

REVIEW

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Transforming natural waste into biochar for sustainable environmental remediation

Mohammad Amir Qureshi^{1*}, Shazia Parveen² and Mohd Shabbir^{3*}

*Correspondence:
maq248@gmail.com;
shabbirmeo@gmail.com

¹ Department of Applied Sciences & Humanities, KCC Institute of Technology and Management, Knowledge Park-III, Greater Noida, Uttar Pradesh 201306, India

² Department of Chemistry, College of Science, Taibah University, 46423 Yanbu Governorate, Saudi Arabia

³ Department of Applied Sciences, School of Engineering and Technology, CGC University, Mohali, Punjab 140307, India

Abstract

Increasing urbanization and industrial expansion has severely affected water quality on earth, motivating researchers to explore modern approaches to address this issue. Adsorption and degradation of pollutants have been primary methods for wastewater treatments, and adsorption has been simplest. Biochar, nanobiochar, derived from pyrolyzed biomass, are highly efficient adsorbents to remove industrial pollutants, thereby enhancing water quality for safe consumption. This review paper is all about biochar, with an in-depth discussion of its structural and functional properties, and applications. The synthesis of biochar is systematically analyzed, encompassing both conventional and advanced methodologies with critical evaluation of their respective advantages and limitations. Special emphasis is placed on advanced thermochemical conversion techniques and their role in tailoring biochar/nanobiochar for environmental remediation. Sustainability perspectives of using biochar are included by the end of the review paper.

Keywords: Biochar, Nano-biochar, Environmental remediation, Adsorption, Pollutants removal, Wastewater treatment

1 Introduction

Water is vital to all life on Earth, which makes it one of the most heavily exploited natural resources. When its quality deteriorates, the health of living organisms and the surrounding environment is adversely affected [1]. Poor water quality also limits its suitability for many essential uses. This degradation is mainly driven by pollutants released through untreated or inadequately treated wastewater. Key sources of such contamination include rapid industrial development, mining operations, agricultural activities, domestic waste, and urban runoff [2]. These pollutants ranging from heavy metals and antibiotics to dyes and hydrocarbons, pose significant health hazards because of their high toxicity and potential carcinogenic effects [3]. The management of polluted wastewater has become a significant environmental and societal challenge across many regions of the world [4]. Various wastewater treatment technologies such as ion exchange, membrane filtration, and adsorption have been developed to address this issue. Adsorbents including carbon nanotubes (CNTs), activated carbon, polymeric resins, and fly ash have been widely applied in wastewater remediation [5]. However, their high cost and complex processing requirements limit their large-scale



implementation, prompting researchers to seek alternative materials with comparable performance [6]. Consequently, the use of natural materials for pollutant adsorption has gained considerable attention as a cost-effective and sustainable strategy. A growing body of research focuses on developing eco-friendly, low-cost bio-adsorbents capable of supporting long-term, sustainable wastewater management. These bio-adsorbents offer several advantages: they are environmentally benign, readily available, simple to process, and generate minimal secondary pollution [7].

The increasing volume of waste generation, coupled with the growing need for efficient waste management strategies, has driven the conversion of renewable biomass into biochars (BCs) as a cost-effective and sustainable solution [8]. BCs are carbon-rich materials produced as by-products of the thermal decomposition of biomass under limited oxygen conditions. Biomass itself includes agricultural residues, farm by-products, animal manure, paper industry waste, and various other organic materials. Interest in biomass has surged in recent years due to its potential to be transformed into high-value products such as biochars. As the only renewable carbon-based resource capable of contributing to climate mitigation through CO₂ neutrality, biomass has emerged as a cornerstone of global efforts toward sustainable resource utilization and environmental protection [9, 10].

Several studies in the literature have highlighted the diverse applications and benefits of biochars (BCs). For instance, the mechanisms through which biochars regulate pollutant presence in water, facilitate contaminant removal, and support soil remediation have been extensively investigated. Similarly, the agronomic benefits of biochars have been highlighted, particularly their effectiveness as compost additives that enhance composting efficiency, promote humification, and stimulate microbial activity [11, 12]. Their findings also indicated that BCs could reduce greenhouse gas and NH₄ emissions, immobilize heavy metals, and function as soil amendments to improve soil quality and plant growth, while mitigating drought and salinity stress. Additionally, the role of BCs in municipal wastewater treatment, industrial wastewater decontamination, and stormwater management, underscoring their potential contribution to sustainable environmental management have been explored [13]. Wei Xiang et al. reviewed recent advancements in biochar (BC) production and highlighted their diverse applications, with particular emphasis on the use of BC-based technologies in wastewater treatment [14]. Similarly, Shaon Kumar Das et al. examined both the beneficial and adverse impacts of BC application in pollutant remediation. By synthesizing findings from numerous studies, they demonstrated how BCs can contribute to reducing greenhouse gas emissions, enhancing wastewater reuse, minimizing fertilizer-related pollution, and mitigating nutrient depletion, land degradation, and soil erosion. Their work also provided new insights into the potential of BCs for heavy metal removal, pollutant separation, and renewable energy generation [15].

This review article provides a comprehensive analysis of the properties of biochars (BCs) generated through different preparation techniques, including standard BCs, nano-BCs, and BC-based composites. It further explores the mechanisms involved in the removal of heavy metals, dyes, agricultural pollutants, pharmaceutical contaminants, toxic gases, and airborne particulate matter. In addition, the review evaluates the

performance of BCs derived from various biomass sources such as agricultural wastes, animal manure, bagasse, paper waste, and husk in the remediation of these pollutants.

2 Biochar and its properties

The term “biochar” (BC), also known as “charred biomass” or “black carbon,” was first documented in the Amazon basin in the late twentieth century. The word originates from the Greek *bios*, meaning life, and *char*, referring to a solid carbon-rich material [16]. Biochar is a sustainable and multifunctional organic substance produced through the pyrolysis of manure, organic solid wastes, and agricultural or forestry residues at moderate temperatures (<700 °C) under limited oxygen availability [17–21]. In addition to being primarily composed of carbon (C), biochar contains important macronutrients such as phosphorus (P), potassium (K), hydrogen (H), and oxygen (O), as well as magnesium (Mg), all of which contribute to enhanced crop productivity for a wide variety of crops globally [22–24].

Due to its tunable physicochemical properties, biochar (BC) has garnered significant research interest in advanced oxidation processes (AOPs) over the past few decades [25]. Its exceptional features including a high specific surface area (SSA), abundant surface functional groups (such as –COOH, –OH, and >C=O), diverse porous structures, mineral content, low cost, and strong ion exchange capacity, make BC a highly effective and versatile adsorbent for a wide range of pollutants [26–29]. BC is widely employed to mitigate fertilizer runoff, improve soil structure and fertility, and enhance biomass production [30, 31]. Additionally, it can reduce the mobility and bioavailability of environmental contaminants in soil or sediments through adsorption or chelation, thereby limiting the adverse effects of hazardous pollutants, including hydrophobic organic compounds, on plants and organisms. These distinctive properties of BC play a crucial role in influencing the transformation, transport, and bioavailability of pollutants within soil systems [32, 33].

The properties of biochar (BC) are primarily determined by the feedstock and the conditions of pyrolysis, especially temperature and duration. While different biomasses produce distinct BC types, general trends exist: increasing pyrolysis temperature yields BC with higher carbon content, greater porosity, and larger surface area, but lower volatile content and bulk density. Similarly, longer processing times enhance carbon content and surface area [20, 34, 35]. However, the mineral composition of the feedstock also critically influences BC’s characteristics and its suitability for various applications. Furthermore, the process conditions including temperature, residence time, heating rate, and pressure, dictate the co-products and maximum yields. For instance, low-temperature pyrolysis (300–400 °C) produces low-porosity BC, while moderate temperatures (400–700 °C) create highly porous BC with significant aromaticity. This structure facilitates electron donor interactions, and the presence of surface oxygen and nitrogen groups can enhance functionality by acting as electron acceptors [36, 37].

The high adsorption capacity of biochar (BC) is a key property for immobilizing pollutants and nutrients. While BC particles can range from centimeters to micrometers depending on the pyrolysis method, reducing their size significantly enhances this capacity. Shrinking particles to the micro-scale (10–600 µm) increases the number of available adsorption sites. Further reduction to the nanoscale (≤100 nm) dramatically

improves properties by maximizing the surface-to-volume ratio, which amplifies surface energy, adsorption potential, and biological efficacy. According to IUPAC guidelines, the pores within nano-BC are categorized as micropores (<2 nm), mesopores (2–50 nm), and macropores (>50 nm). Nano-BC has emerged as a promising alternative to overcome conventional BC's limitations by improving its structural, chemical, and physical properties [38–43]. Nano-biochar (nano-BC) exhibits a unique set of physicochemical properties that distinguish it from bulk biochar, including diverse elemental composition, aromaticity, surface functionality, and pore structure [44]. Its nanoscale dimensions endow it with a substantially larger specific surface area (SSA) and a stable, distinctive nanostructure [45]. These features, combined with a high density of oxygen-containing functional groups and carbon defects, lower hydrodynamic radii, and more negative zeta potential, significantly enhance its adsorption capability and catalytic activity compared to its macro-scale counterpart [46, 47]. The structural and physicochemical properties of nano-biochar (nano-BC) differ significantly from those of bulk biochar, a distinction that underpins its growing appeal for addressing environmental pollution and low crop yields [48]. Nano-BC can exist in both soluble and insoluble forms, with its solubility such as the soluble carbon in dairy manure biochar, decreasing as pyrolysis temperature increases. Key characteristics like its high specific surface area (SSA), extensive microporosity, surface functionality, and often alkaline nature make it uniquely effective. These properties enable nano-BC to adsorb a wide spectrum of contaminants, including herbicides, toxic metals, and organic pollutants, while also improving soil health by neutralizing acidity and enhancing nutrient retention and microbial activity [49–51].

Both biochar and its advanced derivative, nano-biochar (nano-BC), are widely regarded as highly sustainable and cost-effective alternatives to conventional adsorbents like activated carbon (AC), MOFs, and carbon nanotubes. While conventional AC typically boasts higher surface areas, biochar distinguishes itself through its low production cost owing to their production from waste feedstock, exceptional versatility, and the additional advantage of soil amendment properties. Nano-biochar further enhances this value proposition, offering improved environmental mobility and a substantially greater surface area [52]. Biochar and nanobiochar adsorbents are highly cost-effective, particularly when derived from agricultural waste. In comparison to commercial granular activated carbon, it is significantly cheaper. High-quality activated carbon is energy-intensive and expensive to produce, and other adsorbents such as carbon nanotubes (CNTs) and metal–organic frameworks (MOFs) are generally much more expensive, often requiring complex, high-energy synthesis. Nanobiochar is more expensive than bulk biochar due to top-down approaches (ball-milling, sonication), still it remains competitive with other nanotechnologies. Biochar and nanobiochar are somewhat superior to other adsorbents regeneration and stability fronts [47, 53].

