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REVIEW

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Revolutionizing sustainability of agroecosystems using nano-biochar solutions: Agricultural and environmental perspectives

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Abstract

Background: Achieving sustainability of agroecosystems in the face of increasing environmental challenges and diminishing natural resources demands innovative and multifunctional materials. Carbon capture from biomass residue is a promising approach and represents a climate-resilient solution that utilizes the synthesis of advanced substances, such as nano-biochar (NBC). *Objective*: This review assesses the potential of NBC as a sustainable advanced tool for boosting crop productivity and fortifying ecological resilience. *Methods*: A comprehensive review of recent scientific literature was conducted to investigate NBC properties, production methods, analytical techniques, and field application methods; systematic analyses and syntheses were performed. The analyzed studies focused on soil fertility management, pollutant remediation, nutrient dynamics, and reduction of greenhouse gas (GHG) emissions. *Results*: NBC has distinct biochemical characteristics including a high specific surface area, a porous structure, and a multitude of surface functional groups. These characteristics contribute to multifunctional effectiveness in terms of agroecosystem sustainability. NBC enhances soil fertility, stimulates plant development, improves nutrient retention, sequesters heavy metals, reduces GHG emissions, and positively affects the rhizosphere. Recent advances in production methodologies have improved the efficiency of NBC. This has resulted in an increase in the number of NBC applications in the agricultural sector. Despite these advances, operational challenges remain unresolved. These challenges include the feasibility of large-scale production, standardization of NBC properties, and long-term environmental impacts. *Conclusions*: NBC offers substantial prospects for sustainable agroecosystems. This solution transforms biomass residues into valuable harvested carbon materials. These substances protect the environment and enhance food safety. Future research should focus on optimizing scalable production methods. In addition, the long-term application and incorporation of NBC into climate-resilient farming practices are needed to completely understand its agroecological benefits.

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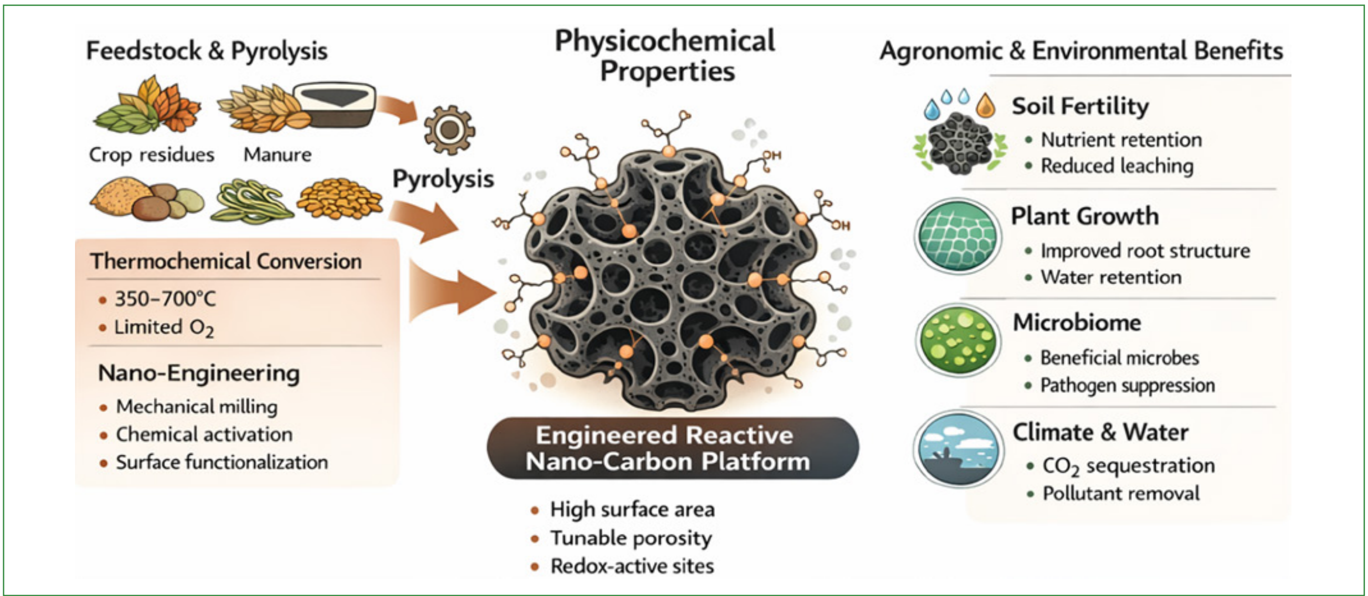
Graphical abstract

Nano-biochar (NBC) offers a versatile carbon platform characterized by elevated surface reactivity. NBC facilitates nutrient retention, pollutant remediation, microbiome regulation, and GHG mitigation.



Keywords: nanoparticles, biochar, sustainability, bioremediation, low inputs, GHG emissions, farming systems

Introduction

Sustainable farming enables food security worldwide. It drives national growth and protects natural ecosystems (Rehman *et al.*, 2022; Alharby *et al.*, 2026). Current farming activities must resolve several instantaneous and long-term sustainability threats that affect production. Soil degradation, environmental stressors (Abdelkader *et al.*, 2024a; Suliman *et al.*, 2024), and chemical pollution are major agricultural concerns (Veni *et al.*, 2020; Voronina *et al.*, 2024). Success in the agricultural sector depends on soil characteristics and, therefore, requires quality enhancement to achieve the maximum fertilizer benefits (Selim, 2020). Applying synthetic pesticide in line with intensive agricultural activities and poor soil management practices has produced a three-way resource-depleting impact. This adverse impact triggers soil nutrient loss, organic compound destruction, and substantial erosion leading to decreased productivity (Ahmed *et al.*, 2019; Rashmi *et al.*, 2022).

Agriculture faces critical challenges in maintaining consistent production owing to water shortages. This critical situation has worsened owing to the impact of climate change (Legg, 2021). Sustainable technological approaches enhance agricultural output while mitigating environmental harm (Abdelkader *et al.*, 2025). Scientists recognized nano-biochar (NBC) as an innovative approach for agricultural and environmental management owing to its numerous advantages (Khan *et al.*, 2021; Rajput *et al.*, 2022; Sammar Raza *et al.*, 2023 ; Shafiq *et al.*, 2023; Shiade *et al.*, 2024a). Biochar improves soil health, reduces greenhouse gas (GHG) emissions, and serves as a mechanism for carbon sequestration and harvesting carbon (Pandian *et al.*, 2024; Ullah *et al.*, 2024, 2025).

The benefits of biochar are determined by three fundamental factors, namely, feedstock selection, processing duration, and thermal pyrolysis temperature (Adekiya *et al.*, 2026; Sri Shalini *et al.*, 2021). Using oak sawdust as a feedstock material leads to better long-term effects and higher productivity (Zhao *et al.*, 2025). However, biochar has limitations owing to its limited porosity, reactivity, and particle size (Özgün *et al.*, 2025). Nanotechnology techniques for biochar modification have become crucial for addressing these challenges (Dhanapal *et al.*, 2024). Nanotechnology allows researchers to produce materials at the nanometer scale, extending to 100 nm (Abdelkader *et al.*, 2024b; Kah *et al.*, 2019). NBC exhibits improved effectiveness as a soil amendment, largely because of its superior interaction with soils and more efficient adsorption of water components, which stems from its increased surface area and enhanced adsorption properties (Zhang *et al.*, 2020; Ndoung *et al.*, 2021).

NBC increases nutrient availability, water retention, and microbial growth. NBC reduces fertilizer, pesticide, and herbicide use and improves soil carbon storage (Wang *et al.*, 2022). NBC's porosity, surface charge, and colloidal stability facilitate the effective adsorption and immobilization of heavy metals and organic pollutants (Ahmed *et al.*, 2025). The high oxygen functionality and aromatic clusters present in plant-derived NBC promote heavy metal sorption (Sharma *et al.*, 2023). Furthermore, carbon sequestration via NBC stabilizes organic carbon, consequently reducing CO_2 and CH_4 emissions (Lan *et al.*, 2025; Torabian and Farhangi-Abriz, 2025). NBC's gradual nutrient release decreased land-based topsoil loss and environmental eutrophication. NBC provides functional living conditions for several bacteria (Shafiq *et al.*, 2023). When trash becomes valuable, farmers can choose to dispose of biowaste as an environment-friendly option, particularly because forest wood and other wood materials contain phenanthrene, pyrene, and methylmercury (Xiao *et al.*, 2020).

