

## Review

## Open Access

# Nanobiochar functions as a multifunctional amendment for soil health, plant stress tolerance, and climate-resilient farming

Muhammad Adil<sup>1\*</sup>, Isma Gul<sup>2</sup>, Amna Munir Leghari<sup>3</sup>, Safdar Bashir<sup>4</sup>, Syed Ali Asghar Shah<sup>5</sup>, Hasnain Farooq<sup>6</sup>, Siqi Lu<sup>7</sup> and Yu Tao<sup>1\*</sup>

Received: 14 April 2026

Revised: 8 May 2026

Accepted: 3 June 2026

Published online: 2 July 2026

## Abstract

Nanobiochar, biochar-derived particles < 100 nm, offers transformative potential for sustainable agriculture through dramatically enhanced properties: 0.4- to 97-fold increases in specific surface area, 0.5- to 48.5-fold higher pore volume, and improved surface functionality. This review provides the first comprehensive, agriculture-centric synthesis of nanobiochar research, integrating findings from 2013 to 2026 and reporting quantitative median enhancements derived from published studies: surface area increases by 650%, pore volume by 480%, cation exchange capacity by 320%, nitrogen use efficiency by 77%, water retention by 39%, and crop yield by 18%. Heavy metal uptake in contaminated soils is reduced by 84%–95%, while nutrient leaching decreases by 30%–50%. We uniquely embed nanobiochar applications within established sustainable farming practices, conservation tillage, water-efficient cropping systems, and precision agriculture, and within a circular economy framework linked to the UN Sustainable Development Goals (SDGs 1–3, 6, 12, 13, and 15). A multi-level mechanistic framework elucidates nanobiochar–plant interactions from molecular to field scales, including root colonization, nutrient-uptake enhancement, stress-signalling modulation, and microbial community shifts. Synthesis methods (ball milling, sonication, centrifugation, hydrothermal) are critically evaluated for agricultural scalability and energy efficiency. Crucially, this review provides a balanced assessment of environmental risks: phytotoxicity, effects on soil organisms, transport in soil systems, and regulatory gaps, topics largely overlooked previously. By identifying key knowledge gaps and proposing a targeted research roadmap, we aim to accelerate the translation of nanobiochar from laboratory innovation to climate-smart agricultural practice, contributing to global food security and environmental resilience.

**Keywords:** Nanobiochar, Sustainable agriculture, Soil health, Plant stress mitigation, Nutrient management, Contaminant immobilization, Climate-smart agriculture, Water use efficiency

## Highlights

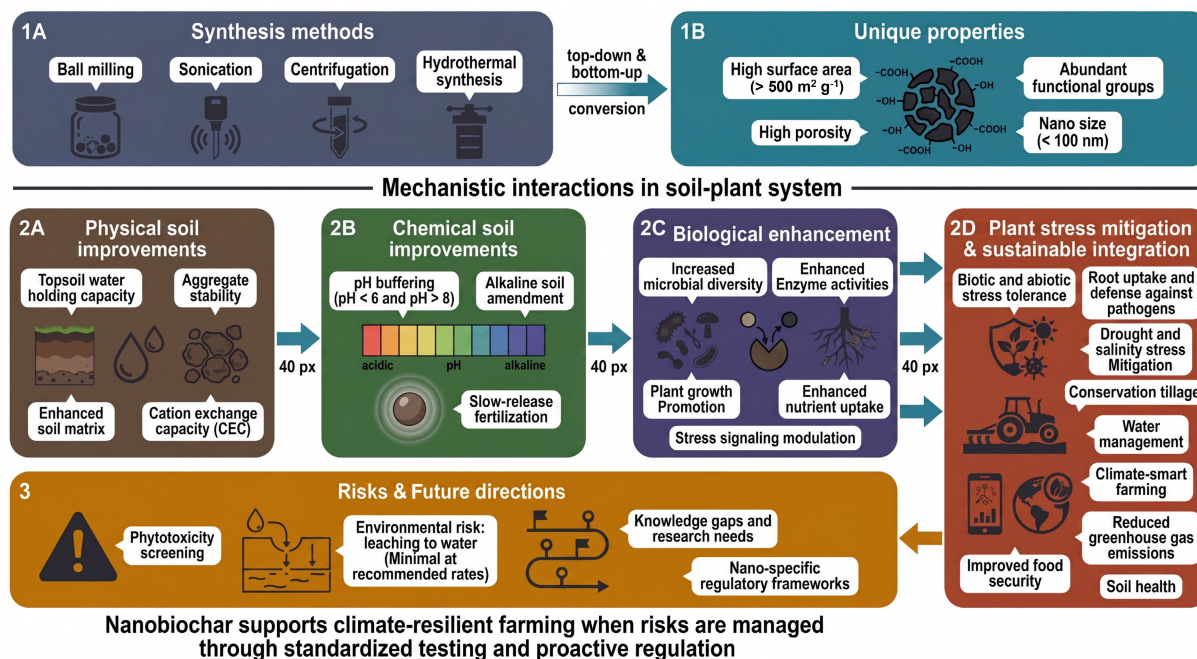
- First agriculture-centric synthesis of nanobiochar research (2013–2026) reporting quantitative median enhancements derived from published studies: surface area (+ 650%), pore volume (+ 480%), CEC (+ 320%), N-use efficiency (+ 77%), and crop yield (+ 18%).
- A multi-level mechanistic framework is elucidated for nanobiochar-plant interactions, including root colonization, nutrient-uptake enhancement, and stress-signaling modulation.
- Substantial contaminant immobilization (84%–95% heavy metal reduction) and nutrient retention (30%–50% reduced leaching) are demonstrated across multiple published investigations, enhancing food safety and fertilizer efficiency.
- Nanobiochar applications are integrated within circular economy principles and linked to contributions toward UN Sustainable Development Goals (SDGs 1–3, 6, 12, 13, and 15).

\* Correspondence: Muhammad Adil ([adiluf34@gmail.com](mailto:adiluf34@gmail.com)); Yu Tao ([yutao0325@sina.com](mailto:yutao0325@sina.com))

Full list of author information is available at the end of the article.

- A balanced assessment of environmental risks (phytotoxicity, soil organism effects, transport) and regulatory gaps is provided, alongside a targeted research roadmap for climate-resilient agriculture.

## Graphical abstract



## Introduction

Global agriculture faces unprecedented challenges in the 21<sup>st</sup> century, including feeding a projected population of 9.7 billion by 2050, adapting to weather extremes caused by climate change, reversing soil degradation, and minimizing environmental impacts while maintaining productivity<sup>[1,2]</sup>. These interconnected issues require innovative, sustainable solutions that can simultaneously boost agricultural output, enhance resource efficiency, and restore ecosystem health. This need is particularly urgent in dryland farming systems, where water scarcity and soil degradation significantly limit productivity<sup>[3]</sup>.

Biochar, a carbon-rich solid produced by pyrolyzing biomass under oxygen-limited conditions, has emerged over the past two decades as a valuable agricultural amendment, initially recognized for its capacity to improve soil fertility and sequester carbon. It also enhances soil properties, retains nutrients, increases water retention capacity, and reduces greenhouse gas emissions<sup>[1,4,5]</sup>. Recent research shows that applying biochar can significantly raise crop yields and water-use efficiency, especially in water-scarce situations<sup>[6]</sup>. Nevertheless, the agronomic potential of conventional bulk biochar is constrained by its inherently modest specific surface area, limited porosity, and relatively low density of surface functional groups, which restrict its performance in advanced agricultural applications<sup>[7]</sup>.

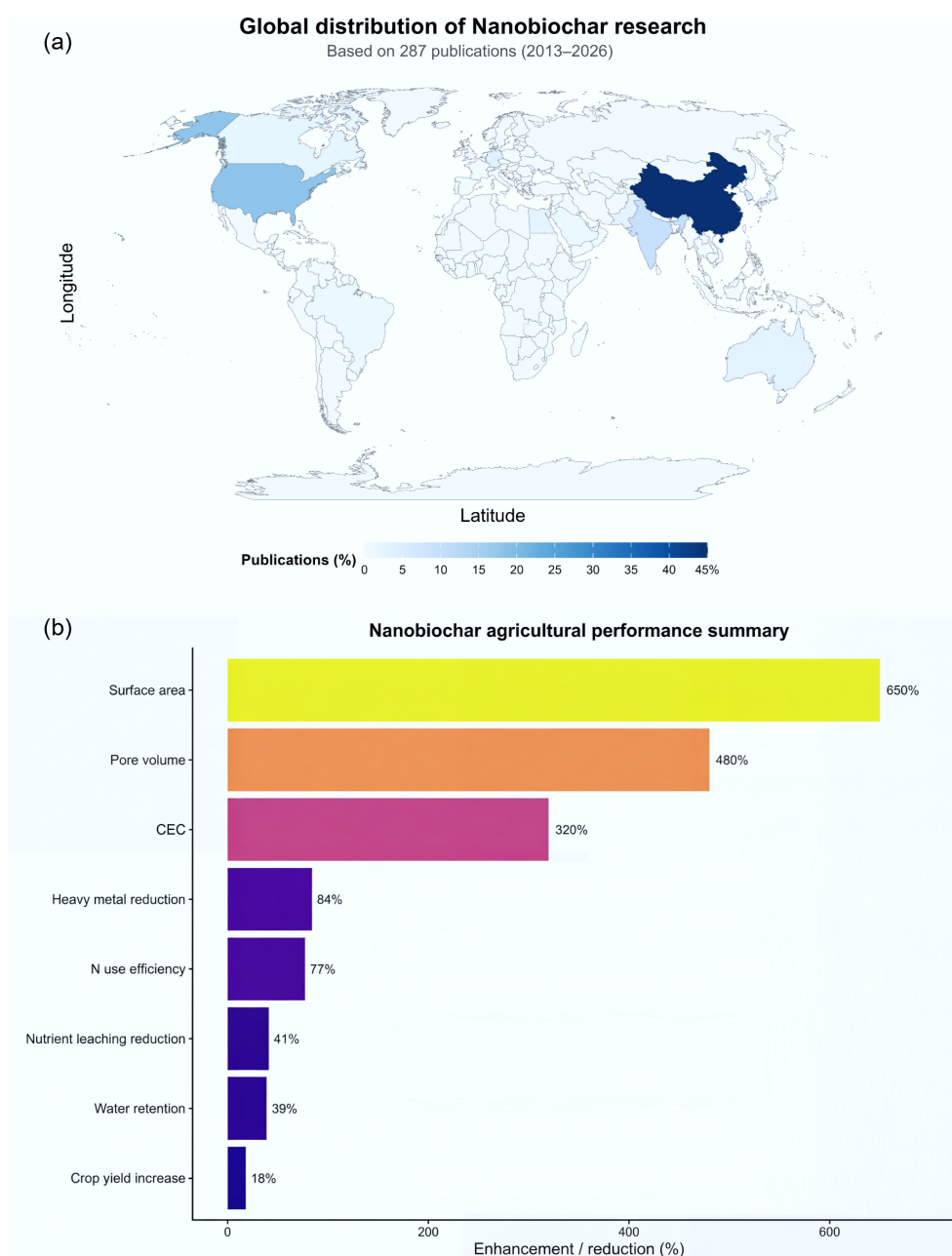
The convergence of biochar science with nanotechnology has given rise to nanobiochar, a material that transcends the limitations of bulk biochar while retaining its sustainable foundation<sup>[8,9]</sup>. Reducing biochar particles to the nanoscale via top-down methods (e.g., ball milling, sonication, centrifugation) or bottom-up hydrothermal synthesis triggers dramatic improvements in physicochemical properties<sup>[10,11]</sup>. Based on a comprehensive synthesis of the published literature, we identified that specific surface area can increase

from 0.4- to 97-fold relative to the parent bulk biochar, while pore volume can rise from 0.5- to 48.5-fold, depending on feedstock, pyrolysis conditions, and synthesis method<sup>[12,13]</sup>. These enhancements are accompanied by a marked increase in surface oxygen-containing functional groups that govern nutrient binding and contaminant interactions. Such transformations fundamentally alter the behavior of the material in soil-plant systems, expanding its potential far beyond that of conventional biochar.

Although several reviews have catalogued nanobiochar production methods or environmental applications<sup>[9,10,14]</sup>, and a recent comprehensive review on 'Nano-Black Carbon'<sup>[15]</sup> provided a broad biogeochemical perspective, the present review is the first to offer an agriculture-centric, quantitative synthesis that integrates nanobiochar's property enhancements directly within established sustainable farming practices, such as conservation tillage, water-efficient cropping systems, and precision agriculture, and explicitly links them to circular economy principles and the UN Sustainable Development Goals. Furthermore, we provide a multi-level mechanistic framework spanning molecular to field scales and present a balanced assessment of environmental risks (phytotoxicity, effects on soil organisms, transport, and regulatory gaps), topics that have been largely overlooked in earlier compilations. **Figure 1** provides a global overview of nanobiochar research contributions and summarizes the median enhancements in key agricultural properties.

Nanobiochar research represents a paradigm shift in the utilization of biomass-derived carbon materials for agriculture. The field has expanded exponentially over the past decade, reflecting the scientific community's recognition of nanobiochar's capacity to address multiple stress factors simultaneously, including salinity, drought, and heavy metal toxicity<sup>[18,19]</sup>.