3 Fabrication and functionalization/modification of biochar and nanobiochar

BC can be produced from diverse types of waste biomass, such as wood waste, agricultural residues, food waste, animal manure, and municipal or industrial sludge. A wide variety of feedstocks can be utilized, such as switchgrass (*Panicum virgatum* L.), rice (*Oryza sativa* L.), maize husks, hardwoods, peanut (*Arachis hypogaea* L.) hulls, pecan (*Carya illinoensis*) shells, bark, sugarcane (*Saccharum officinarum* L.), animal manure,

sewage sludge, urban yard waste, industrial byproducts, and aquaculture residues, is used to make BC [23]. Feedstocks are the traditional materials that are readily available, discarded, or inexpensively obtained for the synthesis of BC [54]. Broadly, biomass can be classified into two main categories: non-woody biomass, which includes animal and poultry manure, agricultural and crop residues, as well as urban and industrial waste materials; and woody biomass, characterized by high bulk density, low void space, high calorific value, and low moisture and ash content [55].

3.1 Conventional methods

Historically, biochar production involved two techniques: the pit method, where wood was stacked and smothered with soil to smolder anaerobically, and the mound method, where partially burned wood was immediately covered with soil. Over time, these traditional methods were gradually replaced by more advanced and contained systems, including clay burners, firebrick pits, and brick kilns [56, 57]. While conventional pyrolysis has been extensively researched and has demonstrated the effectiveness of biochar in various applications. But there are certain practical limitations such as the need for temperature-controlled reactors, reliance on a consistent energy supply and the limited volumes of material that can be feasibly produced. Energy consumption, cost, environmental and health risks are other limitations of the conventional methods and need for advanced methods arise [58]. Structural and physicochemical properties of biochar such as surface area, oxygen-containing functional groups, and aromaticity are crucial for their applications. Advanced methods and some modifications are supposed to improve these properties to broaden the application areas over the conventional methods.

3.2 Advanced methods

Though the basic process remains same; new techniques including pyrolysis, gasification, torrefaction, and hydrothermal carbonization have become popular due to technological advancements. These processes produce larger and better-quality BC. The three primary byproducts of thermally processing biomass are charcoal, biogas, and bio-oil.

Pyrolysis is the thermal decomposition of biomass in the absence of oxygen, producing charcoal as the primary product [59]. Because it rapidly generates biochar (BC) and simultaneously yields value-added products such as syngas and bio-oil, pyrolysis is considered one of the most efficient and versatile biomass conversion methods. During pyrolysis, the chemical bonds within biomass break down, leading to the formation of new functional groups on the BC surface, including $-\text{NO}_2$, $-\text{CH}_3$, $-\text{OH}$, and $-\text{COOH}$ [20, 60, 61]. The nature of pyrolysis, whether slow or fast, is mainly governed by the residence time of the feedstock, furnace temperature, and heating and heat-transfer rates [62, 63]. Slow pyrolysis, or conventional pyrolysis, occurs at relatively low temperatures (450–500 °C) and involves gradual heating for several minutes or longer. This process produces a high yield of BC and is regarded as environmentally sustainable. Gas evolution occurs slowly, thereby reducing the release of harmful gases. Fast pyrolysis, by contrast, rapidly heats biomass with a moisture content below 10% to much higher temperatures (850–1250 °C), usually within a few seconds. This method favors the production of bio-oil and gases while generating only a small amount of BC [64–66].

Pyrolysis is widely used for producing biochar (BC), typically carried out at 400–500 °C under oxygen-limited conditions. Factors such as temperature, heating rate, residence time, and feedstock characteristics significantly influence the yield and physicochemical properties of the resulting BC [67]. Although traditional pyrolysis generates less waste than many other conversion methods, it also presents several limitations, including non-uniform product distribution due to non-selective heating, high energy consumption, and longer times required to reach target temperatures. To address these drawbacks, several advanced pyrolysis techniques have been developed, including: (i) Microwave-assisted pyrolysis, (ii) Steam-assisted pyrolysis, and (iii) Co-pyrolysis. Microwave-assisted pyrolysis has become particularly prominent in BC production. Its advantages include low operational cost, selective and rapid heating, high energy efficiency, non-contact heat transfer, instantaneous control of heat input, and simple automation with enhanced safety [68]. Studies report that BC produced via microwave pyrolysis typically exhibits higher specific surface area (SSA) and pore volume compared to BC obtained through conventional pyrolysis [39]. Steam-assisted pyrolysis is a traditional modification that promotes the development of macro-, meso-, and micropores as volatile components are released, thereby increasing SSA and pore volume. This method enables the production of BC with soil-amending and fertilizing properties from vegetable waste while simultaneously generating a steam-diluted vapor-phase fuel [69]. Additionally, steam helps remove surface contaminants, improving the adsorption capacity of the resulting BC [70]. Co-pyrolysis, a thermal decomposition process involving two or more raw materials, offers an effective approach to enhancing product yield and overcoming the limitations associated with the pyrolysis of a single feedstock. Research indicates that co-pyrolysis can optimize pore structure, reduce ash content, increase calorific value, enhance adsorption performance, and minimize waste generation [71, 72]. A summary of BC preparation methods is presented in Fig. 1.

Gasification is a thermochemical process that converts solid biomass into a gaseous mixture (e.g., CH₄, CO, H₂, CO₂) by treating it with a limited amount of a gasifying

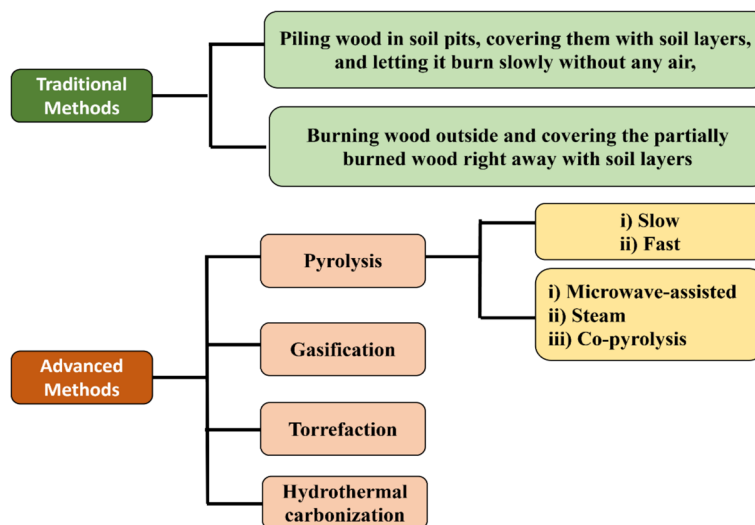


Fig. 1 Synthetic methods of BC

medium such as air, oxygen, or supercritical water at high temperatures (700–1000 °C). Biochar is a solid byproduct of this process. The reaction rate and output are influenced by the oxygen equivalency ratio, gas pressure, feedstock type, and the gasifying agent used. A significant challenge in gasification is tar formation, which complicates the process and reduces hydrogen yield [73–77].

Torrefaction is another method used for biochar (BC) production, carried out at 200–300 °C under anaerobic conditions and atmospheric pressure. This process enhances the physicochemical properties of biomass and is considered a mild form of pyrolysis due to its lower operating temperatures and its ability to selectively decompose hemicellulose, the most reactive biomass component [78, 79]. Hydrothermal carbonization (HTC) is also a mild thermochemical conversion process, typically performed at 180–250 °C and pressures below 45 bar for short reaction times. Owing to its suitability for high-moisture feedstocks and favorable operating conditions, HTC can convert materials such as sewage sludge into BC without any pretreatment. One of HTC's major advantages over methods like pyrolysis, gasification, or incineration is its unique capacity to transform wet biomass into carbon-rich products with relatively high yields, eliminating the need for energy-intensive steps such as dewatering and drying [80–82].

High-temperature thermochemical conversion techniques for biochar synthesis have their own advantages such as increased surface area, stability, higher carbon content, large pore volume, and higher efficiencies, but there are associated environmental and operational trade-offs. Reduced yield along with the number of oxygen-containing functional groups lead to limitation of these adsorbents for some contaminants [83, 84]. Further elevated temperatures required in these processes are associated with high energy consumption, lowering of equipment durability, and increased ash content, make these processes costly and less efficient at some levels. Temperature optimization for higher efficiency and yield remains challenging. Further, advanced thermochemical conversion techniques tailor the physicochemical properties of biochar for enhanced adsorption of industrial pollutants e.g. tailored biochar produced at temperatures in the range of 500–700 °C provides high pH and abundant functional groups, enhancing ion exchange and complexation with metal ions; chemical activation and enhanced aromatic structure at high-temperature pyrolysis (up to 900 °C) helps to capture organic pollutants; developing specialized surface chemistry to improve the retention of hydrophobic gaseous contaminants [85, 86].

3.3 Nano-biochar (NBC) synthesis

Interest in NBC has grown due to rising environmental pollution and declining crop yields under continually changing environmental conditions. NBC possessed larger fractions of C, O and H, which support the phenolic components [87]. Owing to its large SSA, functional groups, surface hydrophobicity, and porosity, NBC exhibits strong adsorption capacity for toxic metals, polychlorinated biphenyls, herbicides, and aromatic hydrocarbons, and also has the ability to neutralize acidic soils [48]. Negatively charged wheat straw NBC increased the nutrient recycling and improved the soil fertility and prevented the nutrient loss through leaching [40]. The trace element content increased in the soil due to high adsorption of NBC [88]. Plantation of alfalfa in NBC containing soil increased the nutrient content and water status of a heavily weathered

and low fertile soil of Chinese Loess Plateau. It was due to increased soil porosity and water infiltration possibly. NBC is more functionalized and possess higher surface area than raw BC. So, on addition of NBC into the soil, the cation exchange capacity obviously increased which simultaneously increased the nutrient content of soil. NBC is also showed better water retention, absorption and adsorption ratio than raw BC [89, 90]. Figure 2 shows the sustainable use of NBC in plant growth by enhancing the mobilization of soil phosphorus and adsorption of toxic heavy metals. The other section of the Fig. 2, also shows the carbon and nitrogen cycles to increase the amount of trace elements in the soil. These trace elements were further used by the plant for its growth.

