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FROM BULK TO NANO: BIOCHAR-BASED SEED COATINGS AND THE EMERGING POTENTIAL OF NANOBIOCHAR

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ABSTRACT
Growing demand for sustainable crop production has increased interest in seed coating methods that enhances nutrient-use efficiency, support microbial growth, and promote early seedling establishment while reducing dependence on chemical inputs. Nanobiochar, produced by reducing the size of biochar particles and functionally modifying their surfaces, combines biochar's porous structure and surface functionality with enhanced reactivity and loading capacity. Together, these characteristics makes nanobiochar as a potentially multifunctional material for seed coatings. This review critically evaluates nanobiochar-based seed coatings, with particular emphasis on feedstock- and pyrolysis-dependent properties, nanosynthesis and functionalization strategies, characterization techniques, coating technologies, and the mechanisms governing nutrient and microbial delivery. It also examines the potential of nanobiochar to enhance germination and seedling establishment, improves nutrient availability, reduces drought, salinity, and heavy-metal stress, and suppress soil-borne pathogens. Evidence derived directly from seed-coating studies is distinguished from mechanisms inferred from bulk-biochar applications and other nanoparticle-based seed treatments. In addition, the review considers the environmental and agronomic implications of nanobiochar, including its potential contributions to carbon management, reduction of agrochemical use, and economic feasibility. Particular attention is given to material variability, coating stability, nanoparticle aggregation, environmental fate, non-target effects, food-safety concerns, and the limited availability of field-scale and multi-season evidence. Overall, nanobiochar-based seed coatings represent a mechanistically promising but empirically emerging technology. Their agronomic, environmental, and economic benefits require systematic validation under standardized, field-relevant conditions.

KEYWORDS: Nanobiochar; Seed coating; Nanotechnology; Seed priming; Nutrient delivery; Stress mitigation; Sustainable agriculture

INTRODUCTION
Furthermore, the increasing demand for eco-friendly agricultural practices has increased the requirement for innovative seed technologies that improve crop productivity while reducing environmental impacts (Shelar et al., 2023). Conventional agricultural systems heavily rely on synthetic fertilizers and pesticides, leading to nutrient losses through leaching and runoff, environmental pollution, declining soil health, and reduced input use efficiency (Rouphael and Colla, 2021). Moreover, climate change-induced abiotic stresses (drought, salinity, and temperature extremes) often affect seed germination and early seedling establishment (Wu et al., 2024; Zhang et al., 2022). In this context, biochar-based seed coatings have emerged as a promising, environmentally sustainable solution to improve coating performance due to their ability to enhance seed germination, nutrient availability, moisture retention, and early seedling establishment (Zhang et al., 2023, 2022). Although nanobiochar retains the feedstock and pyrolysis dependent characteristics of its parent biochar, nanosizing substantially increases its specific surface area, exposes additional reactive sites, and enhances dispersibility and adsorption properties (Chaubey et al., 2024; Jiang et al., 2023). These modifications may improve its functionality as a carrier material in seed coating applications (Bolan et al., 2023) while preserving the beneficial physicochemical characteristics given during biochar production. These unique physicochemical properties may facilitate the formation of a more uniform coating layer, improve the localized and controlled delivery of nutrients, biofertilizers, and biostimulants, and boost water retention in the immediate vicinity of the seed during germination (Xu et al., 2020; Zhang et al., 2023). Furthermore, nanobiochar has the potential to function as a multifunctional carrier capable of integrating nutrients, plant growth-promoting microorganisms, and other bioactive compounds within a single seed coating

formulation, thereby improving input use efficiency and lowering environmental losses (Bolan et al., 2023; Rocha et al., 2019). In spite of these promising attributes, research expressly investigating nanobiochar as a seed coating material remains scarce (Jiang et al., 2023; Sani et al., 2023), and its mechanisms of action, long-term biosafety, formulation strategies, and field-scale performance have not yet been fully understood (Zhang, 2025). Therefore, a comprehensive analysis of the current knowledge is timely to identify existing research gaps, evaluate the possible advantages of nanobiochar over conventional biochar, and provide future directions for the creation of next-generation sustainable seed coating technologies.

1. Biochar and Nanobiochar: Production and Characterization

1.1 Feedstock Selection and Pyrolysis Conditions

The choice of precursor biomass and pyrolysis parameters, such as peak temperature and residence time, fundamentally determines the carbonaceous framework and functional-group composition that dictate the material's surface reactivity(Osman et al., 2022). Furthermore, feedstock categories and their typical applications are presented in Table 1.

Table 1: Utilization of Different Feedstocks in Biochar Production

Feedstock Category	Common Examples	Typical Use and Characteristics
Agricultural Residues	Rice straw, wheat straw, sugarcane bagasse, corn stover	High availability; extensively used for large-scale carbon sequestration and soil-moisture retention (Mohan et al., 2018)
Woody Biomass	Pine chips, eucalyptus wood, bark, hardwood sawdust	High carbon content and structural stability; these feedstocks are therefore highly suitable for increasing soil porosity and long-term carbon sequestration (Fawzy et al., 2021)
Animal Manure	Swine manure, poultry litter, dairy manure	Rich in phosphorus (P) and nitrogen (N), these feedstocks are primarily used as biofertilizers for soil-nutrient restoration (Ding et al., 2016)
Industrial/Urban Waste	Sewage sludge, municipal solid waste, paper mill sludge	These feedstocks facilitate waste-volume reduction and the stabilization of heavy metals/contaminants (Mohamed et al., 2022)
Algal Biomass	Macroalgae (seaweed), microalgae (*Spirulina*)	These materials, which exhibit significant mineral and nutrient density, often incorporate functional groups that provide effective biostimulant activity (Parmar et al., 2023)

Pyrolysis temperature strongly influences the physicochemical properties of biochar and its suitability for agricultural applications, including seed coating. Furthermore, it governs biochar yield, elemental composition, surface chemistry, porosity, specific surface area, pH, nutrient availability, and adsorption capacity(Osman et al., 2022). Low temperatures generally produce higher yields and retain more oxygen-containing functional groups, such as hydroxyl and carboxyl groups, which increase surface reactivity(Fawzy et al., 2021). In contrast, high temperatures promote carbonization, thereby increasing aromaticity, surface area, porosity, pH, and carbon stability. However, biochar yield declines because volatile compounds are lost (Xiao et al., 2018). Additionally, pyrolysis temperature regulates nutrient retention, microbial colonization, and the adsorption of nutrients and bioactive compounds(Ren et al., 2025). Therefore, the temperature should be optimized according to the intended agricultural use. For nanobiochar, the properties produced during pyrolysis remain important because nanosizing enhances the characteristics of the parent biochar rather than replacing them(Bhandari et al., 2023). Thus, selecting suitable pyrolysis conditions before nanoscale processing is essential for developing nanobiochar with the properties required for effective seed coating(Chausali et al., 2021). Effects of pyrolysis temperature on pH, ash content, and carbon content are presented in Table 2.

Table 2: Physicochemical Properties of Biochars Derived from Different Feedstocks and Pyrolysis Temperatures

Feedstock Category	Feedstock	Pyrolysis Temperature (°C)	Pyrolysis Method / Heating Rate	pH	Ash (%)	Carbon (%)	BET SSA (m^2/g)	Ref.
Agricultural Residue	Cottonseed hull	350	Slow	7.0	5.7	77.0	4.7	(Tomczyk et al., 2020)
Agricultural Residue	Cottonseed hull	800	Slow	9.2	9.2	90.0	322.0	(Tomczyk et al., 2020)

Agricultural Residue	Peanut shell	300	Slow	7.8	1.2	68.3	3.1	(Guo et al., 2020)
Agricultural Residue	Peanut shell	350	Slow	10.4	7.1	64.3	14.0	(Tomczyk et al., 2020)
Agricultural Residue	Peanut shell	450	Slow	11.1	16.9	70.8	14.0	(Tomczyk et al., 2020)
Agricultural Residue	Peanut shell	550	Slow	10.6	7.1	73.7	18.6	(Tomczyk et al., 2020)
Agricultural Residue	Peanut shell	650	Slow	10.6	24.4	74.6	28.1	(Tomczyk et al., 2020)
Agricultural Residue	Peanut shell	700	Slow	10.6	8.9	83.8	448.2	(Guo et al., 2020)
Agricultural Residue	Vine pruning	350	Slow	10.3	8.3	64.7	8.1	(Tomczyk et al., 2020)
Woody Biomass	Hardwood	400	Slow	7.5	3.2	79.0	15.4	(Guo et al., 2020)
Woody Biomass	Hardwood	500	Slow	8.2	4.2	84.8	26.6	(Guo et al., 2020)
Woody Biomass	Palm shell	600	Slow	6.1	6.7	90.6	220.0	(Guo et al., 2020)
Woody Biomass	Rice husk	600	Slow	9.9	47.0	54.5	114.9	(Guo et al., 2020)
Woody Biomass	Mulberry wood	550	Slow	10.6	9.8	77.0	58.0	(Tomczyk et al., 2020)
Woody Biomass	Mulberry wood	650	Slow	10.6	9.8	80.1	24.5	(Tomczyk et al., 2020)
Animal Manure	Cow manure	500	Slow	10.2	67.5	43.7	21.9	(Zhao et al., 2013)
Animal Manure	Pig manure	500	Slow	10.5	48.4	42.7	47.4	(Zhao et al., 2013)
Animal Manure	Shrimp hull	500	Slow	10.3	53.8	52.1	13.3	

