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Biochar as a smart carrier for agrochemicals: Controlled release, nutrient use efficiency and environmental risk mitigation

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Abstract

Biochar has evolved from a conventional soil amendment into a multifunctional carrier for the controlled delivery of fertilizers and agrochemicals. Its high surface area, porous architecture, cation exchange capacity and diverse surface functional groups provide opportunities to adsorb, retain and gradually release nutrients and pesticides. This review synthesizes evidence on biochar production, physicochemical properties, surface engineering, composite formulation and controlled-release mechanisms relevant to agronomic applications. Particular attention is given to adsorption-desorption processes and stimuli-responsive release governed by pH, soil moisture, temperature and enzyme activity. The review examines the potential of engineered biochar systems to improve nitrogen, phosphorus, potassium and micronutrient use efficiency while reducing nutrient losses and agrochemical mobility. Evidence from laboratory, soil-column, greenhouse and field studies indicates that surface modification with polymers, zeolites, metal oxides and other complementary materials can extend release periods and improve nutrient recovery. Biochar-based carriers also show promise for reducing pesticide mobility, heavy-metal bioavailability and selected environmental risks. However, variability in feedstock and pyrolysis conditions, limited multi-season field validation, production costs, regulatory uncertainty and the need for standardized performance criteria remain major barriers to large-scale adoption. Emerging opportunities include nano-biochar, multifunctional carriers, precision application and artificial-intelligence-assisted formulation design. Future research should integrate long-term agronomic validation, life-cycle assessment, techno-economic analysis and environmental risk assessment to establish application-specific design criteria. Biochar-based smart carriers therefore represent a promising systems approach for improving resource-use efficiency while supporting sustainable and environmentally responsible crop production.

Keywords: Agrochemicals, biochar, controlled release, nutrient use efficiency, pesticides, smart fertilizers, sustainable agriculture

1. Introduction

Conventional agricultural practices rely heavily on the application of chemical fertilizers and pesticides, yet their efficiency remains disappointingly low, with nutrient losses reaching 40–90% through leaching, volatilization, and fixation (Jayasree and Thomas, 2026) ^[1]. This inefficiency translates into substantial environmental costs, including eutrophication of aquatic ecosystems, greenhouse gas emissions, and soil degradation. Simultaneously, the overuse of agrochemicals poses significant risks to non-target organisms and human health through bioaccumulation and contamination of groundwater and surface waters (Chen *et al.*, 2024) ^[2]. The emerging field of smart agrochemical delivery systems seeks to address these dual challenges by engineering materials that release active ingredients in response to environmental conditions, thereby synchronizing nutrient availability with crop demand and minimizing unintended environmental fate of applied chemicals (Hou *et al.*, 2021) ^[3].

Among the diverse materials investigated for controlled-release applications, biochar a carbon-rich, porous material produced from the pyrolysis of biomass has emerged as a particularly promising platform (Sashidhar *et al.*, 2020) ^[4]. Unlike synthetic polymers or expensive inorganic carriers, biochar can be sustainably produced from agricultural residues at relatively low cost,

while simultaneously sequestering carbon and improving soil properties. Recent advances in biochar engineering and surface modification have transformed this material from a simple soil amendment into a sophisticated smart delivery platform capable of tailoring the spatiotemporal release of nutrients, pesticides, and other agrochemicals (Hassan *et al.*, 2024) ^[5]. This transformation aligns with the circular bioeconomy paradigm, wherein agricultural waste is valorized into high-performance materials for sustainable agriculture (Flores-Céspedes and García-Fuentes, 2026) ^[6].

The rationale for biochar-based agrochemical carriers is multifaceted. First, biochar possesses inherent properties high surface area, porosity, and tunable functional groups that enable strong and reversible interactions with a wide spectrum of organic and inorganic compounds (Bahia, 2022) ^[7]. Second, biochar can be engineered through post-treatment strategies such as chemical modification, coating with biopolymers or synthetic polymers, or assembly with complementary materials (e.g., zeolites, metal oxides) to achieve stimuli-responsive release kinetics (Sun and Liang, 2026) ^[8]. Third, beyond its role as a carrier, biochar itself confers agronomic and environmental benefits, including improved soil water retention, enhanced cation exchange capacity, and reduced leaching of contaminants (Sarraf *et al.*, 2024) ^[9]. This multifunctionality positions biochar-based systems as integrative solutions that simultaneously optimize agrochemical efficacy, enhance nutrient use efficiency, and mitigate environmental risks three imperatives for future global food security and environmental stewardship.