NBC improves soil structure and nutrient delivery, boosts cation exchange capacity (CEC), and reduces fertilizer needs (Liu *et al.*, 2021). It also holds water well because of its extensive pores (Shafiq *et al.*, 2023). Biochar nanoparticles protect plant roots by preventing excess salt entry and salt buildup in the rhizosphere (Sun *et al.*, 2022). NBC provides beneficial microorganisms and supports metabolic substances that protect plants from diseases while improving nutrient uptake (Rizwan *et al.*, 2024). NBC's capacity to modulate the soil pH facilitates enhanced nutrient uptake by plants and fosters more resilient soil environments (Shafiq *et al.*, 2023). Moreover, its characteristics render it suitable for applications in precision farming and soil bioremediation.

This is a promising approach for developing sustainable agricultural activities (Rajput and Minkina, 2024). Therefore, it is essential to develop multifunctional and environmentally sustainable solutions to mitigate climate change (Sampathkumar *et al*., 2020). Traditional soil amendments and synthetic fertilizers often demonstrate reduced nutrient use efficiency, increased nutrient leaching, and environmental pollution and provide a noncompetitive strategy for enhancing soil fertility (Marcińczyk and Oleszczuk, 2022). Most biomass residues remain underutilized, posing disposal challenges, despite representing a valuable carbon resource. The transformation of these residues into high-value materials aligns with the principles of circular bioeconomy and climate-smart farming practices (Yaashikaa *et al*., 2020).

This review investigates the role of NBC as a multifunctional carbon nanomaterial derived from biomass waste. In addition, this study evaluated the potential of NBC to support sustainable climate-resilient agricultural practices. The conceptual basis for carbon harvesting within circular bioeconomy models was analyzed. Physicochemical properties of NBC, including nanoscale size, specific surface area, porous structure, and prevalence of reactive functional groups, were investigated. This study explains how NBC works in ecosystems, focusing on its interactions with nutrients (adsorption and desorption) and the ability of NBCs to exchange cations, remove pollutants, interact with microbes, and reduce GHG emissions.

A structured literature review was employed to combine existing knowledge. Relevant peer-reviewed publications were chosen from scientific databases, including Google Scholar, Web of Science, and Scopus. The applied search strategy focused on keywords pertaining to NBC production, physicochemical characterization, soil applications, environmental remediation, GHG emissions, and plant responses.

Literature published until 2026 was screened, evaluated, and critically analyzed to incorporate the latest developments. Experimental outcomes derived from laboratory, greenhouse, and field investigations were integrated with mechanistic explanations and conceptual models. Reasonable and comparative analyses were employed to evaluate the ability of NBC to enhance reactivity and multifunctionality compared to those of bulk biochar. This review is based on evidence that NBC has the potential to serve as an effective climate-smart circular carbon material.

Properties of NBC

NBC refers to biochar particles engineered to have nanoscale dimensions of up to 100 nm (Dhanapal *et al*., 2024). Nanoscale particles have physical and chemical properties that distinguish them from bulk biochar (Verma *et al*., 2023a; Xu *et al*., 2024). The structures of NBC provide various benefits, including bioremediation, agricultural use, catalysis, and energy utilization (Xu *et al*., 2024).

High surface area

Biochar synthesized at the nanoscale demonstrates a greater surface area than bulk or micron-sized biochar (Shafiq *et al*., 2023). These dimensions allow biochar to present a multitude of concealed internal and external surface sites. Therefore, the interactions of NBC with soil substances are increased. This expanded surface area provided numerous active sites for adsorption, ion exchange, and surface-mediated reactions (Shafiq *et al*., 2023). Accordingly, their efficacy in pollutant extraction, reaction catalysis, and nutrient absorption has been markedly enhanced.

Enhanced porosity

NBC has a hierarchical pore structure with distinct regions comprising micropores (<2 nm), mesopores (2–50 nm), and macropores (>50 nm) (Lian *et al*., 2022). The transport and storage dynamics of various materials are controlled by this multiscale porous structure. Consequently, the improved porosity of NBC promotes the adsorption of gases, organic compounds, and heavy metals. Furthermore, the increased structural complexity of the soil results in an improved water-holding capacity, leading to enhanced microorganism colonization in the agroecosystem (Shiade *et al*., 2024b).

Improved dispersibility and stability

NBC particles dissolve easily in soil and water owing to their small size and high surface energy (Raczkiewicz *et al*., 2024). The tiny NBC particles exhibited longer suspension lifetimes because they resist aggregation. Improved dispersion enables materials to perfectly cover the treated areas (Li *et al*., 2024b).

High reactivity

NBC's elevated chemical reactivity stems from its substantial surface area and the presence of various reactive functional groups, including hydroxyl, carboxyl, and carbonyl groups (Zaidi *et al*., 2025). Consequently, the reactive properties of NBC promote efficient compound interactions, thereby enabling its function as a catalyst in chemical processes and as a nutrient carrier for water purification (Dhuldhaj *et al*., 2023).

Quantum effects

Quantum-mechanical effects in nanoscopic systems modify the magnetic and electrical properties and alter optical interactions within materials (Cui *et al*., 2025). In contrast, analyses of bulk biochar materials did not reveal these phenomena. However, when biochar is reduced to the nanoscale, quantum confinement makes the material sensitive to light, which is useful for applications such as energy storage and electrochemical detection (Sammar Raza *et al*., 2023).

Surface functionalization

Surface functionalization allows the addition of chemical groups to the NBC surface via oxidation, amination, and other treatments. This process creates —OH, —COOH, and $—NH_2$ groups (Lian *et al*., 2022). NBC can acquire functional groups that act as binding agents, thereby improving the uptake of molecules and ions. The surface transformation of NBC yields application-specific materials that can perform pollutant-selective adsorption, serve as nutritional delivery systems, and support catalytic nanoparticles (Verma *et al*., 2023b; Nosratabad *et al*., 2024a).

Adsorption capacity

NBC possesses excellent adsorption properties for various substances owing to its porous structure, surface chemistry, and large surface area (Bhandari *et al*., 2023a). These include heavy metals (e.g., Pb^{2+}, Cd^{2+}, Cr^{6+}), organic pollutants (e.g., pesticides, pharmaceuticals), and dyes and industrial contaminants. The impact of NBC on bioremediation and wastewater treatment is attributed to its unique characteristics (Bhandari *et al*., 2023b; Moulick *et al*., 2024).

Nutrient retention

Nutrients are retained in NBC and then released gradually, thereby functioning as sustained-release fertilizers (Elsabagh *et al*., 2026). This mechanism enhances nutrient utilization efficiency, diminishes fertilizer leaching, and fosters improved plant growth by enhancing soil fertility (Lian *et al*., 2022).

Antimicrobial activity

NBCs exhibit bactericidal and fungicidal activities via the generation of reactive oxygen species and surface charge-mediated interactions. The antimicrobial properties of this material can be used for plant disease control, maintenance of plant health, biomedical systems, and packaging methods (Nishshankage *et al*., 2024).

Catalytic activity

NBC acts as both a catalyst and a support for materials involved in reactions during reduction processes and chemical breakdown. Its numerous active sites, along with specific functional groups, work together to enhance its catalytic activity (Goswami *et al*., 2022). NBC functions effectively as a catalyst or support material for catalytic activities, including Fenton-like reactions, photocatalysis, and electrocatalysis, for environmental and energy applications (Xu *et al*., 2024).

NBC shows promise as a valuable nanomaterial because of its large surface area, increased porosity, good dispersibility, strong reactivity, potential for surface modification, and possible quantum effects (Shafiq *et al*., 2023). These combined properties allow it to be effectively used for cleaning pollutants, providing nutrients, operating chemical stations, sensing applications, and energy storage (Fig. 1).