1.2 Physicochemical Properties of Biochar vs. Nanobiochar

Nanobiochar differs from conventional bulk biochar primarily in particle size rather than chemical composition; however, this reduction in scale can substantially alter its surface-related properties. Compared with bulk biochar, nanobiochar generally exhibits a larger specific surface area, greater pore volume, modified pore-size distribution, and enhanced surface functionality(Chaubey et al., 2024). These changes are associated with a smaller hydrodynamic radius, a more negative zeta potential, and a higher density of oxygen-containing functional groups (Osman et al., 2022),(Liu et al., 2018). The more negative zeta potential may improve colloidal stability in coating suspensions and enhance the electrostatic interaction of nanobiochar with cationic contaminants (Jiang et al., 2023). Nanobiochar is characterised by a distinctive nanostructure, increased porosity, greater catalytic activity, enhanced surface reactivity, and a higher abundance of active surface sites relative to bulk biochar(Bhandari et al., 2023). Collectively, these properties may improve the regulation of nutrient and contaminant transport and uptake at the particle scale(Bhandari et al., 2023). Nevertheless, the magnitude of these improvements is highly dependent on the feedstock, pyrolysis conditions, and milling or fractionation method(Tomczyk et al., 2020),(Osman et al., 2022). Nanobiochar should therefore not be regarded as a uniform material, but rather as a class of size-reduced biochars whose properties vary according to their production history, which necessitates precise control over mechanical processing parameters to ensure consistency in agricultural applications (Naghdi et al., 2017).

Specifically, milling techniques such as ball milling or planetary milling can significantly alter the physical structure and functional group density of nanobiochar, often leading to variations in its interaction with seed coats (Jiang et al., 2023). The physicochemical parameters distinguishing bulk biochar from nanobiochar are discussed in (Table 3).

Table 3 Properties of Biochar versus Nanobiochar Across Size, Surface, Charge, and Composition Dimensions.

Parameter	Bulk/Macro-Scale Biochar	Nano-Biochar	Sources
Catalytic Activity	Lower	Higher	(Chaubey et al., 2024),(Jiang et al., 2023)

Adsorption capacity for pollutants (heavy metals, pesticides, PCBs, PAHs)	Standard	Significantly enhanced	(Bhandari et al., 2023; Chaubey et al., 2024; Jiang et al., 2023)
***π–π* interaction capacity**	Standard	Enhanced (more aromatic surface density per unit volume)	(Jiang et al., 2023)
Ion-exchange capability for metal cations	Standard	Higher (greater density of cation-exchangeable groups)	(Bhandari et al., 2023)
Regulation of Nutrient and Contaminant Transport	Bulk soil-level regulation	Efficient particle-level regulation	(Bhandari et al., 2023)
Co-precipitation and complexation capacity (e.g., carbonate, sulfate, aluminosilicate groups)	Less abundant	More abundant (notably in municipal-waste-derived nano-biochar)	(Bhandari et al., 2023)
Graphitic character	Lower hardness and abrasion resistance	Markedly higher (preserved from the high-temperature, bulk-scale biochar precursor)	(Jiang et al., 2023)

1.3 Techniques for Nanobiochar Synthesis and Functionalization

Nanobiochar development has progressed from conventional particle-size reduction to an integrated, engineering-based approach that combines both structural and surface modifications to achieve specific agricultural functions(Jiang et al., 2023),(Osman et al., 2022),(Osman et al., 2022). Furthermore, the process starts with converting biomass into biochar through thermochemical methods, such as pyrolysis or hydrothermal carbonization, followed by nanoscale conversion using techniques including ball milling, ultrasonication, and high-energy grinding(Kianfar et al., 2022),(Bhandari et al., 2023),(Bhandari et al., 2023). These methods first modify the structural orientation of biochar by reducing particle size, increasing surface area and porosity, and improving colloidal stability(Jiang et al., 2023). Moreover, subsequent surface engineering through oxidation, alkali activation, or heteroatom doping introduces reactive functional groups that enhance hydrophilicity, cation exchange capacity, adsorption capacity, and compatibility with nutrients and microorganisms(Chen et al., 2022),(Osman et al., 2022).

The engineered nanobiochar is further functionalized to serve as a multifunctional platform for sustainable agriculture. Furthermore, biochar–biopolymer composites address two persistent weaknesses of biochar-only coatings: adhesion to the seed surface and antimicrobial activity. Chitosan–biochar (CS–BC) composite coatings on wheat outperformed both uncoated and chitosan-only controls, with the CS–BC 4:1 formulation increasing germination energy by 30% (87.8% vs. 67.6%), germination percentage by 20% (89.5% vs. 74.8%), and germination index by 66% (18.6 vs. 11.2), and raising soil organic carbon by 12% — an effect attributed to biochar improving soil structure and nutrient/water retention while chitosan boosts seed vigor and provides antimicrobial protection (Mustafazade et al., 2025). Biopolymers such as chitosan, alginate, and starch are established coating components for enhancing adhesion, protecting microorganisms, and enabling controlled nutrient release (Sujatha et al., 2023), and current reviews position biochar as a functional filler within biodegradable polymer matrices in eco-friendly seed coatings (Biswal et al., 2026). At the nanoscale, electrospun biopolymer nanofibers with tunable release kinetics have demonstrated precise agrochemical delivery in seed coatings, increasing seedling biomass by 12–29% (Xu et al., 2020); chitosan-based nanomaterials likewise form semi-permeable films on seeds and modulate germination-related enzyme activity (Chakraborty et al., 2020). Furthermore, extending the biopolymer-composite concept to nanobiochar — rather than micrometer-scale biochar particles — constitutes a promising next step, but direct comparative data on the adhesion strength, film integrity, and antimicrobial performance of nanobiochar–polymer hybrids on seeds remain unavailable. Functional engineering through nutrient impregnation, polymer coating, or composite formation enables controlled nutrient release, improved seed adhesion, and enhanced physicochemical stability. In contrast, biological engineering immobilizes beneficial microorganisms such as plant growth-promoting rhizobacteria, phosphate-solubilizing bacteria, and mycorrhizal fungi to improve microbial survival and rhizosphere colonization (Backer et al., 2018). Thus, the performance of nanobiochar is governed not only by its synthesis technique but also by the integration of structural, chemical, functional, and biological modifications, providing a rational framework for designing next-generation seed coating materials with enhanced nutrient delivery, microbial compatibility, and stress resilience(Bhandari et al., 2023).

2. Seed Coating Technologies and Formulations

2.1 Coating Methods

Seed coating constitutes a seed-enhancement technology involving the application of exogenous materials to the seed surface to improve seed handling, sowing precision, protection against biotic and abiotic stresses, and the targeted delivery of active ingredients(Halmer, 2008; Javed et al., 2022). Depending on the amount of coating material applied and the degree of seed modification, coating methods are broadly classified into seed dressing, film coating, encrusting, and pelleting(Afzal et al., 2020). Seed dressing is the least intensive approach, involving the application of a thin layer of powder or liquid formulations with minimal change to seed size, primarily for delivering pesticides, micronutrients, or microbial inoculants(Orzali et al., 2023). Film coating encapsulates the seed within a thin polymeric layer (typically <10% increase in seed weight), ensuring uniform distribution of active ingredients while preserving the seed's original size and shape(Rocha et al., 2019),(Pedrini et al., 2016). In contrast, encrusting applies thicker layers (approximately 10–500% weight increase) that partially modify seed morphology and provide greater loading capacity for nutrients, biostimulants, and beneficial microorganisms(Dadlani and Yadava, 2023). Pelleting represents the most extensive coating method, substantially increasing seed size and producing nearly spherical pellets that facilitate precision sowing and accommodate high concentrations of fertilizers, crop protectants, and biological inputs(Dadlani and Yadava, 2023),(Rocha et al., 2019). Thus, coating method selection is governed by seed characteristics, the desired loading of active compounds, planting requirements, and the balance between coating thickness and seed physiological performance(Khan et al., 2023).