This review systematically synthesizes the available evidence on: (i) synthesis methods and their scalability for agricultural

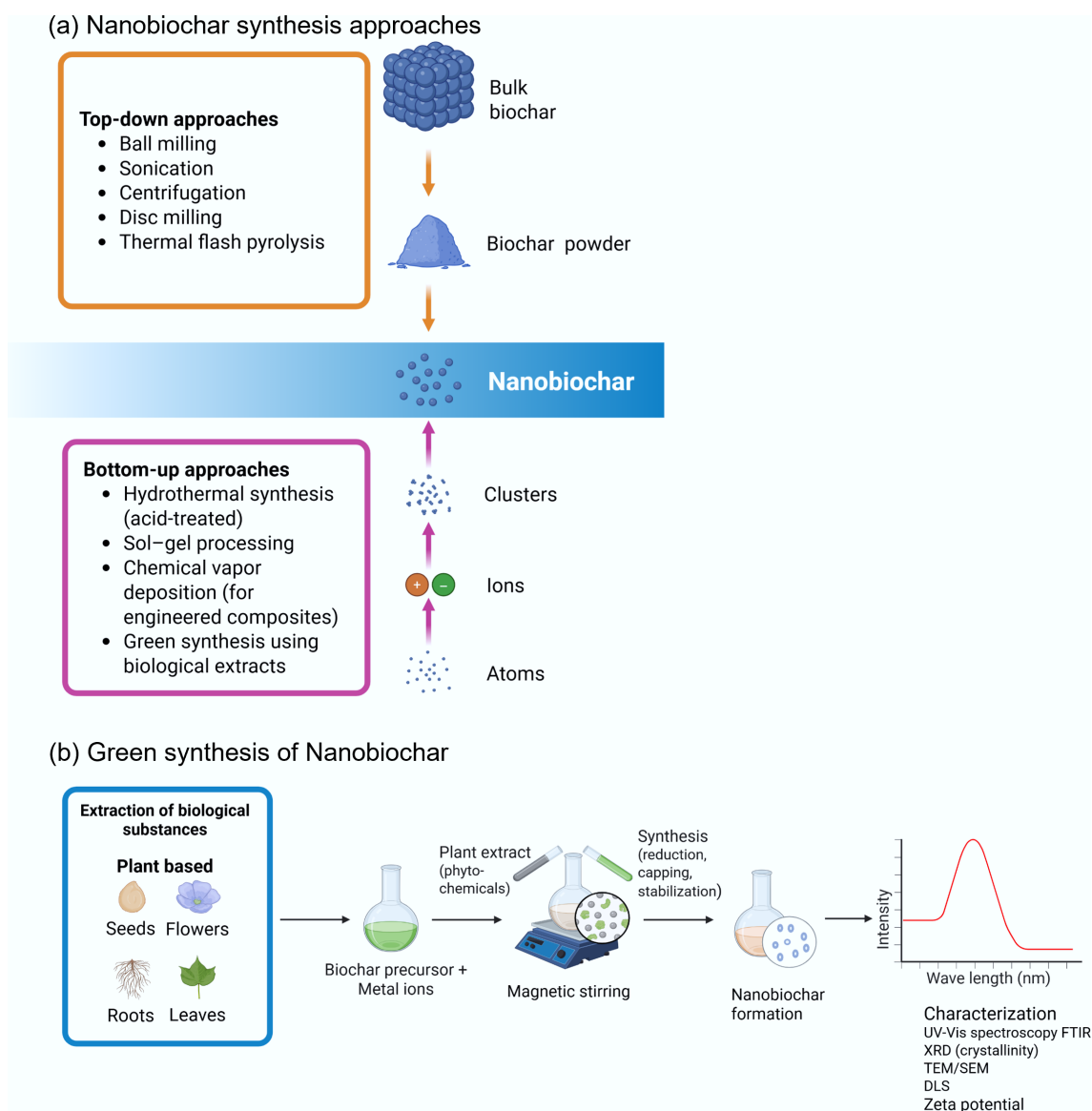


**Fig. 1** Global research landscape and agricultural performance of nanobiochar (2013–2026). **(a)** Map of publication contributions by country, with China leading at 45%, followed by the USA (18%), India (9.5%), and others. **(b)** Median enhancements in key agricultural parameters: surface area (+ 650%), pore volume (+ 480%), CEC (+ 320%), heavy metal reduction (84%), nitrogen use efficiency (+ 77%), nutrient leaching reduction (41%), water retention (+ 39%), and crop yield (+ 18%) (compiled from<sup>[10–13,16,17]</sup>).

production; (ii) physicochemical properties governing soil–plant interactions; (iii) impacts on soil physical, chemical, and biological health; (iv) mechanisms driving plant growth promotion and stress mitigation; (v) immobilization of heavy metals and organic contaminants in agricultural soils; (vi) integration with water-efficient farming and precision agriculture; (vii) environmental fate, phytotoxicity, and risk assessment; and (viii) alignment with circular economy and climate-smart agriculture frameworks. By consolidating quantitative data, critically evaluating mechanistic understanding, and identifying priority knowledge gaps, we outline a targeted research roadmap to accelerate the translation of nanobiochar from laboratory innovation to climate-resilient, on-farm practice, thereby contributing to global food security and environmental sustainability.

## Nanobiochar synthesis and properties

Transforming waste biomass into nanobiochar for agricultural use requires an understanding of synthesis mechanisms, critical process parameters, and scalability constraints. The four principal methods employed in agricultural research are ball milling, sonication, centrifugation (as a separation technique), and hydrothermal synthesis. Each approach imparts distinct physicochemical characteristics that govern agronomic performance. Figure 2 summarizes the top-down, bottom-up, and green-synthesis paradigms for nanobiochar production alongside key characterization techniques.



**Fig. 2** Synthesis approaches for nanobiochar production. **(a)** Top-down methods fracture bulk biochar into nanoscale particles through mechanical or physical forces, while bottom-up approaches assemble nanobiochar from molecular or ionic precursors. **(b)** Green synthesis employs plant extracts as reducing and capping agents to generate stable nanobiochar under mild conditions. The resulting materials are characterized by a suite of spectroscopic and microscopic techniques including UV-Vis, FTIR, XRD, TEM/SEM, DLS, and zeta potential analysis.

## Ball milling

Ball milling is the most widely adopted technique, accounting for approximately 42% of reported agricultural nanobiochar preparations<sup>[10,20]</sup>. This mechanochemical method uses the kinetic energy of grinding media to fracture bulk biochar particles through compression, shear, and impact. The process reduces particle size to the nanoscale while simultaneously exposing internal pore surfaces, creating reactive edge sites, and, in wet-milling environments, introducing oxygen-containing functional groups beneficial for nutrient retention<sup>[12]</sup>. Adjustable parameters—milling time, rotational speed, ball-to-biochar ratio, media type, and wet vs dry conditions—allow tailoring of product properties for specific soil–plant applications. Prolonged milling increases surface area and reduces particle size, but excessive duration can promote particle aggregation and diminish returns<sup>[21]</sup>. Wet milling generally produces more uniform particle sizes, better colloidal stability, and higher O/C ratios than dry milling, making it preferable for agricultural formulations<sup>[22,23]</sup>.

## Sonication

Sonication accounts for roughly 24% of agricultural nanobiochar preparations<sup>[24,11]</sup>. Ultrasonic cavitation generates intense local hot-spots and shock waves that mechanically disintegrate suspended biochar particles while preserving or even augmenting oxygen-rich functional groups. Sonication is energy-efficient, can be performed in water without organic solvents, and typically yields nanobiochars with higher O/C ratios than dry-milled equivalents, indicating greater surface polarity that enhances interactions with soil nutrients and plant roots<sup>[11]</sup>.

## Centrifugation and separation

Although centrifugation does not directly synthesize nanobiochar, it is an essential post-processing step for isolating narrow size fractions from polydisperse suspensions. When combined with prior size-reduction techniques, differential centrifugation enables the collection of particles with well-defined hydrodynamic diameters, which is



critical for studying size-dependent effects on soil processes and for meeting regulatory uniformity standards. Feedstock source influences the achievable particle size: plant-derived biochars tend to produce smaller nanoparticles than manure-derived ones, offering higher surface reactivity and nutrient-binding capacity<sup>[25]</sup>.

## Hydrothermal synthesis

Hydrothermal synthesis is a bottom-up approach that yields 'biochar nanodots' with distinctive properties. Concentrated acid mixtures oxidize and cleave bulk biochar into ultra-small particles with abundant oxygen-rich functional groups, yielding hydrodynamic diameters significantly smaller than those obtained by sonication. Crucially, hydrothermal synthesis delivers an approximately 10-fold higher yield than sonication, a decisive advantage for agricultural scalability<sup>[26]</sup>. The resulting nanobiochar exhibits high surface polarity, excellent colloidal stability, and enhanced surface area, all of which support nutrient retention and root-interface interactions.

## Scalability and agricultural considerations

Translating nanobiochar from laboratory to field demands scalable, energy-efficient, and cost-effective production. Ball milling currently offers the greatest scalability, with industrial mills capable of continuous ton-scale processing, though energy consumption remains substantial (100–1,000 kWh t<sup>-1</sup> depending on target particle size and feedstock)<sup>[20]</sup>. Integrating nanobiochar production with on-farm biomass waste management aligns with circular economy principles and could improve the overall energy balance if pyrolysis off-gases are used to power milling operations. Recent developments in AI-based optimization and precision agriculture may further reduce application rates and costs while enhancing agronomic benefits<sup>[27]</sup>.

## Physicochemical properties relevant to agriculture

The transition from bulk biochar to nanobiochar triggers profound changes in material properties that directly govern agricultural outcomes. Across diverse feedstocks and synthesis conditions, consistent patterns emerge: surface area, pore volume, surface functionality, and cation exchange capacity all increase dramatically, while colloidal behavior shifts toward greater mobility in soil pore networks. These interrelated changes underpin the ability of nanobiochar to enhance nutrient retention, improve water availability, and immobilize contaminants.

### Surface area enhancement

Surface area enhancement is the most frequently reported and agriculturally significant effect of nanobiochar formation. A synthesis of the literature reveals a median increase of 6.5 times in surface area, with some values reaching up to 97 times higher in wheat straw biochar pyrolyzed at 500 °C<sup>[28,10]</sup>. This substantial rise in surface area directly improves nutrient adsorption, water retention, and microbial habitat availability in soils. In dryland farming systems, where water and nutrient retention are vital challenges, these improvements could greatly boost crop yields and resource efficiency<sup>[6]</sup>. The agricultural significance of enhanced SSA is multifold: it provides more sorption sites for cationic nutrients (e.g., NH<sub>4</sub><sup>+</sup>, K<sup>+</sup>), increases water film retention capacity, and creates expansive habitats for soil microorganisms. The inverse relationship between particle size and external surface area,  $SSA \propto 1/\text{diameter}$ , means that the nanoscale dimensions achieved by intensive milling directly amplify the reactive interface between nanobiochar and the soil solution.

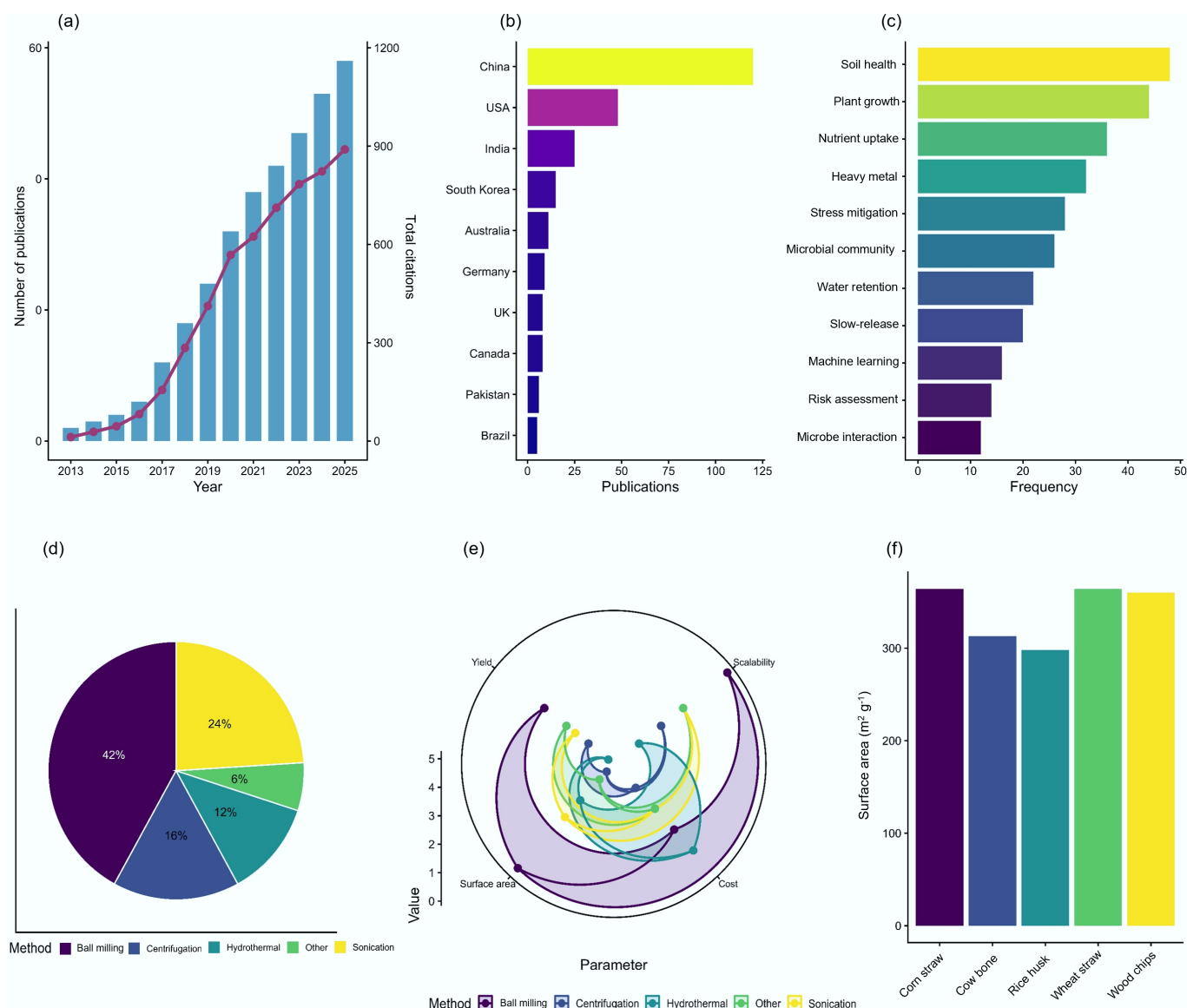
The increase in surface area largely depends on the pyrolysis temperature of the biochar precursor. Materials produced at lower temperatures generally show the most significant relative increases because their initial surface areas are small and they contain more residual organic matter, which can be broken down or removed during milling, revealing more surface for soil interactions. In contrast, high-temperature biochars already have developed porosity and larger surface areas, limiting further improvements but offering better stability for long-term carbon storage in soils<sup>[12,13]</sup>. The processes that improve surface area have direct implications for agriculture. Reducing particle size increases the external surface area in proportion to the inverse of the particle diameter, providing more sites for nutrient adsorption and microbial growth. Ball milling damages pore walls, exposing previously inaccessible internal porosity and transforming closed pores into open structures capable of holding water and nutrients. Mechanochemical breaking of covalent bonds creates new reactive surfaces at fracture planes, aiding nutrient binding. In wet milling, dissolving soluble parts can generate additional porosity, improving water retention<sup>[22,23]</sup>. Bibliometric analysis and synthesis pathways of agricultural nanobiochar research are shown in Fig. 3.

### Pore volume and porosity

Pore volume shows similar trends, with median increases of 4.8 times across ball-milled agricultural nanobiochars. The connection between surface area and pore volume growth is not strictly proportional, indicating that milling affects pore structure differently depending on the initial pore size distribution. This understanding is essential for tailoring nanobiochar properties for specific agricultural purposes. Materials with high microporosity may experience pore collapse or blockage during milling, potentially reducing water retention. Conversely, those with mesoporous structures often benefit from enhanced accessibility without losing structural integrity, thus improving water retention and nutrient diffusion<sup>[13]</sup>. The changed pore structure of nanobiochar-amended soils has been demonstrated to increase water storage and availability in rainfed cropping systems, which is particularly important in water-scarce environments<sup>[29]</sup>.

