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# Synthesis characterization and applications of nano biochar derived from waste biomass

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## Abstract

Biochar, a carbon-rich product of biomass thermochemical conversion, has been widely applied in soil amendment, carbon sequestration, water treatment, and environmental remediation. Converting biochar into nanoscale materials has attracted growing attention, as nanosizing and surface engineering can alter surface area, pore accessibility, surface chemistry, charge, and reactivity. However, the reported benefits of nano-biochar (N-BC) depend strongly on feedstock, processing conditions, particle size, functionalization, and application context, making cross-study comparison difficult. This review adopts a process–property–mechanism–performance–risk perspective rather than a descriptive synthesis-and-application summary. Top-down and bottom-up production routes, thermochemical conversion, activation, and functionalization strategies are examined for their effects on physicochemical properties and functional performance. Contaminant-removal mechanisms electrostatic interaction, pore filling, $\pi$–$\pi$ interaction, hydrogen bonding, ion exchange, surface complexation, precipitation, and redox processes-are analyzed in relation to contaminant type and environmental conditions, and N-BC performance is benchmarked against conventional biochar and other carbon-based adsorbents across water treatment, soil remediation, agriculture, catalysis, energy, and emerging biomedical applications. Laboratory findings are considered alongside nanoparticle mobility, aging, persistence, ecotoxicity, bioaccumulation, regeneration, recovery, and human-health risk, together with field-scale evidence and the challenges of synthesis reproducibility, standardized characterization, life-cycle assessment, techno-economic analysis, scalability, and regulatory governance. Based on this evaluation, the review outlines priority research needs, including standardized reporting protocols, realistic and long-term matrix testing, safe-by-design functionalization, recovery and regeneration strategies, integrated life-cycle and techno-economic assessment, and harmonized regulation. The proposed process–property–mechanism–performance–risk–deployment framework links material design to application performance and environmental safety, supporting the transition of N-BC toward responsible, commercially viable deployment.

**Keywords:** Nano-biochar, Biomass valorization, Adsorption mechanisms, Environmental remediation, Ecotoxicity, Life-cycle assessment

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## 1 Introduction

Biochar is a carbon-rich material produced through the thermochemical conversion of biomass under oxygen-limited conditions. Its porous structure, high carbon content, and diverse surface functional groups have made it attractive for applications in agriculture, environmental remediation, carbon sequestration, and water treatment. Recent advances in nanotechnology have enabled the development of nano-biochar (N-BC), a nanoscale derivative that exhibits enhanced physicochemical properties relative to conventional biochar [5, 15].

Compared with bulk biochar, N-BC possesses a markedly higher specific surface area, improved pore architecture, greater surface reactivity, more abundant functional groups, and enhanced catalytic activity. These characteristics increase the number of active adsorption sites and strengthen interactions with nutrients, pollutants, and biological systems, broadening its applicability across environmental, agricultural, biomedical, and energy-related fields. Compared with conventional carbon-based nanomaterials such as carbon nanotubes, graphene, and activated carbon whose synthesis is often complex and energy-intensive N-BC can be produced from renewable biomass through simpler, more cost-effective, and more environmentally sustainable routes [30, 87].

The physicochemical properties of N-BC vary considerably with feedstock type, production conditions, and post-synthesis modification. Elemental composition, surface charge, aromaticity, pH, cation exchange capacity, porosity, and zeta potential are key parameters governing adsorption efficiency and environmental behavior [32]. The nanoscale dimensions of N-BC also confer greater hydrodynamic mobility than conventional biochar, enabling enhanced transport through soil and aquatic environments and more efficient contaminant capture [60]. Surface engineering and functionalization strategies including metal oxide doping and amine-group modification have further improved its capacity to adsorb heavy metals and emerging contaminants [93]. For example, Vishnu et al. [79] developed a surface-engineered, super paramagnetic N-BC with amine-functionalized cobalt/ferrous silica coatings that showed superior copper and lead adsorption compared with unmodified biochar. More recently, biochar–metal nanoparticle composites have been shown to broaden this functional advantage further, improving the removal of heavy metals, organic contaminants, and other inorganic pollutants across aqueous, soil, and air matrices [6].

N-BC has consequently emerged as a promising material for removing heavy metals, pesticides, antibiotics, dyes, and other environmental contaminants, with its high adsorption capacity attributed largely to the abundant active sites generated during carbonization and nanoscale processing, which can increase surface area several-fold relative to conventional biochar [9]. Beyond remediation, N-BC has demonstrated potential for enhancing soil fertility, nutrient retention, plant growth, carbon sequestration, wastewater treatment, energy storage, catalysis, and biomedical applications. In soil systems specifically, recent work highlights that N-BC not only immobilizes contaminants through electrostatic adsorption, surface complexation, ion exchange, and precipitation, but can itself influence contaminant transport, rhizosphere pollutant interactions, and soil microbial and faunal communities, underscoring the need to evaluate its ecological footprint alongside its remediation benefits [93].

Despite this growing interest, significant challenges remain around scalable production, environmental fate, ecotoxicological impact, long-term stability, and human-health risk. The existing literature is fragmented across disciplines, and studies often differ substantially in synthesis routes, characterization approaches, and performance metrics, making it difficult to draw generalizable conclusions or compare findings across studies. This fragmentation has been corroborated by recent bibliometric evidence showing that N-BC research remains concentrated in a narrow set of environmental journals with limited cross-disciplinary integration, and that key aspects such as environmental risk and long-term contaminant transport remain comparatively underexplored relative to synthesis and short-term performance studies [86]. A critical, integrated synthesis of recent developments is therefore needed to consolidate current understanding, expose research gaps, and identify priorities for future work.

This review addresses that need by critically examining the synthesis approaches, characterization techniques, adsorption mechanisms, and emerging applications of N-BC. Particular attention is given to its role in environmental remediation, agriculture, healthcare, and energy-related technologies, alongside a critical assessment of current limitations, safety concerns, and the research and regulatory priorities required to support its transition toward sustainable, real-world deployment (Table 1).

## 2 Advanced techniques for nano-biochar production

Nano-biochar (N-BC) can be synthesized through a variety of physical, chemical, thermochemical, and biological approaches that enable precise control over particle size, morphology, porosity, and surface chemistry. These production techniques significantly influence the physicochemical characteristics and application potential of N-BC in environmental remediation, agriculture, catalysis, energy storage, and biomedical fields [59]. Depending on the synthesis strategy, N-BC production methods can be broadly classified into top-down, bottom-up, thermochemical conversion, chemical functionalization, and green synthesis approaches (Fig. 1).

**Table 1** Comparison of recent reviews on nano-biochar and the specific contribution of the present review

| Review | Main focus | Major contribution | Remaining limitation |
|---|---|---|---|
| Ramanayaka et al. [59] | Production, properties, applications, toxicity | Foundational overview | Limited recent evidence |
| Khare [27] | Production and feedstock–process–property relationships | Detailed synthesis perspective | Limited integration of risk and deployment |
| Bhandari et al. [9] | Production, characterization, environmental applications | Environmental perspective | Limited cross-sector comparison |
| Xu et al. [83] | Precursors, synthesis, functionalization, applications | Recent synthesis/application framework | Limited integration of standardization and deployment |
| Saraugi and Routray [64] | Sustainable production, scale-up, applications, risk | Sustainability and scale-up | Limited process–mechanism integration |
| Zhang [86] | Occurrence, transport, environmental risks | Soil environmental-risk perspective | Limited application-performance integration |
| Wang et al. [80] | Properties, feasibility, remediation, scalability | Engineering/deployment perspective | Primarily environmental-remediation focused |

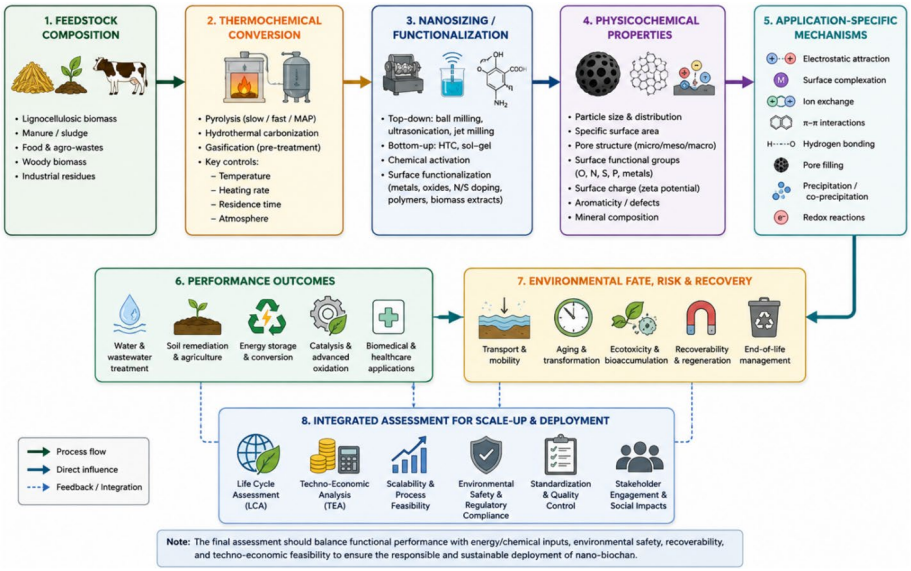



**Fig. 1** Process–property–performance framework for nano-biochar production

### 2.1 Top-down approaches

Top-down approaches convert pre-existing bulk biochar into smaller particles through mechanical or physical processes. Ball milling, wet milling, ultrasonication, centrifugation, and related separation techniques are among the most frequently reported approaches [58, 59].

Ball milling reduces biochar particle size through repeated impact, compression, and shear forces. It can increase accessible surface area and expose previously inaccessible pores; however, the magnitude of these changes depends strongly on the parent biochar and milling conditions. Systematic comparisons indicate that surface-area changes vary with feedstock, pyrolysis temperature, milling duration, wet/dry conditions, and milling intensity [58]. High-energy ball milling of oil-palm-derived biochar, for instance, produced particles of approximately 95 nm after 30 min and 30 nm after 150 min, but further milling promoted agglomeration and increased particle size, illustrating that milling duration and nanosizing efficiency are not linearly related. More recently, a one-step ball-milling protocol applied to rice-straw biochar demonstrated that resulting N-BC enhanced ammonium adsorption and reduced ammonia volatilization relative to conventional biochar, linking milling-induced property changes directly to functional soil performance [75]. Continuous ball-milling operation has also been reported to generate particles as fine as 10 microns while offering advantages in scale-up compared with double-disc milling, which remains less widely adopted owing to higher operating costs [64]. Thus, longer milling should not automatically be interpreted as better nanosizing, excessive milling can increase energy demand, broaden particle-size distributions, alter surface chemistry, and promote aggregation after dispersion.

Ultrasonication uses acoustic cavitation to disrupt aggregates and facilitate dispersion of fine particles. It is useful for laboratory-scale suspensions, but measured size depends on dispersion medium, sonication power, duration, concentration, and

analytical method. Reported N-BC size should therefore distinguish primary particle size from hydrodynamic aggregate size whenever possible.

Critical assessment: Top-down processing is relatively simple and compatible with existing biochar production, but it is strongly dependent on the starting material. Nanosizing may mainly expose existing pores and functional groups rather than create new chemistry. Improvements in adsorption should therefore be evaluated against surface area, pore volume, functional groups, aggregation, surface charge, and energy demand rather than particle size alone.

### 2.2 Bottom-up and hydrothermal approaches

Bottom-up approaches generate carbonaceous nanostructures from molecular precursors or biomass-derived intermediates. Hydrothermal carbonization (HTC) is particularly relevant because it can process wet biomass under comparatively mild conditions and generate carbon-rich materials with abundant oxygen-containing surface groups [83]. More aggressive variants have also been reported: bulk biochar produced from bovine dung and soybean straw has been digested in a high-pressure hydrothermal reactor with concentrated nitric and sulfuric acid to yield nanobiochar, illustrating that bottom-up and acid-assisted top-down elements can be combined within a single process [29]. Sophisticated bottom-up routes, including hydrothermal synthesis and microwave-assisted pyrolysis, continue to show promising results for tailoring nanostructure [54].

HTC changes the balance between carbonization and oxygen-containing functionality according to temperature, residence time, biomass composition, and reaction medium. It can therefore be useful where surface oxygen functionality and aqueous compatibility are important. However, HTC-derived nanocarbon can differ from mechanically milled pyrolytic biochar in aromaticity, pore structure, mineral distribution, and surface chemistry; the two should not automatically be treated as equivalent.