Formation of NBC

The NBC production sequence begins by selecting appropriate biomass materials as the starting point (Zaidi *et al*., 2025). Different biomass sources, including rice husk, maize stover, wheat straw, forestry waste, and municipal solid waste, determine the final NBC composition while affecting its porosity, structure, and functional properties (Sharma *et al*., 2022; Kumar *et al*., 2024). Residues are dried and ground before carbonization, and these pretreatment steps help to reduce the moisture levels to below 10% and improve the surface area of NBC (Kumar *et al*., 2022). The pretreated biomass enters the pyrolysis or carbonization process within limited oxygen conditions at temperatures between 300 and 700°C. Low-temperature pyrolysis at 300–500°C is the optimal condition for NBC manufacturing when the end product is intended for agricultural applications (Ghodake *et al*., 2021), as it maintains surface functional groups while preserving elevated CEC (Kannan *et al*., 2024; Kumari, 2025). Surface area and adsorption capacity can be enhanced via posttreatment physical activation with steam or CO_2 (Rajput *et al*., 2022).

After pyrolysis, biochar particles are reduced to nanomaterials using a top-down method. Mechanical ball milling is typically performed to achieve particle sizes of up to 100 nm. Nanoscale production (Fig. 2) requires multiple dispersion and stabilization techniques, including ultrasonication, high-energy milling, and cryogenic grinding (Sarmah *et al*., 2023). Surface modification and functionalization of NBC are used to introduce reactive groups (e.g., —COOH, —OH, $—NH_2$) and to incorporate metal ions such as Fe, Zn, and Cu (Li *et al*., 2022; Gao *et al*., 2025). These modifications enable NBC to bind pollutants and nutrients (Zhang *et al*., 2020). The final testing of NBC is often implemented using analytical instruments, such as SEM/TEM (scanning electron microscope/transmission electron microscope) and BET (Brunauer-Emmett-Teller) tests, in addition to FTIR (Fourier transform infrared) spectroscopy, XPS (X-ray photoelectron spectroscopy), and CHNS (carbon, hydrogen, nitrogen, and sulfur) or EDX (energy-dispersive X-ray) total elemental assessments (Raut *et al*., 2025; Mishra *et al*., 2026).

Characterization techniques

NBC characterization must be thorough to determine whether the chemicals meet multiple product specifications. A complete description of the materials is required for this method. Examination of NBC particles using SEM or TEM has determined the appearance and length of the particles (Xiao *et al*., 2020). Raman and FTIR spectroscopy data provided enhanced spectroscopic insights into the interaction of NBC with contaminants and nutrients. These analytical techniques can identify NBC's hydroxyl, carbonyl, and carboxyl surface groups (Omar *et al*., 2025a).

Chemical identification, including FTIR spectroscopy, identified aromatic C = C, O—H, and C = O links (Yue *et al*., 2025). Functional groups of NBCs at the liquid-air interface react with different molecules (Table 1). BET surface area analysis provides researchers with precise NBC surface area and internal space properties, and its large surface area promotes natural absorption (Torabian and Farhangi-Abriz, 2025). For successful filtering, the NBC must contain nutrients that retain and reject elements. The researchers used an X-ray diffraction (XRD) analyzer to examine the structure of graphite and minerals in their samples (Liu *et al*., 2019; Özgün *et al*., 2025).

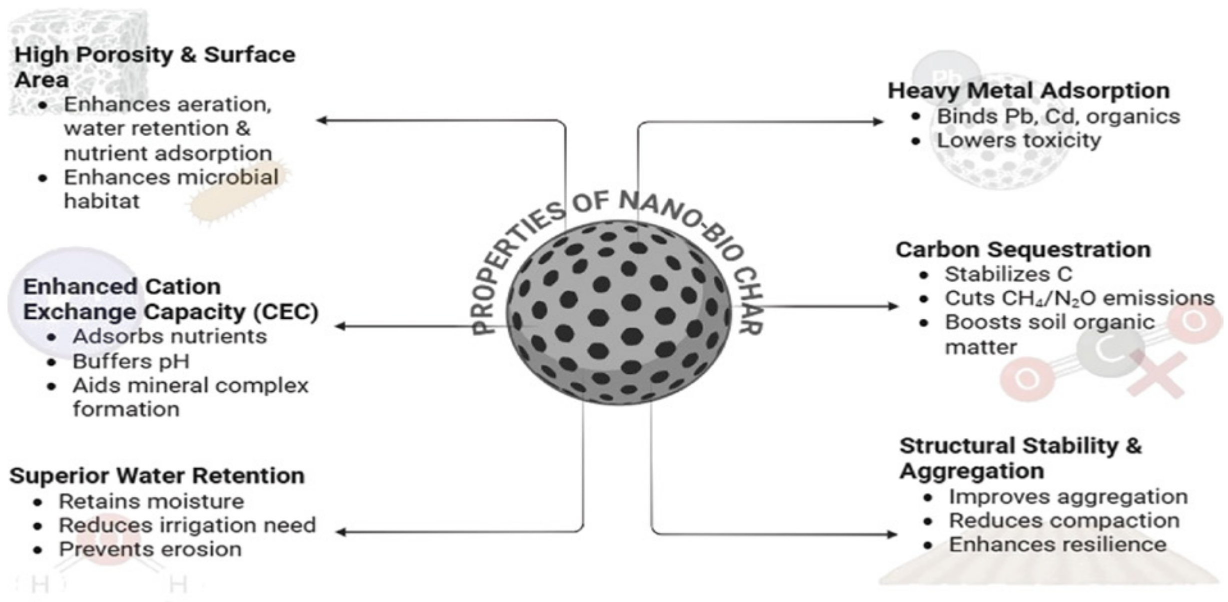


Fig. 1. Via its distinctive physical and chemical properties, nano-biochar acts as an agent to restore soil vitality, contain pollutants, and enhance agroecosystem development.

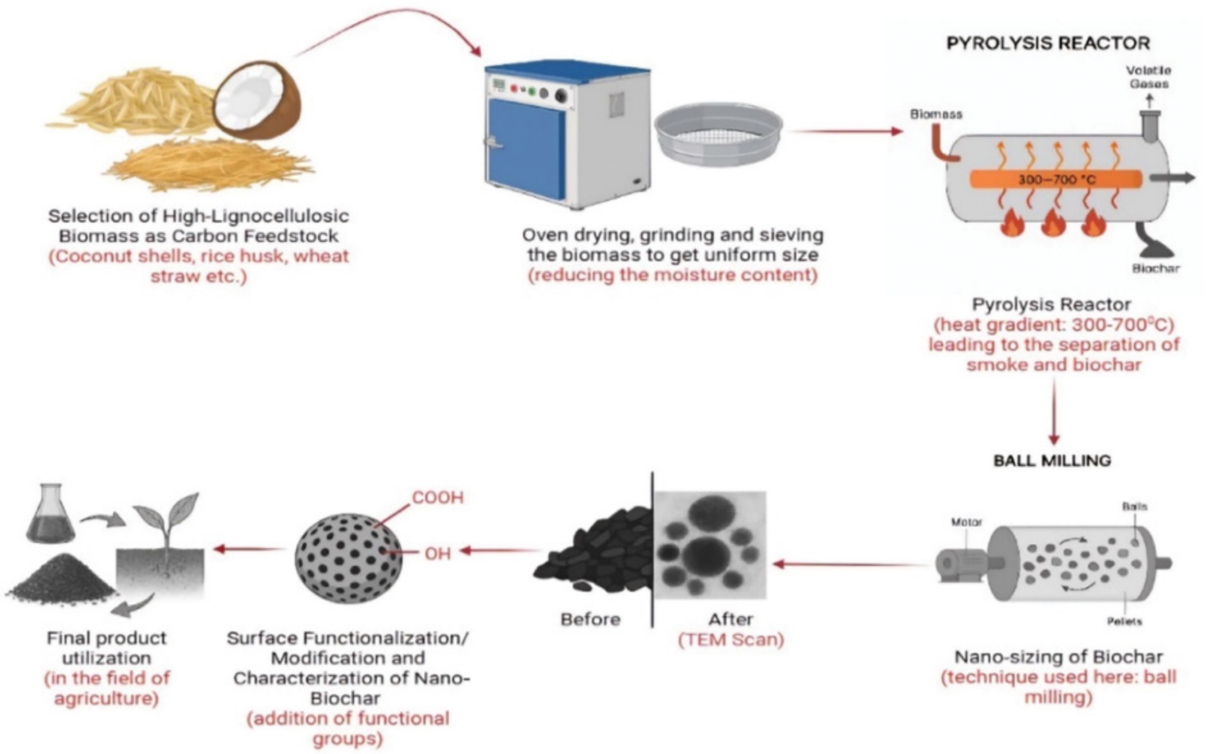


Fig. 2. Nano-biochar is produced from lignocellulosic feedstock via the processes of synthesis, nano-sizing, and surface modification techniques.