### Surface chemistry and functional groups

Molar elemental ratios shed light on the chemical changes during nanobiochar formation that influence agricultural performance. The O/C ratio, reflecting surface polarity and the density of oxygen-containing functional groups, increases in 78% of reported nanobiochar comparisons for agriculture, with a median rise of 1.4 times<sup>[10]</sup>. This boost results from various mechanisms: mechanochemical formation of radical sites that react with atmospheric oxygen or milling fluid; uncovering oxygen-containing groups previously hidden; and, in wet milling, hydrolysis reactions that transform ethers and esters into hydroxyl and carboxyl groups, both crucial for nutrient binding in soils. Higher O/C ratios in agricultural use are linked to increased cation exchange capacity, improved nutrient retention, and greater affinity for polar pesticides and their breakdown products<sup>[13,23]</sup>. These surface chemical traits are especially vital for immobilizing heavy metals in contaminated soils, a rising concern in many intensive farming practices<sup>[19,30]</sup>. Drawing on mechanistic insights from carbon-based nanomaterials broadly (e.g., graphene oxide, carbon nanotubes), one can infer that the high density of carboxyl and hydroxyl groups on nanobiochar facilitates inner-sphere complexation with metal ions (e.g., Pb<sup>2+</sup>, Cd<sup>2+</sup>, Cu<sup>2+</sup>), a mechanism that is central to both nutrient retention and contaminant immobilization in soils<sup>[15]</sup>. Property enhancement of agricultural nanobiochar is shown in Fig. 4.



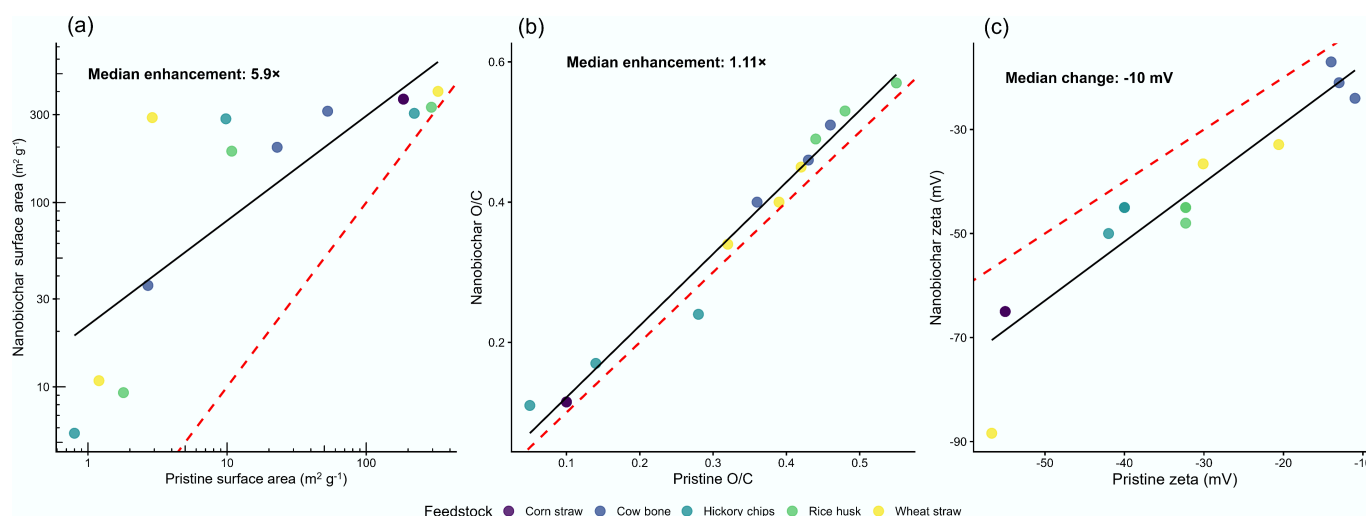
**Fig. 3** Bibliometric analysis and synthesis pathways of agricultural nanobiochar research. **(a)** Annual publication trend showing exponential growth during 2013–2025. **(b)** Top contributing countries, with China as the leading contributor. **(c)** Key research themes during 2022–2025. **(d)** Synthesis method distribution. **(e)** Multi-criteria performance comparison of synthesis methods. **(f)** Feedstock-dependent surface area after nanobiochar production. Data compiled from [10–13,16,17].

## Zeta potential and colloidal stability

Zeta potential, which measures surface charge and colloidal stability, shows consistent changes during nanobiochar formation that have significant implications for agricultural use. In 85% of reported comparisons, agricultural nanobiochar's zeta potential becomes more negative, with median shifts of  $-8.7$  mV for ball-milled materials and  $-12.4$  mV for sonicated samples [10,11]. This change indicates an increase in surface groups that can lose protons, creating negative surface charge at typical soil pH. Many nanobiochars used in agriculture reach zeta potentials of  $-40$  to  $-60$  mV, placing them in the 'good stability' range where electrostatic repulsion prevents clumping and allows movement through soil pore networks, facilitating the delivery of nutrients and amendments across the root zone [25,31]. This improved mobility could help distribute amendments more evenly throughout the soil profile, potentially enhancing the effectiveness of precision agriculture methods [32,33].

## Cation exchange capacity

Cation exchange capacity significantly increases when nanobiochar is formed, with median improvements of 3.2 times compared to bulk precursors, and values range from  $15.2$  to  $87.4$  cmol kg<sup>-1</sup> depending on feedstock and processing conditions [13,34]. This boost results from three mechanisms: larger surface area providing more exchange sites per unit mass; greater density of oxygen-rich functional groups that act as exchange sites; and exposure of previously inaccessible exchange sites within the biochar matrix. Soils amended with high-CEC nanobiochars show 30%–50% reductions in nutrient leaching losses, especially for  $\text{NH}_4^+$  and  $\text{K}^+$ , while maintaining higher plant-available concentrations in the root zone [18,35]. Enhanced nutrient retention is especially beneficial in sandy soils and areas with high rainfall or irrigation, where nutrient leaching often limits productivity and leads to environmental pollution [36,37]. The mechanisms of cation retention parallel those observed for engineered carbon nanomaterials, where abundant



**Fig. 4** Property enhancement of agricultural nanobiochar. **(a)** Surface area enhancement showing a median 5.9-fold increase; **(b)** O/C ratio enhancement indicating increased surface polarity; **(c)** Zeta potential change showing more negative values for nanobiochar. Data compiled from [10–13].

surface carboxyl groups govern metal–carbon interactions through electrostatic and coordination bonding pathways, further reinforcing the conclusion that nanobiochar's CEC is primarily driven by surface oxidation. Physicochemical properties of bulk biochar and nanobiochar derived from different feedstocks are shown in Table 1.

## Soil health improvement and plant growth promotion

### Soil physical properties

Nanobiochar amendment fundamentally alters soil physical properties through mechanisms different from those of bulk biochar, with significant implications for farming productivity and soil health. The nanoscale particles bond more tightly with soil aggregates, coating mineral surfaces and filling inter-particle pores rather than merely occupying large pores, leading to markedly different effects on soil physical behavior. When applied at rates of 0.5%–1.0% to agricultural soils, nanobiochar increases microporosity by 15%–30% while reducing macroporosity by 10%–20%, resulting in a net rise in total porosity of 5%–15% [16,35]. The change in pore size distribution indicates nanobiochar's ability to fill and modify existing pore structures instead of creating new macropores like bulk biochar does. Soil moisture content under simulated rainfall rises from 28% in control soils to 39%–47% in nanobiochar-amended treatments, with the effect persisting through multiple wetting-drying cycles [16,35]. This enhanced water retention directly reduces irrigation needs, a key factor in water-scarce agricultural regions where irrigation consumes 70% of freshwater withdrawals. Plant-available water increases by 25%–40% in nanobiochar-amended sandy soils, with the greatest gains seen in coarse-textured soils that naturally have low water retention [16]. For rainfed agriculture, this improved water-holding capacity helps buffer crops against short-term drought stress, supporting productivity during dry spells between rainfall events. These improvements in soil water dynamics align with meta-analytical findings on the benefits of conservation tillage and better water management practices in dryland cropping systems [29]. Multifunctional roles of nanobiochar in sustainable agriculture are summarized in Fig. 5.

Nanobiochar application encourages the formation of water-stable soil aggregates through various mechanisms. Nanobiochar particles serve as nucleation sites for aggregate formation, with soil

minerals and organic matter attaching to the reactive surfaces. Microbial metabolites produced in response to nanobiochar amendment bind particles together, while fungal hyphae enmesh particles into stable macroaggregates [31]. This results in a 10%–11% reduction in soil loss under simulated rainfall, with the most significant erosion control observed on sloping agricultural lands where soil conservation is vital for sustainable production [16,35]. Improved soil structure and lower erosion levels support long-term agricultural sustainability, particularly in vulnerable landscapes [3].

### Soil chemical properties and nutrient dynamics

The improved surface reactivity of nanobiochar directly impacts soil chemical properties and nutrient dynamics. Nanobiochar addition raises soil CEC by 15%–40%, depending on application rate, soil type, and nanobiochar features [13,34]. This increase stems from both the intrinsically high CEC of nanobiochar and the stimulation of soil organic matter formation, which provides additional exchange sites. The higher CEC leads to better retention of cationic nutrients. Ammonium leaching is reduced by 30%–50% in nanobiochar-treated sandy soils, with effects lasting through several leaching events [16]. Potassium retention improves by 25%–45%, especially critical for K<sup>+</sup>-requiring crops grown on sandy or highly weathered soils where K<sup>+</sup> leaching is a major issue.

Phosphorus behavior in nanobiochar-amended soils is complex. Total P leaching drops by 40%–45%, showing improved P retention near roots, while plant-available P increases by 20%–30%, indicating that nanobiochar not only helps retain P but also keeps it in forms crops can access [16,34]. Nanobiochar surfaces directly adsorb phosphate via ligand exchange with surface hydroxyl groups, forming inner-sphere complexes that resist leaching but remain available to plants through root-induced desorption. Indirectly, nanobiochar stimulates phosphatase enzyme activity in soil, speeding up the mineralization of organic P into forms plants can use [31]. These nutrient processes are especially relevant for improving nitrogen use efficiency in cropping systems, a key aim for sustainable intensification [6].

### Plant growth promotion

Nanobiochar application consistently improves plant growth parameters across various crop species and growing environments.

**Table 1** Physicochemical properties of bulk biochar and nanobiochar derived from different feedstocks

| Property category                               | Parameter                                                        | Wheat straw biochar  | Wheat straw nanobiochar | Wood chip biochar     | Wood chip nanobiochar | Significance for cyanobacterial colonization                                            | Ref.    |
|-------------------------------------------------|------------------------------------------------------------------|----------------------|-------------------------|-----------------------|-----------------------|-----------------------------------------------------------------------------------------|---------|
| Physical properties                             | Particle size range                                              | 50–500 $\mu\text{m}$ | 25–180 nm               | 100–800 $\mu\text{m}$ | 40–220 nm             | Nanoscale dimensions increase available surface area for cyanobacterial cell attachment | [10]    |
|                                                 | Specific surface area ( $\text{m}^2 \text{g}^{-1}$ )             | 85.3 $\pm$ 12.4      | 342.6 $\pm$ 28.7        | 112.7 $\pm$ 15.8      | 398.2 $\pm$ 31.5      | Higher surface area provides more binding sites for cyanobacterial adhesins             | [10]    |
|                                                 | Total pore volume ( $\text{cm}^3 \text{g}^{-1}$ )                | 0.08 $\pm$ 0.02      | 0.24 $\pm$ 0.04         | 0.12 $\pm$ 0.03       | 0.31 $\pm$ 0.05       | Mesoporous structure facilitates nutrient diffusion around attached cells               | [10]    |
|                                                 | Average pore diameter (nm)                                       | 15.3 $\pm$ 2.1       | 8.7 $\pm$ 1.2           | 18.6 $\pm$ 2.4        | 9.2 $\pm$ 1.3         | Smaller pores in nanobiochar enhance water retention in dryland soils                   | [10,12] |
|                                                 | Surface roughness (nm)                                           | 85.6 $\pm$ 12.3      | 12.4 $\pm$ 3.1          | 112.3 $\pm$ 15.7      | 15.6 $\pm$ 3.8        | Nanoscale topography mimics natural soil particle surfaces                              | [10]    |
|                                                 | Zeta potential at pH 7 (mV)                                      | −18.7 $\pm$ 2.3      | −38.4 $\pm$ 4.1         | −22.5 $\pm$ 2.8       | −42.3 $\pm$ 4.5       | Higher negative charge promotes electrostatic interactions with cyanobacterial cells    | [11,25] |
| Chemical properties                             | Colloidal stability (h)                                          | < 2                  | 56.3 $\pm$ 7.2          | < 2                   | 62.8 $\pm$ 8.1        | Extended stability ensures prolonged interaction with motile cyanobacteria              | [25]    |
|                                                 | Carbon content (%)                                               | 72.4 $\pm$ 3.2       | 78.6 $\pm$ 3.5          | 81.3 $\pm$ 3.8        | 84.7 $\pm$ 3.9        | High carbon stability ensures long-term persistence in soil                             | [10]    |
|                                                 | Oxygen content (%)                                               | 15.3 $\pm$ 1.8       | 12.4 $\pm$ 1.5          | 11.2 $\pm$ 1.4        | 9.8 $\pm$ 1.2         | Oxygen-containing groups serve as recognition sites for cell surface proteins           | [10]    |
|                                                 | Carboxyl groups ( $\text{mmol g}^{-1}$ )                         | 0.42 $\pm$ 0.08      | 1.38 $\pm$ 0.15         | 0.38 $\pm$ 0.07       | 1.42 $\pm$ 0.16       | Carboxyl groups mediate hydrogen bonding with EPS polysaccharides                       | [12,23] |
|                                                 | Hydroxyl groups ( $\text{mmol g}^{-1}$ )                         | 0.56 $\pm$ 0.09      | 1.62 $\pm$ 0.18         | 0.48 $\pm$ 0.08       | 1.58 $\pm$ 0.17       | Hydroxyl groups contribute to water retention and hydrogen bonding                      | [12,23] |
|                                                 | Phenolic groups ( $\text{mmol g}^{-1}$ )                         | 0.23 $\pm$ 0.04      | 0.78 $\pm$ 0.09         | 0.28 $\pm$ 0.05       | 0.82 $\pm$ 0.10       | Phenolic compounds may stimulate heterocyst differentiation                             | [12]    |
| Surface functional groups (FTIR peak intensity) | Cation exchange capacity ( $\text{cmol kg}^{-1}$ )               | 28.6 $\pm$ 3.5       | 64.3 $\pm$ 5.8          | 32.4 $\pm$ 3.9        | 71.5 $\pm$ 6.2        | Enhanced nutrient retention supports cyanobacterial metabolism                          | [13,34] |
|                                                 | pH (in water)                                                    | 8.7 $\pm$ 0.3        | 7.4 $\pm$ 0.2           | 8.2 $\pm$ 0.3         | 7.1 $\pm$ 0.2         | Near-neutral pH minimizes osmotic stress during colonization                            | [10]    |
|                                                 | Electron donating capacity ( $\mu\text{mol e}^- \text{g}^{-1}$ ) | 98.4 $\pm$ 12.5      | 287.6 $\pm$ 24.3        | 124.7 $\pm$ 15.8      | 326.8 $\pm$ 28.4      | Redox activity facilitates electron transfer to photosynthetic chains                   | [10]    |
|                                                 | O–H stretching ( $3,400 \text{ cm}^{-1}$ )                       | 0.28 $\pm$ 0.04      | 0.72 $\pm$ 0.08         | 0.24 $\pm$ 0.03       | 0.68 $\pm$ 0.07       | Hydroxyl groups enhance hydrogen bonding with cyanobacterial sheaths                    | [11]    |
|                                                 | 3.2 C=O Stretching ( $1,700 \text{ cm}^{-1}$ )                   | 0.18 $\pm$ 0.03      | 0.58 $\pm$ 0.06         | 0.16 $\pm$ 0.02       | 0.54 $\pm$ 0.06       | Carbonyl groups participate in protein recognition                                      | [11]    |
|                                                 | 3.3 C–O Stretching ( $1,100 \text{ cm}^{-1}$ )                   | 0.32 $\pm$ 0.04      | 0.82 $\pm$ 0.09         | 0.28 $\pm$ 0.03       | 0.78 $\pm$ 0.08       | C–O groups indicate polysaccharide-like structures                                      | [11]    |
| Elemental composition                           | Aromatic C=C ( $1,600 \text{ cm}^{-1}$ )                         | 0.45 $\pm$ 0.05      | 0.38 $\pm$ 0.04         | 0.52 $\pm$ 0.06       | 0.44 $\pm$ 0.05       | Aromatic structures contribute to hydrophobic interactions                              | [11]    |
|                                                 | C/N ratio                                                        | 45.6 $\pm$ 4.2       | 42.3 $\pm$ 3.9          | 78.4 $\pm$ 6.5        | 72.6 $\pm$ 5.8        | Lower C/N ratio in straw biochar favors microbial activity                              | [10]    |
|                                                 | H/C atomic ratio                                                 | 0.38 $\pm$ 0.04      | 0.32 $\pm$ 0.03         | 0.35 $\pm$ 0.03       | 0.30 $\pm$ 0.03       | Lower H/C indicates higher aromaticity and stability                                    | [10]    |
|                                                 | O/C atomic ratio                                                 | 0.21 $\pm$ 0.02      | 0.16 $\pm$ 0.02         | 0.14 $\pm$ 0.01       | 0.12 $\pm$ 0.01       | O/C ratio correlates with surface hydrophilicity                                        | [10]    |
|                                                 | Ash content (%)                                                  | 12.3 $\pm$ 1.5       | 9.8 $\pm$ 1.1           | 5.6 $\pm$ 0.7         | 4.8 $\pm$ 0.6         | Ash provides micronutrients for cyanobacterial metabolism                               | [10]    |