2.2 Binders, Adjuvants, and Carrier Materials Used with Biochar

Modern seed-coating technology has developed from a conventional protective treatment into a multifunctional delivery platform capable of incorporating polymers, fillers, nutrients, plant growth regulators, biostimulants, microbial inoculants, and nanomaterials within a single formulation(Xu et al., 2020),(Biswal et al., 2026). An effective coating should provide strong adhesion, uniform coverage, mechanical stability, rapid hydration, adequate gas exchange, and compatibility with seed metabolism without adversely affecting germination or seedling emergence(Bruno et al., 2018). Coating formulations generally comprise binders, fillers, plasticizers, colorants, and active ingredients, each of which can influence coating integrity, release kinetics, and storage stability(Rocha et al., 2019). Although thicker coatings, including encrustations and pellets, provide a greater capacity for loading active compounds, excessive coating thickness may restrict water imbibition and oxygen diffusion, thereby delaying germination when formulations are not properly optimized (Bruno et al., 2018). Accordingly, recent research has focused on biodegradable polymers, controlled-release systems, microbial encapsulation, and nanomaterial-based carriers to improve nutrient-use efficiency and minimize environmental impacts(Shelar et al., 2023). In this context, nanobiochar represents a promising multifunctional coating component because its high surface area, porous structure, and abundant reactive functional groups may support the simultaneous delivery of nutrients, beneficial microorganisms, and bioactive compounds while enhancing coating stability and seed–soil interactions(Zhang et al., 2022).

3.Effects on Seed Germination and Early Seedling Growth

3.1 Seed Priming Effects and Water Imbibition Dynamics

Nanobiochar seed coatings may modify the physico-chemical microenvironment surrounding seeds during the early stages of germination through their active surface functional groups(Zhang et al., 2022). Rather than acting as conventional chemical priming agents, nanobiochar materials may function as localized moisture-retaining phases at the seed–soil interface. Their porous architecture can promote water retention and capillary transport, while surface chemistry may affect wettability and the adsorption of water and dissolved substances(Yang et al., 2023). These properties are particularly relevant during phase I of germination, a period characterised by rapid water uptake, cellular rehydration, and metabolic activation(Upretee et al., 2024). Evidence from rice suggests that biochar-coated seeds exhibit greater water uptake than uncoated seeds, although the magnitude of this effect varies with cultivar and imbibition period(Zhang et al., 2023). In one study, rice seeds coated with biochar consistently absorbed more water during imbibition, indicating that the coating modified the hydration environment surrounding the seed(Zhang et al., 2023).

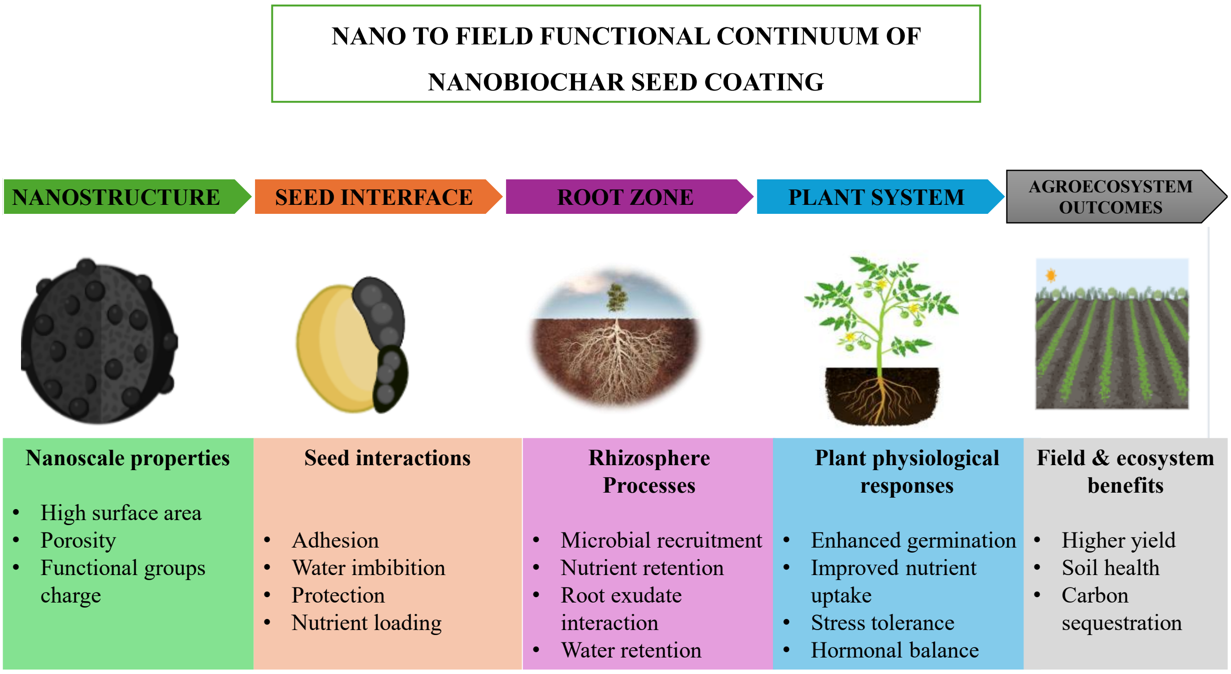

Fig-1: illustrates the **nano-to-field functional continuum of nanobiochar seed coating**, linking material properties with plant and ecosystem-level outcomes. At the nanoscale, high surface area, porosity, and functional groups facilitate nutrient loading, water interaction, and microbial association. At the seed interface, these properties support coating adhesion, water imbibition, seed protection, and nutrient delivery. These effects extend into the rhizosphere and plant system by influencing microbial recruitment, nutrient retention, root interactions, germination, nutrient uptake, and stress tolerance. Ultimately, these interconnected processes may contribute to **higher crop productivity, improved soil health, and carbon sequestration** at the field and agroecosystem levels.

Nevertheless, enhanced water retention should not be equated automatically with accelerated germination. The physical properties of the coating, including its thickness, porosity, swelling behaviour, and degree of saturation, determine whether it promotes or limits seed hydration(Zhou et al., 2026). Studies of coated cereal seeds have demonstrated that water-absorbing coatings can substantially modify imbibition kinetics and, in wheat, prolong the initial hydration phase. Importantly, coating saturation substantially reduced oxygen diffusion to the embryo and was associated with delayed germination(Gorim and Asch, 2017). Likewise, experiments using increasing rates of biochar reported neutral or adverse effects on germination in several plant species, demonstrating that increasing the quantity of biochar does not necessarily improve establishment(Murtaza et al., 2023).

Accordingly, the performance of nanobiochar coatings is likely to depend on an optimal combination of coating thickness and pore structure(Zhang et al., 2023),(Zhang et al., 2022),(Zhang et al., 2022). Moreover, a thin, permeable layer may maintain a favorable water microenvironment, whereas excessive water retention or coating compaction may restrict oxygen diffusion and delay radicle emergence. Direct measurements of imbibition kinetics in biochar-coated seeds have been reported(Accinelli et al., 2023), whereas nanobiochar-specific data remain limited. Therefore, these proposed effects should be considered mechanistic hypotheses that require validation through time-resolved measurements of water uptake and oxygen diffusion.