Table 1. Various methods for the synthesis and characterization of nano-biochar, as well as the author's contributions.

Synthesis method/ characterization	Contribution	Author(s)
Ball milling	Demonstrated the reduction of biochar particles to below 100 nm using high-energy planetary ball milling, increasing surface area and reactivity.	(Li *et al.*, 2024a; Ng *et al.*, 2022)
Ultrasonication	Applied ultrasonication in combination with ball milling to further reduce particle size and disperse particles in colloidal solutions.	(Kwak *et al.*, 2019)
Hydrothermal carbonization (HTC)	Showed that HTC is an energy-efficient method for processing wet biomass, converting it into carbon-rich hydrochar for subsequent nanoscale reduction.	(Singh *et al.*, 2024; Sivaranjanee *et al.*, 2023)
TEM, SEM	Used TEM and SEM to visualize the morphology, surface texture, and nanoscale dimensions of NBC particles.	(Xiao *et al.*, 2019)
FTIR, Raman spectroscopy	Employed FTIR and Raman spectroscopy to identify surface functional groups like hydroxyl, carboxyl, and carbonyl, which affect NBC reactivity.	(Ilić *et al.*, 2022; Gęca *et al.*, 2023)
BET surface area analysis	Used BET analysis to measure the surface area and porosity of NBC, crucial for applications in adsorption and nutrient retention.	(Irewale *et al.*, 2025; H. A. Khan *et al.*, 2021)
Thermogravimetric analysis (TGA)	Evaluated the thermal stability of NBC, providing insight into the decomposition temperatures of different components.	(Sun *et al.*, 2020)
Feedstock type, pyrolysis conditions	Discussed how feedstock type and pyrolysis conditions (temperature, heating rate, and residence time) influence the physicochemical properties of NBC.	(Tomczyk *et al.*, 2020; Behnam and Firouzi, 2023)

Applications of NBC in agriculture and environmental issues

Pyrolysis produces NBC from biomass feedstock under controlled conditions. With particles smaller than 100 nm and a large surface area, NBC exhibits physical and chemical properties such as high surface-to-volume ratios, enhanced surface reactivity, and a high concentration of oxygen-containing functional groups (Table 2).

Soil health improvement and fertility management

Nanomaterial-containing biochar improves soil fertility to a greater extent than conventional restoration methods. The tiny pores of biochar allow it to readily interact with soil particles, store nutrients and microbes, and promote root connections. NBC's structure permits contaminants and nutrients to readily enter soil (Bolan *et al.*, 2023;

Table 2. Applications of nano-biochar (NBC) in agricultural and environmental remediation.

Application area	Pollutants/targets	Mechanism	Type of nano-biochar	Feedstock	Remarks	Reference
Heavy metal removal	Pb, Cd, Zn, Cu, Cr, and Ni	Adsorption, ion exchange, and surface complexation	Sulfhydryl- or carboxyl-functionalized NBC	Rice husk, sewage sludge	Functional groups enhance metal binding.	(Nosratabad *et al*., 2024b)
Organic pollutant removal	Dyes, phenols, pesticides, and antibiotics	π–π interactions, H-bonding, and hydrophobic effects	TiO_2-NBC, Fe_3O_4-NBC, pristine NBC	Maize cob, coconut shell	Doped NB improves photocatalytic degradation.	(Liu *et al*., 2021)
Water/Wastewater treatment	Nutrients (N and P), pharmaceuticals, and microbes	Adsorption, microbial synergy, and filtration	NBC composites (e.g., NBC-clay, NBC-biofilm)	Wood chips, dairy manure	Used in hybrid filters and microbial enhancement.	(Wang *et al*., 2022)
GHG mitigation	CH_4 and N_2O emissions from soils	Adsorption of NH_4^+/NO_3^- and microbial modulation	Pristine NBC, Fe/N-doped NBC	Wheat straw, bamboo	Alters microbial community and suppresses methanogenesis.	(Mehmood *et al*., 2024b)
Nutrient management	N, P, and K retention and delivery	Adsorption, ion exchange, and slow release	Urea-loaded NBC, phosphorus-loaded NBC	Maize stover, cow dung	Enhances fertilizer efficiency and reduces nutrient leaching.	(Khan *et al*., 2021)
Antibiotic resistance mitigation	Antibiotic residues and ARGs	Adsorption, microbial inhibition, and ROS generation	Fe_3O_4-NBC, enzyme-coated NBC	Coconut husk, bagasse	Suppresses ARG propagation and removes antibiotic residues.	(Lian *et al*., 2020)
Soil remediation	Metal-contaminated soils	Immobilization and microbial stimulation	Pristine NBC, modified NBC	Poultry litter, sawdust	Enhances microbial activity and reduces bioavailability.	(Liu *et al*., 2021)
Pesticide degradation	Atrazine, chlorpyrifos, and glyphosate	Catalytic degradation, adsorption, and photo-Fenton reactions	Fe/N co-doped NBC, MnO_2-NBC	Sugarcane bagasse, rice straw	Enhanced degradation under light or Fenton-like conditions.	(Zhang *et al*., 2020)
Soil fertility	Nutrient enhancement and retention	Ion exchange, nutrient adsorption, and slow release	N-loaded NBC, K-loaded NBC	Cow dung, maize stover	Improves nutrient availability and fertilizer use efficiency.	(Mehmood *et al*., 2022)
Soil acidification	pH buffering and liming effect	Surface functional group buffering	Alkaline NBC	Rice husk, bamboo	Raises soil pH and improves microbial activity.	(Zhang *et al*., 2025)
Drought stress	Water retention improvement	Increased porosity and hydrophilicity	Pristine NBC, hydrogel-NBC composite	Faba bean	Enhances soil water-holding capacity.	(Abd El-Moaty *et al*., 2024)
Salinity stress	Salt ion immobilization and microbial support	Adsorption of Na^+/Cl^- and microbial modulation	Functionalized NBC	Sugarcane bagasse	Reduces osmotic stress and enhances plant tolerance.	(Liu *et al*., 2021)
Contaminated cropland	Heavy metal detoxification	Adsorption, complexation, and precipitation	Carboxyl-modified NBC	Sewage sludge, wood waste	Immobilizes toxic metals and reduces crop uptake.	(Zhang *et al*., 2020)
Pesticide residue in soils	Pesticide adsorption and degradation	Photocatalysis and redox interactions	Fe/N-doped NB, MnO_2-NBC	Rice straw, coconut shell	Degrades residual agrochemicals in soil.	(Chandi *et al*., 2024)
Reduced microbial activity	Enhancement of beneficial soil microbes	Habitat provision, pH balance, and nutrient cycling	Pristine NB, biofilm-coated NBC	Bamboo, animal manure	Stimulates the rhizospheric microbial population.	(Shafiq *et al*., 2023)
Greenhouse gas emissions	Mitigation of CH_4 and N_2O from agricultural soils	N adsorption, microbial shift, and redox control	Pristine NBC, Fe-doped NBC	Wheat straw, dairy manure	Reduces GHG emissions from fertilizer and paddy fields.	(Sultan *et al*., 2024)
Soil pathogen suppression	Disease suppression in the rhizosphere	Antimicrobial activity and immune stimulation in plants	Enzyme-loaded NBC, silver-doped NBC	Maize cob, poultry litter	Reduces fungal and bacterial pathogen loads.	(Arshad *et al*., 2024)
Low organic carbon content	Soil organic matter enrichment	Carbon enrichment and structure stabilization	High-C NBC (pyrolyzed at 500–700°C)	Woody biomass	Long-term improvement in soil carbon and aggregate structure.	(Xie *et al*., 2025b)

Khan *et al*., 2024). NBC adjusts soil properties and creates conditions favorable to bacterial growth.