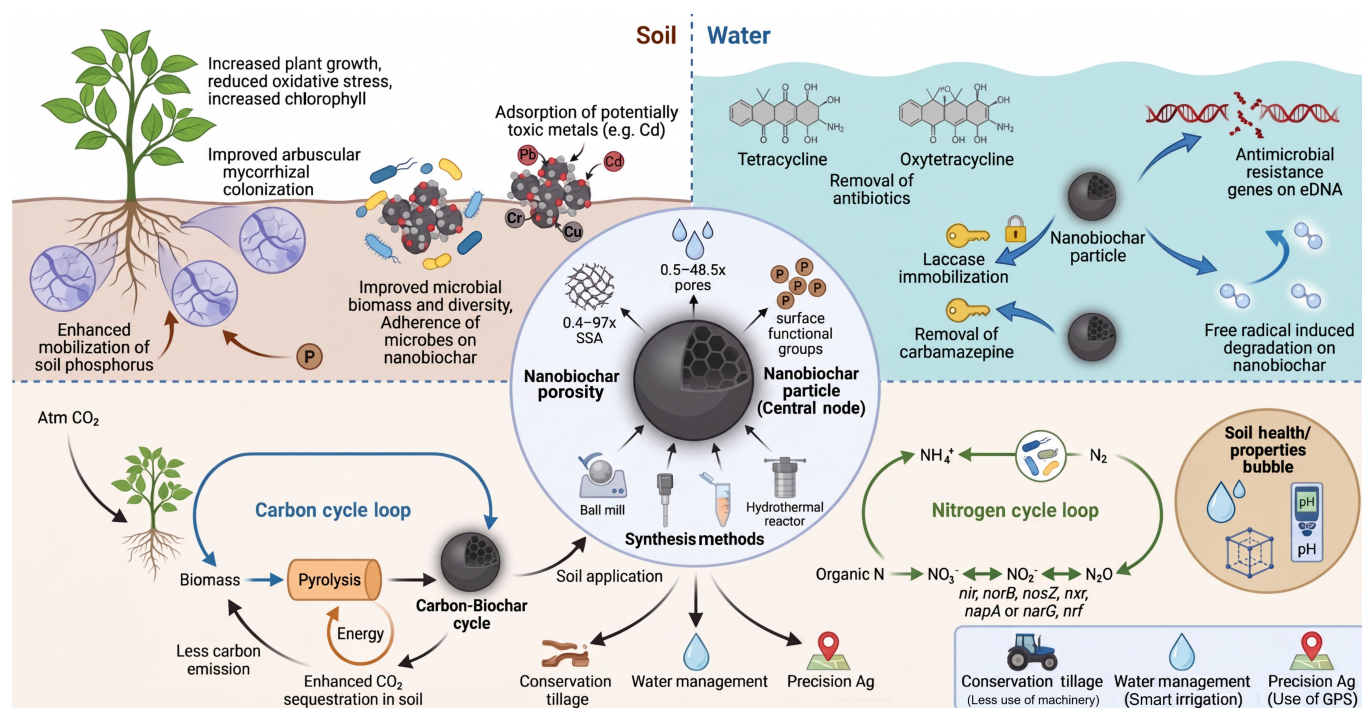
Meta-analyses reveal average increases of 15%–25% in shoot biomass, 20%–30% in root biomass, and 10%–20% in grain yield with nanobiochar used at optimal levels<sup>[9,14]</sup>. These gains are comparable to those achieved through refined agronomic practices, such as conservation tillage and better fertilizer management in dryland systems<sup>[38]</sup>. The mechanisms behind growth promotion are complex, involving both direct and indirect effects<sup>[39]</sup>. Indirect mechanisms largely dominate in most agricultural soils and include: enhanced nutrient availability through improved retention and cycling; better water relations that reduce drought stress; soil pH adjustment towards optimal levels; suppression of soil-borne pathogens; and stimulation of beneficial microbial symbioses<sup>[40]</sup>. Direct mechanisms involve nanobiochar–plant interactions at the root surface, where nanoparticles can adhere to root epidermal cells, forming a protective layer that may influence nutrient uptake and stress signaling<sup>[41]</sup>. Increased root colonization by arbuscular mycorrhizal fungi, facilitated by nanobiochar, further enhances nutrient and water uptake<sup>[31]</sup>. The reliable yield increases linked to nanobiochar amendments are particularly important for global food security. As crop yields must grow significantly to meet projected food

demand, technologies that offer 10%–20% yield improvements without proportional increases in inputs are valuable for sustainable intensification. When combined with improved crop management and stress-tolerant varieties, nanobiochar could help close yield gaps in areas where soil quality is poor or water scarcity is a constraint<sup>[18]</sup>. Soil health improvement and plant growth promotion by nanobiochar are shown in Fig. 6.

## Plant stress mitigation

Nanobiochar's capacity to reduce plant stress, whether abiotic or biotic, highlights one of its most valuable roles in agriculture. During drought conditions, plants amended with nanobiochar retain higher relative water content and photosynthetic rates, with yield reductions cut by 30%–50% compared to unamended controls<sup>[16,17]</sup>. The underlying mechanisms include increased soil water retention, enhanced root growth that accesses deeper water sources, and accumulation of osmolytes such as proline and soluble sugars that help maintain cell turgor. Moreover, nanobiochar amendment upregulates antioxidant enzymes (superoxide dismutase, catalase, peroxidase) that alleviate





**Fig. 5** Multifunctional roles of nanobiochar in sustainable agriculture, illustrating its effects on soil and water quality, plant growth, microbial interactions, pollutant removal, and integration into carbon and nitrogen cycles, along with applications in conservation tillage, water management, and precision agriculture.

oxidative damage under water deficit<sup>[16,42]</sup>. These effects are especially important for rainfed farming in water-scarce areas, where drought stress is a key limiting factor on crop productivity<sup>[3]</sup>.

Under salinity stress, which impacts over 800 million ha of agricultural land worldwide, nanobiochar provides significant protective effects. Plants cultivated in saline soils with nanobiochar amendments show 25%–40% higher biomass than untreated controls, with decreases in  $\text{Na}^+$  accumulation and improved  $\text{K}^+/\text{Na}^+$  ratios<sup>[42]</sup>. The mechanisms involve  $\text{Na}^+$  adsorption on negatively charged nanobiochar surfaces, which reduces  $\text{Na}^+$  availability in the soil solution; improved soil structure that enhances the leaching of soluble salts; and increased antioxidant enzyme activities that scavenge reactive oxygen species produced under salt stress. Specifically, nanobiochar has been reported to boost the activities of superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX), mitigating salt-induced oxidative injury<sup>[31]</sup>. These findings are consistent with broader research on salinity tolerance mechanisms and the potential for amendments to mitigate salt stress in crops<sup>[43]</sup>.

Under heavy metal stress, nanobiochar significantly reduces metal uptake and toxicity in crops grown on contaminated soils. Rice plants cultivated in Cd-contaminated soil exhibit an 86.5%–95.1% decrease in tissue Cd accumulation after nanobiochar addition<sup>[31,41]</sup>. The mechanisms involve both soil-phase immobilization through adsorption, which lowers bioavailable Cd, and root-interface protection via nanobiochar coating on root surfaces. At the cellular level, reduced metal translocation is accompanied by enhanced vacuolar sequestration and elevated synthesis of metal-binding ligands such as phytochelatins, analogous to observations with carbon nanotubes and other carbon-based nanomaterials<sup>[13,30]</sup>. Similar decreases have been noted for Pb, Cu, and Zn in various crop species<sup>[13,30,44]</sup>. These findings hold significant implications for food safety in regions with contaminated agricultural soils, where heavy metal build-up in crops poses health risks to consumers. Recent

progress in microbial strategies for heavy metal remediation complements nanobiochar effects, indicating potential synergistic approaches<sup>[19,45]</sup>.

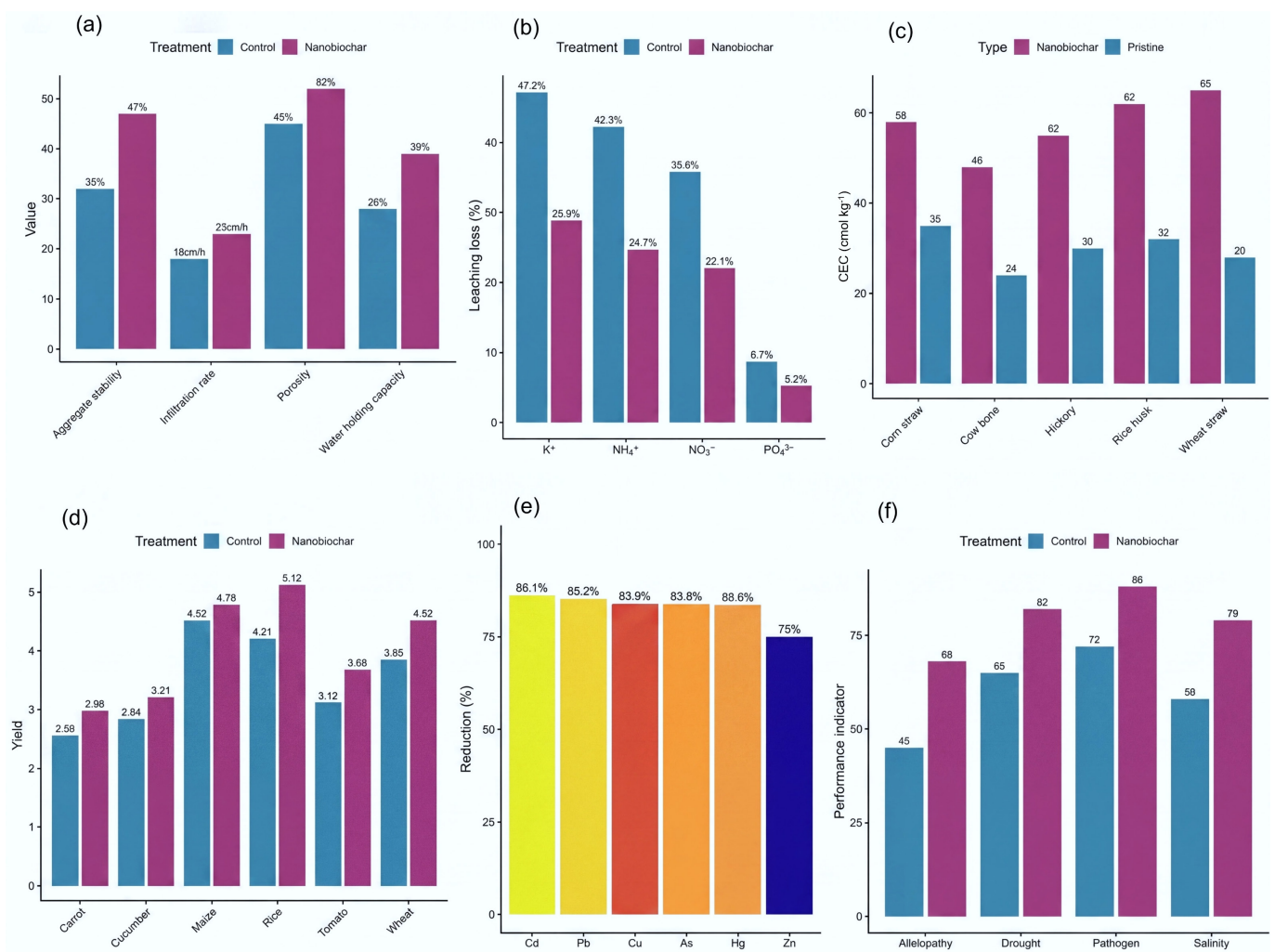
Under biotic stress, emerging evidence suggests nanobiochar can boost plant resistance to pathogens. Application of nanobiochar reduces disease severity in pepper plants infected with bacterial leaf spot by 30%–50%<sup>[46]</sup>. The mechanisms involve direct antimicrobial effects of nanobiochar-associated reactive oxygen species, induction of systemic resistance through priming of defence gene expression, and enhancement of beneficial microbial communities that suppress pathogens<sup>[47]</sup>. This induced systemic resistance is associated with the upregulation of pathogenesis-related genes and activation of salicylic acid- and jasmonic acid-dependent signaling pathways, leading to a more robust plant defense response. These effects could lessen reliance on synthetic pesticides, supporting more sustainable pest management (Table 2).

## Microbial community responses

The addition of nanobiochar to agricultural soils causes significant shifts in soil biological communities and their roles, leading to ripple effects on plant growth, health, and yield.