3.2 Root and Shoot Development Enhancement

The potential of biochar-based seed coatings to promote early seedling development may be attributable to the formation of a localized, water- and nutrient-rich microenvironment around the emerging radicle(Zhang et al., 2023). The high specific surface area and functionalized surface of nanobiochar may further strengthen these interactions, although this nanoscale advantage has yet to be directly demonstrated in seed-coating systems(Bhandari et al., 2023). Unlike soil-applied biochar, which is dispersed throughout a relatively large soil volume, seed-coating application positions the carbonaceous material directly at the seed surface and subsequently near the zone of radicle emergence. Its high surface area and porous structure may enhance water retention and nutrient adsorption, whereas its surface functional groups may regulate nutrient availability and interactions with the developing root system(Hagemann et al., 2017). Consequently, coated seeds may experience more localized access to moisture and nutrients during the transition from germination to seedling establishment(Skrzypczak et al., 2021). Furthermore, evidence from conventional biochar seed-coating studies indicates that coating rice seeds can improve germination and seedling establishment, potentially through enhanced water uptake, respiration, α-amylase activity, and the accumulation of soluble sugars and proteins(Zhang et al., 2023, 2022). More broadly, reviews of biochar-based seed coatings have reported improvements in traits such as root length and root biomass,

supporting the hypothesis that positioning biochar at the seed–soil interface can influence early root development(Zhang et al., 2022).
Evidence from nanoscale biochar systems provides additional, although not coating-specific, support for this interpretation (Thomas, 2021). (Lu et al., 2020) Studies have investigated biochar nanoparticles derived from different feedstocks and pyrolysis temperatures. Furthermore, studies have reported positive effects of biochar nanoparticles on seedling development, although mechanisms specific to nanoparticles remain speculative (Thomas, 2021). This dependence is important because the nanoscale effect should not be attributed solely to particle size; pyrolysis temperature, feedstock chemistry, surface functional groups, residual organic compounds, and particle concentration may all modulate plant responses. Indeed, high-temperature biochar nanoparticles inhibited rice germination and reduced branch length and biomass, illustrating that germination-stage responses and post-germination responses should be distinguished (Jiang et al., 2022). Thus, nanobiochar coatings may be particularly valuable for supporting early root establishment, where localized availability of water and adsorbed nutrients coincides spatially with radicle emergence(Nile et al., 2022), (Shelar et al., 2023). Nevertheless, future studies should directly compare nanobiochar-coated seeds with equivalent bulk-biochar coatings, in addition to uncoated controls. Such a comparison would determine whether the increased surface area and altered surface chemistry associated with nanosizing provide a genuine advantage over conventional biochar rather than merely demonstrating an effect of biochar coating itself.
For experimental evaluation, the most informative endpoints would include the following: primary root length, shoot length, root/shoot biomass ratio, root dry weight, seedling dry matter, root hair development or density, and seedling establishment percentage. These measurements would help distinguish a simple improvement in germination from a genuine enhancement of early seedling vigour(Dadlani and Yadava, 2023). This distinction is particularly important because nanoscale biochar can also produce inhibitory responses at inappropriate concentrations; therefore, a dose-dependent response, rather than an assumption of universally positive effects, should be incorporated into the interpretation(Liu et al., 2021), (Szőllősi et al., 2020).

3.3 Vigour Index and Stress Tolerance at Early Growth Stages

Seedling vigour provides a more integrated assessment of treatment performance than final germination percentage alone because it reflects both successful germination and subsequent seedling development(Qiao et al., 2023). In nanobiochar-coated seeds, parameters (germination percentage, mean germination time, germination index, seedling length, seedling dry weight, and vigour index) can therefore provide a comprehensive evaluation of treatment effects(Nile et al., 2022). The classical vigour index proposed by Abdul-Baki and Anderson is generally calculated as the product of germination percentage and total seedling length, thereby combining germination capacity with early seedling growth(Deswal et al., 2017). A decrease in MGT accompanied by increases in seedling length and biomass would indicate more rapid seedling establishment. Conversely, an increase in final germination without a corresponding improvement in seedling growth would suggest a distinct physiological response(Šerá, 2023).
Nevertheless, the use of vigour indices in nanobiochar research should be distinguished from the mechanisms proposed for other nanoparticle-based seed-priming systems. ZnO, Se, and CeO_2 nanoparticles, as well as chitosan-based nanoparticles, have been reported to enhance germination, seedling growth, and/or stress tolerance through mechanisms involving nutrient delivery, hormonal regulation, antioxidant activity, and the modulation of reactive oxygen species(Singh et al., 2024). For example, CeO_2 nanoparticle priming has been associated with increased root and shoot growth and reduced ROS accumulation in salt-stressed seedlings(Khan et al., 2022). Similarly, Se nanoparticle priming has been linked to enhanced antioxidant activity and improved germination (Setty et al., 2023), whereas chitosan-based nanoparticle priming has reportedly increased vigour index, seedling biomass, and root length, alongside changes in hormonal and antioxidant-related responses(Saharan̥ et al., 2016). Although these findings provide a useful comparative framework, their proposed mechanisms should not be directly extrapolated to nanobiochar without further mechanistic validation.
When nanobiochar is used as a seed-coating material, its primary contribution is more likely to be physical and adsorptive than intrinsically redox-active. Its porous structure and high surface area may regulate the local availability of water and adsorbed nutrients, while its surface functional groups may facilitate interactions with nutrients and other compounds(Kianfar et al., 2022),(Naghdi et al., 2017),(Naghdi et al., 2017). Accordingly, improvements in vigour under drought or other early-stage stresses should initially be interpreted as consequences of changes to the seed microenvironment rather than as evidence of antioxidant activity(Zhang et al., 2023). This distinction is particularly important because biochar nanoparticles have produced both stimulatory and inhibitory effects, depending on factors such as feedstock, pyrolysis temperature, concentration, and plant species(Liu et al., 2021). Under stress conditions, relevant evaluation parameters should therefore include germination percentage, MGT, germination index, vigour index, root and shoot length, seedling dry weight, and stress-tolerance indices. Where feasible, these assessments should be complemented by physiological measurements (relative water content, membrane integrity, and antioxidant enzyme activity)(Li et al., 2021),(Pandya et al., 2024).
A significant research gap persists, as direct and standardized evaluations of vigour indices and stress tolerance in nanobiochar-coated seeds remain limited. Although available evidence suggests that biochar coatings can enhance water uptake and seedling establishment, and that nanoscale biochar can influence germination and early seedling growth, these findings do not establish a universal mechanism for nanobiochar-induced improvements

in vigour(Zhang et al., 2023). Future studies should therefore compare uncoated seeds with bulk biochar and nanobiochar coatings applied at equivalent carbon doses. Germination kinetics, MGT, vigour index, and seedling biomass should be quantified under both optimal and stress conditions. Such a comparative design would provide stronger evidence of whether nanosizing confers a distinct advantage in seed-coating applications.

Furthermore, nanosizing can increase rather than reduce toxicity; therefore, this dose- and size-dependence must temper any claim of nanobiochar superiority. In a benchmark comparison of five nanomaterials with their bulk counterparts, Cu nanoparticles reduced the emerging root length of zucchini by 77% relative to the control and by 64% relative to bulk Cu powder; 15-day biomass reductions were greater for the nano forms (90% for Cu, 75% for Ag, 60% for multiwalled carbon nanotubes) than for bulk Cu (69%); Ag nanoparticles at 500 mg/L decreased biomass by 57% relative to bulk Ag, and shoots accumulated 4.7-fold more Ag from nano than from bulk exposures (Stampoulis et al., 2009). Comparable effects are reported for carbon-based materials: carbon nanoparticles and hydroxyl radicals generated by biochar-based catalysts can inhibit seed germination and seedling root and shoot growth and damage plasma membranes in corn, wheat, and rice (Yang et al., 2022), and nanobiochar derived from hot pepper stalks decreased cucumber seed germination and inhibited root development and seedling growth through oxidative stress and root injury (Liu et al., 2023). In soil, nanobiochar can additionally exert adverse ecotoxicological effects on soil fauna and modify microbial and enzymatic activities (Zhang, 2025). The emerging pattern is a hormetic continuum stimulatory at low doses or favorable particle sizes, inhibitory at higher ones (Santás-Miguel et al., 2023; Szőllősi et al., 2020) — which argues for dose–response screening rather than an a priori assumption of benefit.

4. Nutrient Delivery and Soil-Plant Interactions

4.1 Nutrient Adsorption and Controlled Release Mechanisms

This distinction is particularly important when considering the transition from bulk biochar used as a soil amendment to biochar incorporated into a seed-coating material. Nevertheless, under certain conditions, nutrient-enriched biochars have exhibited controlled-release properties, thereby indicating their potential as nutrient-carrier matrices. For instance, P-enriched Douglas-fir biochar has functioned as a slow-release phosphorus source, with plant growth and phosphorus availability depending on the phosphorus loading within the biochar matrix (Wali et al., 2020). More recently, a biochar-based N–P–K fertilizer system demonstrated the controlled release of multiple nutrients through combined nutrient precipitation and retention within the biochar matrix (Lu et al., 2023). Although these findings establish the material-level feasibility of using biochar as a nutrient carrier, they do not confirm that comparable release kinetics would occur within a seed-coating system (Cidreira et al., 2025; Rodrigo et al., 2025).