NBC repairs damaged soil. Microorganisms perform better, and plants grow more rapidly with even fewer bacteria in the soil (Ahmed *et al*., 2025). Fine holes improve soil surface drainage by allowing water to flow through heavy clay and to deeper layers. NBC creates tighter and more dense soil microaggregates that change soil properties (Adesoyin, 2021). NBC increases soil aggregate formation, prevents erosion, and improves soil performance. This chemical helps soil maintain its barrier (binding heavy metals and organic contaminants). The NBC creates soil from clay and sand without damaging the environment. The use of NBC to encourage root development is harmless because plants naturally absorb nutrients from stable biological structures in the soil (Abed Hussein *et al*., 2022). NBC treatment improves surface water flow and topsoil holding where erosion occurs, causing soil particles to cling together (Zhou *et al*., 2020).

The CEC keeps essential elements, including ammonium (NH_4^+), potassium (K^+), calcium (Ca^{+2}), and magnesium (Mg^{+2}), in the soil. NBC can modify soil pH and increase soil nutrient content (Liu *et al*., 2019). Numerous beneficial microorganisms residing within NBC structures may benefit from a protected environment. These include Azotobacter, Rhizobium, phosphate-solubilizing microorganisms, and arbuscular mycorrhizal fungi. Enzyme-mediated modifications by these bacteria contribute to reduced nutritional content (Zhou *et al*., 2020).

NBC has an inherent capacity to adhere to surfaces via its functional groups, including —COOH, —C=O, and —OH moieties. Functional groups facilitate the binding of organic matter and nutrients, forming stable organic-mineral complexes that persist for extended periods (Ukoba *et al*., 2022). These complexes improve the persistence of organic carbon and nutrient conservation rates. An agricultural system may achieve greater sustainability if NBC structures strengthen soil structure, thereby improving nutrient retention (Zhang *et al*., 2020). These strategies may facilitate the development of more efficient agroecosystems.

Promotion of plant growth and stress tolerance

Owing to its CEC, NBC retains NH_2^+, K^{2+}, Ca^{2+}, and Mg^{2+} and regulates soil pH (Liu *et al*., 2021). NBC enhances nutrient absorption in soil by reducing acidity and salinity (Liu *et al*., 2021; Rajput and Minkina, 2024; Shafiq *et al*., 2023). NBC provides an eco-friendly agroecosystem that helps various fungi and Rhizobium coexist with Azotobacter and phosphate-solubilizing microbes to facilitate nutrient conversion (Zhou *et al*., 2020). In addition, NBC surfaces serve as prompter for nutrients and organic materials through their functional groups (Agrawal *et al*., 2025a).

NBC establishes stable links between soil components that efficiently store organic substances. NBC enhances soil structure by improving nutrient retention mechanisms (Irewale *et al*., 2025). The robust CEC of the NBC enables the retention of vital minerals in the soil.

Microorganisms use enzymes to transform nutrients into usable compounds (Zhou *et al*., 2020). NBC, with its functional groups (—OH, —COOH, and —C=O), efficiently absorbs nutrients and organic matter, forming durable organic-mineral aggregates (Fig. 3). Biomass and carbon are retained during this process. NBC structures improve nitrogen management and safeguard sustainable agricultural futures (Sani *et al*., 2023).

Soil hydraulic qualities originate from pore configurations, particularly the sizes of micropores and mesopores. Polar functional residues in NBC absorb water molecules to enhance soil moisture content (Shafiq *et al*., 2023; Acharya *et al*., 2024). NBC promotes soil water retention by increasing the volume of accessible water spaces (Chen, 2006; Li *et al*., 2021).

Nanobacteria possess unique capacities for the permanent removal of deleterious environmental contaminants (Liu *et al*., 2021; Natasha *et al*., 2022; Pignatello *et al*., 2024; Rajput *et al*., 2022). These contaminants include heavy metals, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and herbicides. Plants may mitigate cadmium (Cd) toxicity when NBC is synthesized

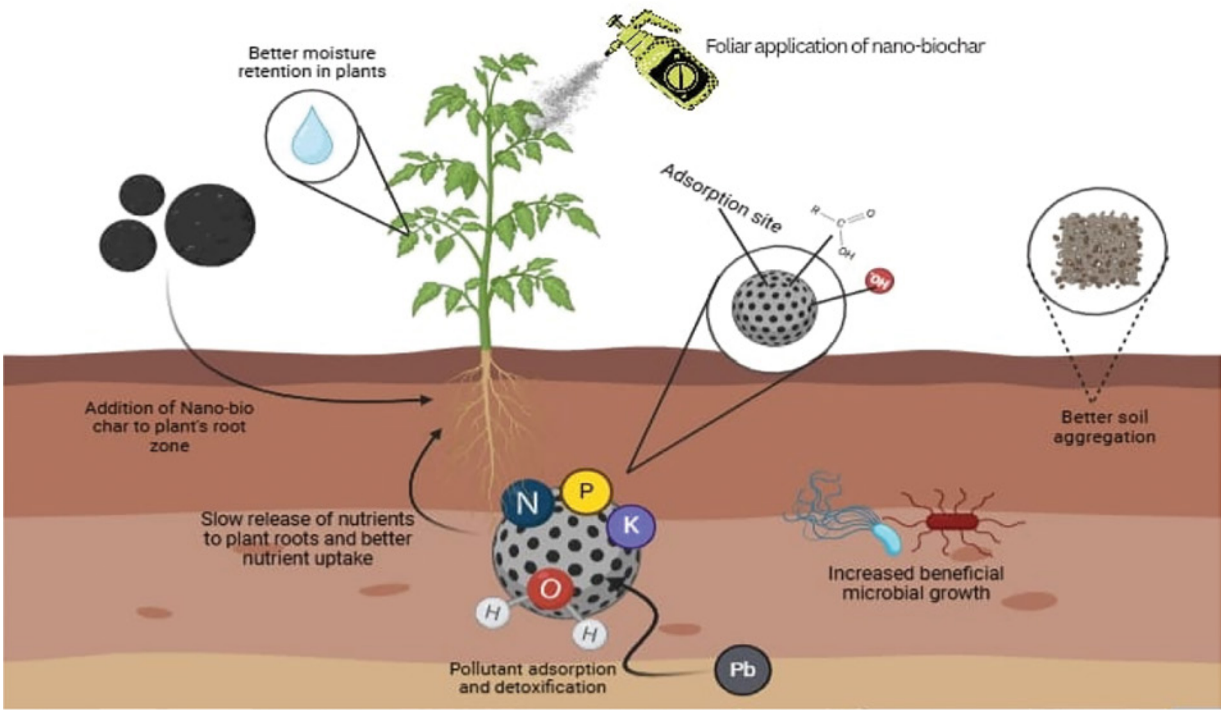


Fig. 3. How nano-biochar enhances soil quality, detoxifies pollutants, and promotes plant development. Nano-biochar increases soil water retention, controls nutrient release, and promotes beneficial microorganisms through root-zone and foliar spraying. Nano-biochar adsorbs heavy metals and aggregates soil, making it a sustainable, precision agriculture and soil health solution.

at 600°C. This technique enhances biological functions and reduces Cd absorption via NBC augmentation (Yue *et al*., 2019).