### Microbial biomass and activity

Nanobiochar amendment reliably enhances soil microbial biomass by 25%–60% across various soil types and cropping systems<sup>[31,25]</sup>. The effect results from multiple mechanisms: providing habitable pore spaces that offer refuge from predation and environmental stress; supplying labile carbon substrates that support microbial metabolism; adjusting soil pH toward optimal levels; and improving nutrient and water availability. The nanoscale architecture of nanobiochar creates a high density of micro- and mesopores that function as protected



**Fig. 6** Soil health improvement and plant growth promotion by nanobiochar. (a) Soil physical properties enhancement with nanobiochar amendment. (b) Nutrient leaching reduction across major nutrients. (c) Cation exchange capacity enhancement across feedstocks. (d) Crop yield enhancement across different crops. (e) Heavy metal uptake reduction. (f) Stress tolerance enhancement under drought, salinity, pathogen, and allelopathic stress. Data compiled from [13,16,17,31,34,35,41].

**Table 2** Agronomic and environmental performance enhancements of nanobiochar amendments across diverse cropping systems and stress conditions

| Category                 | Parameter                                         | Observed effect               | Ref.    |
|--------------------------|---------------------------------------------------|-------------------------------|---------|
| Soil physical properties | Total porosity                                    | Increased by 5%–15%           | [16,35] |
|                          | Soil moisture retention                           | Increased from 28% to 39%–47% | [16,35] |
|                          | Soil erosion loss                                 | Reduced by 10%–11%            | [16,35] |
| Nutrient dynamics        | Ammonium (NH <sub>4</sub> <sup>+</sup> ) leaching | Reduced by 30%–50%            | [16]    |
|                          | Total Phosphorus (P) leaching                     | Reduced by 40%–45%            | [16,34] |
|                          | Plant-available P                                 | Increased by 20%–30%          | [16,34] |
| Plant growth             | Grain yield                                       | Increased by 10%–20%          | [9,14]  |
|                          | Shoot biomass                                     | Increased by 15%–25%          | [9,14]  |
|                          | Root biomass                                      | Increased by 20%–30%          | [9,14]  |
| Stress mitigation        | Drought yield reduction                           | Mitigated by 30%–50%          | [16,17] |
|                          | Cadmium (Cd) tissue accumulation                  | Decreased by 86.5%–95.1%      | [31,41] |
|                          | Salinity stress biomass                           | Increased by 25%–40%          | [42]    |
| Soil biological activity | Bacterial leaf spot severity                      | Reduced by 30%–50%            | [46]    |
|                          | Microbial biomass                                 | Enhanced by 25%–60%           | [25,31] |
|                          | N-cycling enzyme activity                         | Increased by 25%–45%          | [31]    |
|                          | Dehydrogenase activity                            | Increased by 30%–60%          | [31,34] |
|                          | AMF root colonization                             | Increased by 30%–60%          | [40]    |

niches for microorganisms, analogous to the habitable pore environments offered by carbon nanotubes and graphene-based materials. The degree of microbial stimulation varies depending on nanobiochar

properties, application rate, and soil features, with the most significant responses seen in degraded or low-organic-matter soils where microbial communities are resource-limited.

Microbial activity, measured by basal respiration and substrate-induced respiration, increases alongside biomass, indicating that the larger microbial community is metabolically active rather than dormant<sup>[31]</sup>. This increased activity speeds up nutrient cycling, potentially boosting the supply of plant-available nutrients from organic matter breakdown. In the context of sustainable intensification, stimulating native soil biological processes could decrease dependence on synthetic fertilizers while maintaining productivity.

### Microbial community composition

High-throughput sequencing shows changes in microbial community composition with nanobiochar addition. The relative abundance of Proteobacteria, copiotrophic organisms that thrive on more resources, increases by 15%–30%<sup>[31]</sup>. Actinobacteria and Bacteroidetes, which are involved in the breakdown of complex organic matter, also increase. In contrast, Acidobacteria, oligotrophic organisms adapted to low-resource conditions, decrease in relative abundance, indicating a shift towards more resource-rich environments. These changes suggest that nanobiochar fosters a habitat more suitable for fast-growing, nutrient-cycling organisms, while diminishing the advantage of stress-tolerant oligotrophs. Consistent with this copiotrophic shift, the enhanced electron-donating capacity of nanobiochar (reported to exceed  $280 \mu\text{mol e}^- \text{g}^{-1}$ ; Table 1) may directly fuel microbial respiratory chains, supporting the proliferation of metabolically active taxa in a manner that has been documented for other redox-active carbon nanomaterials.

Fungal communities respond similarly, with arbuscular mycorrhizal fungi particularly benefiting from nanobiochar amendment. AMF colonization of crop roots increases by 30%–60%, boosting phosphorus uptake and contributing to the plant growth benefits observed with nanobiochar<sup>[40]</sup>. The mechanism may involve physical protection of hyphae within nanobiochar pores, improved phosphorus availability stimulating plant carbon allocation to symbionts, or direct stimulation of fungal growth by nutrients associated with nanobiochar. Enhanced mycorrhizal colonization has been linked to better drought tolerance and nutrient uptake in several crop species, suggesting synergistic effects with nanobiochar's direct benefits.

### Soil enzyme activities

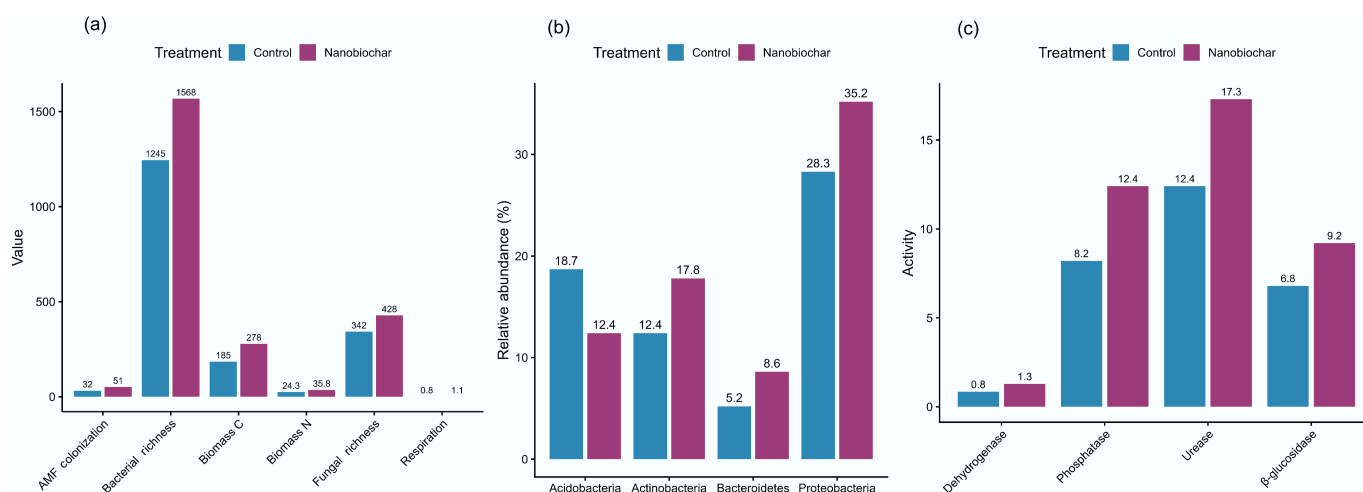
Nanobiochar amendment influences soil enzymes that are involved in nutrient cycling, generally having positive effects on processes that provide plant-available nutrients. Dehydrogenase activity, which indicates overall microbial metabolic activity, increases by 30%–60%, confirming the boost in microbial metabolism seen in biomass measurements<sup>[31,34]</sup>. Enzymes related to carbon cycling ( $\beta$ -glucosidase, cellulase) also show 20%–50% increases in activity, indicating improved decomposition of organic material and microbial biomass turnover.

Nitrogen cycling enzymes (urease, protease) increase by 25%–45%, speeding up the mineralization of organic N into forms available to plants<sup>[31]</sup>. This enhanced N mineralization may help explain the observed improvements in crop N uptake and lower fertilizer needs. However, effects on nitrification and denitrification enzymes are more inconsistent, with some studies showing stimulation and others inhibition, depending on nanobiochar properties and soil conditions. These varying effects have implications for greenhouse gas emissions, as denitrification is a major source of  $\text{N}_2\text{O}$ <sup>[48,49]</sup>. The variable response may be attributed to the dual role of nanobiochar as both an electron donor (stimulating denitrification) and an adsorbent of inorganic nitrogen (reducing substrate availability for denitrifiers), a dichotomy likewise observed with other carbon nanomaterials in agricultural settings.

Phosphatase activity increases by 15%–60%, depending on soil P status and the balance between microbial demand and product feedback inhibition<sup>[32]</sup>. In P-limited soils, boosting phosphatase activity can significantly increase plant-available P from organic sources, reducing the need for P fertilizer. This is especially valuable given the finite supply of phosphate rock and the environmental impacts of P runoff. Microbial community responses to nanobiochar amendment are summarized in Fig. 7.

### Contaminant immobilization in agricultural soils

Agricultural soils around the world are contaminated with potentially toxic metals, pesticides, and emerging organic contaminants that threaten crop quality, food safety, and ecosystem health.



**Fig. 7** Microbial community responses to nanobiochar amendment. **(a)** Increase in microbial biomass and activity parameters. **(b)** Changes in bacterial phylum abundance showing rises in Proteobacteria, Actinobacteria, and Bacteroidetes with a decrease in Acidobacteria. **(c)** Enhancement of soil enzyme activities including dehydrogenase, urease, phosphatase, and  $\beta$ -glucosidase. Data compiled from<sup>[10,25,31,34]</sup>.



Nanobiochar's improved surface reactivity and mobility make it especially effective for *in situ* immobilization of these pollutants.

### Heavy metal immobilization

Nanobiochar shows an excellent ability to immobilize heavy metals in agricultural soils, often outperforming bulk biochar significantly. Surface complexation with oxygen-rich functional groups is a key mechanism for immobilizing most divalent cations. XPS analysis after soil incubation consistently reveals shifts in binding energy, indicating that metal ions bind to surface oxygen atoms on nanobiochar<sup>[48–50]</sup>. For softer metals like  $\text{Hg}^{2+}$  and  $\text{CH}_3\text{Hg}^+$ , complexation with sulfur-containing groups provides exceptional affinity; thiol-modified nanobiochar, produced by ball milling biochar with sulfur-containing reagents, exhibits distribution coefficients orders of magnitude higher<sup>[49,51]</sup>. Cation- $\pi$  interactions play a significant role for metals with electron-deficient character, especially on high-temperature nanobiochars with extensive graphitic domains, contributing 20%–40% of total immobilization energy for  $\text{Pb}^{2+}$  and  $\text{Cd}^{2+}$  on graphitic surfaces<sup>[51]</sup>. Ion exchange with charge-balancing cations associated with surface functional groups provides an additional immobilization pathway, particularly relevant for low-temperature nanobiochars with high cation-exchange capacity. Precipitation of metal hydroxides, carbonates, or phosphates occurs in localized zones of high pH created by nanobiochar particles or when nanobiochar supplies precipitating anions. These multi-mechanism immobilization pathways—surface complexation, cation- $\pi$  interactions, ion exchange, and precipitation—closely parallel those documented for other carbon-based nanomaterials (e.g., oxidized carbon nanotubes and graphene oxide), where the density of oxygen-containing functional groups and the extent of  $\pi$ -conjugated domains synergistically govern metal binding. Sequential extraction after nanobiochar amendment shows that metals transform from easily exchangeable forms into oxidizable and residual fractions, indicating permanent immobilization rather than mere sorption<sup>[31,41]</sup>. This transformation is vital for long-term remediation, as oxidisable and residual fractions resist environmental changes that could remobilize contaminants. Studies on cadmium stabilization in wastewater-irrigated soils have confirmed the effectiveness of combined organic and inorganic amendments, with nanobiochar increasingly playing a crucial role<sup>[30,44]</sup>.

### Organic contaminant immobilization

Nanobiochar also shows a high affinity for organic contaminants in agricultural soils, including pesticides, herbicides, and emerging contaminants such as antibiotics and pharmaceuticals.  $\pi$ - $\pi$  electron donor-acceptor interactions mainly control the immobilization of aromatic contaminants on high-temperature nanobiochars with extensive graphitic domains<sup>[52]</sup>. Hydrogen bonding plays a significant role for contaminants with hydrogen bond donor or acceptor groups, while electrostatic interactions are key for immobilizing ionizable contaminants whose speciation depends on soil pH<sup>[53]</sup>. Hydrophobic partitioning into non-carbonized organic matter domains contributes to low-temperature nanobiochars that retain substantial aliphatic carbon. The increased surface area and accessibility of nanobiochar pores enhance both the capacity and the rate of organic contaminant sorption compared to bulk biochar. Sorption isotherms for pesticides generally show 2–5 times higher maximum capacities for nanobiochar, with a quicker approach to equilibrium<sup>[54]</sup>. This enhanced sorption performance mirrors the well-established behavior of graphitic carbon nanomaterials, where expanded  $\pi$ -conjugated systems and high mesopore volume facilitate rapid mass transfer and high uptake capacity. This improved performance could decrease pesticide

leaching into groundwater while still maintaining efficacy against target pests through controlled release from sorbed phases.

### Antibiotic resistance gene mitigation

The proliferation of antibiotic resistance genes (ARGs) in soils amended with manure or biosolids is a growing threat to agricultural sustainability. Nanobiochar shows a remarkable ability to not only adsorb but also break down extracellular DNA that carries ARGs. Mechanistically, hydroxyl radicals produced on nanobiochar surfaces by persistent free radicals cause eDNA fragmentation, permanently destroying the genetic material<sup>[55]</sup>. The effect depends on size, with nanobiochars showing 5–10 times greater ARG degradation than bulk biochars due to their larger surface area and higher free-radical density. This free-radical-driven degradation is a characteristic property shared with certain carbon nanotubes and graphene oxides, which also generate reactive oxygen species upon contact with aqueous media, and suggests that nanobiochar could be tailored for enhanced ARG mitigation through surface oxidation treatments. Incorporating nanobiochar with other bioremediation methods could further improve the removal of emerging contaminants<sup>[19,56]</sup>.

### Nanobiochar as slow-release fertilizer

The ability of nanobiochar to retain nutrients in plant-available forms while resisting leaching makes it an excellent choice for slow-release fertilizer formulations, a vital need in sustainable agriculture where nutrient use efficiency must be maximized and environmental losses minimized. This slow-release functionality is rooted in the dramatically enhanced surface area, CEC, and functional-group density of nanobiochar relative to bulk biochar, which collectively control nutrient adsorption, desorption kinetics, and long-term availability. Where direct nanobiochar studies exist, we highlight the release profiles; where literature is sparse, mechanistic inferences from analogous carbon-based nanocarriers (e.g., oxidized carbon nanotubes, graphene oxide-based fertilizers) are drawn to illuminate governing principles.