To obtain nano-BC within the desired size range, biomass is first converted into bulk BC, followed by size reduction and sequential fractionation. Several other approaches are also used for synthesizing nano-BC, including (i) impregnation, (ii) chemical co-precipitation, and (iii) direct pyrolysis [21]. Impregnation is the most widely used method. In this technique, solid BC powder is immersed in a solution containing active components, which subsequently adsorb onto the BC surface. Commonly used impregnating agents include $KMnO_4$, $MgCl_2$, and $FeSO_4 \cdot 7H_2O$ [91–93]. The resulting nano-BCs are typically rich in surface functional groups and exhibit high SSA, enhanced porosity, and improved CEC [94]. Chemical co-precipitation

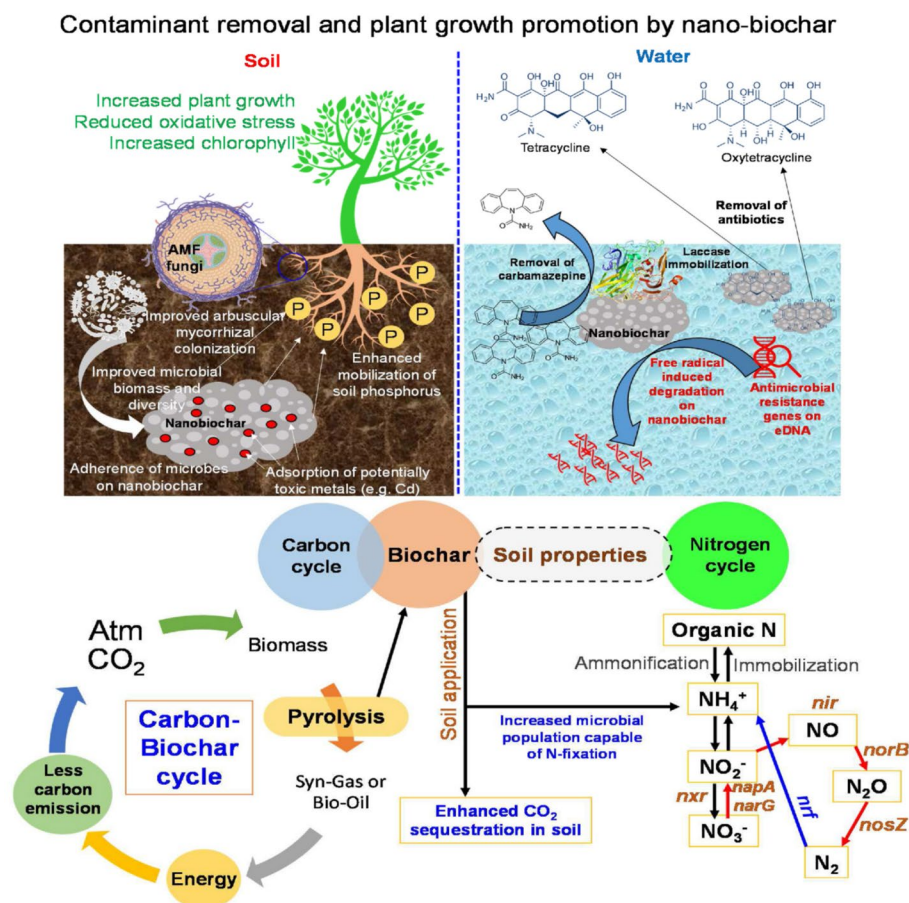


Fig. 2 Mechanisms of contaminant removal and plant growth promotion by NBC and BC involvement in C and N cycle to increase the carbon sequestration and microbial population in the soil. Obtained from [48]

involves depositing metal salts onto BC surfaces through controlled reduction, pH adjustment, or related processes. When optimized, this technique yields homogeneous BC-supported nanoparticles with high purity and well-defined stoichiometry. It also provides effective control over particle size and nanoparticle nucleation and growth rates. Direct pyrolysis refers to the synthesis of metal-rich BC nanocomposites under anaerobic conditions. The resulting materials, enriched with metal oxide nanoparticles, show high efficiency in pollutant removal applications [95–98].

The isolation of nano-biochar (nano-BC) particles post-synthesis is primarily accomplished through sedimentation or membrane filtration. Sedimentation relies on the natural gravitational settling of particles. Achieving the sedimentation of larger particles can take up to 24 h under static conditions to yield the nano-BC fraction. This process can be accelerated using centrifugation, where dissolved BC is spun at high speeds. Following centrifugation, larger particles form a pellet at the bottom, allowing the nano-BC to be extracted from the supernatant. Membrane Filtration employs selective barriers to separate particles based on size. Although more expensive than sedimentation due to the cost of the membranes, this method offers superior control over the final particle size distribution. It is essential for obtaining nano-BC with a specific, desired size. For instance, membrane filtration is the preferred technique when nano-BC particles smaller than 220 nm are required for applications such as electrodes in chemical detection [47, 99–101].

Other recently developed methods for NPs preparations include—(i) ball milling, and (ii) the sol–gel method. Ball milling has been cited as a viable method for producing nano-BC on a large scale and to decrease the particle size [102]. The parenting materials, ball diameter, ball-to-BC mass ratios, running speed, milling time, temperature, and liquid medium presence; are among the operational factors [103]. Scanning electron microscope analysis showed the smallest size was ~100 nm. One of the main obstacles for achieving the best ball milling performances were the dense agglomerates of NPs. The sol–gel method produced a nano-Fe₂O₃ resin/BC composite. The material’s nano-metal oxides were evenly dispersed throughout the porous bulk hydrogel which resulted in a product with a homogeneous pore structure and excellent mechanical strength, thermal stability, and adsorption capabilities. Figure 3 summarizes the methods of synthesis of Nano-BC [104–106].

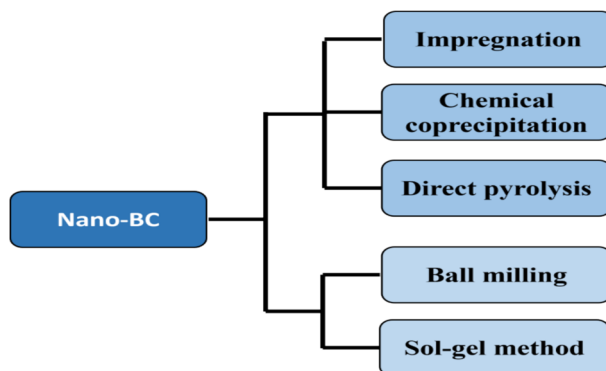


Fig. 3 Synthetic methods of nano-BC

While pyrolysis faces a major challenge in tar formation, which inhibits hydrogen gas yield, other thermochemical methods like torrefaction and hydrothermal carbonization present distinct advantages and drawbacks. Torrefaction serves as an alternative for upgrading biomass properties and is often more economical than pyrolysis. However, the process is time-consuming, taking from several hours to days, which increases operational costs and reduces overall efficiency. Furthermore, torrefaction equipment is more expensive, and the method does not fully decompose the biomass, resulting in a solid product with higher ash content [107]. In contrast, hydrothermal carbonization (HTC) does not require dry feedstock pretreatment and can directly convert wet biomass into biochar at a comparatively higher yield. This characteristic makes HTC highly advantageous for processing moist materials, simultaneously reducing waste and enabling the recovery of metals and other valuable components. The reaction conditions for HTC are also highly cost-effective [108]. Comparison of the conventional and advanced biochar synthesis methods are summarized in Table 1.

The nano-BC obtained through the impregnation method exhibits a highly functionalized surface; however, this approach suffers from poor control over nanoparticle size. In addition, the reducing agents commonly employed are often toxic, and their nature significantly influences the characteristics of the resulting BC nanoparticles [109]. In contrast, the co-precipitation method enables the synthesis of BC NPs with high purity and precise stoichiometry in a cost-effective manner. It also allows better regulation of particle size, and offers a high potential for direct nanoparticle formation in aqueous media [110]. The separation of nanoparticles and the formation of salt-rich by-products are major drawbacks of this method. Maintaining consistent product quality is also challenging, especially when precipitation occurs in a discontinuous manner. In the case of ball milling, nano-BC can be produced on a large scale with relatively small particle sizes; however, this method often leads to the formation of dense agglomerates. In the sol-gel approach, nano-BC is uniformly dispersed throughout the hydrogel matrix, yielding composites with homogeneous pores and excellent thermal and mechanical stability [104, 106].

Several modification strategies such as introducing -COOH groups or impregnating BC with metal species are commonly employed to enhance its adsorption performance. Transforming BC into nano-biochar (NBC) and incorporating multiple functional groups onto its surface further increases its adsorption capacity [111]. The presence of

Table 1 Conventional and advanced biochar synthesis methods' comparison

Characteristics and properties	Conventional biochar synthesis	Advanced biochar synthesis
Methods	Slow/fast pyrolysis, traditional kilns	Microwave-assisted pyrolysis, hydrothermal carbonization, co-pyrolysis
Heating	External conduction/convection	Volumetric/Internal (Microwave)
Reaction time	Slow	Fast
Energy efficiency	Lower	Higher
Feedstock	Dry, agricultural waste	Wet for HTC, complex mixtures
Specific surface area	Lower generally	Very high
Pores	Moderate	Highly porous
Functional groups	Mostly carboxylic/phenolic	Diverse (N-containing, O-rich)

reactive organic species and the reduction in hydrodynamic radius also contribute to improved adsorption behavior. Additionally, the inherent surface hydrophobicity, high specific surface area, and microporous structure of NBC enable it to effectively adsorb and immobilize a wide variety of pollutants [46, 112, 113]. A study reported the use of bamboo charcoal filler to modify polyurethane composite foam, which effectively removed seven organic solvents from wastewater [114]. The adsorption of various heavy metals (HMs) in water is influenced by several factors. The alkaline nature of biochar enhances the removal of Cd and Pb by providing additional binding sites and reducing competition from H⁺ ions. A higher specific surface area (SSA) further improves the adsorption of metals such as Cu and Cr. Additionally, dissolved organic carbon (DOC) can impact biochar’s adsorption efficiency due to its strong binding affinity toward Cu(II) [115].

Coupling agents facilitate chemical interactions with biochar through covalent bonding or strong non-covalent forces such as electrostatic attractions, hydrogen bonding, or hydrophobic interactions enabling effective surface modification (Fig. 4). An alternative strategy involves the direct immobilization of nano catalysts onto biochar, achieved through the pyrolysis of biomass that has been pre-impregnated with a metal salt precursor. Usually, these modifications alter the surface area, covalent interactions and increases the adsorption sites [116]. To enhance the adsorption of heavy metals and polar organic contaminants, biochar should be optimized for a high density of oxygen-containing functional groups, typically achieved through low-to-mid temperature pyrolysis. In contrast, for organic pollutants that rely on π–π interactions, biochars produced at higher temperatures which possess a more developed aromatic structure are more effective.