2. Biochar production, properties and engineering for agrochemical delivery

2.1 Production methods and physicochemical properties

Biochar is conventionally produced through pyrolysis the thermochemical decomposition of biomass in the absence of oxygen at temperatures typically ranging from 300 °C to 900 °C. The choice of feedstock and pyrolysis conditions profoundly influences the resulting biochar's physical and chemical properties, which in turn determine its suitability for specific applications (Neogi *et al.*, 2022) ^[10]. Agricultural residues such as rice straw, corn stalk, sugarcane bagasse, and wood-based materials have been extensively evaluated as biochar feedstocks, each offering distinct advantages and trade-offs (Flores-Céspedes and García-Fuentes, 2026) ^[6]. For instance, silica-rich biochars derived from rice straw exhibit high surface area and tunable dissolution kinetics that facilitate controlled-release applications, whereas lignin-derived biochars from forestry residues provide enhanced aromatic carbon structures beneficial for contaminant adsorption (Nguyen, 2021) ^[11].

Pyrolysis temperature exerts a critical controlling influence on biochar properties. Lower temperatures (300–400 °C) yield biochar with higher oxygen-containing functional groups (carboxyl, hydroxyl, phenolic) and smaller pore sizes, favoring ion exchange and chemical interactions (Chen *et al.*, 2024) ^[2]. Intermediate temperatures (500–600 °C) optimize the balance between surface area and functional group density, with surface areas typically ranging from 200–500 m²/g (Prasiefa and Zullaikah, 2025) ^[12]. Higher temperatures (>700 °C) produce biochar with larger specific surface areas (up to 480 m²/g for catalytically synthesized variants) but reduced oxygen functionality, shifting the adsorption mechanism toward π - π interactions and hydrophobic partitioning (Zangeneh *et al.*, 2026) ^[13]. The activation of biochar either physical (via steam or CO₂) or chemical (using KOH or H₃PO₄) further enhances

porosity and surface area, with some activated preparations reaching 600+ m²/g (Chiam *et al.*, 2020) ^[14].

For agrochemical delivery applications, the critical physicochemical parameters include: (1) specific surface area, determining the number of available adsorption sites; (2) pore size distribution, influencing the size and kinetics of molecules that can be sorbed and released; (3) cation exchange capacity (CEC), reflecting the abundance of negatively charged sites for nutrient retention; (4) functional group composition, governing the strength and selectivity of sorption; and (5) hydrophobicity or hydrophilicity, affecting interactions with both hydrophobic organic agrochemicals and hydrophilic nutrients (Sashidhar *et al.*, 2020) ^[4]. Biochar with larger macropores (>50 nm) facilitates rapid molecular transport and release, whereas biochar rich in micropores (<2 nm) provides high surface area but may slow release kinetics through prolonged diffusional resistance (Yang *et al.*, 2025) ^[15].

2.2 Surface modification and functionalization strategies

Pristine biochar, while capable of adsorbing agrochemicals, often exhibits suboptimal release kinetics either too rapid, failing to achieve meaningful slow-release behavior, or too slow, restricting nutrient availability during critical crop growth stages. Consequently, diverse modification strategies have been developed to tailor biochar properties for specific agrochemical applications (Hassan *et al.*, 2024) ^[5].

Chemical modification represents one of the most direct approaches. Acid treatment with phosphoric acid (H₃PO₄) or nitric acid (HNO₃) oxidizes the biochar surface, increasing oxygen-containing functional groups and enhancing both nutrient adsorption and release kinetics (Ashesh and Devi, 2022) ^[16]. Alkaline treatment with potassium hydroxide (KOH) increases pH and surface charge density, facilitating cation exchange for nutrients like ammonium and potassium (Dong *et al.*, 2026) ^[17]. More sophisticated approaches include the grafting of specific functional groups for example, chitosan-modified biochar (ZBC@CS) with enhanced macropore evolution and increased amine groups (-NH₂) for improved urea sorption, achieving 144.54 mg/g adsorption capacity (Wei *et al.*, 2026) ^[18].