The application of NBC and stress caused by Cd have opposing effects on cell health (Tang *et al*., 2022). During photosynthesis, the production of pigments and lipids is increased. Via surface bonding and electrostatic attraction, the roots of *Brassica chinensis* formed contact sites with NBC, thereby preventing Cd from entering the plants. In addition, the incorporation of potassium and phosphorus components increases the biological efficiency of NBCs (Liu *et al*., 2021; Mehmood *et al*., 2024a).

Controlled release and nanocarrier function for agrochemicals

Nanocarrier systems transport fertilizers, insecticides, and plant nutrient solutions. NBC shows how complex networks deliver agricultural commodities (Ray *et al*., 2025). Owing to their large surface-to-volume ratio and tunable porosity, farmers employ NBC to transport encapsulated agrochemicals into composts (Wang *et al*., 2023). When NBC products are used in farming, fewer agrochemicals leak or evaporate, which improves their efficacy. Although plants absorb potassium chloride, ammonium nitrate, and urea fertilizers, NBC products are distributed equally. Targeted imidacloprid and carbofuran treatments of NBC protect unwanted species from exposure and pollution (Shiade *et al*., 2024b). These findings indicate that NBC salicylic acid and gibberellins assist plants in absorbing treatments (Ghassemi-Golezani *et al*., 2025). NBC matrices enable precise distribution of agents in the rhizosphere, thereby stimulating development, controlling blooming, and enhancing plant resilience to physical stress. Surface modifications, such as those that affect pH responsiveness, molecular gating, and receptor targeting, yield delivery profiles that become progressively optimal (Kumari, 2025).

Water retention and drought mitigation

The numerous polar functional groups and porosity of NBC contribute to substantially improved water retention and thereby enhance water availability to plants. NBC can store moisture in the soil similar to a sponge, providing a variety of advantages for water conservation during dry seasons in sandy soils (Liang *et al*., 2006; Sashidhar *et al*., 2025). The carboxyl and hydroxyl groups present in NBC form hydrogen bonds with water, resulting in a soil with an enhanced ability to store water. NBC reduces the need for irrigation under conditions where prevailing droughts can constrain farm production, creating the impression that it is ordinary for arid zones when water is limited (Abbas *et al*., 2025a). Not only is NBC useful because it improves soil structure and supplies water, but it also plays an important role in the recovery of soil amendments, which helps agricultural systems conserve water (Abbas *et al*., 2025b).

Heavy metal adsorption and contaminant immobilization

Owing to the presence of many oxygen functional groups on its surface, NBC can effectively collect hazardous heavy metals including Cd, Pb (lead), Cr (chromium), Hg (mercury), and As (arsenic) (Ahuja *et al*., 2022). Pollutants and hazardous materials can be removed by surface binding, electrostatic attraction, and ion exchange. Oxidation reactions explain these redox processes. The removal method involves multiple techniques, including surface bonding, electrical processes, and ion exchange (Moulick *et al*., 2024).

Onion skin particles are more effective at removing pollutants when combined with Fe_3O_4 or goethite double hydroxide for NBC production (Omar *et al*., 2025b). The modified NBC enables this material to convert organic pollutants via photochemical reactions similar to the Fenton reaction. NBC removes ciprofloxacin from soil and water during treatment via hydrophobic interactions, π–π stacking, and hydrogen bonds (Yin *et al*., 2022). NBC can effectively collect microplastics and per- and polyfluoroalkyl substances (PFAS) because of its natural stress alleviation properties.

Climate change mitigation and carbon sequestration

NBC meets crucial criteria for addressing climate change challenges. These qualities include its heat resistance and carbon content. According to Lal *et al.* (2021), importantly, soils function as carbon storage systems, with storage periods of decades to centuries. NBC can withstand microbial assault for extended periods. In an effort to reduce GHG emissions, NBC contributes to environmental preservation. This encourages the development of nitrifiers, which, in turn, reduce GHG emissions (Xie *et al*., 2025a). This is beneficial to agriculture because it helps reduce methane and nitrous oxide emissions. NBC also helps stabilize soil and enhances water retention during periods of uncertain climatic events, thereby strengthening the resilience of agricultural systems to climate variability (Sun *et al*., 2020).

Water purification and wastewater treatment

NBC is widely used for water purification and wastewater treatment because it adsorbs nutrients such as NO_3^- and PO_4^{-3}, along with heavy metals, surfactants, and pharmaceuticals (Rahman *et al*., 2025). Treatment of NBC composites with transition-metal doping (Fe [iron] and Mn [manganese]) enables them to activate peroxymonosulfate or H_2O_2, turning the system into an effective mechanism for the degradation of organic pollutants. Dispersed NBC materials can be easily removed using magnets, restoring them to their original state for continued use in small-scale water treatment facilities. NBC is effective for disinfecting polluted water because it disrupts microbial membranes, creating oxidative stress that kills bacteria (Agrawal *et al*., 2025b).

Sensor technology and environmental monitoring

Opportunities exist to enable accurate agricultural surveillance and environmental contamination assessments by integrating radio-frequency identification (RFID) sensors. Electrodes can be combined with NBC (Chen *et al*., 2021; Li *et al*., 2022). This allowed the identification of trace amounts of lead and mercury, as well as nitrates and pesticide residues. During the measurement process, the redox-based detection approach demonstrates high specificity and sensitivity (Virú-Vásquez *et al*., 2025). Fluorescent NBC materials are currently being developed. These materials can detect organic impurities by measuring their fluorescence intensities in real time. This material is useful in biosensor applications that detect pathogens and antibiotics (Emamverdian *et al*., 2025; Tshoko *et al*., 2025).

These applications can be used for real-time field diagnostics and precision agriculture. Functional modification of NBC using aptamers, antibodies, and enzymes makes the material appropriate for these applications (Wang *et al*., 2023).

Circular bioeconomy and waste management

NBC implements circular bioeconomy principles by leveraging biomass waste, such as sugarcane bagasse, coconut shells, and food waste to produce high-value carbonaceous nanomaterials (De Siqueira *et al*., 2026). Agricultural and industrial wastes are diverted from landfills via upcycling, generating beneficial agronomic by-products that support environmental objectives (Pandey *et al*., 2025; Singh *et al*., 2025). The composting process becomes faster when using NBC while simultaneously reducing NH_3 and CH_4 emissions and improving the nutrient content of organic fertilizers. The integration of NBC into pyrolysis and gasification systems enables simultaneous energy production and recovery of valuable materials while building agricultural systems that operate at zero waste and generate energy.

Mechanisms of action in soil and plants

The beneficial effects of NBC in agroecosystems are related to its physicochemical properties and interactions within the soil-plant-microbe system. Its nanoscale size enables NBC to actively interact with the rhizosphere. This leads to changes in nutrient dynamics, microbial activity, and plant physiological responses (Table 3).

Physicochemical interactions

NBC displays numerous functional and structural characteristics that promote the binding and retention of nutrients and contaminants (Dey and Ahmaruzzaman, 2023). Electrostatic forces, hydrogen bonding, van der Waals interactions, and π–π stacking are the primary mechanisms that facilitate interactions between the aromatic parts of NBC and organic/inorganic compounds (Nosratabad *et al.*, 2024b). The NBC exhibited high levels of nutrient absorption, including NH_4^+, NO_3^-, and PO_4^-. When NBC absorbs nutrients such as water during rainfall, the rhizosphere receives a greater quantity of accessible nutrients because fewer nutrients are lost (Rajput *et al.*, 2022).

NBC can efficiently address the hazards posed by organic pollutants and heavy metals using the same technique used for nutrient removal. In contaminated settings, NBC enhances pollutant elimination via π–π interactions with aromatic pollutants, particularly PAHs (Zhao *et al.*, 2022). NBC surfaces can act as buffers against soil acidity by stabilizing nutrients and their movement in the soil, ultimately affecting the amount of nutrients available to plants.

Microbial modulation

NBC promotes the proliferation of microorganisms in the soil via a combination of biochemical and physical mechanisms. NBC products enable beneficial bacteria to invade and protect themselves against natural hazards (Pavlicevic *et al.*, 2022). According to Yasin *et al.* (2025a), NBC increases the abundance of soil microorganisms and their enzymatic activities, including those of dehydrogenase and phosphatase. NBC contributes to the establishment of larger populations of beneficial bacteria, both inside and outside the plant roots. These bacteria enhance plant nutrient absorption and protect plants from diseases, not only via inter-microbial competition but also via microbial signaling (Jaiswal *et al.*, 2021).