It can be concluded that the nanoscale modifications of biochar enhance the efficiency significantly via increasing specific surface area, porosity, and surface functional groups. The process or mechanism of actions shifts from only physical adsorption to combinations of electrostatic interactions, surface complexation and photocatalysis. In terms of

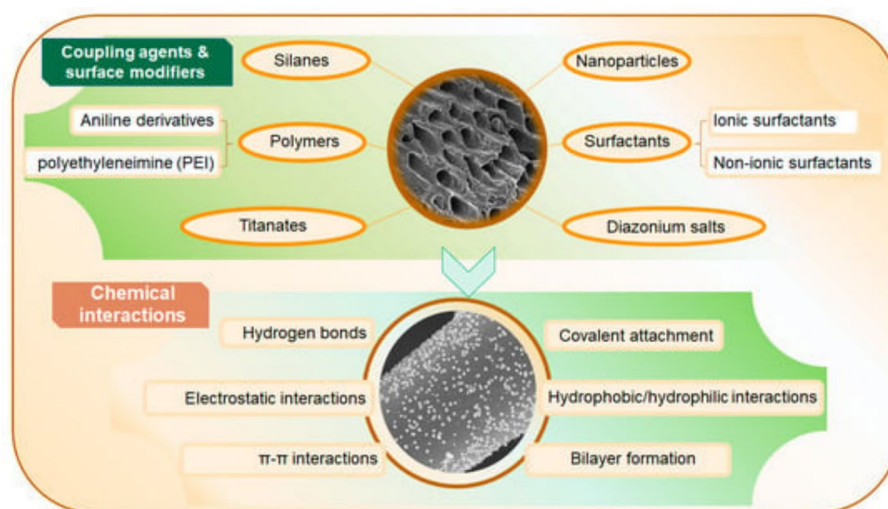


Fig. 4 Biochar surface treatment with coupling agents [116]

kinetics, adsorption rate increases owing to the characteristics of nanobiochar, and the reduced path of diffusion helps to achieve equilibrium in less time. Increased surface functional groups enhance the selectivity towards diverse contaminants, while the incorporation of nanomaterials (magnetic nanoparticles) helps in easy recovery and reusability of these adsorbents. Several modifications in nanobiochar are shown in Fig. 5 [117].

While nanobiochar offers superior performance due to its high specific surface area and enhanced mobility, its nano-scale properties introduce distinct environmental risks compared to bulk biochar. Key concerns include enhanced toxicity to soil microorganisms, potential contamination of the food chain, and the pollution of groundwater via vertical transport. The reduction of biochar to the nanoscale enhances its surface activity, which can subsequently boost toxicity. The resulting effects vary depending on factors such as species, biochar concentration, and type of exposure. Due to their size, nanoparticles of NBC penetrate organisms more easily, a key mechanism that may increase toxicity. Ultimately, whether these effects are toxic or stimulatory correlates significantly with the contaminants present in the biochar [118]. The properties of nanobiochar (nano-BC) and its subsequent impact on soil ecosystems are determined by both feedstock type and pyrolysis conditions. The type of biomass used to make nano-BC affects the amount and bioavailability of pollutants in it. Although nano-BC is widely accepted as an ideal candidate for pollution remediation, inappropriate selection of feedstock, preparation conditions, or techniques can inadvertently generate hazardous components, including heavy metals, polycyclic aromatic hydrocarbons (PAHs),

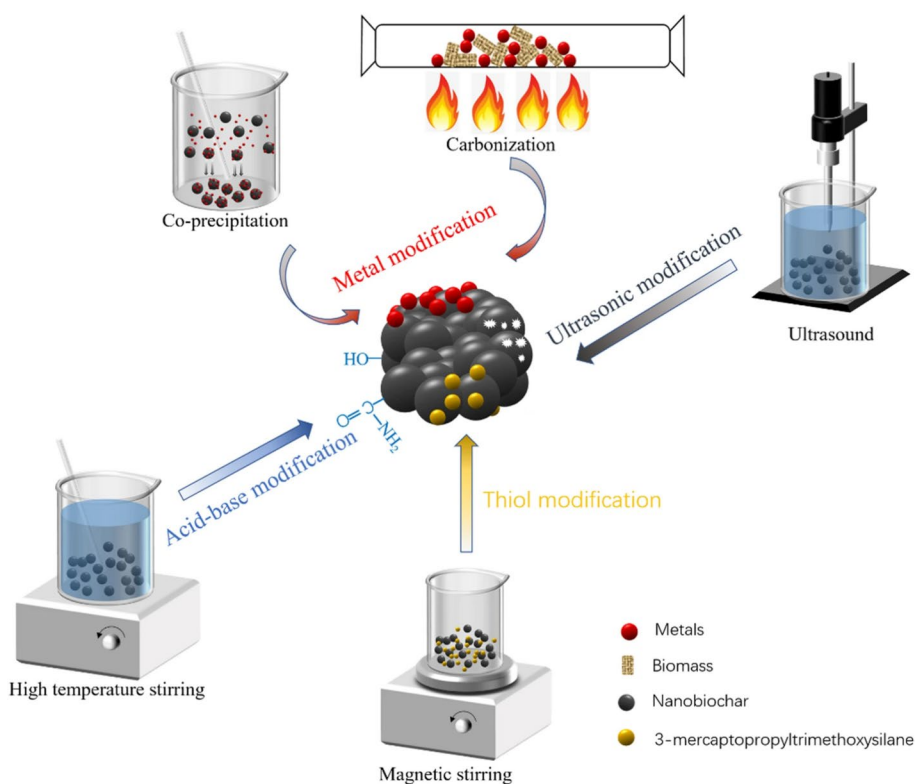


Fig. 5 Biochar and nanobiochar modifications [117]

environmentally persistent free radicals (EPFRs), dioxins, and perfluorochemicals (PFCs). The use of contaminated biomass with inherently high heavy metal concentrations can result in nano-BC that introduces or raises heavy metal levels in the environment. This occurs via leaching and other transport processes. Metal-laden nano-BC in the soil may migrate vertically into groundwater or be taken up by biota, where it poses a risk of bioaccumulation and subsequent enrichment through the food chain [119, 120].

4 Biochar from various sources and pollutants' removal

Water pollution is a critical global issue, particularly in low-income countries where most wastewater receives little to no treatment. Industries often discharge untreated effluents directly into rivers and streams, causing severe degradation of aquatic ecosystems. These contaminants persist in the environment, enter food chains, and pose serious health risks to all living organisms. To mitigate environmental pollution, researchers are increasingly using biochars (BCs) from various sources as cost-effective adsorbents for wastewater treatment. Owing to their tunable properties, BCs are applied to remove organic pollutants, metal ions, and metalloids from both water and air. Their low production cost has encouraged the exploration of diverse biomass feedstocks such as rice husk, orange peel, wood waste, pod husks, and sugarcane bagasse for synthesizing efficient BC-based adsorbents [121–133]. Their role in adsorption is discussed below.

4.1 Agro-waste biochar

Use of low-cost abundant biomass is highly recommended for sustainable environment protection. Teff straw was converted into BTS and HTS using pyrolysis and hydrothermal carbonization, respectively. BTS exhibited a heterogeneous surface and a larger surface area compared to HTS. XRD analysis revealed that HTS was primarily amorphous and mainly composed of $AlPO_4$, whereas BTS showed a crystalline structure with minimal impurities. Overall, the findings indicate that Teff straw is a promising, low-cost feedstock for producing activated biochars suitable for pollutant removal [134]. Corn husk, an agricultural by-product, has been used to produce impregnated-pyrolysis (IP) and pyrolysis-impregnated (PI) biochars for the removal of tetracycline (TCL) and levofloxacin (LEV) from wastewater. The PI biochar demonstrated significantly higher adsorption capacities for both antibiotics than the IP variant. LEV adsorption occurred mainly through hydrogen bonding, F-replacement, electrostatic attraction, and bi-dentate complexation, while TCL removal likely involved complexation, hydrogen bonding, and electrostatic interactions [135]. In another study, biochar derived from alfalfa hay was also employed for efficient TCL removal from water. The surface area and pore volume of alfalfa-derived raw biochar (BCR) were significantly improved through NaOH activation. The activated biochar exhibited a much higher tetracycline (TCL) adsorption capacity than the raw BCR and performed comparably to the commercial activated carbon Calgon F400. Kinetic and isotherm analyses indicated that strong chemisorptive interactions occurred between TCL and the NaOH-activated biochar through multiple adsorption mechanisms [136]. W. Mrozik et al. produced biochars from rice straw, corncobs, and coconut husks/shells to remove various pharmaceuticals from surface waters. Among the tested drugs, tetracycline (TCL) and enrofloxacin showed the strongest adsorption, with coconut husk biochar prepared at 750 °C performing as the

most effective adsorbent. The dominant adsorption mechanism was π - π stacking. Elevated salinity reduced the sorption of oxy-TCL, TCL, and enrofloxacin, but enhanced the adsorption of atrazine, diclofenac, and diuron. Pilot-scale canal water filtration at an aquaculture farm demonstrated that, under real environmental conditions, coconut husk biochar adsorbs pollutants at concentrations 10–500 times lower than those recorded in laboratory experiments [137]. S. Lata et al. employed iron-modified banana pith biochar for arsenic removal from water. Both the raw biomass and untreated biochar showed lower arsenate affinity than the Fe-impregnated material. The study demonstrated that Fe-loaded biochar provides an efficient and economical option for arsenic adsorption [138]. Similarly, Fe₂O₃-modified peanut husk biochar was tested for Cr(VI) removal from wastewater, showing maximum efficiency under acidic conditions ($\text{pH} < \text{pH}_{\text{pzc}}$). The adsorption capacities reached 8.51 mg/g for unmodified BCPH and 75.66 mg/g for the modified MBCPH, highlighting the significant improvement achieved through Fe₂O₃ modification [139].

4.2 Animal manure biochar

W. Huang et al. produced sheep manure (SMB500), pig manure (PMB500), and rabbit feces (RFB500) biochars at 500 °C for methylene blue (MB) adsorption. At an initial MB concentration of 50 mg/L and pH 11, adsorption reached equilibrium in ~210 min. The process followed pseudo-second-order kinetics involving film diffusion, surface adsorption, and intra-particle diffusion. SMB500 adsorption behavior fit the Freundlich model, while RFB500 and PMB500 aligned with the Langmuir model. Adsorption on all three biochars was spontaneous and endothermic, driven mainly by H-bonding and π - π interactions, with maximum regeneration cycles of 8 (SMB500), 5 (RFB500), and 3 (PMB500) [140].