The geometry of a seed coating may substantially alter the relevance of this mechanism (Phillips et al., 2025). In conventional soil applications, biochar is distributed throughout a comparatively large soil volume and interacts with the soil matrix (soil minerals, water, and microorganisms) before nutrients become available to the plant (Nkoh et al., 2021). In contrast, a coating places the carrier directly on the seed and, subsequently, adjacent to the emerging radicle (Skrzypczak et al., 2021). Consequently, even a relatively small nutrient load could theoretically produce a high local nutrient concentration during the early stages of root development. Evidence from biochar-coated rice supports the broader, system-level proposition that seed coating can modify the seed microenvironment and promote early establishment. The optimum treatment increased emergence, root length, and root biomass and was associated with greater seed water uptake and metabolic activity (Zhang et al., 2023). However, this study did not establish a nutrient-release curve for the coating. Therefore, localized controlled release should be presented as a proposed mechanism rather than as a demonstrated property of nanobiochar seed coatings (Zhang et al., 2022),(Zhang et al., 2023).

A key research gap concerns the direct extrapolation of release kinetics measured in bulk biochar-soil or biochar-water systems to a thin seed-coating layer(Lombi et al., 2025). Furthermore, relevant variables include coating thickness, nutrient loading, particle size, moisture availability, coating disintegration, diffusion distance, and the rapidly changing chemical environment surrounding the germinating seed(Lawrencia et al., 2021),(Tian et al., 2016),(Tian et al., 2016). In a P-enriched nanobiochar system, this release mechanism could be evaluated by measuring time-resolved phosphorus release from coated seeds under controlled moisture conditions and relating the release profile to radicle emergence and early phosphorus uptake(Bindraban et al., 2020).

4.2 Rhizosphere Microbial Community Modulation

The microbial dimension of biochar seed coatings is particularly significant because the coating may function not only as a physical carrier but also as a spatially targeted platform for co-delivering carbonaceous materials and beneficial microorganisms(Backer et al., 2018). Biochar's porous structure can provide attachment sites and protected microsites for microbial cells, while its water-retention capacity may help stabilize the microenvironment surrounding the inoculants(Liang et al., 2021). A review focused specifically on biochar-based seed coatings identifies plant-growth-promoting rhizobacteria, rhizobia, and arbuscular mycorrhizal fungi as potential microbial inoculants(Zhang et al., 2022). Furthermore, biochar is proposed as an alternative carrier, given that its porous matrix may support microbial survival. This interpretation is more robust than the generalized claim that biochar "increases microbial diversity," because seed coatings establish a direct physical connection between inoculant placement, seed germination, and subsequent root colonization(Singh et al., 2022).

Nevertheless, microbial delivery should be differentiated from broader modulation of microbial communities. Furthermore, existing studies on seed coatings provide stronger support for biochar's function as an inoculant carrier than for the claim that nanobiochar independently restructures the entire rhizosphere microbial community. Responses may also depend substantially on biochar characteristics (including feedstock, pyrolysis conditions, and surface chemistry)(Singh et al., 2022). For example, (Shabir et al., 2024) reported differences in *Bradyrhizobium* survival among biochars differing in feedstock and pyrolysis conditions, indicating that biochar should not be treated as a uniform microbial habitat. Accordingly, the most defensible mechanistic interpretation is that biochar coatings facilitate the spatially targeted co-delivery of a carbonaceous carrier and beneficial microorganisms. Moreover, subsequent interactions with the developing root may then affect nutrient acquisition and rhizosphere establishment(Joseph et al., 2021), (Bolan et al., 2023).

For nanobiochar, this proposition should therefore be treated as a cautious, testable hypothesis. Nanosizing has been demonstrated to increase the accessible surface area relative to bulk particles — nanobiochar typically shows 0.4–97-fold higher surface area and 0.5–48.5-fold greater total pore volume than bulk biochar, along with more negative zeta potential and additional oxygen-containing functional groups (Chaubey et al., 2024; Jiang et al., 2023) — and may therefore increase the number of sites available for microbial attachment or nutrient adsorption; indeed, the surface features of nanobiochar have been proposed to allow it to function as a carrier for microbes, and biochar surface functional groups are effective for microbial cell adhesion (Bhandari et al., 2023),(Bolan et al., 2023). However, greater surface area does not necessarily improve microbial survival. Inoculant survival in biochar carriers is strongly governed by carrier properties rather than by surface area alone: out of five biochars evaluated as inoculant carriers, only two maintained bacterial viability over extended storage (Rocha et al., 2019), and viability of the phosphate-solubilizing (*Pseudomonas libanensis*)in biochar-based corn seed coatings was best sustained by carriers with near-neutral pH and pore diameters (5–10 μm) compatible with bacterial cell dimensions (0.3–3 μm) (Głodowska et al., 2016). Surface chemistry, pH, residual pyrolysis compounds (e.g., polycyclic aromatic hydrocarbons, volatile organic compounds, and heavy metals) and particle concentration must therefore be considered (Ouyang et al., 2023; Zheng et al., 2023), as must potential antimicrobial effects: carbon-based nanomaterials can damage bacterial membranes and induce oxidative stress, with individually dispersed particles and higher particle concentrations being (Qi et al., 2018) (Liu et al., 2009) more toxic. Furthermore, the interaction is bidirectional, since microbial metabolites can aggregate nanobiochar and reduce its effective surface area and sorption capacity (Jiang et al., 2023). Nanobiochar should consequently not be assumed to be intrinsically superior to bulk biochar for microbial inoculation without comparative studies examining microbial survival and colonization. A direct comparison of bulk biochar + PSB and nanobiochar + PSB could quantify inoculant viability on the seed, rhizosphere population, root colonization, and phosphorus uptake — parameters already shown to be carrier-sensitive in biochar-based PSB seed coatings, in which viability was maintained for up to 22 weeks on biochar and 16 weeks on coated seeds (Głodowska et al., 2016).

4.3 Soil Physicochemical Property Improvements: pH, CEC and Water Retention

Biochar is widely reported to modify soil physicochemical properties, including pH, cation exchange capacity, bulk density, porosity, and water retention (Singh et al., 2022). However, these effects are strongly dependent on application rate, soil texture, initial soil chemistry, and biochar characteristics. A global meta-analysis of agricultural soils showed that the magnitude of the biochar-driven pH response was primarily explained by initial soil pH (31.6%), biochar application rate (27.0%), and biochar pH (12.1%), while sand content (31.6%) was the dominant predictor of the soil CEC response (Sun et al., 2022). A separate meta-analysis likewise found positive effects, reporting that biochar increased soil pH, CEC, and organic carbon by 46%, 20%, and 27%, respectively, while emphasizing that these effects varied among feedstocks and were greater in coarse- and fine-textured soils (Singh et al., 2022). Therefore, this variability precludes direct extrapolation of bulk-soil biochar effects to seed-coating systems.

Furthermore, water-retention responses exhibited comparable scale dependence, with a meta-analysis of 939 observations finding that biochar significantly increased water content at field capacity, particularly in coarse-textured soils (23.8% increase, versus 5.0% in medium- and 7.2% in fine-textured soils), while gains in plant-available water likewise declined as soil texture became finer (25.6%, 20.9%, and 11.5% for coarse, medium, and fine textures, respectively) (Wei et al., 2023). Thus, even for bulk biochar application, water-retention effects are not universal. In a seed coating, the amount of biochar is orders of magnitude smaller than typical soil-amendment rates, which in field trials are commonly applied at the scale of tonnes per hectare (Osman et al., 2022), and the material occupies only a thin layer around the seed. Consequently, it is unlikely that a conventional nanobiochar coating would produce a measurable change in bulk-soil pH, bulk-soil CEC, or whole-pot water-holding capacity. Instead, the scientifically defensible hypothesis is that the coating may modify the microscale environment immediately surrounding the seed and emerging radicle.

This distinction is particularly important when interpreting the literature. Soil studies frequently use substantial biochar application rates, and their reported changes in pH or CEC represent the integrated response of a large soil mass. A seed coating, in contrast, introduces a very small quantity of material into a highly localized region. Therefore, the relevant question is not whether the coating can "improve soil CEC," but whether the coating can create a localized nutrient-retaining and moisture-buffering interface during the short period when the radicle is establishing contact with the surrounding soil. Moreover, the 2023 rice study provides useful evidence for this localized interpretation: the optimal 30% biochar coating enhanced emergence rate by 9.5%, root length by 23.7%, and root dry weight by 49.8% across both water-saving rice varieties and was associated with increased seed water uptake and metabolic activity, but the study did not demonstrate a measurable alteration of bulk-soil pH or CEC (Zhang et al., 2023).