Sol–gel and related bottom-up approaches can provide greater control over particle formation and surface architecture and may be useful for hybrid materials. Their limitations include additional chemical precursors, solvents, catalysts, and processing steps, which can increase cost and environmental burden. Bottom-up routes therefore offer greater structural control but may sacrifice some of the simplicity associated with conventional biochar processing.

### 2.3 Feedstock selection as a primary determinant of N-BC properties

Feedstock selection is a major determinant of N-BC performance (Fig. 2). Agricultural residues, forestry biomass, food-processing wastes, animal manure, sewage sludge, and other residues differ in cellulose, hemicellulose, lignin, protein, ash, and mineral contents. These differences influence carbon yield, aromaticity, pore development, surface functional groups, mineral phases, and N-BC behavior [9, 27, 83].

Lignocellulosic feedstocks such as wood, rice straw, bamboo, corn residues, and coconut residues can generate carbon-rich materials with substantial aromatic structures, whereas manure- and sludge-derived materials generally contain more inorganic minerals. These phases can contribute to ion exchange, precipitation, complexation, and nutrient interactions, but may also introduce concerns regarding contaminant metals and ash-related effects.

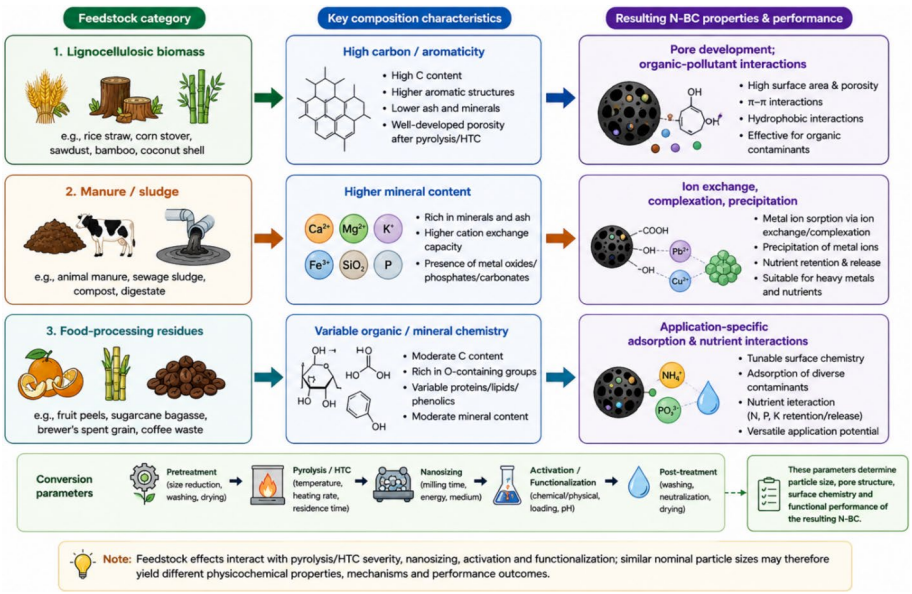



**Fig. 2** Feedstock-dependent pathways controlling nano-biochar properties and performance

Feedstock should therefore be selected according to the desired function rather than simple availability. Carbon-rich feedstocks may be useful where pore development and hydrophobic interactions are important; mineral-rich feedstocks may benefit nutrient retention or metal immobilization; and nitrogen-rich biomass may provide opportunities for N-containing functionalities. Waste streams containing undesirable contaminants require characterization before environmental application.

### 2.4 Thermochemical conversion and pyrolysis conditions

Thermochemical conversion determines the chemical architecture of the parent biochar before nanosizing. Pyrolysis temperature, heating rate, residence time, and atmosphere influence volatile loss, aromatic condensation, pore development, surface oxygen functionality, mineral transformation, and carbon stability.

Higher pyrolysis temperatures generally promote carbonization and aromatic condensation and can increase pore development through volatile release, but may simultaneously reduce some oxygen-containing functional groups. Therefore, higher temperature does not universally produce better N-BC. Materials intended for hydrophobic adsorption or high-temperature catalysis may benefit from greater aromaticity and stability, whereas complexation or hydrogen-bonding applications may benefit from retaining oxygen-containing groups.

Microwave-assisted pyrolysis can accelerate heating and reduce processing time, but claims of improved energy efficiency should be supported by energy balances rather than inferred from shorter reaction times. Sustainable comparison should consider energy per unit mass of N-BC, yield, downstream processing, and functional performance. Pyrolysis and nanosizing should therefore be considered interdependent processing steps.

### 2.5 Chemical activation and surface functionalization

Chemical activation can increase pore development and modify surface functionality through acidic, alkaline, oxidizing, or other treatments. These treatments may improve adsorption by increasing accessible porosity or introducing functional groups capable of binding specific contaminants.

Chemical activation involves a trade-off between functional enhancement and process burden. Chemical consumption, washing, wastewater generation, residual reagents, and neutralization can increase environmental footprint and production cost. Consequently, higher adsorption capacity after activation should not automatically be interpreted as greater sustainability.

Surface functionalization with iron, manganese, titanium, zinc, or other metal-containing phases can introduce redox activity, specific complexation, photocatalysis, or magnetic separation. Such engineered N-BCs can be useful for targeted applications, but stability and leaching of incorporated components must be evaluated under realistic conditions. A modification that improves contaminant removal may introduce secondary environmental risk if the functionalizing component is released during aging or regeneration.

### 2.6 Green synthesis approaches

Green synthesis aims to reduce hazardous chemical inputs through plant-derived compounds, microorganisms, natural polymers, or other renewable materials used as reducing, stabilizing, or functionalizing agents. These approaches may reduce chemical burden and align with circular-bioeconomy principles. Plant-extract-mediated synthesis, in particular, has been increasingly explored as an economical and environmentally friendly alternative to conventional chemical routes for nanomaterial functionalization more broadly, owing to the reducing and capping activity of plant-derived phenolics, flavonoids, and related biomolecules [55], analogous principles are increasingly being extended to biochar-based systems.

However, "green" should not automatically be equated with "sustainable." Assessment should include biomass/extract requirements, water consumption, energy demand, extraction and purification, reproducibility, waste generation, and scalability.

Plant extracts can vary in chemical composition with species, growth conditions, extraction method, and storage. Such variability can affect functionalization and reproducibility. Green synthesis therefore requires standardized protocols before meaningful interlaboratory comparison or industrial transfer.

### 2.7 Comparative evaluation of production routes

The choice of synthesis route should be based on a multi-criteria assessment rather than particle size or adsorption capacity alone (Table 2). Top-down approaches offer operational simplicity but may require substantial energy and can produce aggregation. Bottom-up and hydrothermal routes provide greater control over nanostructure and surface chemistry but may involve more complex processing. Thermochemical conversion offers feedstock flexibility and potential industrial integration, whereas chemical activation

**Table 2** Critical comparison of nano-biochar production strategies: process controls, property outcomes, advantages, limitations, and scale-up considerations

| Production strategy | Key process variables | Main property changes | Major advantages | Principal limitations | Scale-up considerations | Representative references |
|---|---|---|---|---|---|---|
| Ball milling | Milling time, speed, ball size, ball-to-biochar ratio, wet/dry medium | Reduced particle size; increased accessible surface area; altered defects | Simple; compatible with existing biochar | Energy demand; aggregation; broad size distribution | Energy consumption and continuous milling | Ramanayaka et al. [59], Rajput et al. [58] |
| Ultrasonication | Power, frequency, duration, concentration, medium | Improved dispersion; reduced aggregates | Useful for fine-particle dispersion | Reaggregation; energy demand; difficult scale-up | Reactor design and energy efficiency | Rajput et al. [58] |
| HTC | Temperature, pressure, residence time, biomass/water ratio | Oxygen-rich surface; altered carbon structure | Suitable for wet biomass | Pressure requirement; water handling | Reactor throughput and water management | Xu et al. [83] |
| Pyrolysis + nanosizing | Temperature, heating rate, residence time + milling conditions | Tunable aromaticity, porosity and surface chemistry | Flexible and potentially scalable | Multi-step processing | Integration of pyrolysis and nanosizing | Khare [27], Xu et al. [83] |
| Chemical activation | Activating reagent, concentration, impregnation ratio, temperature | Increased pore development and surface functionality | High adsorption performance | Chemical consumption and washing burden | Chemical recovery and wastewater management | Bhandari et al. [9], Xu et al. [83] |
| Metal/oxide functionalization | Metal loading, precursor, pH, temperature | Catalytic, magnetic or complexation sites | Application-specific functionality | Possible metal leaching and added cost | Recovery, stability and regulatory requirements | Xu et al. [83], Wang et al. [80] |
| Green functionalization | Extract composition, concentration, extraction conditions | Modified surface chemistry | Reduced hazardous reagents | Reproducibility and scale-up | Standardization of biological inputs | Xu et al. [83] |

can generate highly functional surfaces at the cost of additional chemical inputs. Green approaches can reduce hazardous reagents but face challenges in compositional variability, reproducibility, and scale-up.

Recent assessments increasingly indicate that a major barrier to N-BC commercialization is not simply producing nanoscale particles, but producing reproducible materials with predictable performance, acceptable environmental risk, recoverability, and economically viable processing requirements [64, 80].

Future production research should therefore move toward integrated process design in which feedstock selection, thermochemical conversion, nanosizing, functionalization, energy consumption, product recovery, and end-of-life management are evaluated together. This approach can support application-specific N-BC while avoiding the assumption that maximum surface area or minimum particle size necessarily represents optimal performance.

## 3 Adsorption mechanisms of nano-biochar (N-BC)

The adsorption behavior of nano-biochar (N-BC) arises from the interaction of its surface area, pore architecture, surface functional groups, aromatic domains, mineral phases, surface charge, and redox-active sites with target contaminants. Although nanosizing can increase the accessibility of reactive surfaces and modify colloidal behavior, enhanced adsorption should not be attributed to particle size or specific surface area alone. Adsorption performance is strongly dependent on feedstock composition, pyrolysis or carbonization conditions, nanosizing strategy, activation or functionalization, contaminant properties, and environmental conditions. Recent reviews and experimental studies demonstrate that N-BC can interact with heavy metals, nutrients, dyes, pharmaceuticals, pesticides, and other emerging contaminants through a combination of pore filling, electrostatic attraction, ion exchange, surface complexation, hydrogen bonding, π–π interactions, cation–π interactions, precipitation, and redox reactions [67, 76]. A recent systematic synthesis of 111 studies spanning 2013–2025 similarly confirms that electrostatic adsorption, ion exchange, co-precipitation, surface complexation, and redox reactions including Cr(VI) reduction to Cr(III)—remain the dominant mechanistic categories reported across the broader biochar literature, reinforcing that N-BC mechanisms build on, rather than depart from, established biochar chemistry [34].

Importantly, these mechanisms should not be considered mutually exclusive. For example, metal-ion removal may involve electrostatic attraction followed by ion exchange and inner-sphere surface complexation, with precipitation becoming important when mineral components and solution chemistry favor the formation of low-solubility phases. In contrast, adsorption of aromatic organic contaminants may involve pore filling together with π–π interactions, hydrophobic interactions, hydrogen bonding, and electrostatic effects. The relative importance of these mechanisms can change with pH, ionic strength, competing ions, dissolved organic matter, contaminant speciation, temperature, contact time, and aging of the N-BC.

Therefore, adsorption capacity reported from a single batch experiment should not be interpreted as a direct measure of intrinsic N-BC quality. Meaningful comparison requires consideration of the material's physicochemical characteristics and the experimental conditions under which adsorption was measured. This distinction is particularly

important because recent studies continue to report higher adsorption by N-BC than bulk biochar, but the magnitude of improvement varies considerably among contaminants and preparation routes. For example, recent rice-straw N-BC research demonstrated approximately 1.9-fold higher ammonium adsorption than bulk biochar, with physical adsorption, ion exchange, electrostatic interactions, and π–π interactions collectively contributing to the observed performance [75].

### 3.1 Physical adsorption, pore filling, and hydrophobic interactions

Physical adsorption involves relatively weak and reversible intermolecular interactions between contaminants and the N-BC surface. These interactions may include van der Waals forces, electrostatic attraction, hydrophobic interactions, and interactions associated with pore confinement. Pore filling is particularly relevant for small molecules that can access micropores and mesopores, where confinement increases contact with the internal carbon surface.

The nanoscale structure of N-BC can increase the accessibility of external and internal surfaces, but the relationship between specific surface area and adsorption capacity is not necessarily linear. A material with a high BET surface area may show limited adsorption of a particular contaminant if its pore-size distribution is incompatible with molecular dimensions or if its surface chemistry has low affinity for the contaminant. Conversely, a material with a lower surface area may exhibit strong adsorption when it contains appropriately positioned functional groups or mineral phases.