Similarly, M. Idreed et al. synthesized guinea manure (GFM-BC) and cattle manure (CTM-BC) biochars for Cu²⁺ removal, achieving maximum adsorption capacities of 43.60 mg/g and 44.50 mg/g, respectively. Both followed Freundlich isotherms and pseudo-second-order kinetics, with thermodynamic results confirming spontaneous and exothermic adsorption [141].

4.3 Bagasse biochar

Sugarcane bagasse (SB) derived biochars were used to remove phenol from water after pyrolysis at 400 °C, 600 °C, and 800 °C. Among the untreated samples, SB pyrolyzed at 600 °C showed the highest phenol removal efficiency (74.2%). Further modification of SB600 with HNO₃ or NaOH improved its adsorption capacity, with HNO₃-treated calcined biochar achieving the highest efficiency (96.1%) [5]. In another study, SB biochar was produced at 500 °C for the adsorption of the insecticide carbofuran. SB500 exhibited greater adsorption under acidic conditions and reduced uptake in alkaline media. The Langmuir model indicated a maximum adsorption capacity of 18.9 mg/g at pH 6 and 45 °C. The spent biochar showed strong regeneration ability, recovering up to 96% of the adsorbed carbofuran. Both batch and fixed-bed experiments confirmed that SB500 is a sustainable and efficient adsorbent for carbofuran removal and recovery from aqueous systems [1]. K. O. Iwuozor et al. produced and characterized biochars from sawdust (SB) and ZnCl₂-modified sugarcane bagasse (SCB) using a low-temperature thermochemical

conversion reactor. The modified materials exhibited improved physicochemical properties, enhancing their potential for pollutant removal [142]. L. Bai et al. synthesized SB-based nano-Fe₂O₃-modified biochar composites via one-pot microwave-assisted pyrolysis for Cr(VI) remediation, achieving an adsorption capacity of 55 mg/g [143]. M. M. Jacob et al. evaluated SB-derived biochars for chlorpyrifos (CPS) removal from wastewater; three BC variants achieved ~89% removal from a 10 ppm solution, with a maximum CPS adsorption capacity of 3.20 mg/g. Thermodynamic analyses indicated that CPS adsorption was spontaneous, exothermic, and primarily governed by physisorption [144].

4.4 Paper waste biochar

Z. Xu et al. produced paper mill sludge biochar (PMSB) at 750 °C and further demineralized it with HCl to obtain DPMSB. PMSB achieved outstanding removal efficiencies for Cu, Zn, and As (all > 95%), while DPMSB showed reduced and variable performance, removing 40.92% Cu, 87.93% Zn, and 94.99% As. The adsorption of these metals followed the Freundlich isotherm, with pseudo-second-order kinetics fitting well for Zn and As, and the Elovich model best describing Cu adsorption [145].

F. Zhao et al. developed a ZnCl₂-modified paper and pulp sludge biochar through multistep pyrolysis for methylene blue (MB) removal. The Zn2PT 350–700 biochar exhibited a high adsorption capacity of 590.20 mg/g at pH 8 (10 mg dose, 24 h). MB adsorption conformed to the Freundlich model and pseudo-second-order kinetics, driven mainly by electrostatic attraction, cation exchange, and π–π interactions, with physical adsorption dominating the overall process [146].

4.5 Husk biochar

P. M. Sanka et al. investigated the removal of heavy metals from industrial wastewater using rice and corn husk biochars (BCs) pyrolyzed at 500 °C, 600 °C, and 700 °C. Rice husk BC produced at 600 °C showed the highest removal efficiencies for Cr (65%), Fe (90%), and Pb (> 90%), whereas corn husk BC at the same temperature exhibited much lower efficiencies (20% for Cr and ~35% for Pb). Overall, rice husk BC consistently outperformed corn husk BC, achieving maximum adsorption within 20–30 min [147].

To address phosphate pollution, rice husk was used to prepare a rice husk biochar–calcite composite (BRH-C), achieving a maximum removal efficiency of 87.3% and adsorption capacity of 1.76 mg/g at low PO₄³⁻ concentrations. BRH-C was most effective at 10–25 mg/L PO₄³⁻, while calcite performed better at 75–125 mg/L. Adsorption followed Freundlich isotherms and second-order kinetics, indicating heterogeneous multilayer chemisorption. However, the presence of salts (NaCl, NaNO₃, KCl, NaHCO₃) reduced phosphate uptake, and BRH-C maintained effectiveness for only two regeneration cycles [148]. M. Burachevskaya et al. assessed biochars (BCs) from wood, sunflower husks, and rice husks for soil remediation. Applied to Calcaric Fluvisol, the BCs significantly improved heavy metal adsorption for Cu(II), Zn(II), and Pb(II), with removal efficiency ranking as wood BC > rice husk BC > sunflower husk BC. All BCs achieved over 77% metal removal in contaminated soil [149]. P. Saravanan et al. used rice husk-derived BC to remove Basic Blue 41 (BB41) and Basic Red 09 (BR09) dyes from water. Under optimized conditions, the biochar removed 80% of both dyes, with maximum

adsorption capacities of 17.60 mg/g for BB41 and 168.49 mg/g for BR09. The negative ΔH and ΔG values indicated that the adsorption was exothermic and spontaneous at low temperatures [150]. Some agricultural waste based biochars and their characteristics are presented in Table 2.

4.6 Challenges and solutions of using nano-biochar

Surface-functionalized nano-biochar (NBC) exhibits a large specific surface area and uniform pore size, resulting in higher pollutant removal efficiency compared to raw biochar [158]. However, its practical application faces several challenges, including low production yield, poor stability, high mobility, precipitation, uncontrolled uptake and accumulation, potential toxicity, and difficulties in recovery [50]. Functionalizing NBC with specific groups can enhance its stability and effectiveness under diverse environmental conditions, but such modifications are still in the developmental stage, and further research is needed to bridge the gap between laboratory studies and field applications. Understanding the mechanisms of pollutant removal requires analyzing the BC network structure, surface functional groups, feedstock types, and synthesis parameters [159]. Scalable methods for NBC production must be developed, prioritizing green and sustainable approaches to minimize cross-contamination from synthesis chemicals. While NBC generally outperforms raw BC, comparative studies with other carbon-based nanomaterials are limited. Economic assessments of NBC synthesis are necessary, yet scarce data on large-scale production restrict accurate evaluation of cost-effectiveness. Additionally, NBC’s high adsorption capacity and transport may pose risks of cross-contamination in different ecosystems. Few studies have examined its toxic

Table 2 Synthesis of agricultural waste based biochars and their characteristics

Biomass precursor	Synthesis process	Properties and application	References
Teff straw	Pyrolysis, hydrothermal carbonization	heterogeneous surface and large surface area	[134]
Corn husk	Pyrolysis	higher adsorption capacity	[135]
Alfalfa hay	Pyrolysis and activation	Large surface area and pore volume, strong chemisorption capacity for tetracycline	[136]
Rice straw	Pyrolysis	conventional catalyst but little expensive	[151]
Rice husk	Flash pyrolysis	High char yield	[152]
Oat hull	Pyrolysis	High functionality, short residence time	[153]
Coconut husks/shells	Slow pyrolysis	High functionality, short residence time, and Low surface area	[154]
Peanut shell	Calcination at 723 K and then sulphonation	High catalytic activities	[155]
Animal manure	Pyrolysis at 500 °C	spontaneous and endothermic adsorption, driven mainly by H-bonding and π - π interactions	[140, 141]
Sugarcane residue	Pyrolysis	Large surface area and porosity, good catalytic activity	[5]
Wood saw dust	Pyrolysis	Oxygenated gasification biochar	[156]
Dried leaves	Slow pyrolysis	better activity, large surface area and porosity due to breakage of functional group	[157]

effects on flora and fauna, making thorough eco-toxicity assessments essential before widespread application [48, 160, 161].

5 Applications of biochar and composites

Biochar, a carbon-rich solid formed through the pyrolysis of biomass in an oxygen-limited environment, offers significant benefits when applied to soil, serving agricultural and environmental purposes alike [162, 163]. Biochar is typically sourced from wood biomass, crop residues, animal litters, and solid wastes through a range of thermochemical techniques, such as hydrothermal carbonization, fast pyrolysis, slow pyrolysis, torrefaction, flash carbonization, and gasification [164]. In recent times, significant research endeavors have focused on biochar-based adsorbents to eliminate contaminants. This approach offers mutually beneficial outcomes, aiding both carbon sequestration and water pollution control. Biochar’s abundant feedstock sources, cost-effectiveness, and advantageous physical and chemical surface properties have demonstrated significant potential for adsorbing water contaminants. The utilization of biochar in pollutants removal faces limitations due to its inherent properties derived from the original feedstock used in the pyrolysis process. The efficacy of biochar in removing different contaminants depends on its specific physical and chemical characteristics, significantly influenced by feedstock type, pyrolysis methods, and conditions [33, 165]. Raw biochar exhibits limited capacity to adsorb pollutants from aqueous solutions, especially in cases of highly concentrated polluted water. Furthermore, the fine particle size of powdered biochar complicates its separation process from the aqueous solution [98, 166]. Several investigations have been conducted to address the aforementioned challenges by developing engineered BCs with innovative structures and their surface properties [167]. Recently, significant research has focused on synthesizing biochar-based nanocomposites for wastewater contaminant removal. This approach not only enhances the physical and chemical properties of biochar but also creates a new composite that integrates the advantages of biochar with those of other nanomaterials [168].

Biochar can be produced from lignocellulosic crop residues, offering great potential to convert vast amounts of biomass waste into value-added resources, from Fig. 6. Biochar production is also advantageous because it takes place under oxygen-limiting conditions, resulting in significantly lower emissions of smoke, suspended particulate matter, and/or greenhouse gases compared to burning or passive composting of crop residues

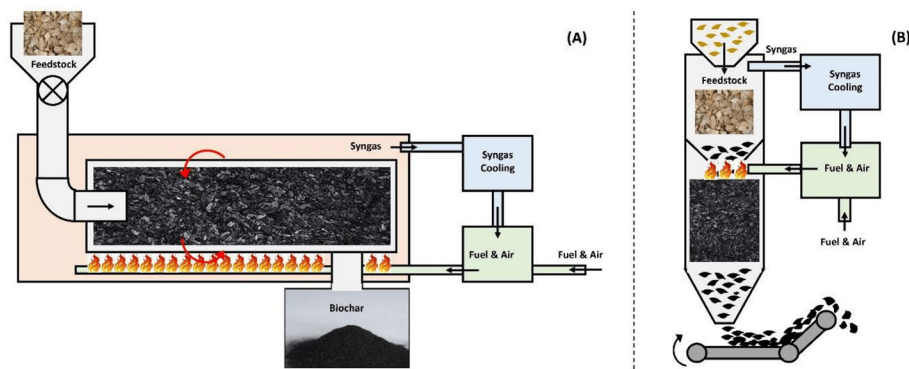


Fig. 6 Biochar production by pyrolysis **A** a horizontal pyrolysis reactor and **B** a vertical pyrolysis reactor [169]

[169]. Nano-biochar among biochars exhibits superior physicochemical properties compared to bulk biochar, including enhanced stability, large specific surface area, unique nanostructure, and high catalytic activity. A thorough understanding of ongoing nano-biochar research is essential for advancing towards real-world applications, encompassing aspects such as preparation methods, characteristic properties, and targeted applications [47, 48].