Metal or metal oxide loading onto biochar surface dramatically enhances its reactivity and sorption capacity. Iron-based modifications are particularly popular: iron oxide nanoparticles on biochar accelerate the reduction of mobile contaminants and enhance the formation of stable heavy metal precipitates (Wang *et al.*, 2025) ^[19]. Manganese oxide loading improves biochar's redox activity, enhancing its capacity for simultaneous denitrification and contaminant removal (Cheng *et al.*, 2026) ^[20]. Magnesium-enriched biochar (MBF), synthesized via pyrolysis of MgCl₂-enriched biomass, achieves slow-release performance of N and P approximately 6–7 times superior to conventional fertilizers, with release controlled by both low-solubility MgP precipitate formation and the "P-trap" effect of MgO (Luo *et al.*, 2021) ^[21].

Composite assembly with complementary materials yields synergistic enhancements in agrochemical delivery. Zeolite-biochar composites leverage zeolite's high ion exchange affinity for ammonium while maintaining biochar's physical barrier properties, resulting in nitrogen use efficiencies (ANUE: 14.08 kg/kg, NRE: 25.32%) that exceed standalone amendments by 18–101% (Dong *et al.*, 2026) ^[17]. Biochar-clay composites (kaolin-infused) further improve slow-release performance through the formation of layered structures that modulate diffusion pathways (Dong *et al.*, 2026) ^[17].

Polymer coating provides an additional layer of release control, acting as a physical diffusion barrier that delays nutrient or agrochemical egress. Starch-based coatings are particularly attractive due to their biodegradability, cost-effectiveness, and demonstrated ability to slow nutrient release while maintaining synchrony with crop demand (Dong *et al.*, 2026) ^[17]. A pinecone biochar coated with cellulose acetate (PBUA formulation) achieved cumulative urea release of only 4.37% within 24 hours and 55.63% after 28 days, conforming to national slow-release fertilizer standards (Yang *et al.*, 2025) ^[15]. Polyvinyl alcohol (PVA) and polyvinyl acetate coatings provide even more pronounced diffusion barriers, with some formulations achieving release kinetics extending over 5–6 months.

Multi-responsive coatings, engineered to release agrochemicals in response to multiple environmental stimuli (pH, moisture, temperature, enzyme activity), represent the frontier of intelligent delivery design. A Ca-alginate/poly(N-isopropylacrylamide) polydopamine (Ca-alginate/PNIPAm@PDA) microsystem exhibited superior pH- and temperature-sensitive release behavior while maintaining effective water retention capacity (Zheng *et al.*, 2020) ^[22]. Similarly, redox- and enzyme-responsive microspheres assembled from zeolite and ferrocenecarboxylic acid-modified carboxymethyl cellulose achieved 80.4–85.2% release of model agrochemical (salicylic acid) in the presence of cellulase or hydrogen peroxide, substantially exceeding control release in water (12.6%) (Hou *et al.*, 2021) ^[3].

2.3 Characterization techniques for performance prediction

Successful deployment of biochar-based agrochemical carriers requires comprehensive characterization linking physicochemical properties to functional performance. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) reveal biochar's internal pore architecture, surface morphology, and degree of coating uniformity. Brunauer-Emmett-Teller (BET) analysis quantifies specific surface area and pore size distribution, providing critical input for diffusion modeling. Fourier-transform infrared spectroscopy (FTIR) identifies functional groups carboxyl, hydroxyl, phenolic, amine and confirms successful surface modification. X-ray diffraction (XRD) characterizes crystalline phases, particularly important for biochar composites containing metal oxides or zeolite. Thermogravimetric analysis (TGA) assesses thermal stability and decomposition profiles, essential for predicting biochar behavior under field conditions involving temperature fluctuations.

For agrochemical delivery specifically, batch adsorption experiments followed by kinetic modeling (Langmuir, Freundlich, Temkin isotherms; pseudo-first-order, pseudo-second-order kinetic models) quantify sorption capacity and mechanistic insights (Wei *et al.*, 2026) ^[18]. Column leaching experiments simulate more realistic field soil conditions, revealing cumulative release patterns and the influence of soil matrix properties on agrochemical bioavailability (Dong *et al.*, 2026) ^[17]. Phytotoxicity assays and greenhouse/field trials ultimately validate the agronomic functionality of biochar carriers, ensuring that slow-release formulations maintain efficacy compared to conventional direct application (da Silva *et al.*, 2025) ^[23].