For aromatic organic contaminants, pore filling can operate together with hydrophobic interactions and π–π interactions. Thus, adsorption of dyes, pharmaceuticals, and pesticides should not be assigned solely to "physical adsorption" without considering molecular size, polarity, aromaticity, and the surface chemistry of the N-BC. Recent work on nano-biochar–contaminant interactions emphasizes that porosity and surface area provide the physical basis for adsorption but that multiple surface interactions determine the final sorption behavior [40, 92], pore filling and π-complexation have likewise been identified as principal mechanisms governing aromatic-organic uptake in related iron-modified biochar/hydrochar composites (Wang et al. 2025).

Critical interpretation: The frequently used statement that N-BC has superior adsorption because of its "high surface area" is therefore incomplete. Accessible pore volume, pore-size distribution, surface chemistry, and contaminant molecular dimensions must be evaluated together.

### 3.2 Electrostatic Interactions

Electrostatic attraction or repulsion is governed by the surface charge of N-BC and the charge/speciation of the contaminant. Surface charge is strongly affected by pH relative to the point of zero charge (pHPZC_{PZC} PZC) and by the ionization state of surface functional groups. At a pH below the pHPZC_{PZC} PZC, protonation may increase positive surface charge, whereas deprotonation at higher pH can increase negative charge.

This mechanism is particularly important for ionic contaminants. Negatively charged N-BC surfaces can favor the adsorption of cationic species such as $Pb2^{+}$, $Cd2^{+}$, $Cu2^{+}$, and $NH_4^{+}$, whereas positively charged or positively functionalized surfaces can enhance

uptake of anionic species such as phosphate, nitrate, chromate, and certain pharmaceutical anions. However, electrostatic attraction can be weakened by increasing ionic strength because dissolved ions compete for surface sites and compress the electrical double layer.

Consequently, adsorption experiments performed in deionized water may overestimate electrostatic contributions relative to natural waters containing competing cations, anions, and dissolved organic matter. The importance of electrostatic interactions should therefore be assessed using pH-dependent adsorption, zeta-potential measurements, ionic-strength experiments, and, where possible, surface spectroscopic evidence rather than inferred solely from adsorption capacity. Recent N-BC studies have identified electrostatic interactions as one component of multi-mechanistic adsorption systems rather than an independent mechanism operating in isolation [13], a conclusion echoed in recent reviews of biochar-based selective heavy-metal removal, which note that competitive adsorption among coexisting ions in real water bodies substantially interferes with electrostatically driven selectivity relative to single-solute laboratory systems [11].

### 3.3 Ion exchange

Ion exchange involves the replacement of exchangeable ions associated with N-BC by ions present in the surrounding solution. Exchangeable $H^+$, $Na^+$, $K^+$, $Ca2^+$, and $Mg2^+$ can participate in the uptake of metal ions or nutrient ions depending on the surface chemistry and mineral composition of the material. Oxygen-containing groups, including carboxyl, phenolic, and hydroxyl functionalities, together with mineral-associated exchange sites, can contribute to the cation-exchange capacity of N-BC.

The contribution of ion exchange is particularly important for metal ions and nutrient species. However, it should not be inferred solely from an increase in adsorption capacity. Evidence for ion exchange is stronger when adsorption is accompanied by measurable release of competing cations into solution, changes in surface composition, or spectroscopic evidence of altered surface coordination.

Recent studies demonstrate that ion exchange can occur simultaneously with electrostatic attraction and π–π interactions. For example, ball-milled rice-straw N-BC exhibited enhanced ammonium adsorption relative to bulk biochar, with ion exchange identified as one of the mechanisms contributing to adsorption [75, 96].

Critical limitation: The relative contribution of ion exchange depends strongly on the initial mineral composition of the parent biochar. Therefore, two N-BC materials with similar particle sizes can exhibit substantially different ion-exchange behavior if their ash and exchangeable-cation contents differ.

### 3.4 Surface complexation

Surface complexation involves the formation of coordination interactions between dissolved contaminants and reactive surface groups. Oxygen-containing groups such as carboxyl, phenolic, hydroxyl, and carbonyl functionalities can coordinate metal ions and form inner- or outer-sphere surface complexes. Nitrogen-containing groups introduced through functionalization may provide additional coordination sites.

Surface complexation is particularly relevant to the adsorption of $Pb2^+$, $Cu2^+$, $Zn2^+$, $Cd2^+$, and other metal ions. The strength and nature of complexation depend on pH,

metal speciation, surface-group density, and competing ions. Higher pH may promote deprotonation of acidic groups and increase metal binding, although precipitation can simultaneously become more important, making it difficult to assign removal exclusively to surface complexation.

Recent mechanistic assessments emphasize that metal adsorption by N-BC generally results from several concurrent processes, including complexation, ion exchange, precipitation, and electrostatic interactions [77], consistent with recent bibliometric reviews of modified-biochar heavy-metal remediation, which likewise identify complexation, co-precipitation, and ion exchange as recurring but rarely isolated mechanistic contributors across the aqueous-phase literature.

Therefore, claims that "complexation is the dominant mechanism" should ideally be supported by FTIR/XPS shifts, XAS where available, changes in surface elemental composition, pH-dependent adsorption, or other direct evidence, rather than by adsorption kinetics alone.

### 3.5 Hydrogen bonding

Hydrogen bonding can contribute to the adsorption of polar organic contaminants containing functional groups such as –OH, –NH, –COOH, and carbonyl groups. N-BC surfaces containing oxygen- and nitrogen-containing functional groups can form hydrogen-bond interactions with pharmaceuticals, pesticides, dyes, and other polar molecules.

The importance of hydrogen bonding depends on both the density and accessibility of donor/acceptor groups on the N-BC surface and the molecular structure of the contaminant. Hydrogen bonding can also interact with electrostatic and π-related mechanisms, making it difficult to isolate experimentally. Recent syntheses of N-BC adsorption mechanisms recognize hydrogen bonding as one of several mechanisms involved in organic-contaminant sorption, particularly where polar functional groups are present.

Critical interpretation: Hydrogen bonding should therefore be treated as a contributing interfacial interaction, rather than automatically classified as either purely physisorption or chemisorption.

### 3.6 π–π and cation–π interactions

Π–π interactions are important for contaminants containing aromatic rings. The aromatic and partially graphitized domains of N-BC can interact with the delocalized π-electron systems of aromatic pollutants through face-to-face or edge-to-face interactions. These interactions can contribute to the adsorption of polycyclic aromatic hydrocarbons, phenolic compounds, pharmaceuticals, dyes, and other aromatic molecules.

The strength of π–π interactions depends on the degree of aromaticity and graphitization of N-BC, the electronic properties of the contaminant, and the presence of electron-donating or electron-withdrawing substituents. Consequently, increasing pyrolysis temperature may alter π-related interactions by increasing aromatic condensation, but this may occur at the expense of some oxygen-containing functional groups [25].

Cation–π interactions can also contribute to the retention of positively charged species near aromatic carbon domains. Recent analyses of N-BC–contaminant interactions identify both π–π and cation–π interactions as relevant mechanisms, particularly for

aromatic organic contaminants and charged species, with cation-π bonding specifically highlighted alongside complexation and electrostatic interaction in recent comprehensive reviews of heavy-metal adsorption by biochar [34].

Thus, aromaticity should be considered together with surface oxygen functionality and pore structure rather than interpreted as an independent indicator of adsorption performance.

### 3.7 Surface precipitation and mineral-mediated immobilization

Surface precipitation differs fundamentally from simple surface adsorption because the contaminant is incorporated into a newly formed low-solubility mineral phase. N-BC derived from mineral-rich feedstocks can contain Ca, Mg, Fe, Al, carbonate, phosphate, silicate, and other inorganic constituents capable of participating in precipitation reactions.

For example, Ca-rich N-BC can promote formation of calcium-phosphate phases during phosphate capture, while Fe- and Al-containing surfaces can promote precipitation or strong retention of phosphate and oxyanions. Similarly, metal ions can become immobilized through carbonate, phosphate, hydroxide, or sulfide mineral formation when environmental conditions favor precipitation.

However, high removal percentages alone cannot distinguish adsorption from precipitation. Increasing pH, changes in dissolved Ca/Mg/Fe concentrations, solid-phase elemental mapping, XRD, XPS, or other spectroscopic/mineralogical evidence may be required to establish precipitation as a dominant pathway [62].

This distinction is particularly important for evaluating regeneration and long-term stability because precipitated contaminants may exhibit different release behavior from reversibly adsorbed contaminants.

### 3.8 Redox reactions and electron-transfer processes

Redox reactions represent an additional mechanism for contaminants whose oxidation state controls their mobility or toxicity. N-BC contains redox-active carbon domains, quinone-like structures, defects, and mineral phases that can participate in electron transfer. Functionalization with Fe, Mn, or other redox-active components may further enhance these processes.

Redox-mediated transformations are particularly relevant to species such as Cr(VI), As, and certain organic contaminants. Reduction of Cr(VI) to Cr(III), for example, can decrease mobility and toxicity while facilitating subsequent surface association or precipitation [34]. However, reduction does not necessarily imply permanent immobilization,the stability of the reduced species and its subsequent association with the N-BC must also be considered.

Therefore, redox transformation should be evaluated together with changes in contaminant speciation rather than inferred solely from total removal.

### 3.9 Synergistic and competitive adsorption mechanisms

In realistic systems, N-BC rarely removes contaminants through a single mechanism. Instead, several processes may operate sequentially or simultaneously. For heavy metals, a representative sequence may involve: electrostatic attraction → ion exchange →

surface complexation → precipitation whereas, aromatic organic contaminants may undergo: pore filling + hydrophobic interactions + π–π interactions + hydrogen bonding depending on molecular structure and N-BC surface chemistry.

The mechanisms can also compete with one another. For example, increasing ionic strength may suppress electrostatic interactions while promoting changes in contaminant speciation. Dissolved organic matter may compete for adsorption sites or coat N-BC surfaces, whereas coexisting metal ions may compete with organic contaminants for functional groups. Notably, a recent review of selective heavy-metal removal by biochar highlighted that most existing studies still focus on single-pollutant systems despite the fact that real water bodies typically contain coexisting multiple metal ions, and that competitive adsorption among these ions can significantly interfere with selective removal efficiency [12]. Similarly, aging of N-BC can oxidize or transform the surface, potentially increasing oxygen-containing groups while altering aromaticity, pore accessibility, aggregation, and contaminant affinity.

Therefore, adsorption measured in single-solute laboratory systems may not represent performance in wastewater, soil pore water, or natural waters containing multiple competing constituents.

### 3.10 Influence of environmental conditions on adsorption mechanisms

The contribution of individual mechanisms is strongly dependent on environmental conditions.

pH: pH affects N-BC surface charge; protonation/deprotonation of functional groups; contaminant speciation; metal hydrolysis; electrostatic attraction; ion exchange; surface complexation; and precipitation. Consequently, an increase in adsorption with pH should not automatically be interpreted as stronger surface complexation because increased pH may simultaneously promote metal hydroxide precipitation.

Ionic strength: Increasing ionic strength can compress the electrical double layer and alter electrostatic interactions. Competing ions may also occupy exchange sites or modify contaminant speciation.

Competing contaminants: In multi-contaminant systems, pollutants may compete for identical adsorption sites. Therefore, adsorption capacities derived from single-solute systems can overestimate performance under realistic conditions.

Dissolved organic matter: Dissolved organic matter may block pores, occupy reactive surface sites, alter colloidal stability, or form complexes with contaminants. It can consequently either suppress or enhance apparent adsorption depending on the contaminant and N-BC chemistry.

Temperature: Temperature can affect diffusion, pore accessibility, adsorption equilibrium, and reaction kinetics. Thermodynamic parameters should therefore be interpreted carefully because apparent enthalpy changes may reflect multiple simultaneous processes rather than a single adsorption mechanism.

### 3.11 Evidence strength for mechanistic assignment

A major limitation in the current N-BC literature is that adsorption mechanisms are sometimes assigned from adsorption capacity, kinetic models, or isotherm fitting alone. This is insufficient for definitive mechanistic interpretation.

For example:

- a pseudo-second-order kinetic fit does not by itself prove chemisorption;
- a Langmuir fit does not prove that adsorption occurs on a perfectly homogeneous surface;
- increased adsorption at higher pH does not prove surface complexation;
- high BET surface area does not prove pore filling is dominant; and
- high removal of a metal at alkaline pH does not necessarily distinguish complexation from precipitation.