5.1 Heavy metals (HM) removal

HMs are toxic environmental pollutants that persist in both soluble and elemental forms. Rapid industrialization and improper waste management have exacerbated soil and water contamination by HMs such as Fe, Cu, Pb, and As. These metals are commonly detected in wastewater, where concentrations exceeding the permissible limit of 5 µg/mL pose significant risks to human health [170]. They can get accumulated to the higher tropic level of living beings through food chain [171]. Water is a fundamental resource for all life on Earth, and contamination with heavy HMs poses serious risks to human health, potentially causing chronic diseases and physiological disorders. Consequently, effective removal of these toxic pollutants from water sources is of critical importance. Arpita Roy et al., produced BC from the shoot and root cultures of in-vitro developed *P. zeylanica* to eliminate chromium (Cr) and cadmium (Cd) from synthetic wastewater. Their findings revealed that a pH of 7 and a BC dosage of 2 mg/mL resulted in the highest removal efficiency. Additionally, the shoot-derived BC demonstrated greater efficacy in removing both Cr and Cd compared to the root-derived BC [172]. Q. Ye et al., studies the Pb²⁺, Cd²⁺, and Ni²⁺ adsorption capacities of BC from cattle manure and cherry wood. Langmuir model occurred through the combination of physical and chemical adsorption [173]. A. Y. Li et al., prepared six different BCs from different raw materials for the removal of HM like cadmium, copper, and lead by loading Mg²⁺. Langmuir model is followed in adsorption which controlled by several interactions. Mg ion loaded BC makes complexes with heavy metals to perform strong ion exchange; that's why mineral precipitation and ion exchange played important role in the adsorption [174]. M. Khadem et al., used BC from jackfruit seed waste for several HM removal at pH 7. The adsorption was exothermic with Langmuir and pseudo second order kinetics followed [175]. S. K. Das et al., prepared BC from tree, weed and crop for the removal of Cd, Pb, Ni, Zn, Cu and As. All the BCs were effective in removing all the HM, but arsenic was the major one and Ni was the minor one. The total COD, total soluble solid, NH₃, total K and N, values decrease additionally the HM content in wastewater also decrease when wastewater pass through the BC filter [176].

5.2 Dye removal

Dyes are colored ionic organic compounds widely used in various industries. However, wastewater discharged from these industries contains numerous pollutants, including dyes, which pose significant environmental and health risks. These effluents adversely affect all living organisms, either directly or indirectly. Many synthetic dyes are known to be carcinogenic and mutagenic, making their removal from both drinking water and industrial wastewater critically important [177]. Hydrothermal carbonization was used to prepare litchi peel BC for the adsorption of congo red and malachite green dyes in

a study. The prepared BC possessed high surface area and pore volume, $1006 \text{ m}^2/\text{g}$ and $0.588 \text{ cm}^3/\text{g}$, and adsorption capacities for both dyes were 404.4 mg/g and 2468 mg/g . The reactivated BC completely removed the adsorbed dyes. The recycling of this BC did not cause secondary pollution also. Figure 7, showed the removal of both the dyes by optimized litchi peel BC [178]. P. Saravanan et al., prepared BC from rice husk for removal of basic red 09 and basic blue 41 from aqueous solution. Results showed that 80% dye removed at optimum conditions at $35 \text{ }^\circ\text{C}$ and pH 7. The Langmuir adsorption followed and optimized BC showed 17.5 mg/g and 168.5 mg/g maximum adsorption for both the dyes. Thermodynamic analysis revealed that the adsorption process was exothermic and occurred spontaneously at low temperatures [150]. G. Ravindiran et al., prepared activated BC from sewage sludge for the removal of acidic blue 210 and acidic blue 7. Pseudo second order kinetic model followed for removing nearly 99.0% acidic blue 210 and 94% acidic blue 7 dyes [179]. A. I. Abd-Elhamid et al., prepared rice straw pyrolyzed activated pre-source BC and milled-BC for the removal of crystal violet (CV) and MB dyes. The adsorption capacity was 91 mg/g for MB and 45 mg/g for CV. The two dyes were poorly adsorbed on to pre-source BC. The removal efficiency was nearly 95% and 93% in case of milled-BC and equilibrium reached within 15 min for both the dyes. The adsorption efficiency increased with rising pH, and the adsorption process was well described by the pseudo-second-order kinetic model [177]. A. Ahmad et al., worked on the removal of aqueous MB by using rice husk BC, cow dung BC and sludge BC. The removal efficiencies were 71–99% for rice husk BC, 97–99% for cow dung BC and 73–99% for sludge BC respectively, at pH 2–11 in 5 days. The adsorption data closely followed the Langmuir isotherm model and the pseudo-first-order kinetic model [180].

5.3 Excessive fertilizer removal

In the past decades, the exhaustive use of pesticides and fertilizers has abruptly increased the crop yield which resulted in the economic growth on cost of environment

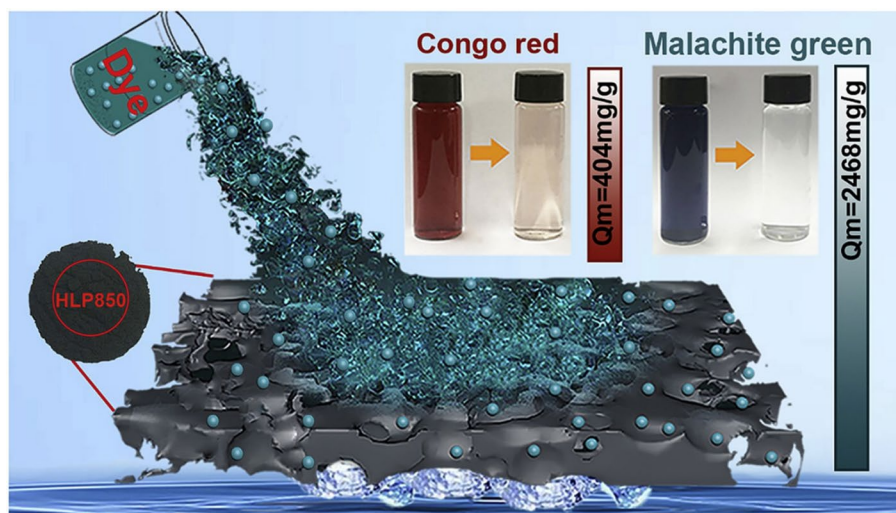


Fig. 7 Pictorial presentation of congo red and malachite green dyes removal by optimized HLP850 leechi peel biochar. Obtained from [178]

and its health. The excessive use of them creates an imbalance in soil quality, its acidification and salinization and excessive release of them in natural water can cause eutrophication which affects the quality of water as well as its ecosystem [181]. M. Liu et al. produced BC from dry sludge at varying pyrolysis temperatures and evaluated its effectiveness in phosphate (PO_4^{2-}) adsorption from aqueous solutions. The adsorption of phosphate increased with rising pH, reaching a maximum capacity of 51.79 mg/g, with the process following the Langmuir isotherm model and pseudo-second-order kinetics. Additionally, the phosphate-loaded BC exhibited a slow release of phosphorus, suggesting its potential as a sustainable fertilizer to enhance crop growth [182]. L. Shang et al. synthesized BC from waste spruce sawdust through nitric acid and sodium carbonate modification. The study revealed that NH_4^+ adsorption occurred predominantly via cation exchange mechanisms. Seedling growth experiments further demonstrated that the NH_4^+ -loaded BC could be recycled into soil as an efficient nitrogen fertilizer, enhancing its potential for sustainable agricultural applications [183]. Various sources of water are rich of nutrients like phosphate, nitrate, ammonium ion, etc. M. Marcinczyk et al., compared the pristine and modified BC in the recovery of nutrients from wastewater and they also studied the factors affecting adsorption. The adsorption was also found to be controlled by surface precipitation and ligand/ion exchange. Modification through metals increased the phosphate and nitrate adsorption. The desorption of nutrients was majorly dependent on pH. Figure 8 shows both pristine BC and engineered BC for the treatment of contaminated water. Different ways of nutrient-BC interactions showed in the figure. These interactions are usually used in pollutant removal. The figure also shows the disadvantages faced in the absence of BC [184]. B. Wang et al., group prepared BC from different feed stock and coal gangue for PO_4^- by one step pyrolysis. The maximum adsorption, 7.9 mg/g at pH 4.0, of modified BC was 4.6 times higher than pristine BC. The phosphate loaded BC can be used as a slow release fertilizer to promote seed germination [185].

5.4 Pharmaceutical pollutants removal

Antibiotics, extensively used in both humans and animals, are emerging pollutants that require urgent attention. Notably, most antibiotics are excreted in an unchanged form.

