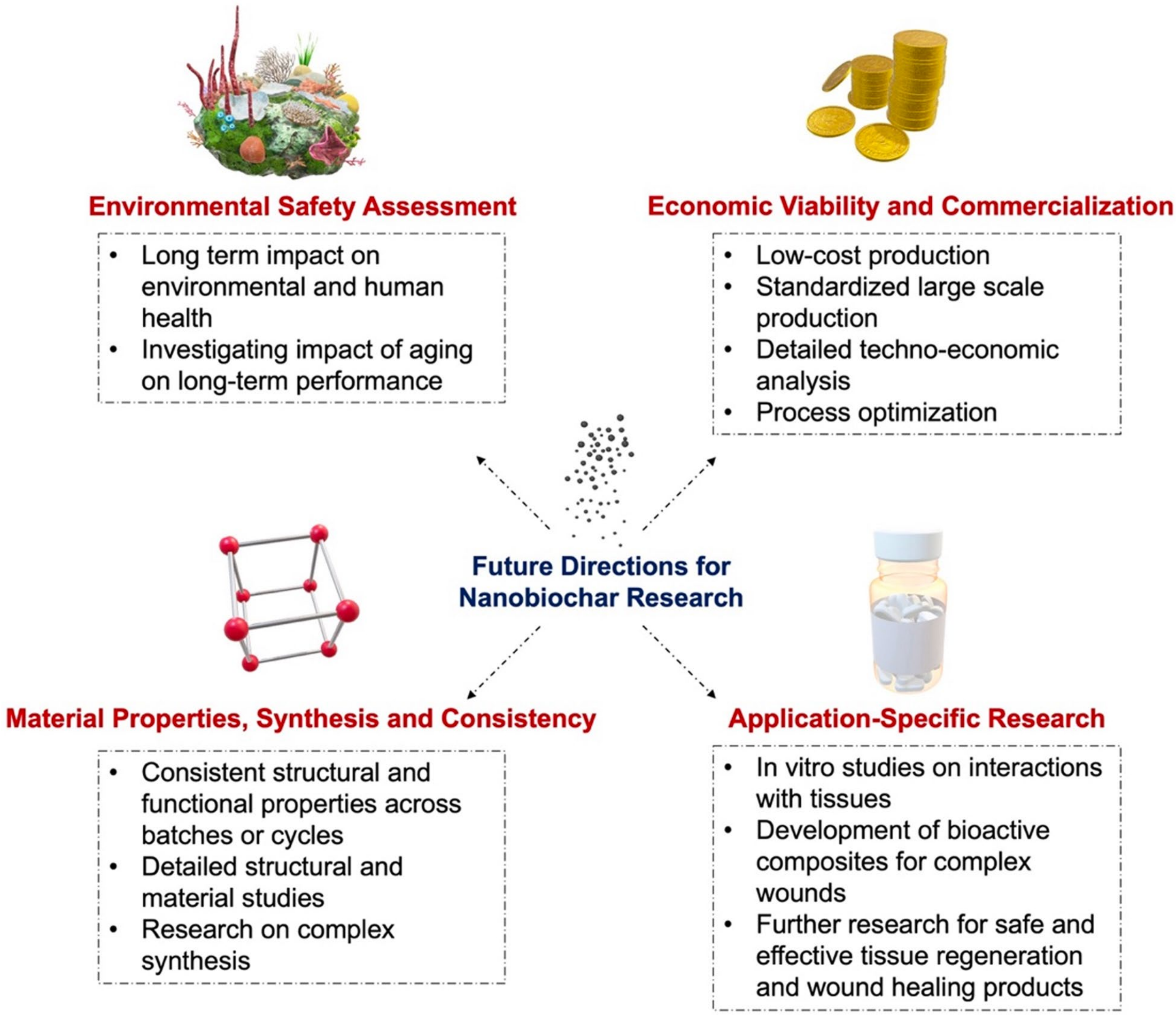


Fig. 5 Research priorities in advancing biochar nanocomposites for commercial applications

- Consistency in the properties of nanobiochar and biochar nanocomposites over multiple production cycles and across different feedstock batches needs to be improved. One major challenge in using biochar nanocomposites for medical applications is the inconsistency in their physical properties. The parent biomass, production methods, and functionalization processes closely determine the properties of biochar and biochar-based nanocomposites. Hence, ensuring the maintenance of the exact structural and functional properties across multiple production cycles remains a significant challenge.
- Detailed structural and material studies are required. Poor durability and short lifetimes of 3D porous materials limit their widespread incorporation in electrochemical devices. More material and structural engineering research is needed to establish processes that yield 3D mesoporous layered carbon materials with high durability and longer lifespans, particularly for applications in environments with low temperatures.
- Market feasibility studies on nanobiochars and biochar nanocomposites are urgently needed. There is a gap between technological advancements and the market adoption of biochar-based carbon materials as electrodes in capacitors and batteries. Greater process optimizations and assessment of economic viability are essential to increasing their acceptance across various sectors.

10 Conclusion

Nanobiochar and biochar nanocomposites represent a novel class of biomaterials with wide applications in the environmental and agricultural sectors. The integration of nanobiochar and biochar nanocomposites into diverse and underexplored sectors such as medicine, energy, and construction presents a promising pathway towards sustainable development. Their small size, large surface-to-volume ratio, and high porosity and adsorption properties enable the incorporation and tagging of multiple bioactive compounds. Association of biochar with nanoparticles and other biomolecules enhances their properties and expands their applications. By extending their application beyond environmental remediation, these multifunctional materials can play a pivotal role in advancing low-carbon technologies and addressing global sustainability challenges. The main limitation is maintaining consistency in the structure and functional attributes of the developed nanocomposites. Environmental safety assessment and aging properties of those materials remain key points of concern when they are widely used. Process optimization, toxicity analysis, life cycle assessment, and environmental monitoring are needed to make the application of nanobiochar and biochar nanocomposites sustainable and safe.

Acknowledgements

The authors thank Symbiosis International (Deemed University), Pune, India for research support.

Author contributions

All authors contributed to the conception and design of the study. Visualization, investigation, data collection, and writing of the original draft were performed by Pooja Singh. Abhijeet Pathy and Sharoni Sharma contributed to the literature search and data collection, writing, reviewing, and editing. Supervision, reviewing, and editing were done by Manikprabhu Dhanorkar and Anne Naeth. Validation, formal analysis, writing, reviewing, and editing were done by Scott Chang. All authors have read and approved the final manuscript.

Funding

Open access funding provided by Symbiosis International (Deemed University). Partial funding was received from the Canada First Research Excellence Fund as part of the University of Alberta's Future Energy Systems research initiative (RES0037090) for conducting this study. Abhijeet Pathy was also supported by a Vanier Canada scholarship. Openaccess funding provided by Symbiosis International (Deemed University).

Data availability

The data sets used or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests

Scott X. Chang is an EBM of the journal Biochar, but he was not involved in the peer-review or handling of the manuscript. The authors have no other competing interests to disclose.

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Received: 9 May 2025 Revised: 8 September 2025 Accepted: 11 September 2025
Published online: 21 January 2026

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