By controlling bacterial quorum-sensing mechanisms, the current study demonstrated that NBC affects how microorganisms interact via signals. According to Wang *et al.* (2022), NBC plays a role in shaping microbial community behavior, including the formation of bacterial clusters on or near the root surface.

Nanointerfaces and root uptake

An extremely close contact with plant root surfaces is enabled by NBC at the nanoscale. They establish a very close relationship with the organism, making the processes of nutrition, transport, and signaling easier to perform (Abbas *et al.*, 2025c).

Table 3. Mechanisms of action of nano-biochar (NBC) in soil and plants.

Mechanism	Details	Category	Author(s)
Physicochemical interactions: Nutrient adsorption	NBC's high cation exchange capacity (CEC) and negative surface charge enable it to adsorb nutrients such as NH_4^+, NO_3^-, and PO_4^{3-}, thereby improving nutrient retention and availability.	Physicochemical interactions	(Deb, 2024)
Physicochemical interactions: Nutrient adsorption	NBC prevents nutrient leaching by increasing the availability of essential nutrients in the rhizosphere, thereby improving nutrient use efficiency.	Physicochemical interactions	(Das and Ghosh, 2023)
Physicochemical interactions: Contaminant immobilization	NBC immobilizes toxic contaminants, such as heavy metals (Cd^{2+}, Pb^{2+}) and organic pollutants, via π–π interactions, thereby reducing their bioavailability and toxicity.	Physicochemical interactions	(Fu *et al.*, 2021)
Microbial modulation: Habitat creation	NBC's porous structure supports microbial colonization, protecting beneficial microbes from predation and environmental stress and thereby enhancing microbial activity.	Microbial modulation	(Yasin *et al.*, 2025b)
Microbial modulation: Enhanced activity	NBC increases microbial biomass and enzyme activities (e.g., dehydrogenase and phosphatase), facilitating organic matter decomposition and nutrient cycling.	Microbial modulation	(Lu *et al.*, 2023)
Microbial modulation: Promotion of beneficial microbes	NBC enhances populations of beneficial microbes, such as PGPR, mycorrhizal fungi, and nitrogen-fixing bacteria, boosting nutrient acquisition and pathogen suppression.	Microbial modulation	(Jaiswal *et al.*, 2021; Jaiswal *et al.*, 2025)
Microbial modulation: Microbial signaling	NBC may modulate microbial signaling through quorum sensing, influencing microbial community dynamics and biofilm formation on root surfaces.	Microbial modulation	(Wang *et al.*, 2022)
Nanointerfaces and root uptake: Root interaction	NBC's small size allows it to penetrate soil pores and interact with root surfaces, enhancing nutrient uptake by plants.	Nanointerfaces and root uptake	(Liu *et al.*, 2019; Abou El-Nasr *et al.*, 2025)
Nanointerfaces and root uptake: Signal transduction	NBC may influence root exudates and plant hormone signaling (e.g., auxins and cytokinins), thereby stimulating root growth and architecture.	Nanointerfaces and root uptake	(Lian *et al.*, 2022)
Nanointerfaces and root uptake: Nanocarrier role	NBC may act as a nanocarrier, delivering agrochemicals or micronutrients in a controlled, targeted manner, thereby optimizing plant nutrition.	Nanointerfaces and root uptake	(Kappen *et al.*, 2025)

Root interface penetration

Because of its diminutive size, NBC can approach the root interface closely, even when lying on the root epidermis and root hairs. It can also penetrate the microscale pores of soil. A high concentration of nutrients and bioavailable chemicals is enabled by the short distance, which, in turn, encourages nutrient absorption by plant roots (Li *et al*., 2023).

Support for signal transduction

NBC can also alter root exudate composition, thereby enhancing plant hormone signaling. This has the potential to improve root architecture, elongation, and lateral root formation in plants (Tripathi *et al*., 2024). It would seem that there is evidence suggesting that NBC may interact with specific hormones produced during root exudation, which are upstream of active substances that influence root development. These hormones include the auxins and cytokinins. However, it is still in its developmental stage (Gulsah *et al*., 2025).

Nanocarrier

NBC has the potential to serve as an effective nanocarrier for agrochemicals and micronutrients and can also deliver a sustained release of these materials. Even at lower doses, this allows for the intake of chemicals and nutrients in sequential phases. This enables precision agriculture with greater accuracy and reduces the risk of environmental damage from chemicals introduced into the environment (Fig. 4).

Current limitations and future research prospects

PRODUCTION CHALLENGES AND STANDARDIZATION

Until recently, the lack of appropriate, explicit, and scalable manufacturing procedures has been the primary obstacle to implementing NBC applications. Ultrasonication and ball milling are two examples of readily available top-down processes. Both methods are new. NBC undergoes unintended changes during processing, resulting in distinct physicochemical features. NBC, synthesized from various materials and processed using different techniques and post-synthesis conditions, exhibits unique behaviors in soil systems (Sun *et al*., 2024). This is because differences in the surface areas, pore structures, and functional groups caused by processing are the main factors. Therefore, standard procedures are essential to address the challenges of numerous studies on performance assessment and repeatability.

ENVIRONMENTAL AND ECOTOXICOLOGICAL CONCERNS

Although scientists are not yet aware of the environmental impact of NBCs, they are derived from biomass and are gaining societal acceptance because they offer environmental benefits that are more eco-friendly than those of manufactured nanomaterials (Gaur, 2022; Chandran and Chandra, 2026; Khattak *et al*., 2026). NBCs, which are 90% smaller than conventional nanoparticles and contain active chemicals, can elicit a wide range of responses from the surrounding environment (U. Kumar *et al*., 2021; Zhuo *et al*., 2022). NBC can cause the accumulation of contaminants within organisms, the deterioration of soil bacteria, and the potential for pollution crises in water resources. According to Kumar *et al.* (2021), NBCs are introduced into the environment via the waste products they produce. The environmental pollutants include heavy metals and PAHs. Because of the limited understanding of the propagation of suspended NBC, the spread of NBC in soil and aquatic systems remains uncertain.

REGULATORY AND POLICY GAPS

Because NBC does not meet the requirements of either category, it is classified as a product that falls between conventional biochar and engineered nanoparticles. According to Lehmann *et al.* (2021), the National Broadcasting Corporation operates in a regulatory environment characterized by unpredictability.