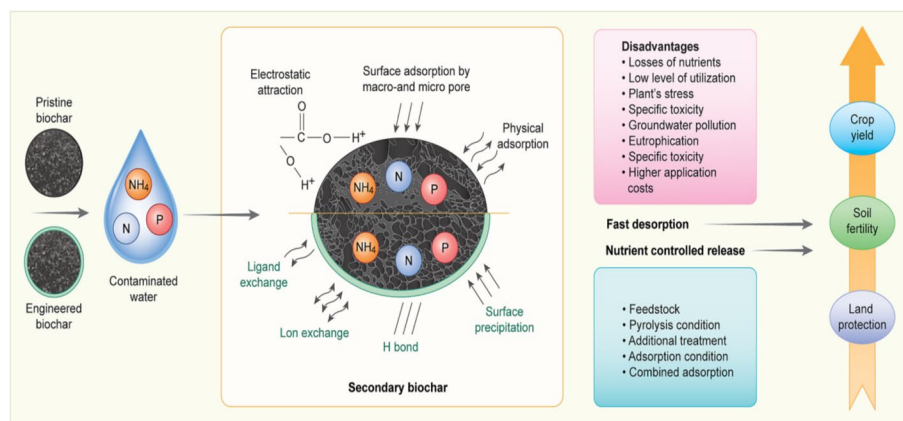


Fig. 8 Fertilizer based biochar obtained through adsorption via different mechanism. Obtained from [184]

Surface runoff generally leads to the release of a significant portion of antibiotics into the aquatic environment (Fig. 9), posing risks to both ecosystems and human health [186]. Furthermore, Cu is commonly added to livestock feeds as a growth stimulant, and antibiotics are administered simultaneously, resulting in the coexistence of antibiotics and heavy metals in aquatic environments. Antibiotics, being ionic compounds, have a tendency to form complexes with copper, potentially amplifying the risks and complicating pollution scenarios [187]. Therefore, effective processes must be developed to simultaneously remove antibiotics and Cu from aqueous environments. Currently, various treatment methods such as adsorption, biodegradation, and electrochemical techniques are employed to eliminate antibiotics and heavy metals. Among these, adsorption technology has attracted increasing attention due to its high removal efficiency and cost-effectiveness. Among the array of adsorbents available, biochar has emerged as a particularly noteworthy option due to its economic benefits, efficiency, and environmentally friendly nature, drawing even greater focus [188–190].

Antibiotics' presence in natural environment contributes to detrimental environmental impacts, including the development of resistance to antibiotics in bacteria and the disruption of endocrine systems in aquatic life [191]. Oxytetracycline, a widely used broad-spectrum antibiotic from the tetracycline group, is employed to treat various infectious diseases in both humans and animals, and has also been used as a growth promoter and food additive in livestock [192]. In a study, macro, colloidal, and nano biochar were prepared to evaluate the effect of particle size on oxytetracycline removal from urine waste. Colloidal biochar exhibited the highest removal capacity due to its large surface area, and low desorption was observed as a result of strong adsorption onto the biochar. The removal of other nutrients was around 20%, suggesting that the treated residue could be repurposed as a fertilizer [158].

Nanostructured biochar was developed from pomegranate peels in a study and that demonstrated high adsorption capacity (142 mg g^{-1}) for ciprofloxacin antibiotic. The adsorption capacity of nano biochar was found 26 folds higher than that of bulk biochar for ciprofloxacin. Adsorption studies concluded about hydrophobic and π - π

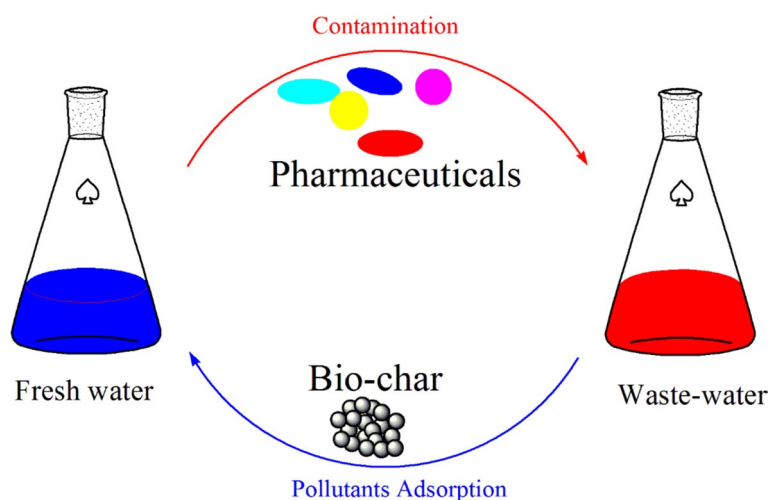


Fig. 9 Pharmaceutical pollutants' removal loop via adsorption on biochar

interactions (Fig. 10) responsible for antibiotic removal [193, 194]. Magnetic nano biochar was prepared by ball milling method for the removal of tetracycline and Hg(II) to reclaim polluted irrigation water. More than 268 mg tetracycline and 127 mg Hg(II) were removed by per gram of prepared nano biochar and that hybrid nano biochar composite was easily recovered with a magnet after use [195]. A novel nano-biosorbent of size in the range of 22.48–26.23 nm was prepared from crosslinked nano-silica with nano biochar and chitosan for the fast and efficient adsorptive removal of Congo red dye and erythromycin antibiotic pollutants. Pseudo-second-order model fitting confirmed the overall chemisorption phenomenon of adsorption involving hydrophobic and π - π interactions resulting into excellent removal efficiency from real water around 89–98% [196].

Nano-biochar not even removes the organic pollutant via adsorption but also via photo-catalytic degradation. Nano-biochar can provide excellent support for photo-catalysts such as ZnO. Nano-biochar/ZnO photo-catalyst were developed and employed for photo-catalytic breakdown of phenol. In the synthesis process of photo-catalyst, in-situ precipitation along with the carbonization processes was employed, utilizing carbon nanocomposites as both the template and the carbon source. Impressive results in stability and durability prospects were displayed by these composites, achieving a photo-degradation rate of 95%. This suggests that incorporating carbon nano-composites could effectively mitigate the ZnO photo-corrosion [197]. Recently, a novel core-shell phosphorus (P)-laden biochar/ZnO/g-C₃N₄ nanocomposite was developed, demonstrating exceptional catalytic performance for atrazine degradation and serving as a promising controlled-release nano-fertilizer to enhance P utilization efficiency. And atrazine photo-degradation reached its peak with rates as high as 85.3% within a duration of 260 min by photo-catalytic degradation through that composite [198].

5.5 Toxic gases removal

Hydrogen sulfide (H₂S) and carbon dioxide (CO₂) are widespread contaminants generated during oil and gas production and processing, wastewater treatment, fossil fuel combustion, and landfill gas emissions (Fig. 11). Their presence is expected to have corrosive effects, troublesome gas discharges, and pose safety hazards. Along with the light hydrocarbons, natural gas can contain varying concentrations of CO₂, water, nitrogen, sulfur compounds, aromatic compounds, and trace quantities of helium and mercury.

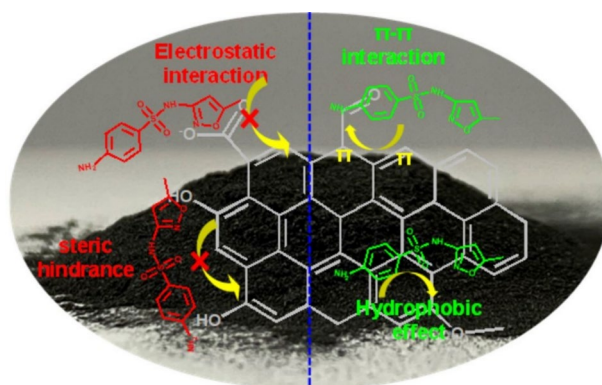


Fig. 10 Chemical interactions between pollutants and biochar

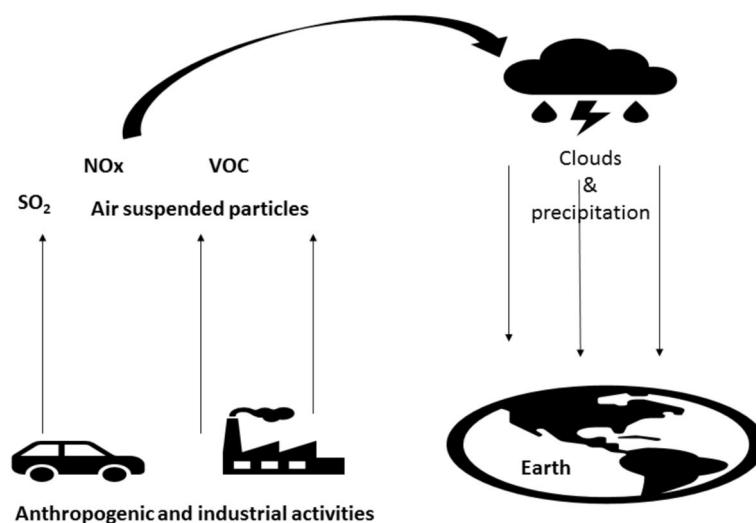


Fig. 11 Gaseous and air suspended pollutants' contribution to wastewaters

Several processes are employed to remove CO₂ and H₂S (acid gases) from natural gas, with absorption and adsorption being the most common. In absorption, solvents such as monoethanolamine and diethylamine are used to capture the acid gases. Although the selectivity of this type of separation is relatively high, still not considered as sustainable due to the associated cost for high energy requirements in solvent regeneration and space requirements [199, 200]. Another alternative to absorption is adsorption, where contaminants are captured from the gas mixture using porous solid adsorbents. Commonly employed adsorbents in the treatment of natural or produced gas to eliminate acid gases include those derived from carbon, silica, and metal–organic frameworks adsorbents. Porous solid adsorbents may possess amorphous and/or crystalline structures at both the macro- and nanoscale. Biochar, in particular, is primarily amorphous but contains localized crystalline domains of aromatic compounds. Since the feedstock and processing conditions influence the nature of biochar, it can exhibit diverse molecular architectures and variable topologies, making its characterization challenging [201–203].

Research literature shows that BCs are proficient at eliminating metal vapors, notably elemental mercury (Hg⁰), ozone, nitrogen oxides (NO_x), as well as acidic gases (H₂S, SO₂, CO₂), and various organic contaminants such as volatile organic compounds, aromatic compounds, and odorous substances. There are several mechanisms for the removal of gaseous contaminants, including precipitation, adsorption, and size exclusion were proposed in past. Potential industrial applications include the remediation of gaseous emissions from incinerators, waste-to-energy plants, kilns, biomass- and coal-fired boilers or cookers, cremation facilities, smelters, wastewater treatment plants, and agricultural operations such as livestock farming. The combination of these industrial applications, along with the renewable, cost-effective, and sustainable characteristics of BCs, suggests promising prospects for advancing and expanding biochar technology within the air pollution control industry [204]. Sulfur compounds in diesel fuel can generate SO_x gases during combustion, leading to significant environmental issues. Modified

nano biochar was developed in a study to remove sulfur gases from diesel fuel and the results demonstrated that total sulfur adsorption was spontaneous and proceeded via an endothermic process. Regeneration and reusability tests were found excellent after five sorption and desorption runs [205]. An electrochemical sensor based on nano-biochar, obtained from orange peel waste by hydrothermal carbonization 180 °C, was developed to determine sulphites and nitrites in water samples. Developed sensor exhibited excellent electrochemical properties for the detection of sulfites and nitrites in water. It demonstrated the promising capability of nano-biochar for the simultaneous electrochemical oxidation of sulphites and nitrites in real wastewater samples [206]. Nano-BCs not only helps in adsorption of pollutants from wastewater but also helps in controlling emission of pollutants via adsorbing gases in in the combustion of fuels, and so forth used as fuel additives also. Sugarcane nano-biochar was prepared as an excellent alternative to conventional metallic-based fuel additives. The impact of fusel oil ratio, concentration of sugarcane NBC, and engine speed on both the performance of the engine and the characteristics of exhaust emissions when operating a diesel engine were studied. Fusel oil/nano-BCs reduced NO_x emissions by up to ~20.51% and unburned hydrogen emissions by up to ~14.6%, while increasing CO emissions by up to ~33% [207].