5. Role in Abiotic and Biotic Stress Mitigation

5.1 Drought and Salinity Stress Alleviation

Drought and salinity impair germination and early seedling establishment through reductions in water availability, induction of osmotic imbalance and ion toxicity, and escalation of oxidative stress (Sabouri et al., 2024). As a soil amendment, biochar has been extensively investigated for alleviating these constraints. A meta-analysis of 939 observations found that biochar significantly increased soil water content at field capacity, particularly in coarse-textured soils (23.8% increase, versus 5.0–7.2% in medium- and fine-textured soils), while gains in plant-available water declined from 25.6% to 11.5% as soil texture became finer (Wei et al., 2023). The water-retention benefits of biochar therefore cannot be generalized across soil types.

These findings provide a conceptual basis for examining biochar in seed coatings: its porous structure and water-holding capacity could, in principle, establish a localized moisture-buffering environment around the imbibing seed, and a review of biochar-based seed coatings identifies high porosity, water-holding capacity, and nutrient content as potentially beneficial characteristics for seed establishment (Zhang et al., 2022). However, direct evidence remains limited. In the most relevant controlled evaluation to date, biochar used as a seed coating on restoration substrates (mine tailings, coarse granitic sand, and potting soil) produced strongly species- and substrate-specific outcomes: coating enhanced white clover establishment, with an approximately fivefold biomass increase at harvest on the potting soil mix, but had neutral effects on sand or tailings, and improved purple prairie clover germination only in some cases, with benefits that did not persist (Cann et al., 2024). Coating performance thus varied with formulation, species, and environmental conditions rather than producing a consistent improvement in germination — a pattern consistent with the general observation that seed enhancement technologies for dryland restoration remain context-dependent and largely unvalidated under field conditions (Svejcar et al., 2021),(Davies et al., 2024), (Davies et al., 2024).

Moreover, a similar limitation applies to salinity stress. Meta-analyses of soil-applied biochar report improved crop productivity in salt-affected soils, with increased crop yield (e.g., 20.8%), reduced soil salinity (−9.6%), reduced Na^+ and Cl^- contents (12.5% and 23.4%), and slightly lower soil pH (−2.2%) (Zhang et al., 2025), with the largest productivity benefits in sulfate-dominated saline soils (Wu et al., 2024). These responses, however, operate across a comparatively extensive soil–root volume and reflect soil-scale application rates; they cannot be attributed to the effects of a thin seed coating. In a nanobiochar coating, the proposed mechanism would instead involve localized water buffering and modification of the immediate seed–soil interface — a mechanism distinct in kind from the reactive oxygen species-scavenging effects reported for some nanoparticle-based seed-priming systems, in which nanoparticles internalized by seeds modulate ROS homeostasis within the oxidative window and enhance antioxidant enzyme activity (e.g., superoxide dismutase, catalase, guaiacol peroxidase) (Shelar et al., 2023), (Nile et al., 2022).

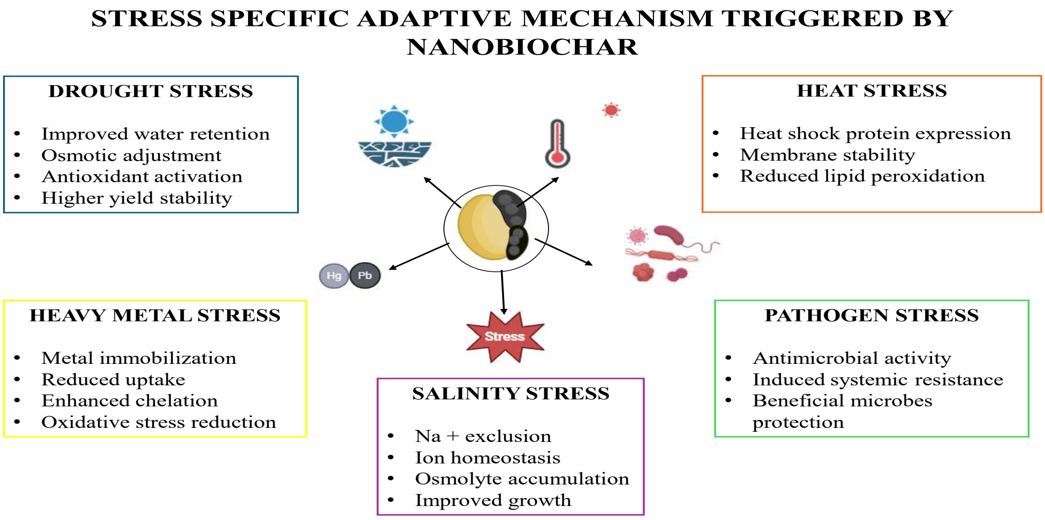

Fig-2:the stress-specific adaptive mechanisms potentially triggered by nanobiochar seed coating **under different environmental and biological stresses. Under** drought stress, **nanobiochar may improve water retention, osmotic adjustment, antioxidant activity, and yield stability. Under** heat and salinity stress, **it may promote heat-shock protein expression, membrane stability, ion homeostasis, Na^+ exclusion, and osmolyte accumulation. Under** heavy-metal and pathogen stress, **nanobiochar may contribute to metal immobilization, reduced uptake, enhanced chelation, antimicrobial activity, and induced systemic resistance. Overall, these interconnected mechanisms may enhance plant resilience by maintaining** water balance, cellular stability, nutrient and ion homeostasis, and defense responses **under diverse stress conditions.**

Accordingly, nanobiochar should not yet be characterized as a proven treatment for drought or salinity tolerance. Current evidence supports a plausible mechanism, although direct validation remains unavailable (Cann et al., 2024). Key variables (particle size, pore structure, pyrolysis temperature, coating thickness, binder composition, and soil texture) may determine whether the coating enhances local water retention or instead restricts oxygen and water movement — a risk already documented for biochar-containing coatings, in which increasing the biochar fraction reduced coating integrity, compressive strength, and time to disintegration (Zhang et al., 2023). The potential of nanobiochar seed coatings to mitigate drought and salinity therefore remains an important hypothesis that requires direct evaluation under controlled water-potential and salinity conditions.

5.2 Heavy Metal Immobilization and Reduced Uptake

Among the proposed stress-mitigation functions of biochar, heavy metal immobilization is supported by comparatively strong experimental evidence. A meta-analysis of 74 peer-reviewed studies encompassing 1,298 independent observations reported that biochar application reduced plant tissue concentrations of the heavy metals (Cd, Pb, Cu, and Zn) by 38%, 39%, 25%, and 17%, respectively (Roy et al., 2025). Moreover, subsequent meta-analyses corroborate these magnitudes for individual metals: soil Cd bioavailability decreased by 30.5% and Cd accumulation in roots, shoots, leaves, and grains by 31.3%, 34.0%, 25.3%, and 43.1%, respectively (Zhang et al., 2025), and Cd contents decreased by 24.9–45.0% across cropping systems (Duan et al., 2023).

These effects arise through several interacting mechanisms: electrostatic attraction and surface adsorption onto the carbon matrix, ion exchange with cations on the biochar surface (e.g., Ca^{2+}, Mg^{2+}), complexation with oxygen-containing functional groups (−COOH, –OH), and precipitation of sparingly soluble hydroxide, carbonate, and phosphate phases — the latter promoted by biochar-induced increases in soil pH (Guo et al., 2020). However, the meta-analytic evidence also indicates that immobilization efficacy varied with biochar type, application rate, soil properties, contamination level, and plant species, such that the overall results could not be generalized across the compiled studies (Roy et al., 2025). Feedstock, application rate, biochar pH, soil pH, and soil cation exchange capacity are consistently identified as dominant moderators (Duan et al., 2023), with manure-derived biochars exhibiting the greatest capacity to reduce heavy-metal bioavailability (Roy et al., 2025), and biochars with a pH of 6.5–8.5 applied at rates above 2% decreasing Cd absorption in crops (Zhang et al., 2025). In bulk systems, moreover, the immobilization outcome appears more strongly driven by the soil system than by the plant system itself (Teng et al., 2025).

Furthermore, these findings provide a mechanistic rationale for investigating nanobiochar as a localized metal-immobilizing material. Nanosizing increases accessible surface area and alters surface reactivity relative to bulk particles (Chaubey et al., 2024), (Jiang et al., 2023), potentially enhancing interactions with metal ions in the vicinity of the germinating seed and developing root. Nevertheless, this proposed seed–rhizosphere localization pathway has not been demonstrated to the same extent as the metal-immobilization effects of bulk biochar applied to soil. Accordingly, it would be inappropriate to claim that nanobiochar seed coatings directly immobilize heavy metals. A more defensible interpretation is that the demonstrated metal-retention capacity of biochar provides a basis for examining whether nanobiochar coatings can locally reduce metal bioavailability near emerging roots. Future studies should directly quantify key endpoints (soil-solution metal concentrations, metal speciation, root uptake, and metal translocation) in plants grown from coated seeds.