Mechanistic conclusions become stronger when multiple independent techniques converge. Recent comprehensive reviews similarly call for greater use of molecular-level characterization tools—including XPS and XRD—to move beyond capacity-based inference toward direct mechanistic evidence. Recommended evidence includes:

| Proposed mechanism | Useful supporting evidence |
|---|---|
| Pore filling | BET, pore-size distribution, molecular-size comparison |
| Electrostatic interaction | Zeta potential, pH-dependent adsorption, ionic-strength experiments |
| Ion exchange | Release of $Ca^{2+}$/$Mg^{2+}$/$K^{+}$/$Na^{+}$, exchange-capacity measurements |
| Surface complexation | FTIR/XPS shifts, XAS, surface elemental changes |
| Hydrogen bonding | FTIR shifts, molecular structure and functional-group analysis |
| $\pi$–$\pi$ interaction | Aromaticity/graphitization characterization, molecular-structure comparison |
| Precipitation | XRD, SEM–EDS, elemental mapping, solution chemistry |
| Redox transformation | XPS/XANES or other oxidation-state analysis |
| Multi-mechanistic adsorption | Integration of complementary evidence rather than one measurement |

This evidence-based approach is important for distinguishing correlation from mechanism and substantially strengthens the scientific rigor of the review.

### 3.12 Critical comparison of adsorption mechanisms

The major adsorption mechanisms should therefore be interpreted according to contaminant class and material properties rather than ranked universally.

| Contaminant/material interaction | Dominant or potentially important mechanisms | Key N-BC properties | Major controlling conditions | Main uncertainty |
|---|---|---|---|---|
| $Pb^{2+}$, $Cd^{2+}$, $Cu^{2+}$ | Ion exchange, complexation, electrostatic attraction, precipitation | –COOH/–OH groups, CEC, minerals, charge | pH, competing cations, mineral composition | Relative contribution of complexation vs precipitation |
| Cr(VI) | Electrostatic attraction, reduction, complexation/precipitation | Positive sites, redox-active groups, Fe-containing phases | pH, redox conditions, Fe/mineral content | Long-term stability of reduced Cr |
| Phosphate | Electrostatic attraction, ligand exchange, precipitation | Ca/Fe/Al minerals, positive surface sites | pH, competing anions, Ca/Fe availability | Dependence on mineral phase |

| Contaminant/material interaction | Dominant or potentially important mechanisms | Key N-BC properties | Major controlling conditions | Main uncertainty |
|---|---|---|---|---|
| Ammonium | Ion exchange, electrostatic interaction, pore-associated retention | CEC, surface charge, pore structure | pH, competing cations | Performance in real wastewater/soil |
| Aromatic pharmaceuticals | π–π, pore filling, hydrophobic interactions, H-bonding | Aromaticity, porosity, functional groups | pH, ionic strength, DOM | Competition in real matrices |
| Dyes | Electrostatic attraction, pore filling, π–π, H-bonding | Charge, aromatic domains, pore structure | pH, dye charge, ionic strength | Aggregation and size exclusion |
| Pesticides/PAHs | Hydrophobic interactions, pore filling, π–π | Aromaticity, pore structure | Organic matter, concentration | Desorption and aging |
| Mixed contaminants | Multiple concurrent mechanisms | Heterogeneous surface/minerals | pH, ionic strength, DOM, competition | Mechanistic attribution |

### 3.13 From adsorption capacity to practical performance

The practical value of N-BC should not be judged exclusively by maximum adsorption capacity (qmaxq_{max} qmax). Other parameters—including adsorption rate, selectivity, performance in realistic matrices, regeneration efficiency, contaminant recovery, material recovery, stability, production energy, chemical consumption, and life-cycle impacts—must also be considered.

For example, a highly functionalized N-BC may exhibit greater adsorption capacity than unmodified material but require substantially more chemicals, washing, energy, or separation steps. Similarly, a highly mobile N-BC may improve contaminant contact while simultaneously increasing the risk of nanoparticle transport and contaminant co-migration in soil. Recent environmental-risk assessments emphasize that N-BC mobility can facilitate both beneficial contaminant interaction and undesirable environmental transport.

Thus, the optimum N-BC is not necessarily the material with the highest adsorption capacity, but the material that provides the best balance between adsorption performance, selectivity, regeneration, recoverability, environmental safety, energy demand, and economic feasibility. This distinction is essential for moving N-BC research from laboratory-scale adsorption experiments toward practical environmental deployment.

### 3.14 Critical synthesis

Overall, N-BC adsorption should be understood as a dynamic and multi-mechanistic interfacial process rather than a single adsorption phenomenon. The relative contribution of pore filling, electrostatic attraction, ion exchange, surface complexation, hydrogen bonding, π–π/cation–π interactions, precipitation, and redox reactions depends on the relationship among N-BC structure, surface chemistry, contaminant properties, and environmental conditions.

Recent literature supports the occurrence of multiple simultaneous mechanisms, but mechanistic certainty remains limited in many studies because adsorption is frequently inferred from kinetic or equilibrium models rather than demonstrated using

complementary physicochemical evidence [34]. Future studies should therefore combine adsorption experiments with spectroscopic, mineralogical, electrochemical, and microscopic characterization under realistic multi-component conditions.

This mechanistic perspective also provides a direct link to the broader process–property–performance–risk framework developed in this review: synthesis conditions determine surface and structural properties; these properties control contaminant interactions; environmental conditions determine the relative contribution of individual mechanisms; and the resulting performance must ultimately be evaluated alongside regeneration, recoverability, environmental fate, and life-cycle feasibility (Fig. 3).

## 4 Characterization of nano-biochar (N-BC)

Comprehensive characterization is essential for establishing the relationship between N-BC synthesis, physicochemical properties, functional performance, and environmental behavior. Unlike conventional bulk biochar, N-BC is strongly influenced by particle size, aggregation state, accessible surface area, pore architecture, surface charge, functional-group distribution, mineral composition, and colloidal stability. No single analytical technique can adequately describe all of these characteristics; therefore, a

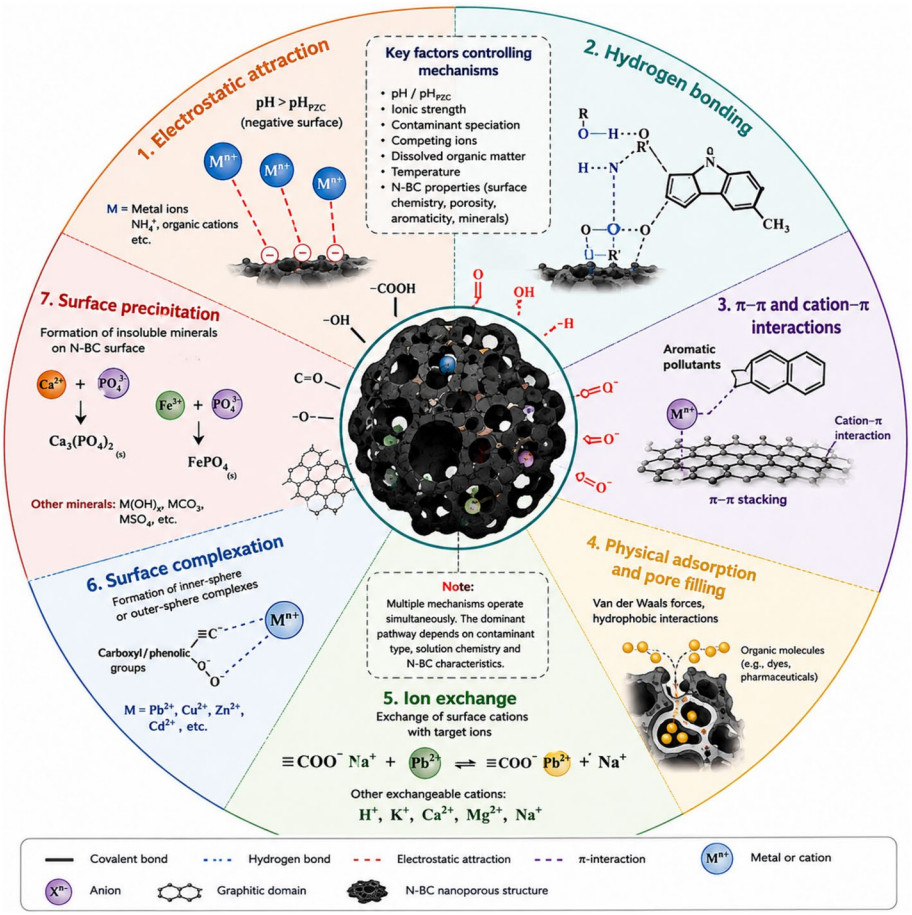



**Fig. 3** Illustrates the major adsorption mechanisms involved in contaminant removal by nano-biochar, including physical adsorption, chemisorption, ion exchange, surface complexation, precipitation, and π–π interactions

combination of morphological, structural, chemical, surface, and colloidal analyses is required [9, 58, 59, 83]. A recent Scopus-based bibliometric analysis of N-BC research spanning 2016–2025 confirms that terms such as pyrolysis, surface area, FTIR, particle size, and zeta potential remain central to the field's methodological core, while emerging thematic clusters increasingly emphasize soil-matrix interactions, microbial community effects, and biodegradation—signaling a shift from purely physicochemical characterization toward more holistic, ecosystem-level assessment [24, 33, 39 , 43, 49].

Importantly, characterization should not be treated simply as a collection of analytical measurements. The primary objective is to establish structure–property–function relationships. For example, particle-size reduction may increase accessible surface area but can also increase aggregation and environmental mobility; higher pyrolysis temperatures may increase aromaticity and structural stability while reducing some oxygen-containing functional groups; and chemical functionalization may improve contaminant affinity while increasing chemical inputs or the potential for leaching of incorporated components. Thus, characterization data should be interpreted in relation to the synthesis route, target application, environmental conditions, and potential risks rather than as isolated material descriptors.

A useful characterization framework for N-BC can therefore be organized into six complementary domains: (i) morphology and particle size, (ii) surface area and pore structure, (iii) surface chemistry and functional groups, (iv) elemental and mineral composition, (v) crystallinity and carbon structure, and (vi) surface charge and colloidal stability.

### 4.1 Morphology and particle-size characterization

Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are widely used to examine the morphology, particle dimensions, surface texture, pore architecture, and aggregation state of N-BC. SEM provides information about external morphology and surface structure, whereas TEM can provide higher-resolution information on nanoscale features and internal structures. These techniques are particularly useful for confirming morphological changes caused by milling, activation, pyrolysis, or functionalization [9, 58].

However, microscopy-derived particle size should not automatically be considered equivalent to the effective particle size of N-BC in environmental systems. N-BC particles can aggregate or form colloidal clusters in aqueous media, and their apparent hydrodynamic size may differ substantially from the primary particle dimensions observed by TEM or SEM. Recent soil-column transport studies illustrate this distinction directly: dynamic light scattering (DLS) measures the hydrodynamic diameter, which incorporates the surrounding electric double layer rather than the true particle diameter, and number-weighted rather than intensity-weighted DLS output is recommended for a closer approximation of actual N-BC particle size in migration studies [81]. Consequently, particle-size characterization should ideally be complemented by DLS, nanoparticle tracking analysis (NTA), or related dispersion-based techniques when environmental transport or suspension behavior is being evaluated.

This distinction is particularly important because nanosizing can simultaneously increase contaminant accessibility and environmental mobility. Experimental

soil-column studies have demonstrated that nano-biochar exhibits greater migration potential than conventional biochar, with transport influenced by particle size, surface charge, soil texture, moisture conditions, and water flow. Consequently, enhanced mobility may facilitate contaminant transport into deeper soil layers and potentially groundwater, emphasizing the need to evaluate the environmental fate of nano-biochar alongside its remediation efficiency [35]. Therefore, the desirable particle size for an adsorption application may not necessarily be the desirable particle size from an environmental-safety perspective.

Critical consideration: Reporting only a mean particle size is insufficient. Studies should preferably report particle-size distribution, aggregation state, measurement medium, dispersion protocol, and analytical method.

### 4.2 Specific surface area and pore structure

Brunauer–Emmett–Teller (BET) analysis is commonly used to determine specific surface area, while adsorption–desorption isotherms can provide information about pore volume and pore-size distribution. These parameters are highly relevant to contaminant adsorption because they determine the accessibility of internal and external surfaces.

Nanosizing can expose previously inaccessible surfaces and alter pore accessibility. However, specific surface area should not be regarded as a universal predictor of adsorption capacity. A material with a high BET surface area may exhibit relatively low adsorption for a particular contaminant if its pores are inaccessible or poorly matched to the molecular dimensions of the contaminant. Conversely, a material with a lower surface area may exhibit high adsorption when it possesses specific functional groups or mineral phases with strong chemical affinity. Comparative biochar characterization work illustrates this trade-off well: one recent reactor-effect study found that a biochar with the higher BET surface area (336 $m^2\ g^{-1}$ versus 299 $m^2\ g^{-1}$) did not necessarily dominate on every performance metric, since the two materials also differed in elemental composition, point-of-zero-charge, and surface charge heterogeneity, all of which independently influence ionic-contaminant removal [23].