5.6 Air suspended particles removal

Air deposition contributes to the presence of sulfur compounds, nitrogen compounds, mercury compounds, various heavy metals, as well as certain pesticides and industrial by-products. Large surface area and surface charge on nano-BCs is known to be responsible for excellent adsorption ability towards pollutants. Various functionalities developed on the surface of nano-BCs usually enhance the efficiency of adsorption via chemical or physical interactions. Electrostatic forces, hydrophobic and π - π interactions, ion exchange and coordination complexation type of interactions usually known in the category of chemical interaction while Vander walls forces are known for physical adsorptions [208]. A study reported the removal of Cd (II) from contaminated systems using ball milling synthesized nano-biochar embedded in Ca-alginate beads. Enhanced surface functionality (which is characterized by oxygen-containing groups such as carboxylic, hydroxyl groups etc.) facilitated effective sorption, promoting Cd(II)-Ca(II) ion exchange. pH-dependent changes in Cd(II) sorption underscored the importance of oxygen-containing surface groups [209]. Thiol-modified ball-milled BC developed for the elimination of Hg(II) and efficiency was found very well with a higher sorption rate of 320.1 mg g^{-1} , than unmilled BC (105.7 mg g^{-1}) [210]. The amino-functional silica-coated magnetic nano-BCs were derived from *Cynodon dactylon* in another study and showed enhanced adsorption rates, reaching upto 220.4 mg g^{-1} for Cu and 185.4 mg g^{-1} for Pb, respectively [211].

During decontamination process both the mechanisms i.e., adsorption and degradation play crucial role and there are factors which influence the superiority of one on another. For both the mechanisms, adsorption of contaminants over biochar materials carried out first and then degradation happen next with the help of microbes or the reactive species [36, 212]. Inorganic pollutants including heavy metals, and highly stable organic compounds follow adsorption mechanism predominantly. When the biochar system is modified to be highly catalytic or active for biological action, then

degradation mechanism is followed predominantly. Along with these, initial concentration of pollutants, their retention over adsorbents, and pyrolysis temperatures affect the decontamination mechanism. Higher initial concentration, flow rate, and lower pyrolysis temperatures promote adsorption mechanism [213].

5.7 Mechanisms involved in pollutants' removal

A set of physical and chemical mechanisms are involved in the removal of pollutants which utilize the characteristics including their high specific surface area (SSA), porous structure, and various functional groups on the surface. Both biochar and nanobiochar are known for their good adsorption properties. Since, nanobiochar have increased surface area over biochar, NBC offers enhanced surface reactivity and faster adsorption kinetics along with high mobility [214]. Physical adsorption is the primary mechanism which acts in both the cases of BC and NBC. Higher pyrolysis temperature suggested the higher adsorption capacities as discussed earlier. Electrostatic interaction between cationic pollutants (heavy metals and organic cations) and the negatively charged BC plays primary role, and lower pH media protonate the adsorbents and help to remove the anions as well. Oxygen containing functional groups help in direct ion exchange mechanism of pollutants' removal since some metal ions can form stable complexes. Graphene-like structure generated, act as electron donors, participate in π - π interactions to attract electron-deficient contaminants [157, 215]. NBC are supposed to have more exposed graphitic structure and higher surface area make them of highly efficient (Fig. 12). Furthermore, NBC can produce reactive oxygen species for catalytic degradation mechanisms for organic contaminants such as pesticides, pharmaceuticals and synthetic dyes.

6 Conclusion and future perspectives

The contamination of natural water resources poses severe risks to all living organisms and their surrounding ecosystems. This pollution primarily comes from industrial discharges and unchecked anthropogenic activities. These activities are depleting natural water resources, driving scientists to develop efficient methods for water decontamination and reuse. While various technologies exist to remove industrial pollutants, many remain economically unviable for large-scale application. So, researchers are looking for

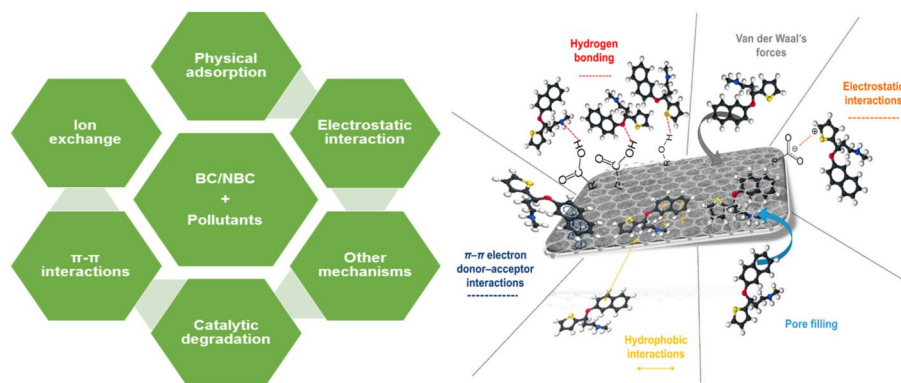


Fig. 12 Mechanisms responsible for pollutants' removal [157]

materials which are cost effective, and biomass/biochar emerges as a top priority for this job. This review article focuses on the in-depth studies about BCs including properties of BC, preparation methods of BC/nano-BC, and removal of different kinds of industrial pollutants by using BCs from different sources. Some review articles published earlier also discussed role of BCs in pollutant adsorption and removal of different kinds of contaminants like heavy metals, dyes, antibiotics, fertilizers, and toxic gases. Different modes of working of BC in pollutants removal or as a secondary fertilizer, and the parameters of pollutants' adsorption such as porosity of the material, the role of pyrolysis temperature to generate different pore size BCs are well discussed [36, 37]. Brief history, introduction and different preparation methods of BC have been discussed to set the background of research and it will give handy information about BC [56, 57]. Various methods for biochar (BC) production have been extensively explored, encompassing both traditional techniques and advanced approaches. Among different preparation methods, pyrolysis was thought to be the best of obtaining BC [61]. The by-products, charcoal, biogas, bio-oil, from BC preparation methods can be used in common household practices.

The techniques for transforming biochar into nano-BC are also explored, such as impregnation, co-precipitation, direct pyrolysis, ball milling, and the sol-gel method. Impregnation can be utilized to functionalize the surface of nano-BC and to increase the porosity, SSA and CEC. For generating nano-BC of highest purity and perfect stoichiometry, chemical co-precipitation can be preferred [195]. After preparing the nano-BC, membrane can be used to get the desired size nano-BC [101]. Ball milling is another method to produce nano-BC on a large scale and sol-gel is the method to produce nano-BC of excellent mechanical strength, high thermal stability and good adsorption capacity [102, 178]. Preparation methods greatly affect the adsorption process and sustainable use of nano-BCs and such are the techniques decided pre-fabrication to get best results for specific applications [48]. Discussion on various preparation methods of BC/nano-BC will be helpful to choose a best suited method for available feed stock of biochar. The effects of each pollutant on the life of individual beings have been discussed to validate the point that why it is important to remove the pollutants from the source of its origin and to remove them if they get accumulated into the different zones of environment. The kinetics and key parameters for pollutant removal are detailed in each respective section, providing useful insights for researchers. NBC can be used for the adsorptive removal of emerging pollutants. These emerging pollutants are a group of pharmaceuticals and personal care products (PPCPs), detergents, and pesticides [216, 217]. Antibiotics are another class of pollutants which are highly hydrophilic as well as resistant to biodegradation. These pollutants may enter the biosphere through potable water [218, 219]. Some emerging pollutants may interfere with the metabolic activities of human [220]. The removal percentage of tetracycline from drug polluted soil has increased with ball milled NBC to 96.36%, which was way higher than bulk BC [221]. This result was attributed to the increased activity of soil microorganisms through adsorption and degradation of TC by NBC [222]. NBC has also showed a considerable adsorption capacity, 609–2098 mg/kg for galaxolide, which was much higher than active carbon [223]. This review article additionally focuses on the use of biochar from different sources like agricultural waste, animal manure, bagasse, paper waste, and husk for the removal

of above-mentioned pollutants. This whole information will be helpful to give ideas to researchers to design their work to removal pollutants in specifically or generally.

A holistic approach to biomass utilization, one that maximizes biochar production alongside other value-added products while also enhancing biochar quality, can significantly improve the sustainability and efficiency of biorefineries. This can be achieved by fine-tuning every stage of the biorefinery process, from feedstock selection and co-product generation to optimizing pyrolysis conditions and integrating complementary technologies. Such strategies support a zero-waste model and create diverse revenue streams. As the biochar market continues to grow rapidly, future research should focus on understanding the long-term effects of biochar on carbon sequestration and its environmental applications [224]. Synthesizing biochar from valorized agro-waste is a practical application of circular economy principles, converting waste into a value-added product. This process advances sustainable waste management by reducing negative environmental impacts, protecting ecosystems, conserving natural resources, and encouraging responsible resource use. It supports environmental re-engineering that enhances resource recovery, advances a green and circular economy, and optimizes environmental management for sustained productivity across all sectors of human activity [225]. Engineering of designer biochars to achieve higher removal efficiency for heavy metals and organic pollutants like dyes and pharmaceuticals, integrating smart optimization techniques (e.g., machine learning), and technology expansion to remove emerging pollutants such as microplastics could be further future prospects in this area.

Large-scale biochar production from feed stock obtained from waste biomass offers a sustainable and cost-effective solution for wastewater treatment. This enables circular economy principles by transforming waste from agriculture, forestry, and sludge into valuable resources, along with the cost effectiveness over activated carbon. It provides significant carbon sequestration, while considering optimization of feedstock and management of operational energy. Sustainability assessment becomes important while choosing some new materials for the applications directly related to human health. Since BC and NBC plays great role in environmental remediation, waste minimization, helping soil fertility, contributing to resource circularity, there might be some challenges concerning sustainability. Optimizing pyrolysis parameters, evaluation of toxicity of BC/NBC, recovery of the pollutants and adsorbents, leaching of the loaded materials are to be evaluated to get benefits in accordance to sustainability.

Declaration of AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used AI in order to language editing. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Author contributions

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