5.3 Suppression of Soil-Borne Pathogens and Biotic Stress

Biochar has demonstrated considerable potential for suppressing plant diseases, with a global meta-analysis reporting that soil biochar amendment reduced disease severity by approximately 47.5% and increased plant biomass by approximately 44% (Yang et al., 2022). However, the magnitude of suppression varied with biochar feedstock, pyrolysis temperature, and application rate — with straw-derived biochars showing the strongest mean effects — indicating that suppression should not be assumed across all biochar–soil–pathogen combinations (Yang et al., 2022).

Furthermore, several mechanisms may underlie these responses, with reviews of biochar-mediated disease suppression emphasizing three principal processes: induction of systemic resistance, enhancement of the rhizosphere competence of the microbial community, and sorption of phytotoxic compounds of plant and/or microbial origin (Iacomino et al., 2022). Biochar can also modify soil pH, nutrient availability, and moisture conditions and provide porous niches for beneficial microorganisms (Jaiswal et al., 2017). Collectively, these effects may enhance microbial competition and antagonism or stimulate plant resistance to pathogens. Nevertheless, suppression remains strongly context-dependent: across a review of 61 articles comprising 117 experimental case studies, fungal pathogens accounted for 55% of cases, and reported suppression efficiencies ranged from 50% (nematodes) to 96% (bacteria) and up to 100% (oomycetes and viruses) depending on the pathogen group (Iacomino et al., 2022).

Seed coating may involve a distinct mode of action because the material is positioned directly on the seed surface. In this configuration, porous biochar could serve as a carrier for beneficial microorganisms and position them near the emerging radicle — an application already identified in biochar-based seed-coating research, which lists microbial inoculant delivery among the technology's prospective functions (Zhang et al., 2022). However, most quantitative evidence for disease suppression derives from biochar incorporation into bulk soil rather than from thin biochar- or nanobiochar-based coatings; the extent to which seed coating can suppress disease therefore remains uncertain (Yang et al., 2022), (Iacomino et al., 2022). Moreover, the coating formulation itself may affect germination and seedling development, with higher biochar loadings reducing coating integrity and accelerating coating disintegration (Zhang et al., 2023). Accordingly, this benefit is more appropriately framed as the potential suppression of soil-borne pathogens and biotic stress rather than as generalized pest resistance. Direct pathogen-challenge experiments using nanobiochar-coated seeds are needed before disease suppression can be regarded as an established advantage.

6. Environmental and Agronomic Sustainability Outcomes

6.1 Potential Contribution to Carbon Efficiency and Greenhouse-Gas Mitigation

Biochar is widely recognized for its potential to retain a portion of biomass-derived carbon in a relatively stable form following pyrolysis (Fawzy et al., 2020). An isotope-based meta-analysis estimated the mean residence time of the recalcitrant biochar carbon pool at ~556 years (97% of total carbon), versus ~108 days for the labile pool (3%) (Wang et al., 2015), and a global meta-analysis of 64 studies (736 treatments) found that biochar application increased soil organic carbon stocks by 13.0 Mg ha^{-1} on average (+29%) in field experiments (Groß et al., 2021). Furthermore, soil biochar application can modify greenhouse-gas fluxes, although the direction and magnitude of these responses are strongly condition-dependent. A global meta-analysis of 129 field studies found that biochar application significantly increased soil CH_4 and CO_2 emissions by an average of 15% and 16%, respectively, while decreasing N_2O emissions by 38%, with responses significantly modulated by management strategies, biochar characteristics, and soil properties; overall global warming potential and greenhouse-gas intensity nevertheless decreased by 23% and 41%, and crop yield increased by 21% (Zhang et al., 2020). Earlier syntheses report comparable N_2O reductions (30.9% (He et al., 2016); 16% (Song et al., 2016)) together with variable and often positive CO_2 fluxes, which were suppressed when biochar was added to fertilized soils (He et al., 2016), and the relative contribution of biochar characteristics to emission responses ranged from 29% for N_2O to 71% for CO_2 (Zhang et al., 2020).

However, the carbon-sequestration argument requires substantial qualification when applied to seed coating. Carbon-accounting assessments of biochar are premised on field-scale application rates — with recommended cropland rates commonly on the order of 20–30 t ha^{-1} (Song et al., 2016) — whereas a seed coating deposits only a limited mass of nanobiochar on each seed. Consequently, the direct carbon-storage contribution of a seed coating is negligible relative to bulk soil biochar application, and any accounting that aggregates coating-derived carbon across a hectare would still represent a trivial fraction of the amendment rates at which biochar's sequestration benefits have been quantified (Groß et al., 2021).

Therefore, the more defensible sustainability pathway is indirect. If nanobiochar coating improves nutrient-use efficiency, reduces crop losses, or enhances establishment, it could reduce the quantity of external agricultural inputs required, thereby lowering the emissions embedded in fertilizer and pesticide production, transportation, and application. Within fertilizer granule systems, such input reduction is already documented: replacing urea with biochar-coated urea allowed a 20% nitrogen-rate reduction with no loss of oilseed rape biomass (Jia et al., 2021). These indirect climate benefits should, however, remain hypothetical until demonstrated experimentally for seed-coating systems. It is therefore preferable to frame this subsection as a *potential* contribution to carbon efficiency and greenhouse-gas mitigation, rather than claiming that nanobiochar seed coating itself provides substantial carbon sequestration.

6.2 Potential Reduction in Chemical Fertilizer and Pesticide Dependency

The potential reduction in fertilizer and pesticide requirements represents a particularly relevant sustainability pathway for nanobiochar seed coatings. Biochar has a porous structure and chemically active surfaces that can retain nutrients, and its possible use as a microbial carrier may facilitate simultaneous delivery of nutrients and beneficial microorganisms; reviews of biochar-based seed coatings have identified nutrient delivery, improved plant performance, and microbial inoculant transport as prospective applications (Zhang et al., 2022). In bulk systems, the synergy is real but bounded: a meta-analysis of field studies found that biochar combined with inorganic fertilizer increased yield by 15% relative to fertilizer alone, whereas biochar applied alone did not increase yield (Ye et al., 2019), and a rice-system meta-analysis found that co-applying biochar with synthetic fertilizer increased nitrogen-use efficiency by 35.1% while decreasing nitrogen inputs and improving economic returns (Omidvar et al., 2026).

However, enhanced nutrient availability does not automatically translate into reduced fertilizer requirements. Demonstrating fertilizer substitution requires experiments that evaluate coated seeds under reduced fertilizer rates, compare them with conventional recommendations, and assess nutrient uptake, growth, and final yield. The same principle applies — with an additional complication — to pesticide use. Although bulk biochar is associated with disease-suppressive effects, including an average 47.5% reduction in disease severity and a 44% increase in plant biomass in a global meta-analysis (Yang et al., 2022), and biochar enhances the sorption of many pesticides in soil (Twagirayezu et al., 2024), strong sorption has a dual effect: by reducing pesticide bioavailability, biochar-amended soil can impair herbicide efficacy, requiring higher rather than lower application rates for equivalent weed control (Mohamed et al., 2022). Reduced bioavailability can also slow pesticide degradation and increase persistence (Gámiz et al., 2017). Therefore, such evidence does not demonstrate that fungicide or herbicide applications can be proportionally reduced when biochar-coated seeds are used.

The principal potential advantage of seed coating lies in spatial targeting: the active material is placed in close proximity to the seed and developing root rather than distributed throughout the soil volume, thereby potentially enabling smaller quantities of material to produce localized effects. Nevertheless, reductions in fertilizer and pesticide use should be regarded as downstream and currently unquantified possibilities rather than established outcomes. Field experiments incorporating reduced fertilizer and pesticide treatments are required to determine whether nanobiochar coatings can substitute for conventional inputs without compromising crop yield.

6.3 Economic Viability and Scalability for Farmers

Economic feasibility remains an important but insufficiently investigated aspect of nanobiochar seed coating. Furthermore, costs extend beyond feedstock availability to include pyrolysis, grinding or nanosizing, surface functionalization, nutrient loading, microbial incorporation, binders, coating operations, quality control, and transportation. Plant-scale biochar production costs have been reported at 98–353 US$ t^{-1} depending on facility and region (Maliutina et al., 2023), and nanosizing adds further energy and processing demands: ball-milling conditions (mill type, ball size, speed, duration, medium) must be optimized before cost-effective large-scale production of biochar-based nanomaterials becomes feasible (Yameen et al., 2024), although process design can reduce energy use, as demonstrated for cryogenic pre-conditioning relative to ultrasonic post-treatment (Naghdi et al., 2017).