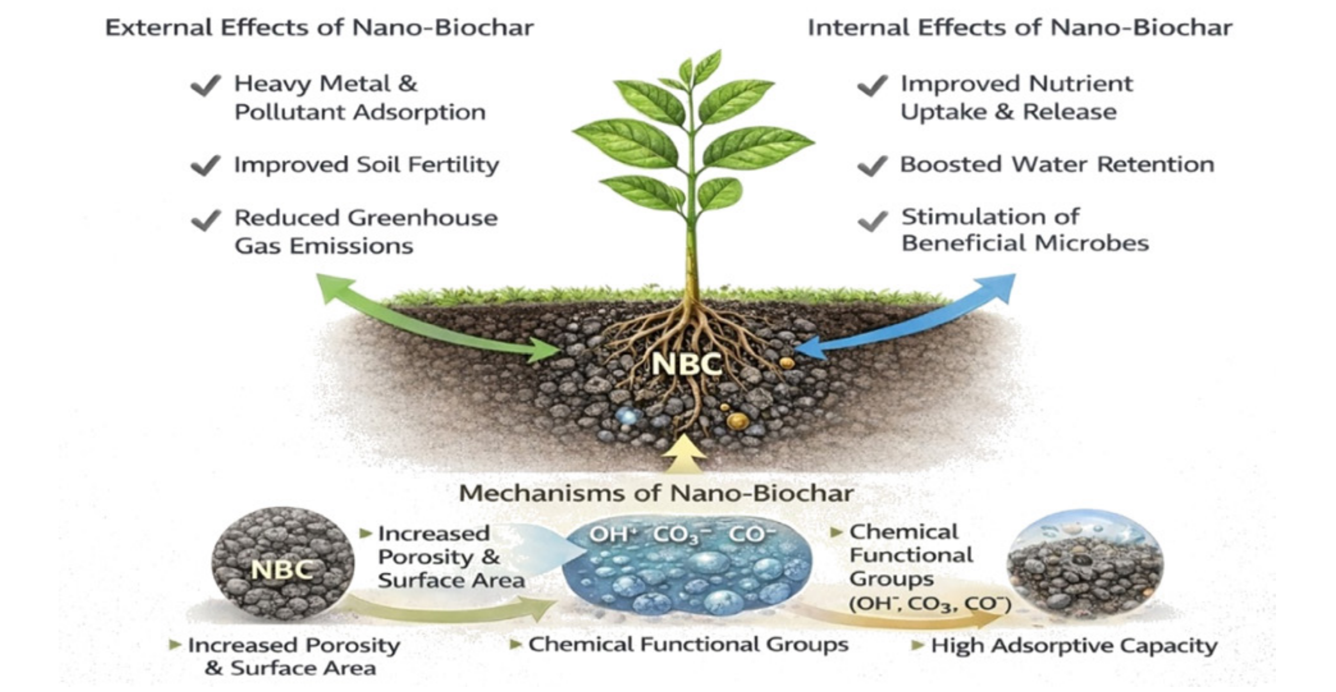


Fig. 4. The diagram illustrating how nano-biochar (NBC) functions in the rhizosphere to improve soil quality and plant performance. Its nanoscale structure and abundant surface functional groups increase adsorption and retention of nutrients, water, and contaminants, thereby enhancing nutrient use efficiency, supporting beneficial microbial activity, mitigating pollutants and heavy metals, and contributing to lower greenhouse gas emissions.

Establishing appropriate quality standards, safety requirements, and authorization procedures for agricultural and environmental safety is challenging. As there are no regulations in place, the extensive commercial usage of NBC is not possible, which is a barrier to its use.

Future research prospects

DEVELOPMENT OF GREEN AND SCALABLE SYNTHESIS METHODS

Research will require developers to develop affordable and environment-friendly synthetic procedures for NBC. Microwave-assisted pyrolysis, hydrothermal carbonization, and biological processes offer promising alternatives to energy-intensive mechanical methods for NBC (Rathnayake *et al*., 2021). Utilizing agricultural residues and industrial waste streams for NBC production supports circular economy principles and reduces ecotoxicity.

COMPREHENSIVE RISK ASSESSMENT AND LIFE CYCLE ANALYSIS (LCA)

Life cycle assessments of environmental risks identify the long-term impact of NBCs during application. NBC requires further examination of its survival patterns across various soils and its interactions with microbes in real-world environments (Park *et al*., 2025). These assessments enable the development of secure design approaches and regulatory choices.

ADVANCING NBC-SOIL-PLANT INTERACTION MODELS

Current knowledge of the effects of NBC on nutrient cycling mechanisms, as well as its actions on microorganisms and plant physiology, remains inadequate. Research employing systems biology, combined with metagenomics and transcriptomics, should analyze the NBC mechanisms by which microbes affect plant-microbe interactions, nutrient uptake, and abiotic stress responses (Chen *et al*., 2022). This knowledge will facilitate the development of new-generation NBC variants designed for specific crops and soil environments.

FIELD TRIALS AND LONG-TERM MONITORING

The research on NBC materials has been conducted in artificial settings, namely, laboratories and greenhouses. Field testing conducted across a range of agroclimatic conditions should be expanded by conducting broader trials at multiple locations. Researchers must evaluate the effects of NBC on yield, parameters that influence soil health, and its stability across multiple growing seasons (Shaheen *et al*., 2019, 2022). The resistance of NBC to changing agricultural threats such as drought, salt damage, and insect pests will be evaluated via long-term scientific investigations that will provide valuable insights.

INTEGRATION INTO CLIMATE-SMART AGRICULTURE AND POLICY FRAMEWORKS

NBC can serve not only as a solution for agricultural carbon enhancement but also as a climate-smart technology, reducing GHG emissions while simultaneously strengthening the capacity to control carbon emissions. NBC's agricultural system should be investigated in this study, and conservation tillage, cover cropping, and proper nutrient management should be considered (Wang *et al*., 2022). Consequently, this will help prevent the agricultural system from becoming sustainable. Consequently, responsible commercialization promotes open rules, NBC-specific risk assessment tools, and certification methods, thereby subjecting the NBC's entry into global markets to accountability.

CONCLUSION

The National Biodiversity Conservation Initiative is a game-changing, sustainable method that represents an evolving environmental and agricultural management system. At the same time, functional group interactions between NBC and its own physicochemical properties, including a broad surface area and pore network, contribute to the maximal benefits of soil nutrient conservation, higher fertility, and greater plant yield. These interactions also increase plant yield. These advantageous outcomes can be achieved using several functional groupings provided by NBC. Owing to its compact dimensions, NBC can establish enhanced interactions with a wide variety of soil pathogens, thereby enabling improved interactions with a wide variety of bacterial species and plant root systems. Owing to its one-of-a-kind composition, NBC offers a window of opportunity to address environmental concerns, such as reducing pollution, sequestering carbon, and reducing GHG emissions.

Recent studies have shown that the use of NBC in agricultural settings increases crop yield, improves nutrient use efficiency, and protects plants against biological and environmental threats. NBC offers several benefits. It is effective in managing heavy metals, breaking down organic pollutants, and improving soil quality. These capabilities play an important role in the restoration of damaged ecosystems. Although NBC faces three primary problems concerning its production techniques, environmental assessment standards, and regulatory requirements, it has great potential within its manufacturing processes. Researchers in the pharmaceutical industry must focus their efforts on various agroecosystem studies of the effects of NBC to improve application techniques and adopt more cost-efficient manufacturing processes. NBC is an example of modern green technology that serves as a transformative solution for agricultural practices and environmental management systems. The findings of scientific research and the adoption of relevant NBC will result in the establishment of stable and efficient agricultural systems, thereby preserving global sustainability.

LIST OF ABBREVIATIONS

NBC	nano-biochar
FAO	Food and Agriculture Organization
IPCC	Intergovernmental Panel on Climate Change
CEC	cation exchange capacity
FTIR	Fourier transform infrared (spectroscopy)
SEM	scanning electron microscope
TEM	transmission electron microscope
BET	Brunauer-Emmett-Teller (surface area analysis)
XPS	X-ray photoelectron spectroscopy
CHNS	carbon, hydrogen, nitrogen, and sulfur (analysis)
EDX	energy-dispersive X-ray (spectroscopy)
TGA	thermogravimetric analysis
XRD	X-ray diffraction
HTC	hydrothermal carbonization
PCBs	polychlorinated biphenyls
PAHs	polycyclic aromatic hydrocarbons
ARGs	antibiotic resistance genes
GHG	greenhouse gas
ROS	reactive oxygen species
RFID	radio-frequency identification
PFAS	per- and polyfluoroalkyl substances
PGPR	plant growth-promoting rhizobacteria
LCA	life cycle analysis

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this study.

ETHICS STATEMENT

No ethical approval or informed consent was required. The review was conducted following relevant guidelines, and all sources were properly cited and accurately represented in accordance with accepted ethical publishing standards.

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AUTHOR CONTRIBUTIONS

VE contributed to the investigation, methodology, data analysis, software, and writing – original draft preparation. SK and AA contributed to the methodology, data analysis, visualization, and writing – original draft preparation. MA contributed to the conceptualization, data curation, formal analysis, validation, and writing – original draft preparation. ZFRA contributed to the conceptualization, supervision, data curation, validation, review and editing, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

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DATA AVAILABILITY

Data is available upon request.

DECLARATION OF AI-ASSISTED TECHNOLOGIES IN THE MANUSCRIPT PREPARATION PROCESS

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

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