Therefore, BET results should be interpreted together with micropore and mesopore volume; pore-size distribution; pore accessibility; surface functional groups; contaminant molecular size; surface charge; and adsorption performance. This is particularly important when comparing N-BC produced by different feedstocks or synthesis routes because apparent differences in BET area may arise from pyrolysis conditions, activation, ash content, degassing procedures, or nanosizing intensity rather than nanoscale dimensions alone.

### 4.3 Fourier-transform infrared spectroscopy (FTIR)

Fourier-transform infrared spectroscopy (FTIR) is widely used to identify surface functional groups such as hydroxyl, carboxyl, carbonyl, aromatic C=C, C–O, and other oxygen- or nitrogen-containing functionalities. These groups can participate in hydrogen bonding, electrostatic interactions, ion exchange, and surface complexation during contaminant adsorption.

FTIR is particularly valuable when used to compare N-BC before and after contaminant exposure. Changes in peak position, intensity, or band shape can provide

evidence that specific functional groups participate in adsorption. However, FTIR peak shifts alone should not be interpreted as definitive proof of a particular adsorption mechanism because several functional groups may contribute simultaneously.

For example, a change in the carboxyl band following metal adsorption may support surface interaction, but distinguishing surface complexation from ion exchange or precipitation requires complementary evidence such as XPS, elemental analysis, XRD, or solution-phase ion measurements.

Thus, FTIR is most informative when interpreted as part of a multi-technique mechanistic assessment rather than as an independent proof of adsorption mechanism.

### 4.4 X-ray photoelectron spectroscopy (XPS)

X-ray photoelectron spectroscopy (XPS) provides information on surface elemental composition and chemical states and is particularly useful for evaluating changes in surface chemistry following activation, functionalization, and contaminant adsorption.

XPS can help determine C/O/N/S ratios; oxidation states; metal incorporation; surface functional groups; changes in chemical bonding; and contaminant-associated surface species. For engineered N-BC, XPS is particularly valuable for determining whether metal or heteroatom functionalization produces the intended chemical modification. After adsorption, changes in the binding energies or relative abundance of C, O, N, S, Fe, Mn and other elements can provide stronger evidence for surface complexation or redox processes. Recent feedstock-blending studies further demonstrate the diagnostic value of combined XPS/FTIR/zeta-potential analysis: incorporating refuse-derived fuel into a biochar blend produced measurable shifts in surface nitrogen and calcium content alongside a reduction in oxygen-containing functional groups, changes that would not have been resolved by any single technique in isolation [52].

Nevertheless, XPS is a surface-sensitive technique and therefore provides information from only a shallow surface region. Results should consequently be integrated with bulk elemental analysis and other structural methods when evaluating heterogeneous N-BC.

### 4.5 X-ray diffraction (XRD) and mineralogical characterization

X-ray diffraction (XRD) is used to identify crystalline mineral phases and assess structural ordering within N-BC. This information is particularly important for mineral-rich N-BC because Ca-, Mg-, Fe-, Al-, Si-, and P-containing phases can substantially influence contaminant immobilization.

For example, the presence of Ca- or Fe-containing minerals may contribute to phosphate retention through precipitation, while Fe-bearing phases can influence adsorption and redox transformation of oxyanions and metals.

XRD can therefore help distinguish surface adsorption from mineral-mediated precipitation, especially when new crystalline phases appear following contaminant exposure.

However, XRD has limited sensitivity to poorly crystalline and amorphous carbon structures. Consequently, absence of a detectable diffraction peak should not be interpreted as evidence that a particular element or phase is completely absent.

### 4.6 Raman spectroscopy

Raman spectroscopy provides complementary information on the carbon structure of N-BC, particularly aromaticity, graphitic ordering, structural defects, and disorder. The D and G bands are commonly used to evaluate changes in carbon organization.

The ratio or relative intensity of these bands can provide information about the degree of structural disorder and graphitization. These characteristics are relevant to adsorption and redox behavior because aromatic domains may participate in π–π interactions and electron-transfer processes.

However, Raman parameters should not be interpreted as direct measures of adsorption capacity. Increased graphitic ordering may strengthen aromatic interactions but may also coincide with a reduction in certain oxygen-containing functional groups. Thus, Raman results should be considered together with FTIR/XPS data.

### 4.7 Elemental composition and mineral analysis

Elemental analysis and energy-dispersive X-ray spectroscopy (EDS/EDX) provide information on the elemental composition of N-BC. These measurements are important for evaluating C, H, N, O and mineral-associated elements and for verifying the incorporation of metals or other elements during functionalization.

EDS coupled with SEM can also provide spatial information through elemental mapping. This is particularly useful for determining whether functionalizing elements are uniformly distributed or concentrated in localized regions.

However, EDS is generally semi-quantitative and has limitations for light elements and very small surface regions. Consequently, EDS results should not be used as the sole evidence for elemental composition or chemical state. Bulk elemental analysis, XPS, ICP-based methods, or other complementary techniques may be required depending on the research question.

### 4.8 Surface charge, zeta potential, and colloidal stability

Zeta potential is particularly important for N-BC because nanoscale particles can remain suspended and undergo aggregation, transport, and deposition in environmental media. Zeta-potential measurements provide an indication of electrokinetic surface behavior and can help explain changes in dispersion stability and electrostatic interactions. Compared with bulk biochar, N-BC has been reported to exhibit greater zeta potential magnitude and smaller hydrodynamic radii, properties that directly enhance its capacity for controlled adsorption and release behavior, for example in agrochemical-carrier applications.

Surface charge can influence attraction or repulsion of ionic contaminants; aggregation; colloidal stability; soil mobility; interaction with dissolved organic matter; and adsorption under different pH conditions.

However, zeta potential is not equivalent to the absolute surface charge of a particle. Its magnitude depends on the dispersion medium, ionic strength, pH, particle concentration, and measurement conditions. This medium-dependence has also been demonstrated for engineered nanoparticles more broadly: atmospheric aging of nanoparticle surfaces has been shown to progressively alter zeta potential through hydroxylation and

organic-species adsorption, with the aged surface state reversible only through specific reconditioning treatments—underscoring that a single zeta-potential measurement captures only a transient surface state rather than an intrinsic material property [7].

Therefore, N-BC mobility studies should ideally report zeta potential together with pH, ionic strength, hydrodynamic diameter and aggregation state. This is particularly relevant to environmental-risk assessment because enhanced dispersibility may increase contaminant contact but can also increase nanoparticle transport.

### 4.9 Thermal stability and surface reactivity

Thermogravimetric analysis (TGA) and differential thermal analysis (DTA/DSC) can provide information on thermal stability, volatile fractions, organic-matter decomposition, and changes associated with functionalization. These measurements are useful when N-BC is intended for high-temperature catalytic or energy applications and can also provide information about the stability of surface modifications.

The thermal stability of N-BC should, however, be distinguished from its environmental persistence. A material that is thermally stable is not necessarily resistant to oxidation, microbial transformation, photochemical aging, or physicochemical alteration under environmental conditions. Recent work on biochar redox behavior specifically highlights that electron-exchange capacity and redox-active moieties are subject to aging effects that are not captured by thermal-stability metrics, and that quantifying these aging-dependent redox changes is essential for reliable long-term performance prediction [38].

Accordingly, thermal analysis should not be used as a surrogate for long-term environmental stability.

### 4.10 Characterization of functionalized and engineered N-BC

Characterization requirements become more stringent when N-BC is modified with metals, metal oxides, heteroatoms, polymers, magnetic phases, or other functional components. In such cases, it is necessary to establish not only whether the modification occurred but also where the functionalizing component is located, its chemical state, its loading level, its stability, and its potential for release.

A robust characterization strategy may therefore combine:

- SEM/TEM + EDS → morphology and elemental distribution
- BET → accessible surface area and porosity
- FTIR/XPS → surface functional groups and chemical states
- XRD → crystalline/mineral phases
- Raman → carbon structure and defects
- Zeta potential/DLS → surface charge and colloidal behavior

For metal-functionalized N-BC, leaching experiments under relevant pH and ionic-strength conditions should also be incorporated because improved contaminant removal may be accompanied by release of the incorporated metal.

### 4.11 Aging and post-application characterization

One major gap in the existing N-BC literature is that characterization is often performed only on the freshly synthesized material. However, N-BC properties can change after exposure to water, soil, oxygen, dissolved organic matter, microorganisms, repeated adsorption–desorption cycles, or other environmental stresses.

Aging can alter surface oxygen functionality; aromaticity; pore accessibility; aggregation; surface charge; mineral phases; contaminant binding; and colloidal mobility. Therefore, characterization before and after aging should be incorporated into long-term studies. This is particularly important because the material responsible for initial contaminant removal may not be chemically identical to the material present months or years after environmental application.

### 4.12 From individual measurements to an integrated characterization framework

A major limitation of N-BC research is that characterization data are often reported independently, making it difficult to establish clear relationships between material properties and functional performance. An integrated structure–property–performance framework is therefore needed to connect synthesis conditions with morphology, surface area, pore structure, surface chemistry, mineral composition, surface charge, and colloidal behavior [6, 15].

For nanosizing-based improvements, SEM/TEM, BET, pore-size distribution, zeta potential, FTIR, and XPS can collectively determine whether enhanced performance results from increased surface accessibility, pore development, altered surface chemistry, or electrostatic interactions. Importantly, increased surface area or reduced particle size alone should not be considered sufficient evidence of superior performance because aggregation, pore accessibility, and surface chemistry also influence adsorption [75, 81].

Similarly, FTIR, XPS, XRD, EDS, and BET can be integrated to distinguish the effects of functionalization on reactive groups, mineral phases, elemental composition, surface area, and pore structure. This is particularly important because engineered N-BC may improve contaminant affinity while simultaneously increasing synthesis complexity, chemical consumption, cost, or the risk of component release [6, 93].

Following contaminant exposure, changes in FTIR/XPS, XRD, SEM–EDS, and solution chemistry can provide complementary evidence for ion exchange, surface complexation, precipitation, and other immobilization mechanisms. Such evidence is more reliable than assigning mechanisms solely from adsorption capacity or kinetic and equilibrium models [34, 46].

Environmental stability should likewise be evaluated using zeta potential, DLS, aging, leaching, FTIR, XPS, and XRD to assess aggregation, mobility, surface transformation, contaminant retention, and release of functional components. This is particularly important because N-BC mobility may facilitate contaminant transport under certain soil and environmental conditions [81, 86].

Overall, N-BC characterization should move beyond isolated measurements toward an integrated feedstock and synthesis → material properties → mechanisms → functional performance → environmental fate and safety framework. Such integration can improve mechanistic interpretation, reproducibility, and application-specific material

**Table 3** Integrated characterization framework for nano-biochar: information obtained, relevance, limitations, and recommended complementary analyses

| Technique | Primary information | Relevance to N-BC performance | Key limitation | Recommended complementary analysis |
|---|---|---|---|---|
| SEM | Surface morphology, aggregation, particle dimensions | Morphological changes and surface structure | Limited internal/nanoscale information | TEM, DLS |
| TEM | Primary particle size, internal morphology | Confirms nanoscale structure | Sample preparation and aggregation artifacts | DLS/NTA, SEM |
| BET | Surface area, pore volume | Accessibility of adsorption sites | Surface area alone does not predict adsorption | Pore-size distribution, FTIR/XPS |
| DLS | Hydrodynamic size | Dispersion and mobility | Sensitive to aggregation and assumptions | TEM/SEM, zeta potential |
| FTIR | Functional groups | H-bonding, complexation and surface interactions | Peak overlap; indirect mechanistic evidence | XPS, adsorption experiments |
| XPS | Surface elemental composition and chemical states | Surface complexation, functionalization, redox | Surface-sensitive; limited depth | FTIR, XRD, ICP/EDS |
| XRD | Crystalline/mineral phases | Precipitation and mineral-mediated adsorption | Poor sensitivity to amorphous phases | XPS, SEM–EDS |
| Raman | Carbon ordering, defects, aromaticity | $\pi$–$\pi$ interactions and electron transfer | Indirect relationship with adsorption | FTIR/XPS |
| EDS/EDX | Elemental distribution | Metal/oxide incorporation and mapping | Semi-quantitative; limited light-element detection | XPS, ICP |
| Zeta potential | Electrokinetic surface behavior | Electrostatic interactions and colloidal stability | Medium-dependent | DLS, pH-dependent tests |
| TGA/DSC | Thermal stability and decomposition | Process stability and functionalization | Does not directly represent environmental persistence | Aging studies |
| ICP-based analysis | Bulk elemental/mineral composition and leaching | Metal loading and release | Requires digestion/extraction | XPS, EDS, leaching tests |

design while identifying the performance–stability–safety trade-offs associated with nanosizing and functionalization.