The macroeconomic evidence is sobering. A systematic assessment of biochar production and use scenarios in six developing and middle-income countries found environmental benefits in all modeled cases but positive net economic benefit only where simple production methods and low labor costs prevailed; gasifier-based systems yielded no profit in any scenario (Owsianiak et al., 2020). Farmer acceptance is an independent constraint — in Western Kenya, farmers remained hesitant to adopt biochar despite maize and sugarcane yield increases of 32%, even with subsidies (Kannan et al., 2024) — and scalability is further limited by feedstock availability, production cost, infrastructure, and quality standards (Ravindiran et al., 2024). Moreover, yield-response data argue for optimal rather than maximal rates: a meta-analysis of field studies found that biochar application rates above 10 t ha^{-1} did not further increase crop yield (Ye et al., 2019).

Seed coating could improve the economics of biochar use because the quantity required per hectare may be substantially lower than that needed for bulk soil amendment, and coating-based delivery also avoids the handling problems of bulk biochar powder (Zhang et al., 2022). However, this potential advantage must be weighed against the additional costs of nanosizing and formulation. Furthermore, commercial scalability will depend on compatibility with existing seed-treatment machinery, storage stability, coating uniformity, and microbial viability. Existing studies demonstrate the technical feasibility of incorporating biochar into seed-coating formulations (Zhang et al., 2023), (Mustafazade et al., 2025), but they also highlight formulation specific responses for example, higher biochar loadings reduce coating integrity, compressive strength, and time to disintegration (Zhang et al., 2023).

Nanobiochar seed coating should therefore not yet be characterized as an economically proven technology for farmers. A meaningful economic assessment should consider the following: cost per treated hectare, coating dose, processing costs, yield benefits, fertilizer and pesticide savings, and comparisons with conventional seed treatments. The absence of field-scale cost–benefit studies remains a major research gap.

Limitations and Future Prospects

Despite its multifunctional potential, nanobiochar seed coating remains an empirically sprouting technology: research on nanobiochar is still in its early stage, with most studies addressing its physicochemical properties and environmental remediation functions rather than seed coating applications (Jiang et al., 2023; Sani et al., 2023). Much of the supporting evidence is therefore derived from bulk soil-applied biochar, from nanobiochar studied in remediation contexts, or from seed-priming experiments based on other nanoparticles, none of which reproduce the thin-film geometry of a seed coating (Chaubey et al., 2024; Nile et al., 2022). Consequently, this limits extrapolation because soil-amendment studies commonly apply biochar at rates on the order of tonnes per hectare (Osman et al., 2022), whereas seed treatments deposit orders of magnitude smaller quantities of active material per unit area. Biochar properties also vary substantially with feedstock, pyrolysis conditions, and nanosizing parameters — including the milling conditions that govern nanobiochar particle size and surface energy — thereby complicating cross-study comparison and formulation standardization (Ippolito et al., 2020; Yameen et al., 2024). The stability, adhesion, and mechanical durability of nanobiochar coatings during storage and mechanized sowing remain insufficiently characterized, even though attrition and dust-off are recognized determinants of coated-seed quality in conventional coating systems (Pedrini et al., 2016), and increasing the biochar fraction in coatings reduces compressive strength and accelerates disintegration (Zhang et al., 2023). Nanosizing further introduces aggregation behavior and environmental mobility that are specific to the nanoscale (Jiang et al., 2023; Zhang, 2025). Finally, although biochar is generally considered beneficial, its effects on non-target soil organisms and the environmental fate of nanoscale particles require further evaluation: nanobiochar can be transported within soil profiles, exert adverse ecotoxicological effects on soil fauna, and facilitate the dispersal of associated contaminants (Zhang, 2025).

Dust-off and abrasion losses from coated seeds are routinely quantified with the Heubach dustmeter, a gravimetric laboratory method widely adopted by pesticide manufacturers and by seed and pesticide industry associations in many countries (Accinelli et al., 2020). In this test, a 500 g subsample of seeds is tumbled at constant speed in a

metal rotating drum and purged with pressurized air for 30 min, and the detached coating fragments captured on a paper filter are weighed and expressed as grams of dust per 100 kg of seeds or per 10,000 seeds (Accinelli et al., 2020). Moreover, across 45 commercial seed lots of seven species (sugar beet, oat, barley, wheat, spelt, pea, and maize), abrasion potential measured by this method varied significantly with species, treatment company, and the number and combination of active ingredients (Zwertvaegher et al., 2016), and the measured dust mass can be converted into an active-ingredient loss per hectare by combining dust release, residue concentration in the dust, and seed rate (Krahner et al., 2021). Two caveats are directly relevant to nanobiochar coatings. First, the Heubach test may underestimate actual dust-drift risk because it incompletely reproduces the mechanical stress of pneumatic metering; supplementing the protocol with surrogate field dust better distinguishes the anti-abrasive properties of different seed treatments (Foqué et al., 2017; Schaafsma et al., 2017). Second, while film coating is known to minimize dust production (Rocha et al., 2019), no published Heubach-based dust-off data exist for biochar- or nanobiochar-coated seeds — a critical knowledge gap, because abraded nanoscale coating fragments would represent a direct release pathway of nanoparticles into the environment during sowing. Quantifying dust-off with the Heubach protocol (or an amended version including field dust) should therefore constitute a mandatory metric in any future formulation study and sustainability assessment of nanobiochar coatings.
Therefore, future studies should prioritize standardized dose–response experiments and direct comparisons among uncoated, bulk-biochar-coated, and nanobiochar-coated seeds under identical conditions, given that both dose and formulation critically determine performance (Rocha et al., 2019; Ye et al., 2019). Field-scale, multi-season, and multi-crop trials are needed to validate localized mechanisms beyond the laboratory and greenhouse settings that currently dominate the biochar literature (Singh et al., 2022). Because nanobiochar exhibits distinct transport behavior in soil, tracer-based studies of particle fate — including interactions with soil biota — should accompany agronomic evaluations (Zhang, 2025). Furthermore, co-formulation with beneficial microorganisms can leverage biochar's established carrier function, which enhances inoculant persistence and root colonization, but requires formulation-specific validation of viability (Bolan et al., 2023; Głodowska et al., 2016). Responsive nutrient-release systems developed for nano-enabled seed treatments and biochar-based controlled-release fertilizers offer templates for tunable coating design (Cidreira et al., 2025; Shelar et al., 2023). Ecotoxicological assessment, life-cycle analysis, and techno-economic modeling which have already revealed large variability in the environmental and economic performance of biochar systems across feedstocks, production methods, and regions should be extended to nanobiochar coatings (Roberts et al., 2009),(Terlouw et al., 2021),(Owsianiak et al., 2020). Thus, nanobiochar seed coating should be considered a mechanistically promising but insufficiently validated strategy, requiring demonstrated agronomic efficacy, environmental safety, and economic viability before large-scale adoption.

CONCLUSION

This review focuses on nanobiochar as a promising platform for multifunctional seed coating, integrating the porous structure, surface functionality, nutrient-retention capacity, and microbial-carrier potential of biochar with the improved reactivity associated with nanosizing. Evidence shows potential benefits for seed establishment, nutrient delivery, stress mitigation, and rhizosphere interactions; however, much of the supporting evidence remains unexplored from bulk biochar applications or other nanoparticle-based seed treatments. Scale-dependent responses, material variability, coating stability, microbial compatibility, environmental fate, and economic feasibility remain sparsly resolved. Therefore, nanobiochar seed coating should be regarded as a mechanistically promising but empirically early-stage technology which requires standardized testing, field validation, safety assessment, and techno-economic evaluation before wider agricultural adoption.

CRediT authorship contribution statement

Podeti Srija: Writing – review & editing, Writing – original draft, Conceptualization. **Raja Kalimuthu:** review & editing, Supervision, Conceptualization. **Kannan Pandian:**Writing – review & editing. **Senthilkumar Murugaiyan:** Writing – review & editing. Writing – review & editing. **D. Ramesh:** Writing – review & editing, Conceptualization. **K Parameswari:** Writing – review & editing, Conceptualization. **Ajay Govindaraj:** Writing – review & editing**. Lokesh Thirumurugan:** review & editing, Conceptualization

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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