3. Controlled-release mechanisms and technologies

3.1 Adsorption and desorption fundamentals

The controlled release of agrochemicals from biochar carriers fundamentally depends on understanding and optimizing the

adsorption-desorption equilibrium and kinetics. Adsorption of organic agrochemicals (pesticides, herbicides) to biochar occurs primarily through non-polar interactions: π - π interactions between aromatic carbon structures and agrochemical aromatic rings; hydrophobic partitioning into the lipophilic biochar matrix; hydrogen bonding with surface oxygenated functional groups; and pore filling, where molecules occupy the inner volume of biochar pores (Bahia, 2022) ^[7]. The dominant mechanism varies with agrochemical properties: highly hydrophobic compounds (e.g., polycyclic aromatic hydrocarbons, PAHs) favor hydrophobic partitioning and π - π interactions, while polar agrochemicals (e.g., triazine herbicides) preferentially interact via hydrogen bonding and electrostatic attraction to oxygenated functional groups (Sun and Liang, 2026) ^[8].

For nutrients and inorganic agrochemicals, ion exchange mechanisms dominate. Biochar's negatively charged functional groups (carboxylate, phenolate) retain cationic nutrients (NH_4^+ , K^+ , Ca^{2+} , Mg^{2+}) through electrostatic attraction, while some biochar preparations possess limited anion exchange capacity for phosphate and nitrate (Luo *et al.*, 2021) ^[21]. The kinetics of adsorption typically follows a pseudo-first- or pseudo-second-order model, with rapid initial sorption (often within 24–72 hours for batch experiments) followed by slow approach to equilibrium (Wei *et al.*, 2026) ^[18].

Desorption the release of sorbed agrochemicals from biochar occurs when environmental conditions favor reversal of adsorption interactions. In soil environments, water infiltration and solubilization drive desorption, while competitive sorption with other soil organic matter can accelerate agrochemical release (Liu *et al.*, 2023) ^[24]. For coated biochar carriers, desorption kinetics are governed not only by the strength of adsorption to the biochar core but also by water permeation through the coating matrix, creating the phenomenon of "diffusion-limited release" wherein the coating itself becomes the rate-limiting step (Dong *et al.*, 2026) ^[17]. This distinction is particularly important: uncoated biochar typically releases sorbed nutrients within 7 days (>80% cumulative release), whereas starch-coated biochar-based carriers may extend the release window to 4–8 weeks, dramatically altering the synchrony between nutrient supply and crop demand (Dong *et al.*, 2026) ^[17].

3.2 Stimuli-responsive release systems

Beyond passive physical barriers, engineered biochar carriers can respond dynamically to environmental stimuli, triggering agrochemical release when specific conditions are met. pH-responsive release is particularly valuable because soil pH varies with soil type, microbial activity, and depth, creating microenvironments where pH-sensitive carriers activate at ecologically relevant conditions. A quinclorac herbicide-loaded biochar carrier (280CPFe) exhibited differential release rates of 21%, 56%, and 90% at initial pH values of 3, 5, and 11 respectively, demonstrating clear pH-dependence and potential for reduced leaching in neutral to slightly basic soils (Chen *et al.*, 2024) ^[2]. The mechanism involves protonation or deprotonation of surface functional groups, altering electrostatic interactions with sorbed molecules.

Moisture-responsive release exploits the fact that water ingress into biochar pores facilitates desorption and diffusion. Urea-impregnated biochar loaded with hydroxyapatite (U-HAP) exhibited moisture-dependent release: at 30% soil moisture, the nitrate concentration improved by 198% relative to control, whereas at 80% moisture, the improvement reached 224%,

demonstrating the critical role of soil water content in governing release kinetics (Gao *et al.*, 2025) ^[25]. This responsiveness allows agrochemical availability to track soil water status, delivering nutrients when water availability is sufficient for root absorption and reducing release during drought stress when nutrient uptake is minimal.

Temperature-responsive release capitalizes on the temperature-dependent solubility of agrochemicals and the thermal sensitivity of polymer coatings. Poly (N-isopropylacrylamide) (PNIPAm)-based coatings exhibit a sharp volume phase transition at their lower critical solution temperature (LCST), typically around 32 °C. Below this temperature, the polymer is hydrophilic and swollen, restricting agrochemical diffusion; above it, the polymer becomes hydrophobic and collapsed, accelerating release (Zheng *et al.*, 2020) ^[22]. While soil temperatures typically remain relatively stable, diurnal and seasonal variations provide opportunities to tailor release kinetics to growth stage-specific demands.