#### Nitrogen fertilizer

Nitrogen exhibits ideal slow-release properties when combined with nanobiochar. Ammonium adsorbed on nanobiochar cation-exchange sites exhibits release patterns lasting 60–90 d in soil studies, aligning with the nitrogen needs of many grain crops<sup>[57,58]</sup>. In wheat straw-derived nanobiochar, Lateef et al.<sup>[57]</sup> demonstrated a biphasic release: approximately 40% of adsorbed  $\text{NH}_4^+\text{-N}$  was released within the first 15 d to satisfy early crop demand, while the remaining fraction desorbed slowly over the next 50–70 d before plateauing. This pattern contrasts sharply with soluble N fertilizers, which release virtually all nitrogen within days, often leading to losses via leaching and denitrification before peak crop uptake. Nitrate, which isn't held on cation exchange sites, behaves differently. However, nanobiochar can be engineered to retain nitrate through surface modification with multivalent metal cations (e.g.,  $\text{Mg}^{2+}$ ) that introduce positively charged sites for anion exchange. For instance, Mg-modified nanobiochar exhibits substantial nitrate retention via the formation of  $\text{Mg-NO}_3$  surface complexes<sup>[59]</sup>. Additionally, nitrification inhibitors can be co-loaded onto nanobiochar, delaying the microbial conversion of ammonium to nitrate and thus synchronizing N supply with crop demand, an approach that mirrors the use of carbon nanocarriers for controlled release of agrochemicals.

#### Phosphorus fertilizer

Phosphorus notably benefits from nanobiochar-based slow-release formulations. Cow bone-derived nanobiochar, rich in hydroxyapatite,



releases phosphorus over 120–180 d in soil, with a cumulative release of 65%–75% of the total phosphorus by the end of a cropping season<sup>[13]</sup>. The release mechanism involves slow dissolution of hydroxyapatite in response to plant-driven depletion of soil phosphorus, maintaining near-constant phosphorus concentrations in the soil solution throughout the growing season. For nanobiochars lacking inherent phosphorus, surface modification with magnesium or calcium ions creates P-retentive materials: phosphate adsorbs via ligand exchange with surface hydroxyl groups and forms sparingly soluble surface precipitates (e.g., Mg-phosphate) that gradually dissolve as plant uptake lowers solution P<sup>[59]</sup>. This dual adsorption–precipitation mechanism is analogous to that of Mg-functionalized carbon nanotubes, where the solubility product of surface precipitates governs controlled phosphorus release. By keeping phosphorus in plant-available yet immobile forms, nanobiochar-based phosphorus fertilizers could significantly enhance P use efficiency while reducing eutrophication risks from agricultural runoff.

### Potassium and other nutrients

Potassium shows 40%–50% reductions in leaching loss when applied as nanobiochar-adsorbed K<sup>+</sup> compared to soluble KCl fertilizer<sup>[57]</sup>. The release kinetics mirror those of NH<sub>4</sub><sup>+</sup>, with rapid initial release meeting early demand followed by sustained supply that matches crop uptake patterns. Calcium and magnesium are effectively supplied by bone-derived nanobiochars, which contain substantial Ca and Mg in their mineral phases, with release extending over multiple cropping seasons<sup>[13]</sup>. Silicon, a beneficial nutrient for cereals, is efficiently supplied by rice husk nanobiochar, which retains the feedstock's intrinsic Si in plant-available orthosilicic acid form; rice plants amended with this material exhibited 35% higher Si uptake and corresponding improvements in lodging resistance and blast disease tolerance<sup>[60]</sup>. The sustained Si release is attributable to the slow dissolution of amorphous silica nanoparticles embedded in the carbon matrix, a process governed by soil moisture and pH.

### Fertilizer use efficiency

The slow-release features of nanobiochar-based fertilizers directly enhance fertilizer use efficiency. Nitrogen use efficiency improves by 30%–50% compared to traditional fertilizers, meaning less N fertilizer is needed to reach the same yield<sup>[57,58]</sup>. Phosphorus use efficiency improves even more substantially owing to reduced fixation in high-P-sorbing soils and the maintenance of plant-available P pools over longer periods. The economic benefits are notable, with potential reductions in fertilizer costs while maintaining or boosting yields, along with environmental advantages such as less N leaching into groundwater, lower N<sub>2</sub>O emissions, and decreased P runoff into surface waters. These gains in nutrient use efficiency support broader efforts to optimize fertilizer management in cropping systems<sup>[6]</sup>.

## Integration with sustainable agricultural practices

### Conservation tillage systems

The integration of nanobiochar with conservation tillage practices provides synergistic benefits for soil health and crop productivity. Conservation tillage, including no-tillage and reduced tillage systems, has been widely adopted to lower soil erosion, improve water conservation, and increase soil organic matter<sup>[29,61]</sup>. Nanobiochar amendment could complement these benefits by further enhancing soil structure, water retention, and nutrient availability. In no-tillage systems, where crop residues are left on the soil surface, the high surface

area and microbial stimulatory effects of nanobiochar could accelerate residue decomposition, releasing nutrients while the nanobiochar simultaneously retains them against leaching<sup>[29,61]</sup>. The enhanced aggregate stability conferred by nanobiochar could also mitigate the risk of surface compaction sometimes associated with long-term no-tillage. Although dedicated field trials combining nanobiochar with conservation tillage remain scarce, the mechanistic synergies described warrant systematic investigation as a priority research area.

### Water-efficient cropping systems

Nanobiochar's capacity to enhance soil water retention is especially vital for water-efficient cropping systems in water-scarce areas. In dryland farming, where crop yields rely solely on rainfall, technologies that increase plant-available water in the root zone can significantly boost yield stability and water use efficiency<sup>[3,29]</sup>. Meta-analyses have demonstrated that improved soil water management through conservation practices can raise both grain yield and water use efficiency in wheat and maize systems. Nanobiochar might further amplify these benefits by boosting soil water retention and extending the period during which crops can access stored water between rains. In irrigated systems, nanobiochar's water retention advantages could lessen irrigation needs, reduce production costs, and conserve limited water resources. The synergy of nanobiochar with precision irrigation methods, including drip irrigation and soil moisture sensors, could facilitate more accurate matching of water supply to crop demand while reducing losses to deep drainage<sup>[33,62]</sup>. Recent advances in nanotechnology applications for improving irrigation efficiency suggest substantial potential for integrated approaches.

### Precision agriculture integration

The integration of nanobiochar with precision agriculture technologies provides opportunities to optimize application rates and placement based on variability within fields in soil properties and crop needs. Variable-rate application of nanobiochar could target areas of greatest requirement, for instance, sandy regions with low water and nutrient retention or contaminated zones that need enhanced metal immobilization. The colloidal stability and mobility of nanobiochar in soil pore networks could enable delivery throughout the root zone via irrigation systems, potentially achieving more uniform distribution than surface-applied bulk amendments<sup>[33]</sup>. Recent advances in AI-driven optimization of agricultural amendments could further refine nanobiochar use: machine learning algorithms trained on soil, crop, and climate data can forecast optimal application rates and timing for specific contexts, maximizing agronomic benefits while reducing costs and potential environmental risks<sup>[27,32]</sup>. Integration with IoT-enabled soil sensors could enable real-time soil condition monitoring and adaptive management of nanobiochar-amended soils.

### Circular economy and climate-smart agriculture

The shift from linear agricultural models to circular systems that minimize waste and maximize resource efficiency is one of our most urgent challenges. Producing nanobiochar from agricultural waste biomass and applying it to boost soil health and crop yields demonstrates circular economy principles in action. The main feedstocks for nanobiochar are agricultural wastes such as rice husk, wheat straw, corn stover, sugarcane bagasse, peanut shells, and animal manures. These materials, often seen as disposal issues or burned in fields (thereby contributing to air pollution), can become valuable resources through nanobiochar production. The pyrolysis process not only turns waste biomass into useful products but also generates energy that can power farm operations or local communities.

Biochar's potential for carbon sequestration has long been recognized, and the stable aromatic carbon resists microbial mineralization, persisting in soils for centuries to millennia. Nanobiochar maintains this stability while providing enhanced agricultural benefits that justify its production. When applied to agricultural soils, nanobiochar sequesters carbon while also improving soil health and reducing the need for fertilizers—a triple climate benefit. Life cycle assessment indicates significant climate advantages, with greenhouse gas emissions lowered per ton of dry feedstock processed into nanobiochar compared to open burning or landfilling<sup>[63]</sup>. When nanobiochar replaces fossil fuel-derived fertilizers and reduces N<sub>2</sub>O emissions from agricultural soils, further emissions reductions are realized. The circular agriculture and sustainable development contributions of nanobiochar are shown in Fig. 8.

Nanobiochar's agricultural uses support several UN Sustainable Development Goals. For SDG 1 (No Poverty), nanobiochar soil amendments boost crop yields and lower fertilizer needs, enhancing farm profitability for smallholders with limited resources. For SDG 2 (Zero Hunger), improved agricultural productivity and stress resilience help ensure food security, while slow-release nutrient formulations make fertilizer use more efficient. For SDG 3 (Good Health and Well-being), reduced contaminant absorption in crops enhances food safety, and lower pesticide requirements through disease suppression benefit farmworkers' health. For SDG 6 (Clean Water and Sanitation), decreased nutrient leaching helps protect groundwater and surface water quality. For SDG 12 (Responsible Consumption and Production), turning agricultural waste into valuable resources exemplifies circular economy principles. For SDG 13 (Climate Action), carbon storage in soils, lower nitrogen oxide emissions from fertilizers, and the replacement of fossil fuel-derived fertilizers aid climate mitigation efforts. For SDG 15 (Life on Land), soil enhancement, reduced erosion, and contaminant immobilization help protect land ecosystems and sustain soil health for future generations.

## Environmental fate, phytotoxicity, and risk assessment

The properties that make nanobiochar effective for agricultural use, such as its small size, high mobility, and reactive surfaces, also raise

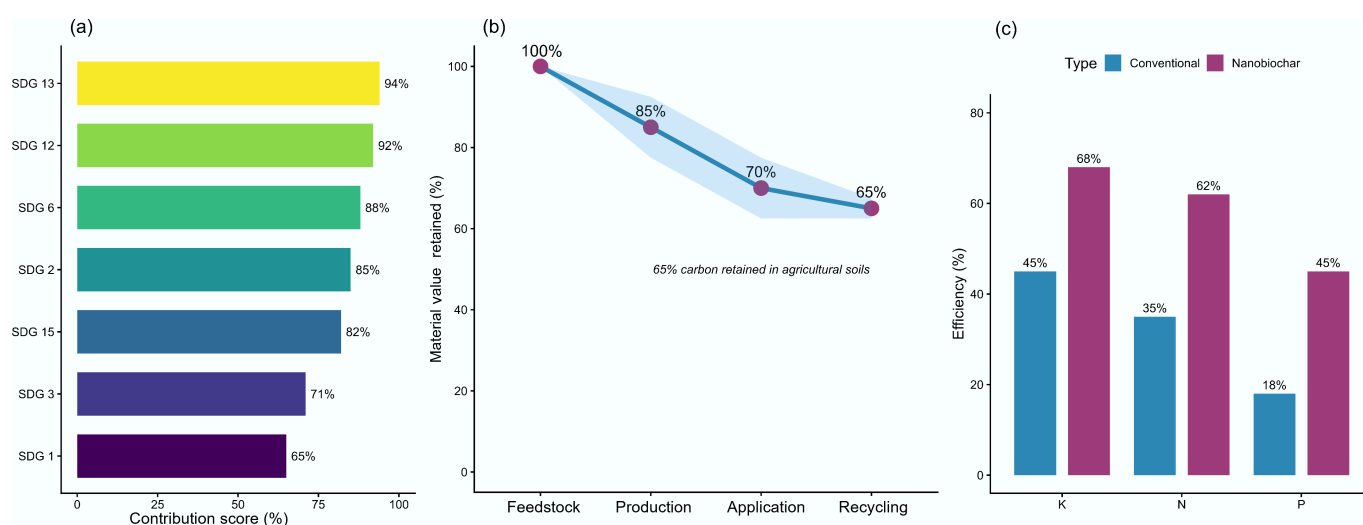
concerns about potential environmental and health risks. Responsible development of nanobiochar for agriculture therefore requires a thorough assessment of its transport pathways, biological effects, and regulatory context. Key mechanistic challenges are illustrated in Fig. 9.

## Transport and fate in soil systems

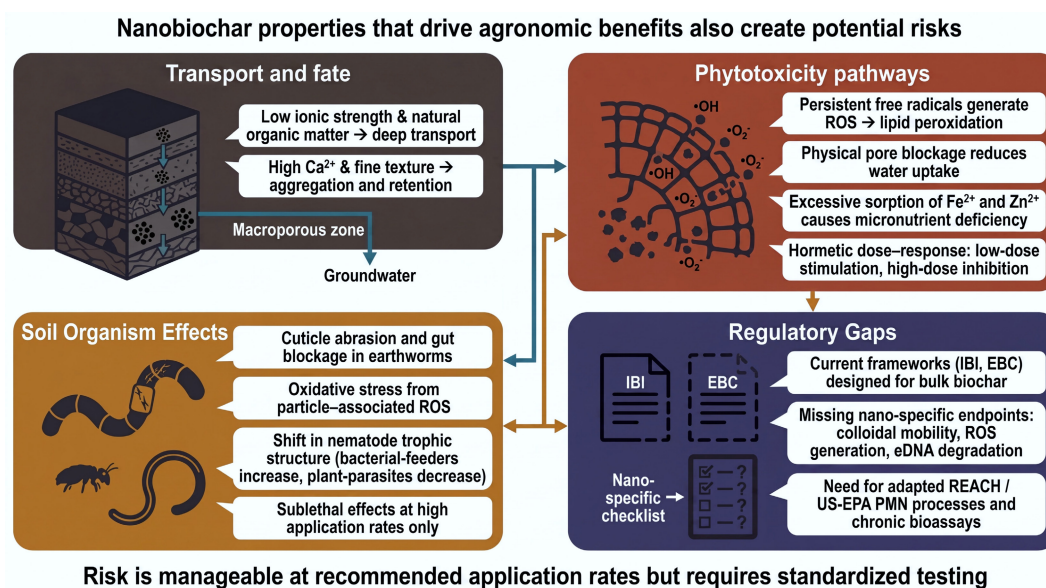
Nanobiochar's colloidal stability allows it to move through soil profiles much farther than bulk biochar, with 40%–70% of nanobiochar particles eluting through 10 cm columns compared to less than 5% for micron-sized biochar<sup>[64]</sup>. For agricultural use, this mobility has two sides: it facilitates the delivery of nanobiochar throughout the root zone for beneficial purposes, yet it simultaneously raises concerns about leaching below the root zone into groundwater or lateral migration to adjacent ecosystems. Solution chemistry greatly affects transport, with low ionic strength encouraging maximum mobility, while high ionic strength reduces mobility through double-layer compression and increased particle clumping<sup>[64]</sup>. The presence of natural organic matter generally boosts nanobiochar movement via steric stabilization and competitive adsorption to soil mineral surfaces that would otherwise trap nanoparticles. On the other hand, divalent cations (Ca<sup>2+</sup>, Mg<sup>2+</sup>) encourage clumping and retention through cation bridging between negatively charged surfaces. Soil properties also play a role, with coarse-textured soils allowing greater movement than fine-textured soils, where physical filtering and attachment to clay surfaces retain nanoparticles. Understanding these transport mechanisms is vital for predicting nanobiochar behavior in agricultural soils and developing application methods that optimize benefits while reducing off-site movement.