### 4.13 Critical comparison of characterization techniques

See Table 3.

### 4.14 Standardization and reporting requirements

A major challenge in comparing N-BC studies is the absence of fully standardized characterization and reporting practices. The same material may be reported using different particle-size definitions, BET protocols, dispersion conditions, surface-area measurements, and terminology. This limits reproducibility and can produce apparently conflicting conclusions.

Future studies should therefore report, at minimum: (1) feedstock identity and composition; (2) pyrolysis/HTC temperature and residence time; (3) nanosizing method and

operating conditions; (4) particle-size distribution and measurement method; (5) BET surface area and pore-size distribution; (6) surface functional groups; (7) elemental and mineral composition; (8) surface charge/zeta potential with measurement conditions; (9) aggregation/hydrodynamic size in relevant media; (10) aging and stability characteristics; (11) functionalization loading and leaching where applicable; and (12) adsorption/application performance under clearly defined experimental conditions.

Such standardized reporting would allow more reliable comparison among studies and facilitate the development of predictive structure–property relationships.

### 4.15 Critical synthesis

Characterization should therefore be regarded as the link between N-BC production and functional performance, rather than as a descriptive inventory of analytical measurements. Particle size determines part of the accessible interface, but surface area, pore architecture, surface chemistry, mineral composition, aromaticity, surface charge, and aggregation collectively determine how N-BC interacts with contaminants and environmental matrices.

Importantly, no single characterization parameter can establish superior N-BC performance. High BET surface area does not necessarily imply high adsorption capacity; nanoscale dimensions do not guarantee colloidal stability; the presence of functional groups does not by itself prove surface complexation; and thermal stability does not necessarily indicate environmental persistence. Mechanistic conclusions become more reliable when multiple independent characterization techniques converge on the same structure–function interpretation.

This integrated characterization framework directly supports the broader process–property–mechanism–performance–risk concept developed in this review. It also provides the analytical basis for evaluating whether engineered N-BC offers a genuine functional advantage over conventional biochar while maintaining acceptable environmental stability, recoverability, and deployment feasibility.

## 5 Action mechanisms of nano-biochar (N-BC) in various applications

The multifunctional performance of nano-biochar (N-BC) is governed by its unique physicochemical properties, including a high specific surface area, hierarchical porous structure, abundant surface functional groups, tunable surface chemistry, and enhanced catalytic activity. These characteristics facilitate efficient interactions with contaminants, nutrients, microorganisms, and biomolecules through multiple physicochemical and biochemical processes [59]. Unlike conventional biochar, the nanoscale dimensions of N-BC provide a greater density of reactive sites and improved mass transfer, thereby enhancing adsorption capacity, catalytic efficiency, electron transfer, and molecular interactions.

The mechanisms underlying the diverse applications of N-BC include adsorption, ion exchange, surface complexation, precipitation, catalytic oxidation, redox reactions, electron transfer, nutrient retention, controlled release, and antimicrobial activity. These processes collectively contribute to the efficient removal of environmental contaminants, improved nutrient-use efficiency, enhanced soil fertility, pathogen suppression, and superior electrochemical performance. Consequently, N-BC has emerged as

**Table 4** Characterization techniques commonly used for nano-biochar and the information obtained

| Technique | Property measured | Information obtained | Major applications |
|---|---|---|---|
| BET | Surface area | Porosity, pore volume | Adsorption studies |
| SEM | Morphology | Surface texture, particle size | Material characterization |
| TEM | Nanostructure | Internal morphology | Nanomaterial analysis |
| FTIR | Functional groups | Surface chemistry | Adsorption mechanism |
| XRD | Crystallinity | Mineral phases | Structural analysis |
| Raman | Graphitization | Carbon defects | Carbon structure |
| XPS | Surface chemistry | Chemical bonding | Functionalization |
| EDX | Elemental composition | Elemental mapping | Doping confirmation |
| Zeta Potential | Surface charge | Colloidal stability | Suspension stability |

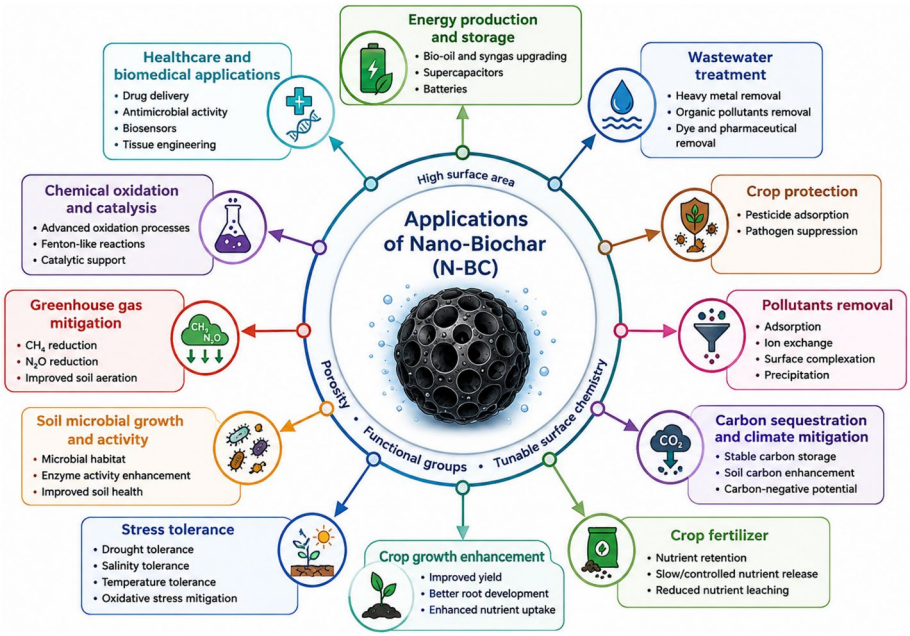



**Fig. 4** Schematically illustrates the major application domains of nano-biochar

a versatile nanomaterial with significant potential in environmental remediation, water and wastewater treatment, sustainable agriculture, catalysis, energy storage, and biomedical engineering.

The following sections comprehensively discuss the principal action mechanisms governing the performance of N-BC across these application domains, highlighting the underlying mechanisms, recent technological advances, and future prospects (Table 4 and Fig. 4).

## 6 Application-specific action mechanisms and performance of nano-biochar

The multifunctional behavior of nano-biochar (N-BC) is determined by the interaction between its surface chemistry, pore architecture, aromatic carbon domains, mineral composition, surface charge, redox activity, and nanoscale dispersion and the

characteristics of the target application. These properties can facilitate adsorption, ion exchange, surface complexation, precipitation, electron transfer, catalytic oxidation, nutrient retention, controlled release, and interactions with biological systems. However, the contribution of individual properties differs substantially among applications, and increased nanoscale surface area does not necessarily translate into superior performance under all conditions.

A critical assessment of the literature indicates that N-BC performance is highly application- and matrix-dependent. In water treatment, for example, surface functional groups, mineral phases, pore accessibility, and surface charge determine interactions with metals, nutrients, dyes, and pharmaceuticals. In catalysis, redox-active sites and incorporated metal or metal-oxide phases may be more important than surface area alone. In agriculture, the relevant properties extend beyond adsorption capacity to include nutrient retention, soil aggregation, water availability, microbial interactions, plant uptake, and potential nanoparticle mobility. Similarly, biomedical applications require substantially greater consideration of biocompatibility, dose, degradation, sterilization, and long-term safety than is generally required for environmental adsorption.

Consequently, reported performance values should not be directly compared without considering feedstock, synthesis conditions, particle size, functionalization, contaminant concentration, pH, ionic strength, contact time, application matrix, and experimental scale. A high removal efficiency obtained in a single-solute laboratory system, for example, may not translate into equivalent performance in real wastewater containing competing ions and dissolved organic matter. Similarly, an engineered N-BC with improved functional performance may require additional chemical modification, energy input, or downstream recovery. The following sections therefore evaluate N-BC applications from both mechanistic and translational perspectives.

### 6.1 Air-pollutant adsorption and remediation

N-BC has been investigated for the capture and transformation of airborne pollutants because its porous structure and surface chemistry can provide accessible sites for interactions with volatile organic compounds (VOCs) and particulate pollutants. The removal of gaseous contaminants is primarily associated with pore filling, van der Waals interactions, hydrophobic interactions, and surface-specific interactions, while catalytic or photocatalytic N-BC composites may additionally promote chemical transformation of adsorbed pollutants.

Bhandari et al. [9] reported a toluene adsorption capacity of approximately 120 mg $g^{-1}$ for corn-stover-derived N-BC, compared with reported values of approximately 20–60 mg $g^{-1}$ for conventional biochar under different preparation and experimental conditions. Although this comparison suggests an advantage of nanosizing, the values should not be interpreted as a universal N-BC-to-biochar performance ratio because the reported materials may differ in feedstock, surface area, pore structure, pyrolysis conditions, and adsorption protocols. The reported N-BC surface area of approximately 300 m2 $g^{-1}$ provides a plausible structural basis for enhanced adsorption, but surface chemistry and pore accessibility may also contribute substantially.

Zhang et al. [88] reported an agricultural-waste-derived N-BC with a specific surface area of approximately 350 m2 $g^{-1}$ and a reported formaldehyde adsorption capacity of

approximately 150 mg $g^{-1}$. The reported enhancement under mildly acidic conditions illustrates the importance of environmental conditions in controlling pollutant–surface interactions. However, laboratory adsorption capacities obtained under controlled atmospheric conditions should not automatically be extrapolated to indoor or industrial environments where humidity, co-contaminants, temperature fluctuations, and continuous flow can alter adsorption performance.

Beyond passive adsorption, engineered N-BC can act as a catalyst or catalyst support. Li et al. [37] reported approximately 90% benzene degradation using iron-oxide-doped N-BC under UV irradiation. The enhanced performance was associated with increased surface area and catalytic reactivity. In such systems, however, the contribution of adsorption should be distinguished from that of catalytic degradation because rapid initial pollutant removal may partly reflect surface uptake rather than complete mineralization.

N-doped biochar has also been explored for particulate-matter capture, including $PM_{2.5}$ [74]. The porous structure can facilitate particle retention, but practical deployment requires evaluation under continuous-flow conditions, realistic humidity, pressure drop, regeneration, and long-term structural stability.

Critical assessment: The available evidence indicates that N-BC can provide advantages for air-pollutant removal, but the current evidence is predominantly laboratory-based. Future research should prioritize continuous-flow testing, humid-air conditions, regeneration, competitive adsorption, pressure-drop analysis, pollutant breakthrough curves, and long-term stability. For catalytic systems, studies should additionally quantify pollutant mineralization and catalyst stability rather than relying only on percentage removal.

### 6.2 Contaminated-water treatment

Water and wastewater treatment represents one of the most extensively investigated applications of N-BC. Its performance against heavy metals, organic pollutants, dyes, pharmaceuticals, and nutrients results from the combined effects of surface complexation, ion exchange, electrostatic interactions, pore filling, π–π interactions, hydrogen bonding, mineral precipitation, and, in engineered systems, redox or catalytic transformation.

Giannakoudakis et al. [19] reported lead adsorption capacities approaching 200 mg $g^{-1}$ for agricultural-waste-derived N-BC. Bhandari et al. [9] further highlighted ion-exchange contributions in the removal of cadmium and arsenic. Tayyab et al. [76] reported lead and cadmium removal efficiencies of approximately 96% and 91%, respectively, under specific pH conditions, with complexation proposed as an important mechanism. These findings are broadly consistent with recent syntheses of the wider biochar literature, which report that engineered or modified biochars can achieve heavy-metal removal efficiencies in the region of 75–95%, and that nano-architected or surface-functionalized variants specifically can raise adsorption capacity substantially above unmodified biochar—for example, a biochar–ZnS nanocomposite reportedly achieved sorption capacities roughly tenfold higher than the unmodified parent material [57, 85]. A recent meta-analysis spanning multiple modification strategies similarly found that, relative to pristine biochar, modification increased aqueous-phase heavy-metal adsorption capacity

by approximately 208% and removal rate by 110% on average, reinforcing that reported N-BC advantages should be benchmarked against this broader modified-biochar baseline rather than against pristine biochar alone [17, 18]. These findings demonstrate the capacity of N-BC to interact strongly with metal contaminants, but the different studies also illustrate why direct comparison of adsorption values is problematic. Adsorption capacity is influenced by initial concentration, pH, adsorbent dosage, contact time, competing ions, temperature, and the chemical composition of the N-BC.