## Phytotoxicity

While nanobiochar generally promotes plant growth, high application rates or specific nanobiochar types can cause phytotoxic responses. Seed germination studies show hormetic dose–response relationships, with wheat seed germination increasing at low concentrations, but decreasing at higher ones<sup>[64]</sup>. The underlying mechanisms include: direct oxidative stress from particle-associated reactive oxygen species (ROS), which can cause lipid peroxidation and membrane damage; physical blockage of root pores, reducing water and nutrient uptake; and nutrient imbalances when nanobiochar excessively sorbs essential



**Fig. 8** Circular agriculture and sustainable development contributions of nanobiochar. (a) Contribution scores to Sustainable Development Goals. (b) Material flow efficiency in circular economy showing carbon retention in agricultural soils. (c) Nutrient use efficiency improvement with nanobiochar-based fertilizers compared to conventional fertilizers. Data compiled from previous studies<sup>[10,57,58]</sup>.



**Fig. 9** Environmental risk mechanisms of agricultural nanobiochar. The figure illustrates four interconnected domains critical for safe use: (i) transport and fate (ionic strength, NOM, cation bridging); (ii) phytotoxicity pathways (ROS from persistent free radicals, root blockage, micronutrient imbalance); (iii) soil organism effects (cuticle abrasion, oxidative stress, nematode trophic shifts); and (iv) regulatory gaps where existing bulk-biochar standards lack nano-specific endpoints for mobility, ROS, and eDNA degradation. Risks remain manageable at recommended rates but demand standardized testing and proactive regulation.

micronutrients (e.g.,  $\text{Zn}^{2+}$ ,  $\text{Fe}^{2+}$ ) at high loading rates. Notably, high-temperature nanobiochars with extensive graphitic domains and persistent free radicals are more prone to generate ROS than low-temperature variants that contain ample functional groups capable of quenching radicals, a structure–activity relationship well established for carbon nanotubes and graphene derivatives. Phytotoxic effects are usually observed only at application rates far above the recommended agricultural range (typically > 2%–5% w/w vs recommended 0.1%–1.0%). Nonetheless, the variability in response highlights the necessity for feedstock- and process-specific phytotoxicity screening as part of routine nanobiochar characterization. Standardized germination and root elongation tests, such as those described by the OECD and US EPA, should be adopted to ensure safe application thresholds.

## Effects on soil organisms

Limited but increasing evidence indicates that nanobiochar can cause sublethal effects in soil organisms, especially at high concentrations. Earthworms exposed to nanobiochar-amended soils show reduced growth and reproduction at high application rates, though no deaths are observed<sup>[9]</sup>. Collembola populations similarly decline at high loadings. Soil nematode communities respond in a feeding-group-specific manner: bacterial-feeders increase due to enhanced microbial prey, while plant-parasitic nematodes decline, likely owing to improved plant health and induced resistance<sup>[31]</sup>. Toxicity mechanisms to soil fauna include physical effects (abrasion of cuticles, gut blockage), oxidative stress from ROS and persistent free radicals, and indirect effects through alterations in food source quality or habitat structure. The observed organismal responses are consistent with those reported for other high-surface-area carbon nanomaterials, where size, shape, and surface chemistry collectively determine bio–nano interactions. Importantly, long-term, multi-generational studies are needed to ascertain whether the sublethal effects observed at high concentrations translate to population-level impacts under realistic field exposure scenarios. Since recommended agricultural application rates are much lower than those that produce observed effects, the risk to

soil fauna could be acceptable, but this must be confirmed across different soil types and climatic conditions.

## Regulatory considerations

Current regulatory frameworks for nanomaterials do not specifically cover nanobiochar, leading to uncertainty about its use in agriculture. The International Biochar Initiative (IBI) and European Biochar Certificate (EBC) provide voluntary quality standards for bulk biochar, but these were not designed to address the unique risks of nanoscale particles, such as enhanced mobility, higher ROS generation capacity, and potential for eDNA degradation. Approaches developed for other engineered nanomaterials, for example, the EU REACH regulation and the US EPA's Pre-Manufacture Notification (PMN) process for new chemical substances, could serve as templates, but they must be adapted to account for the specific properties of carbonaceous particles derived from biomass. Priority research areas include: (i) real-world fate studies tracking nanobiochar in field soils under varying hydrological regimes; (ii) chronic, multi-trophic toxicity assessments to evaluate food-chain transfer and bioaccumulation; (iii) development of quantitative structure–activity relationship (QSAR) models linking physicochemical traits (size, surface area, O/C ratio, persistent free radical density) to ecotoxicological endpoints; and (iv) establishment of standardized test protocols for dispersion, dosimetry, and sample preparation. Proactive engagement with regulatory agencies early in the development cycle would facilitate the creation of fit-for-purpose safety standards, support market access, and foster public trust in nanobiochar technologies.

## Challenges, knowledge gaps, and future directions

Despite substantial progress, agricultural nanobiochar research is still in its formative stage, and several fundamental challenges must be systematically addressed before its benefits can be reliably translated



into field-scale practice. Below, we synthesize the most critical knowledge gaps and propose a targeted research roadmap.

### Scalability and production economics

Most nanobiochar synthesis remains confined to the laboratory scale. To produce agricultural-relevant quantities, issues such as energy efficiency, process economics, and consistency of quality must be addressed. Ball milling, the most scalable current method, needs optimization of continuous rather than batch operation for agricultural uses. Yield optimization is crucial, as current yields are generally low. Increasing yields while keeping nanometric sizes requires a fundamental understanding of fragmentation mechanisms and size-dependent separation techniques, with agricultural economics requiring yields that ensure feasibility. Energy efficiency must be improved, as ball milling energy use ranges from 100–1,000 kWh ton<sup>-1</sup> depending on target size and feedstock traits. For agricultural purposes, energy costs should be minimized to compete with traditional fertilizers and soil amendments. Combining nanobiochar production with bioenergy generation could enhance overall energy balance, with pyrolysis gases powering milling processes. Variability in feedstock poses a challenge for consistent product quality, as nanobiochar properties differ significantly based on feedstock origin even under identical processing conditions. Predictive modelling linking feedstock composition to nanobiochar traits would support better feedstock selection and quality control.

### Standardization and characterization

The field lacks standardized protocols for agricultural nanobiochar characterization, making cross-study comparisons and regulatory approval more difficult. Recommended minimum characterization includes particle size distribution, specific surface area, surface chemistry with emphasis on nutrient-binding functional groups, zeta potential for predicting soil mobility, cation exchange capacity for nutrient retention potential, nutrient content, and contaminant screening. Standard reference materials would allow for interlaboratory comparisons and method validation. Harmonizing experimental approaches, including consistent units for application rates, standardized soil types for comparative studies, and common crop and endpoint choices, would facilitate meta-analyses and the identification of generalizable patterns. Developing a centralized database linking nanobiochar properties to agricultural outcomes could speed up the identification of structure-activity relationships and help guide rational material design.

### Mechanistic understanding

Although nanobiochar-driven yield benefits are reproducible, the underlying plant–soil–material interactions remain poorly resolved. Key mechanistic questions include: (i) What are the relative contributions of direct nutrient supply, water retention enhancement, pH modification, and microbial stimulation to observed growth promotion? (ii) How do nanobiochar particle size, surface chemistry, and dose jointly control the dose–response relationship in different crop–soil combinations? (iii) What are the temporal dynamics of surface oxidation in the soil environment, and how does progressive aging alter nutrient retention, contaminant immobilization, and colloidal mobility? Advanced characterization techniques could offer mechanistic insights, such as stable isotope tracing to monitor nutrient fluxes from nanobiochar to plants; synchrotron-based spectromicroscopy to observe nanobiochar distribution and transformations in soil–plant systems; transcriptomics and metabolomics to assess plant responses at the molecular level; and high-resolution community sequencing to

examine microbial community changes. Gaining a clear understanding of the mechanisms governing nanobiochar–plant interactions at molecular and cellular scales would support the rational design of nanobiochars tailored for specific uses; for instance, materials engineered to maximize phosphorus retention in P-fixing soils, or to improve heavy metal immobilization in contaminated sites.

### Long-term field studies

Long-term field studies are urgently needed, as most existing work relies on laboratory or greenhouse experiments that might not reflect the complexity of real agricultural systems. Multi-year field trials across different soils, climates, and cropping systems, with thorough monitoring, would build the evidence base for farmer recommendations and policy decisions. Important knowledge gaps include: Persistence and transformation: How do nanobiochar properties change over multiple years in soil? Does surface oxidation continue, and how does this impact nutrient retention and contaminant immobilization? Carryover effects: Do benefits last after application stops? Is reapplication needed, and if so, how often? Mass balance: What proportion of applied nanobiochar remains in the root zone vs being transported deeper or lost from the system? Crop rotation effects: How do benefits build up or change across different crops in rotation? Climate interactions: How does nanobiochar performance vary in wet vs dry years? Comprehensive life cycle assessments for agricultural nanobiochar systems are lacking, with critical questions including net energy balance, environmental impacts compared to conventional practices, and optimal scale and application rates for environmental and economic benefits.

### Integration with emerging technologies

The integration of nanobiochar with other emerging technologies creates opportunities to improve agricultural performance. Combining it with microbial bioremediation can enhance the cleanup of contaminated soils by pairing nanobiochar's immobilization ability with the breakdown capabilities of specific microorganisms<sup>[19,56]</sup>. Using zinc oxide or other metal-based nanoparticles alongside nanobiochar could offer extra benefits for crop nutrition and stress resilience<sup>[36]</sup>. AI-based optimization of nanobiochar formulations and application methods might speed up turning research into practical advice<sup>[27,32]</sup>. Long-term research could focus on developing 'smart' nanobiochar formulations that respond to environmental cues, such as releasing nutrients when roots exude compounds, or increasing binding of contaminants when soil pH drops. These advanced materials could further improve the efficiency and precision of nanobiochar in agriculture.

### Regulatory and adoption pathways

Navigating regulatory pathways for new agricultural amendments requires data that are currently limited for nanobiochar. Engaging proactively with regulatory agencies and developing consensus standards would speed up market entry. Farmer adoption depends on demonstrating consistent benefits in real-world conditions through on-farm trials, economic analyses showing returns on investment, and extension programs that communicate best practices for translating research into practice. Creating business models that capture the multiple benefits of nanobiochar, such as yield increases, fertilizer savings, and carbon credits, could enhance economic viability and encourage adoption. Combining nanobiochar production with existing agricultural waste management systems could generate new revenue streams for farmers while addressing waste disposal challenges.



## Conclusions

Nanobiochar merges biochar science and nanotechnology, creating a sustainable material with superior agricultural properties. Research shows it increases surface area (6.5-fold), pore volume (4.8-fold), surface functionality (O/C ratio, 1.4-fold), and cation exchange capacity (3.2-fold), thereby enhancing soil physical traits such as porosity, water retention (39% increase), and aggregate stability. These improvements reduce runoff and leaching, boost water storage, and are especially beneficial in water-scarce systems. Nanobiochar also enhances nutrient retention, cuts nutrient leaching (30%–50% for N, 40%–45% for P), and boosts plant-available nutrients, reducing fertilizer needs without lowering yields. Plant growth sees increases of 15%–25% in shoot biomass, 20%–30% in roots, and 10%–20% in grain yield across crops, via direct and indirect mechanisms. It mitigates stress by lowering heavy metal uptake (86%–95% for Cd), reducing salt stress effects (25%–40%), and improving drought tolerance (30%–50%), while strengthening pathogen resistance. Contaminant immobilization improves food safety by limiting heavy metals and organic contaminants. Slow-release fertilizers match nutrient supply to crop needs, improving efficiency and reducing environmental impact. The research from the lab to the field highlights nanobiochar's potential to address agricultural challenges sustainably. However, translating this potential into widespread practice still faces critical barriers. Key knowledge gaps persist concerning long-term field performance, multi-season persistence and transformation of nanobiochar properties, carryover effects under different rotations, and full mass-balance assessments. Mechanistic understanding of soil–plant–material interactions, especially at the molecular and cellular scales, remains incomplete. Furthermore, scalable and energy-efficient production methods, internationally harmonized characterization standards, and fit-for-purpose regulatory frameworks are urgently required. Addressing these challenges through continued interdisciplinary research and investment is vital to move nanobiochar from laboratory innovation to on-farm climate-smart practice, ultimately supporting global food security, environmental protection, and climate mitigation.

## Ethical statements

During the preparation of this work, the authors used DeepSeek (<https://chat.deepseek.com>) for language refinement. The authors reviewed and edited all content produced with the assistance of this tool, verified its accuracy, and take full responsibility for the integrity and originality of the final manuscript. This work represents the authors' own intellectual contribution, and no AI tool is credited as an author.

## Author contributions

Muhammad Adil, Amna Munir Leghari, Safdar Bashir, Yu Tao, Isma Gul, Hasnain Farooq, Siqi Lu, and Syed Ali Asghar Shah reviewed and drafted the manuscript and finalized it. Muhammad Adil improved the draft and provided valuable suggestions. All authors contributed to the article and approved the submitted version.

## Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Funding

This work was financially supported by the National Natural Science Foundation (No. 41871079) and the Open Foundation of State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences (No. SKLECRA2023).

## Declarations

### Competing interests

The authors declare no competing financial interests.