For organic contaminants, Akash et al. [2] demonstrated the applicability of N-BC for methylene-blue removal, whereas Wu et al. [82] investigated nutrient capture involving phosphorus and nitrogen. These studies broaden the application scope beyond heavy metals, but they also demonstrate that the mechanism is contaminant-specific. Aromatic dyes may interact through π–π interactions and pore filling, whereas nutrient ions may be governed more strongly by ion exchange, electrostatic interactions, ligand exchange, or precipitation.

Critical assessment: The principal limitation of the existing literature is its reliance on single-contaminant batch experiments, which may not adequately represent the complexity of real wastewater. In actual wastewater systems, coexisting metal ions, inorganic ions, dissolved organic matter, suspended solids, and microorganisms, together with fluctuating pH, can influence adsorption performance by competing for active sites, modifying surface charge, obstructing pores, and altering contaminant speciation. This limitation is consistent with recent reviews of selective heavy-metal removal using biochar, which highlight that most studies focus on single-pollutant systems, whereas real water bodies commonly contain multiple metal ions whose competitive adsorption can substantially affect removal efficiency and selectivity [46].

Therefore, future studies should move toward multi-contaminant systems; real wastewater; continuous-flow column experiments; regeneration and reuse; contaminant recovery; adsorbent separation; aging studies; leaching assessment; and life-cycle and techno-economic evaluation. Importantly, maximum adsorption capacity should not be the sole criterion for selecting an N-BC water-treatment material (Table 5).

### 6.3 Catalysis and chemical oxidation

The catalytic behavior of N-BC differs mechanistically from passive adsorption because the material may participate in electron transfer, radical generation, redox cycling, or catalytic activation of oxidants. Surface defects, aromatic domains, oxygen-containing groups, and incorporated transition metals can contribute to catalytic activity.

Bazrafshan et al. [8] reported enhanced degradation of phenolic compounds using iron-oxide-modified N-BC, with degradation efficiencies exceeding 85% under the reported experimental conditions. The authors associated the performance with the large surface area and availability of reactive sites facilitating Fenton-like reactions. Such systems demonstrate an important advantage of engineered N-BC: adsorption can concentrate pollutants near catalytic sites while the reactive phase promotes subsequent transformation.

Similarly, Altintas et al. [4] reported approximately 90% degradation of methylene blue within 60 min using an N-BC/$TiO_2$ system under UV irradiation. The reported

**Table 5** Comparative performance of nano-biochar (N-BC) for the removal of contaminants from aqueous systems under different treatment conditions

| Source material | Treatment method | Contaminant | Adsorption capacity (mg/g) | Removal efficiency | pH Conditions | Surface area ($m^2/g$) | References |
|---|---|---|---|---|---|---|---|
| Coconut Coir | Sol–Gel Synthesis | Organic Pollutants | 250 | 94% | Slightly Acidic | 380 | Nguyen et al. [51] |
| Lignocellulosic Biomass | Phytoremediation | Nitrogen, Phosphorus | 100 | 85% | Neutral | 310 | Sani et al. [63] |
| Bamboo Waste | Batch Adsorption | Benzene | 150 | 91% | Acidic | 340 | Yang et al. [84] |
| Rice Husk | Acid/Base Treatment | Methylene Blue | 180 | 93% | Neutral | 400 | Altintas et al. [4] |
| Agricultural Residue | Microwave-Assisted | Toluene | 130 | 90% | Neutral | 270 | Malpani et al. [44] |
| Banana Peel | Batch Adsorption | Dye | 200 | 90% | Neutral | 300 | Mahmoud et al. [42] |
| Corn Stover | Ion Exchange | Arsenic | 160 | 91% | Slightly Acidic | 290 | Bhandari et al. [9] |
| Coconut Shell | Adsorption Column | Heavy Metals | 240 | 92% | Neutral | 330 | Al-sareji et al. [3] |
| Maize Straw | Batch Adsorption | Pesticides | 140 | 85% | Acidic | 310 | Mohan [47] |
| Sugarcane Bagasse | Phytoremediation | Heavy Metals | 160 | 89% | Neutral | 300 | Açıkgöz et al. [1] |
| Rice Straw | Microwave-Assisted | Toluene | 200 | 90% | Neutral | 340 | Malpani et al. [44] |
| Olive Mill Waste | Chemical Doping | Phosphorus | 110 | 86 | Neutral | 280 | Mechnou et al. [45] |
| Coffee Grounds | Batch Adsorption | Organic Pollutants | 190 | 92% | Neutral | 300 | Sisay et al. [73] |

enhancement was associated with improved charge separation and reactive oxygen species generation.

However, percentage removal alone does not establish catalytic efficiency. A catalyst should ideally be evaluated according to reaction kinetics, mineralization, oxidant utilization efficiency, catalyst stability, regeneration, metal leaching, and energy requirement. This distinction is particularly important because apparent pollutant disappearance can result from adsorption rather than degradation.

Liu et al. [41] further reported the use of N-BC for heavy-metal immobilization. In such systems, the terminology of "oxidation" and "immobilization" should be carefully distinguished because a change in contaminant speciation does not necessarily guarantee permanent sequestration.

Critical assessment: The key research challenge is therefore to establish whether N-BC functions as a true catalyst, an adsorbent–catalyst hybrid, or primarily an adsorptive support under specific conditions. Future studies should combine pollutant-removal measurements with intermediate identification, mineralization analysis, radical-scavenging experiments, metal-leaching tests, and catalyst-reuse experiments.

### 6.4 Energy production and storage

N-BC occupies an interesting position within energy technologies because biomass conversion can simultaneously generate carbonaceous solids and energy-rich products such as bio-oil and syngas. Pyrolysis and gasification therefore provide opportunities for integrated biomass valorization, although the production conditions required for high-quality N-BC may differ from those optimized for maximum liquid or gaseous fuel production.

Ng et al. [50] reported substantial bio-oil production from agricultural residues, while Gao et discussed syngas generation through biomass gasification. Açıkgöz et al. [1] further demonstrated the relevance of thermally treated biomass to enhanced fuel properties.

However, the statement that these processes demonstrate the "energy-production potential of N-BC" requires qualification because bio-oil and syngas are products of biomass thermochemical conversion rather than direct functions of N-BC itself. N-BC is primarily the solid carbonaceous fraction, although its production is integrated into the overall energy-conversion process.

For energy storage, the porous and electrically conductive structure of N-BC provides opportunities for supercapacitor and battery electrodes. Shell et al. [69] reported a specific capacitance of approximately 250 F $g^{-1}$ for corn-stover-derived N-BC, while Liu et al. [41] reported improved cycling characteristics following iron-oxide modification. More recent work on biochar-based nanocomposite electrodes reports considerably higher performance ceilings when nanoscale metal-oxide or heteroatom components are incorporated: specific capacitances exceeding 400–700 F $g^{-1}$, energy densities approaching 90 Wh $kg^{-1}$, and cycling stability beyond $10^4$ cycles have been reported for optimized biochar nanocomposites, depending on composition and electrolyte [26, 31, 53]. This underscores that the reported capacitance range for N-BC electrodes has continued to widen as nanoscale functionalization strategies mature.

Nevertheless, comparison with commercial carbon electrodes requires consideration of specific capacitance, energy density, power density, rate capability, cycle stability, electrode loading, electrolyte, current density, and mass-normalization procedures. High surface area alone does not guarantee superior electrochemical performance.

Critical assessment: The major opportunity lies in developing integrated biomass-to-carbon-energy systems, but scale-up will depend on feedstock consistency, energy requirements for nanosizing, activation chemicals, electrode fabrication, reproducibility, and end-of-life management. Life-cycle assessment is therefore particularly important for determining whether the environmental benefits of waste-derived N-BC outweigh the additional energy and chemical inputs required for nanoscale engineering.

### 6.5 N-BC in healthcare and biomedical applications

N-BC has been explored for drug delivery, antimicrobial materials, biosensing, tissue engineering, and related biomedical applications because of its high surface area, porous architecture, surface functionalization potential, and ability to interact with biomolecules. However, this application domain requires a substantially different evidence standard from environmental adsorption.

Montané et al. [48] reported the capacity of N-BC to incorporate pharmaceutical molecules, suggesting potential for controlled or sustained delivery. The porous structure may facilitate loading, while surface functionalization can alter drug affinity and release kinetics. However, increased loading capacity does not necessarily imply improved therapeutic performance. Drug-release behavior, physiological stability, cellular uptake, degradation, and dose-dependent toxicity must also be established.

Pormohammad et al. [56] reported antimicrobial potential, while Khosravi Ardakani et al. [28] investigated N-BC-based sensing systems for biomolecules. These findings indicate potential in antimicrobial materials and biosensing, but translation to clinical applications requires rigorous assessment of biocompatibility, reproducibility, sterilization compatibility, batch-to-batch variation, and biological safety.

The antimicrobial mechanism may involve surface interactions, membrane disruption, reactive oxygen species generation, or release of incorporated active components. Li et al. [36] described ROS-associated antibacterial activity under photoexcitation. However, antimicrobial efficacy should be evaluated alongside cytotoxicity toward mammalian cells, because a mechanism capable of damaging microbial cells may also affect host cells.

Critical assessment: Healthcare represents a potentially high-value application but also one of the areas with the largest translational gap. Evidence based primarily on in vitro experiments is insufficient to establish clinical applicability. Future research should prioritize standardized toxicity testing, pharmacokinetics, biodistribution, biodegradation, sterilization, immune response, long-term exposure, and regulatory requirements.

For this reason, claims that N-BC is suitable for clinical drug delivery, wound treatment, or tissue engineering should remain prospective unless supported by sufficiently advanced biological and translational evidence.

### 6.6 N-BC function in agriculture and plant health

Agricultural applications of N-BC differ from conventional adsorption-based environmental applications because the material interacts simultaneously with soil minerals, water, nutrients, microorganisms, roots, and plant tissues. Potential benefits include nutrient retention, improved water availability, modification of soil physicochemical properties, microbial interactions, and mitigation of certain abiotic stresses.

[89] reported improvements in soil-related properties following N-BC application. [70] further reported changes associated with microbial activity and nutrient cycling. El-Ramady et al. [16] discussed the potential of N-BC to improve plant responses under abiotic stress. Field-relevant foliar applications have also been reported, with foliar nano-biochar suspension improving tomato productivity under salt stress through combined morphological, physiological, and biochemical effects [65], and nano-biochar suspensions similarly altering growth, physiological activity, and nutrient content in wheat at the vegetative stage [66].

The mechanisms are likely to involve several processes operating simultaneously. Increased surface area can retain nutrients and dissolved organic compounds, while changes in soil pH and cation-exchange properties can alter nutrient availability. The porous structure may influence water retention and microsite formation, while surface

chemistry and carbon availability can affect microbial colonization. These effects may ultimately influence root development and nutrient uptake.

However, agricultural performance is strongly dependent on soil type, climate, application rate, feedstock, particle size, nutrient status, irrigation regime, crop species, and N-BC chemistry. Therefore, results obtained under controlled pot experiments should not be directly extrapolated to field-scale crop production. A further concern is that nanoscale particles may exhibit greater mobility than conventional biochar. Although this mobility can increase contact with roots and soil constituents, it may also facilitate transport into deeper soil layers or adjacent water systems. Functionalized N-BC may additionally introduce concerns regarding the release of metals or other incorporated components. This concern is supported by research on the environmental fate of nanobiochar (N-BC), which demonstrates that its ability to adsorb pollutants does not necessarily ensure their permanent immobilization. During transport through soil, N-BC can carry adsorbed contaminants and potentially redistribute them across the soil profile. Furthermore, woody N-BC exhibits strongly pH-dependent adsorption of cadmium, oxytetracycline, glyphosate, and hexavalent chromium, illustrating the close relationship between adsorption behavior and particle mobility [59, 86, 91, 94, 95, 96] A recent scientometric analysis of nano-biochar applications in soil systems further identified ecotoxicological risk assessment and biochar–microbe interactions as important research themes, while emphasizing the need for deeper investigation of environmental risks and the development of appropriate assessment frameworks [61, 68, 71, 72, 78]. These findings highlight the need for integrated studies that evaluate contaminant adsorption, particle transport, rhizosphere interactions, and potential human-health risks under realistic soil conditions.

Critical assessment: The agricultural literature should therefore move beyond reporting plant biomass or yield increases and establish dose–response relationships, nutrient-use efficiency, soil microbial responses, root uptake, nanoparticle mobility, persistence, aging, and possible phytotoxicity. Long-term field trials are particularly important because short-term growth stimulation does not necessarily indicate sustained agronomic benefit.