## Author details

<sup>1</sup>College of Environmental Science and Engineering, Yangzhou University, Yangzhou 225127, China; <sup>2</sup>College of Geographical Sciences, Faculty of Geographical Science and Engineering, Henan University, Zhengzhou 450046, China; <sup>3</sup>Department of Horticulture, Ghazi University, Dera Ghazi Khan 32200, Pakistan; <sup>4</sup>Department of Soil and Water Systems, University of Idaho, Moscow, ID 83844, United States of America; <sup>5</sup>School of Social Development, Yangzhou University, Yangzhou 225009, China; <sup>6</sup>Department of Agronomy and Horticulture, University of Nebraska–Lincoln, Lincoln, NE 68583-0915, United States of America; <sup>7</sup>Department of Geography, Sustainability, Community, and Urban Studies, University of Connecticut, Storrs, CT 06269-4148, United States of America

## References

- [1] Ahmad M, Rajapaksha AU, Lim JE, Zhang M, Bolan N, et al. 2014. Biochar as a sorbent for contaminant management in soil and water: a review. *Chemosphere* 99:19–33
- [2] Mohan D, Abhishek K, Sarswat A, Patel M, Singh P, et al. 2018. Biochar production and applications in soil fertility and carbon sequestration – a sustainable solution to crop-residue burning in India. *RSC Advances* 8:508–520
- [3] Ahmed M, Hayat R, Ahmad M, Ul-Hassan M, Kheir AMS, et al. 2022. Impact of climate change on dryland agricultural systems: a review of current status, potentials, and further work need. *International Journal of Plant Production* 16:341–363
- [4] Lehmann J, Rillig MC, Thies J, Masiello CA, Hockaday WC, et al. 2011. Biochar effects on soil biota – a review. *Soil Biology and Biochemistry* 43:1812–1836
- [5] Mohan D, Sarswat A, Ok YS, Pittman CU Jr. 2014. Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent – a critical review. *Bioresour Technol* 160:191–202
- [6] Naz Z, Jahan S, Rashid A, Kamran A, Abd-Allah EF, et al. 2025. Efficacy of modified biochar for enhancing maize photosynthesis and yield under various irrigation regimes. *Scientific Reports* 15:32216
- [7] Tan XF, Liu YG, Gu YL, Xu Y, Zeng GM, et al. 2016. Biochar-based nanocomposites for the decontamination of wastewater: a review. *Biore-source Technology* 212:318–333
- [8] Ramanayaka S, Vithanage M, Alessi DS, Liu WJ, Jayasundera ACA, et al. 2020. Nanobiochar: production, properties, and multifunctional applications. *Environmental Science: Nano* 7:3279–3302
- [9] Rajput VD, Minkina T, Ahmed B, Singh VK, Mandzhieva S, et al. 2022. Nano-biochar: a novel solution for sustainable agriculture and environmental remediation. *Environmental Research* 210:112891
- [10] Chaubey AK, Pratap T, Preetiva B, Patel M, Singit JS, et al. 2024. Definitive review of nanobiochar. *ACS Omega* 9:12331–12379
- [11] Liu G, Zheng H, Jiang Z, Zhao J, Wang Z, et al. 2018. Formation and physicochemical characteristics of nano biochar: insight into chemical and colloidal stability. *Environmental Science & Technology* 52:10369–10379
- [12] Lyu H, Gao B, He F, Zimmerman AR, Ding C, et al. 2018. Effects of ball milling on the physicochemical and sorptive properties of biochar:

- experimental observations and governing mechanisms. *Environmental Pollution* 233:54–63
- [13] Xiao J, Hu R, Chen G. 2020. Micro-nano-engineered nitrogenous bone biochar developed with a ball-milling technique for high-efficiency removal of aquatic Cd(II), Cu(II) and Pb(II). *Journal of Hazardous Materials* 387:121980
- [14] Sani MNH, Amin M, Siddique AB, Nasif SO, Ghaley BB, et al. 2023. Waste-derived nanobiochar: A new avenue towards sustainable agriculture, environment, and circular bioeconomy. *Science of the Total Environment* 905:166881
- [15] Lian F, Xing B. 2024. From bulk to nano: formation, features, and functions of nano-black carbon in biogeochemical processes. *Environmental Science & Technology* 58:15910–15925
- [16] Chen X, Zhou B, Wang Q, Tao W, Lin H. 2020. Nano-biochar reduced soil erosion and nitrate loss in sloping fields on the Loess Plateau of China. *CATENA* 187:104346
- [17] Yang Y, Zhou B, Hu Z, Lin H. 2020. The effects of nano-biochar on maize growth in northern Shaanxi Province on the Loess Plateau. *Applied Ecology and Environmental Research* 18:2863–2877
- [18] Peng W, Cai W, Pan J, Su X, Dou L. 2025. Molecular mechanisms of alfalfa response to abiotic stresses. *Plants* 14:487
- [19] Shan B, Hao R, Zhang J, Li J, Ye Y, et al. 2022. Microbial remediation mechanisms and applications for lead-contaminated environments. *World Journal of Microbiology and Biotechnology* 39:38
- [20] Kumar M, Xiong X, Wan Z, Sun Y, Tsang DCW, et al. 2020. Ball milling as a mechanochemical technology for fabrication of novel biochar nanomaterials. *Bioresource Technology* 312:123613
- [21] Naghdi M, Taheran M, Brar SK, Rouissi T, Verma M, et al. 2017. A green method for production of nanobiochar by ball milling- optimization and characterization. *Journal of Cleaner Production* 164:1394–1405
- [22] Yuan Y, Zhang N, Hu X. 2020. Effects of wet and dry ball milling on the physicochemical properties of sawdust derived-biochar. *Instrumentation Science & Technology* 48:287–300
- [23] Lyu H, Gao B, He F, Zimmerman AR, Ding C, et al. 2018. Experimental and modeling investigations of ball-milled biochar for the removal of aqueous methylene blue. *Chemical Engineering Journal* 335:110–119
- [24] Oleszczuk P, Ćwikła-Bundyra W, Bogusz A, Skwarek E, Ok YS. 2016. Characterization of nanoparticles of biochars from different biomass. *Journal of Analytical and Applied Pyrolysis* 121:165–172
- [25] Song B, Chen M, Zhao L, Qiu H, Cao X. 2019. Physicochemical property and colloidal stability of micron- and nano-particle biochar derived from a variety of feedstock sources. *Science of the Total Environment* 661:685–695
- [26] Behnam H, Firouzi AF. 2023. Effects of synthesis method, feedstock type, and pyrolysis temperature on physicochemical properties of biochar nanoparticles. *Biomass Conversion and Biorefinery* 13:13859–13869
- [27] Li H, Cui X, Sun Y, Zheng P, Wang L, et al. 2025. Advances in microbial remediation of heavy metal-contaminated soils: mechanisms, synergistic technologies, field applications and future perspectives. *Toxics* 13:1069
- [28] Zhang Q, Wang J, Lyu H, Zhao Q, Jiang L, et al. 2019. Ball-milled biochar for galaxolide removal: sorption performance and governing mechanisms. *Science of the Total Environment* 659:1537–1545
- [29] Saini AK, Abrol V, Sharma P, Srinivasarao C, Parmar AS, et al. 2025. Nitrogen-fortified nanobiochar impacts soil properties, root growth and basmati rice yield. *Biochar* 7:102
- [30] Razzaq S, Zhou B, Ullah Z, Zia-ur-Rehman M, Guo H, et al. 2024. Exploring the impact of organic and inorganic amendments, with foliar application of iron nanoparticles, on cadmium stabilization and growth of maize in wastewater irrigated-soil. *Journal of Hazardous Materials Letters* 5:100111
- [31] Liu W, Li Y, Feng Y, Qiao J, Zhao H, et al. 2020. The effectiveness of nanobiochar for reducing phytotoxicity and improving soil remediation in cadmium-contaminated soil. *Scientific Reports* 10:858
- [32] Dhal S, Pal H. 2023. Nanotechnology for climate-resilient agriculture. In *Climate-Resilient Agriculture*, ed. Hasanuzzaman M. Vol 2. Cham: Springer. pp. 863–880 doi: [10.1007/978-3-031-37428-9\\_38](https://doi.org/10.1007/978-3-031-37428-9_38)
- [33] Adeel M, Shakoor N, Mustafa M, Ming X. 2025. Nanotechnology as a new perspective in precision agriculture. In *Agri-Nanotechnology: Innovations for Sustainable Agriculture and Environmental Restoration*, eds Purewal SS, Gahlaut V, Dash SK. Singapore: Springer. pp. 49–82 doi: [10.1007/978-981-96-9756-4\\_3](https://doi.org/10.1007/978-981-96-9756-4_3)
- [34] Xiang W, Wan Y, Zhang X, Tan Z, Xia T, et al. 2020. Adsorption of tetracycline hydrochloride onto ball-milled biochar: Governing factors and mechanisms. *Chemosphere* 255:127057
- [35] Zhou BB, Chen XP, Henry L. 2020. The effect of nano-biochar on soil, water, and nutrient loss of a sloping land with different vegetation covers on Loess Plateau of China. *Applied Ecology and Environmental Research* 18:2845–2861
- [36] Osman KT. 2018. Sandy soils. In *Management of Soil Problems*. Cham: Springer. pp. 37–65 doi: [10.1007/978-3-319-75527-4\\_3](https://doi.org/10.1007/978-3-319-75527-4_3)
- [37] Arshad MA, Ansari N, Umar M, Arshad F, Adil M, et al. 2021. A review on wheat management, strategies, current problems and future perspectives. *Haya: the Saudi Journal of Life Sciences* 6:14–18
- [38] Hafez EM, Osman HS, Gowayed SM, Okasha SA, Omara AE, et al. 2021. Minimizing the adversely impacts of water deficit and soil salinity on maize growth and productivity in response to the application of plant growth-promoting rhizobacteria and silica nanoparticles. *Agronomy* 11:676
- [39] Joseph S, Anawar HM, Storer P, Blackwell P, Chia C, et al. 2015. Effects of enriched biochars containing magnetic iron nanoparticles on mycorrhizal colonisation, plant growth, nutrient uptake and soil quality improvement. *Pedosphere* 25:749–760
- [40] Yue L, Lian F, Han Y, Bao Q, Wang Z, et al. 2019. The effect of biochar nanoparticles on rice plant growth and the uptake of heavy metals: implications for agronomic benefits and potential risk. *Science of the Total Environment* 656:9–18
- [41] Ramzan M, Zia A, Naz G, Shahid M, Ali Shah A, et al. 2023. Effect of nanobiochar (nBC) on morpho-physio-biochemical responses of black cumin (*Nigella sativa* L.) in Cr-spiked soil. *Plant Physiology and Biochemistry* 196:859–867
- [42] Kamran M, Parveen A, Ahmar S, Malik Z, Hussain S, et al. 2020. An overview of hazardous impacts of soil salinity in crops, tolerance mechanisms, and amelioration through selenium supplementation. *International Journal of Molecular Sciences* 21:148
- [43] Razzaq S, Zhou B, Zia-ur-Rehman M, Aamer Maqsood M, Hussain S, et al. 2022. Cadmium stabilization and redox transformation mechanism in maize using nanoscale zerovalent-iron-enriched biochar in cadmium-contaminated soil. *Plants* 11:1074
- [44] Poria V, Jhila P, Rana A, Khokhar J, Singh S. 2022. Pressmud: a sustainable source of value-added products. *Environmental Technology Reviews* 11:187–201
- [45] Aftab ZEH, Aslam W, Aftab A, Shah AN, Akhter A, et al. 2022. Incorporation of engineered nanoparticles of biochar and fly ash against bacterial leaf spot of pepper. *Scientific Reports* 12:8561
- [46] Kong M, Liang J, White JC, Elmer WH, Wang Y, et al. 2022. Biochar nanoparticle-induced plant immunity and its application with the elicitor methoxyindole in *Nicotiana benthamiana*. *Environmental Science: Nano* 9:3514–3524
- [47] Harter J, Krause HM, Schuettler S, Ruser R, Fromme M, et al. 2014. Linking N<sub>2</sub>O emissions from biochar-amended soil to the structure and function of the N-cycling microbial community. *The ISME Journal* 8:660–674
- [48] Liu L, Shen G, Sun M, Cao X, Shang G, et al. 2014. Effect of biochar on nitrous oxide emission and its potential mechanisms. *Journal of the Air & Waste Management Association* 64:894–902
- [49] Lyu H, Xia S, Tang J, Zhang Y, Gao B, et al. 2020. Thiol-modified biochar synthesized by a facile ball-milling method for enhanced sorption of inorganic Hg<sup>2+</sup> and organic CH<sub>3</sub>Hg<sup>+</sup>. *Journal of Hazardous Materials* 384:121357
- [50] Li R, Zhang Y, Deng H, Zhang Z, Wang JJ, et al. 2020. Removing tetracycline and Hg(II) with ball-milled magnetic nanobiochar and its potential on polluted irrigation water reclamation. *Journal of Hazardous Materials* 384:121095
- [51] Dong X, He L, Hu H, Liu N, Gao S, et al. 2018. Removal of 17 $\beta$ -estradiol by using highly adsorptive magnetic biochar nanoparticles from aqueous solution. *Chemical Engineering Journal* 352:371–379

- [52] Ramanayaka S, Tsang DCW, Hou D, Ok YS, Vithanage M. 2020. Green synthesis of graphitic nanobiochar for the removal of emerging contaminants in aqueous media. *Science of the Total Environment* 706:135725
- [53] Naghdi M, Taheran M, Pulicharla R, Rouissi T, Brar SK, et al. 2019. Pine-wood derived nanobiochar for removal of carbamazepine from aqueous media: adsorption behavior and influential parameters. *Arabian Journal of Chemistry* 12:5292–5301
- [54] Lian F, Yu W, Zhou Q, Gu S, Wang Z, et al. 2020. Size matters: nanobiochar triggers decomposition and transformation inhibition of antibiotic resistance genes in aqueous environments. *Environmental Science & Technology* 54:8821–8829
- [55] Rohini P, Jayadev A. 2024. Microplastics on mangrove ecosystem and scope of biodegradation—a review. *Water, Air, & Soil Pollution* 235:590
- [56] Raut SS, Sharma A, Mishra A. 2025. Nano-bioremediation via biochar, zeolite nanocomposites for water quality enhancement: a review. *Water Environment Research* 97:e70151
- [57] Lateef A, Nazir R, Jamil N, Alam S, Shah R, et al. 2019. Synthesis and characterization of environmental friendly corncob biochar based nano-composite – a potential slow release nano-fertilizer for sustainable agriculture. *Environmental Nanotechnology, Monitoring & Management* 11:100212
- [58] Tan M, Li Y, Chi D, Wu Q. 2023. Efficient removal of ammonium in aqueous solution by ultrasonic magnesium-modified biochar. *Chemical Engineering Journal* 461:142072
- [59] Ma S, Jing F, Sohi SP, Chen J. 2019. New insights into contrasting mechanisms for PAE adsorption on millimeter, micron- and nano-scale biochar. *Environmental Science and Pollution Research* 26:18636–18650
- [60] Nafi E, Webber H, Danso I, Naab JB, Frei M, et al. 2020. Interactive effects of conservation tillage, residue management, and nitrogen fertilizer application on soil properties under maize-cotton rotation system on highly weathered soils of West Africa. *Soil and Tillage Research* 196:104473
- [61] Mukherjee D. 2017. Microorganisms: role for crop production and its interface with soil agroecosystem. In *Plant-Microbe Interactions in Agro-Ecological Perspectives*, eds Singh D, Singh H, Prabha R. Singapore: Springer. pp. 333–359 doi: [10.1007/978-981-10-5813-4\\_17](https://doi.org/10.1007/978-981-10-5813-4_17)
- [62] Woolf D, Amonette JE, Street-Perrott FA, Lehmann J, Joseph S. 2010. Sustainable biochar to mitigate global climate change. *Nature Communications* 1:56
- [63] Wang D, Zhang W, Zhou D. 2013. Antagonistic effects of humic acid and iron oxyhydroxide grain-coating on biochar nanoparticle transport in saturated sand. *Environmental Science & Technology* 47:5154–5161
- [64] Saxena M, Maity S, Sarkar S. 2014. Carbon nanoparticles in 'biochar' boost wheat (*Triticum aestivum*) plant growth. *RSC Advances* 4:39948–39954



Copyright: © 2026 by the author(s). Published by Maximum Academic Press, Fayetteville, GA. This article is an open access article distributed under Creative Commons Attribution License (CC BY 4.0), visit <https://creativecommons.org/licenses/by/4.0/>.