### 6.7 Cross-application comparison: performance, limitations and translational barriers

The diverse applications of N-BC are controlled by different combinations of material properties and mechanisms. A property that is advantageous in one application may represent a limitation in another. For example, high surface area is generally desirable for adsorption and catalytic applications, whereas excessive nanoscale mobility may create environmental concerns. Similarly, strong contaminant binding can improve remediation but may complicate regeneration and contaminant recovery (Tables 6, 7; Fig. 5).

### 6.8 Critical synthesis and research priorities

The evidence indicates that N-BC performance is application- and material-dependent, and nanosizing does not inherently guarantee superior performance. Its functionality is governed by the combined effects of feedstock, processing conditions, surface chemistry, pore structure, mineral composition, surface charge, and environmental conditions.

**Table 6** Application-specific structure–mechanism–performance relationships and major translational constraints of nano-biochar

| Application | Key functional properties | Principal mechanisms | Main performance indicators | Major limitations |
|---|---|---|---|---|
| Air remediation | Porosity, aromaticity, surface functionality | Pore filling, physisorption, π–π interactions, catalysis | Breakthrough capacity, regeneration, degradation | Humidity, competitive pollutants, pressure drop |
| Water treatment | Surface area, charge, functional groups, minerals | Ion exchange, complexation, electrostatic attraction, pore filling, precipitation | Capacity, selectivity, kinetics, regeneration | Competing ions, DOM, nanoparticle recovery |
| Catalysis | Defects, redox-active groups, metal phases | Electron transfer, ROS generation, catalytic oxidation | Reaction rate, mineralization, catalyst reuse | Metal leaching, oxidant demand, energy input |
| Energy storage | Conductivity, pore architecture, heteroatoms | Ion storage, charge transfer | Capacitance, energy/power density, cycle life | Activation cost, reproducibility, electrode processing |
| Healthcare | Porosity, functional groups, surface chemistry | Drug loading/release, biomolecular interactions, antimicrobial action | Loading, release, sensitivity, biocompatibility | Cytotoxicity, sterilization, regulatory barriers |
| Agriculture | CEC, surface chemistry, porosity, water retention | Nutrient retention, microbial interaction, water regulation | Yield, nutrient-use efficiency, soil health | Mobility, phytotoxicity, field variability, long-term fate |

Three key insights emerge: (i) surface area alone cannot predict performance, as pore accessibility, functional groups, mineral phases, aromaticity, and dispersion also contribute; (ii) activation and functionalization can improve performance but may increase energy use, cost, leaching, and environmental risks; and (iii) laboratory results may not translate directly to field or commercial systems because of competing contaminants, complex matrices, aging, regeneration, and recovery requirements.

Future research should establish standardized links between production → properties → mechanisms → performance → environmental fate → economic feasibility, supported by realistic multi-contaminant experiments, continuous-flow and field validation, aging and ecotoxicity studies, regeneration and recovery assessment, and application-specific safety evaluation.

Ultimately, N-BC research should move from "performance demonstration" to "performance validation." Practical superiority should be established only when enhanced functionality is accompanied by acceptable reproducibility, energy and chemical requirements, environmental safety, recoverability, cost, and life-cycle performance. This systems-level approach can identify applications where N-BC provides a genuine advantage over conventional biochar and other engineered carbon materials.

## 7 Future perspectives and research directions

Although N-BC has demonstrated potential across environmental, agricultural, energy, catalytic, and biomedical applications, its transition from laboratory research to field and commercial use remains limited. The major challenge is to determine whether nano-sizing provides a measurable advantage under realistic conditions while remaining economically and environmentally sustainable. Future research should therefore adopt an integrated process–property–mechanism–performance–risk–deployment framework.

**Table 7** Effects of nano-biochar (N-BC) on plant growth, soil health, nutrient uptake, and abiotic stress tolerance

| Type of N-BC | Plant species | Porosity ($cm^3/g$) | pH Range | Temperature (°C) | Application | Outcome | References |
|---|---|---|---|---|---|---|---|
| Bagasse | Peas | 0.55 | 6.0–7.0 | 25–30 | Cell growth promotion | Enhanced cell proliferation observed in vitro | Gopalakrishnan et al. [20] |
| Coffee Grounds | Basil | 0.70 | 6.0–7.5 | 22–28 | Essential oil production | Increased essential oil yield in basil | Hasan et al. [21] |
| Waste Paper | Carrot | 0.62 | 6.5–7.0 | 20–25 | Antioxidant level enhancement | Higher antioxidant activity in carrot | Chaudhary et al. [10] |
| Olive Mill Waste | Eggplant | 0.65 | 6.0–7.0 | 22–28 | Soil fertility improvement | Increased soil fertility leads to improved yields | Mechnou et al. [45] |
| Palm Kernel Shells | Strawberry | 0.75 | 5.5–6.5 | 20–25 | Nutrient retention | Retained nitrogen levels, enhancing growth | He et al. [22] |
| Agricultural Residues | Broccoli | 0.60 | 6.0–7.0 | 25–30 | Growth enhancement | Increased biomass and better root development | De Silva et al. [14] |
| Green Waste | Cucumber | 0.70 | 6.0–7.0 | 20–25 | Water retention enhancement | Improved water-holding capacity in soil | Liu et al. [41] |
| Agricultural Waste | Tomato | 0.65 | 6.5–7.5 | 25–30 | Fertilizer amendment | Enhanced nutrient uptake and growth | Zhang et al. [90] |
| Corn Stover | Wheat | 0.70 | 6.0–7.0 | 20–25 | Soil amendment | Improved soil structure and moisture retention | Bhandari et al. [9] |
| Rice Husk | Spinach | 0.60 | 5.5–6.5 | 25–30 | Drought stress mitigation | Increased resilience to drought conditions | Shukla et al. [70] |
| Bamboo | Lettuce | 0.75 | 6.0–7.0 | 22–28 | Pathogen control | Reduced incidence of downy mildew | El-Ramady et al. [16] |

### 7.1 Standardization, reproducibility, and scalable production

Standardized protocols for feedstock selection, carbonization, nanosizing, functionalization, particle-size measurement, and physicochemical characterization are needed to improve reproducibility and enable meaningful comparison among studies.

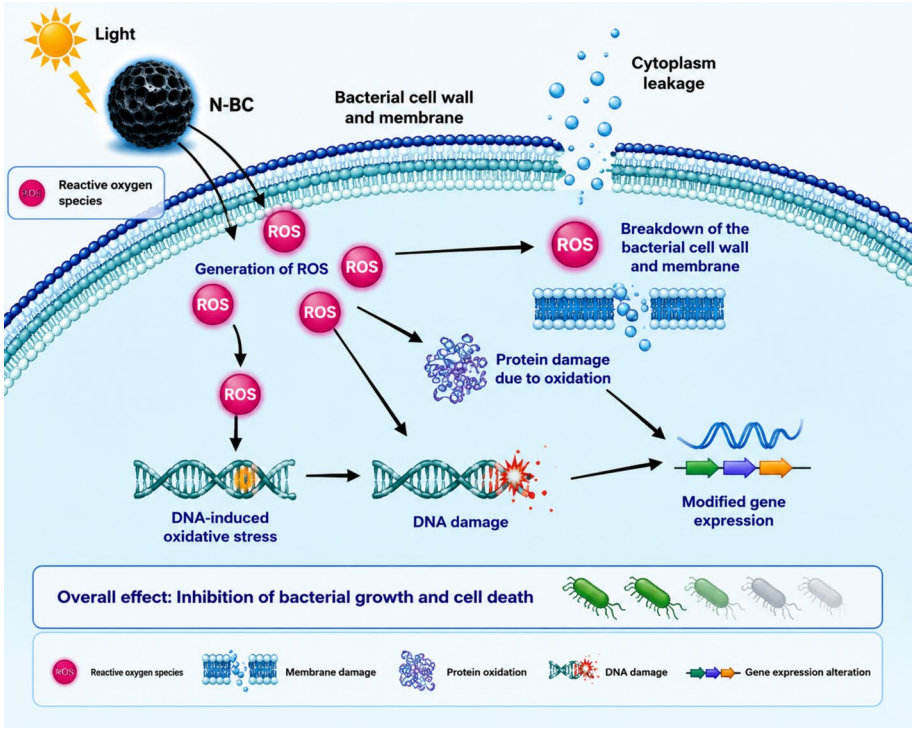



**Fig. 5** The antimicrobial mechanism of N-BC under photoexcitation

Scale-up should emphasize energy- and resource-efficient production, while balancing performance, yield, chemical consumption, stability, and cost.

### 7.2 Application-specific design and AI-assisted optimization

Future N-BC development should move from trial-and-error functionalization toward application-specific material design. AI, machine learning, and computational modeling could facilitate prediction of relationships between feedstock, processing conditions, material properties, and performance, provided that standardized and sufficiently large datasets are available.

### 7.3 Environmental fate, aging, mobility, and ecotoxicity

Long-term changes in N-BC caused by environmental aging may alter its surface chemistry, aggregation, mobility, and contaminant-binding behavior. Future studies should evaluate fresh and aged N-BC under realistic soil and aquatic conditions, including transport, transformation, contaminant release, and ecotoxicological effects across relevant organisms.

### 7.4 Regeneration, recovery, and end-of-life management

Greater attention is required to regeneration, reuse, recovery, and disposal of spent N-BC. Studies should assess regeneration efficiency, energy and chemical requirements, contaminant recovery, material stability, and safe end-of-life strategies to minimize secondary contamination.

### 7.5 Life-cycle and techno-economic assessment

The sustainability of N-BC should be evaluated across the complete life cycle, including feedstock processing, carbonization, nanosizing, functionalization, transportation, application, regeneration, and disposal. LCA and techno-economic analyses should determine whether the additional inputs required for nanosizing are justified by its performance relative to conventional biochar and competing materials.

### 7.6 Regulation and field-scale validation

Harmonized regulatory criteria are needed for particle size, impurities, environmental release, toxicity, and stability of engineered N-BC. Equally important are pilot-scale, continuous-flow, and long-term field studies using real wastewater, contaminated soils, multiple contaminants, and variable environmental conditions to establish whether laboratory performance is transferable to practical systems.

### 7.7 Biomedical translation and safety

Biomedical applications require rigorous evaluation of cytotoxicity, inflammatory responses, cellular uptake, biodistribution, biodegradation, and long-term safety. Translation should proceed systematically from physicochemical characterization and in vitro studies to in vivo evaluation and regulatory assessment.

### 7.8 Priority research agenda

Overall, future N-BC research should prioritize (i) standardization and reproducibility; (ii) application-specific and mechanistic design; (iii) environmental fate, aging, and safety; (iv) pilot- and field-scale validation; and (v) LCA, techno-economic feasibility, regeneration, and end-of-life management. These priorities should be considered together because improving one material property may introduce trade-offs in energy demand, cost, mobility, or environmental risk.

Ultimately, N-BC research should progress from "performance demonstration" to "performance validation." Its practical value should be established on the basis of application-specific performance together with reproducibility, safety, recoverability, sustainability, and economic feasibility, thereby identifying where nanoscale biochar provides a genuine advantage over conventional biochar and other engineered carbon materials.

## 8 Conclusion

Nano-biochar (N-BC) is not simply a smaller form of conventional biochar; nanosizing, activation, and functionalization can substantially alter its surface area, pore structure, chemistry, mineral composition, charge, and colloidal behavior. However, its performance depends strongly on feedstock, processing conditions, application matrix, and operating environment, and maximum surface area or minimum particle size alone cannot predict superior performance.

A key insight of this review is the process–property–mechanism–performance–risk relationship. N-BC functionality results from the interaction of material properties with application-specific mechanisms, including adsorption, ion exchange,

surface complexation, precipitation, π–π interactions, and redox processes. These mechanisms are influenced by pH, ionic strength, competing contaminants, dissolved organic matter, and aging.

Although N-BC shows potential in environmental remediation, agriculture, catalysis, energy storage, and biomedical applications, significant trade-offs and knowledge gaps remain. Enhanced performance may require greater energy and chemical inputs and may increase mobility, leaching, toxicity, or production costs. Moreover, laboratory-scale results do not necessarily translate to field or commercial conditions.

Future research should prioritize standardized production and characterization, realistic long-term and field-scale validation, environmental fate and ecotoxicity assessment, regeneration and recovery, life-cycle assessment, techno-economic feasibility, and AI-assisted material design. Importantly, N-BC should be evaluated not only for functional performance but also for safety, reproducibility, sustainability, and economic viability.

Overall, the field should move from "performance demonstration" to "performance validation." The proposed process–property–mechanism–performance–risk–deployment framework provides a basis for identifying applications where N-BC offers a genuine and sustainable advantage over conventional biochar and other engineered carbon materials.

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**Author contributions**
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