Enzyme-responsive release represents a sophisticated approach leveraging soil microbial metabolism. Biochar carriers assembled with enzymolytic linkages or enzymatically degradable polymers release sorbed agrochemicals in the presence of soil enzymes (cellulase, protease, lipase) produced by soil microorganisms and plant root systems (Hou *et al.*, 2021) ^[3]. This mechanism offers potential for rhizosphere-specific delivery: enzymes concentrated in the rhizosphere can trigger localized release near active root zones, reducing loss to bulk soil and enhancing nutrient acquisition efficiency.

3.3 Kinetic modelling and optimization

The successful translation of biochar-based carriers from laboratory formulations to field-scale implementation requires quantitative kinetic models linking release profiles to agronomic and environmental outcomes. Release kinetics are typically fit to several standard models. The Weibull model (originally developed for materials science) has emerged as particularly effective for biochar-based slow-release systems, characterizing the cumulative release fraction as a function of time with parameters reflecting shape (distribution) and scale (release rate) (Wei *et al.*, 2026) ^[18]. The Higuchi model describes diffusion-controlled release assuming square-root kinetics, applicable when a coating acts as the sole diffusion barrier (Dong *et al.*, 2026) ^[17]. The Korsmeyer-Peppas model provides a dimensionless exponent (n) distinguishing diffusion-controlled ($n \leq 0.5$) from polymer erosion-controlled ($n \geq 1.0$) release mechanisms (Maghsoodi *et al.*, 2020) ^[26].

Advanced characterization now employs artificial neural networks (ANN) to predict release kinetics from biochar properties and environmental conditions. An ANN model for nitrate release from MgFe-LDH@BC composites achieved $R^2 > 0.97$, enabling predictive estimation of release rates under varied temperature, pH, and soil moisture conditions without exhaustive experimental characterization of each combination (Gao *et al.*, 2025) ^[25]. This computational approach accelerates the design of optimized formulations and reduces the experimental burden required for field validation.

4. Nutrient use efficiency enhancement through biochar-based carriers

4.1 Nitrogen dynamics and recovery efficiency

Nitrogen (N) represents the most limited nutrient in many agricultural systems globally, with conventional urea fertilizers exhibiting recovery efficiencies often below 30–40% in field conditions. Biochar-based slow-release formulations

dramatically improve N use efficiency by synchronizing supply with crop demand and reducing loss pathways (leaching, volatilization, denitrification). A starch-coated zeolite-biochar composite fertilizer (SC-ZEO/BCF) applied to rice in saline-alkaline soils achieved nitrogen recovery efficiency (NRE) of 25.32%, exceeding conventional NPK by 270% and substantially surpassing other slow-release formulations (Dong *et al.*, 2026) ^[17]. The mechanism involves multiple synergistic pathways: zeolite's high cation exchange capacity sequesters ammonium (NH_4^+) through electrostatic adsorption, reducing volatilization losses; biochar's porosity and functional groups enhance secondary retention and slow diffusion-based release; and the starch coating acts as a physical barrier, further delaying nutrient egress and synchronizing release with rice growth stages (tillering, panicle differentiation, grain filling) (Dong *et al.*, 2026) ^[17]. Urea-impregnated biochar formulations (UB, UH, UZ with hydroxyapatite) reduced urea release by 4.5–11.5 times compared to urea alone in soil columns (Maghsoodi *et al.*, 2020) ^[26]. In paddy soil experiments, 20 days after application, 76.5–89.9% of applied urea remained unhydrolyzed in the UB, UZ, and U-HAP treatments versus >85% conversion to NH_4^+ in urea-alone controls, demonstrating the critical role of carrier matrix in retarding microbial urea hydrolysis. Critically, the kinetics of extractable NH_4^+ formation showed that after peak concentrations, the biochar-based formulations maintained substantially higher NH_4^+ levels over extended periods (>70 days), implying prolonged nutrient availability throughout the growing season (Maghsoodi *et al.*, 2020) ^[26].

Chitosan-modified biochar slow-release urea fertilizers (ZBC@CS-BUF) exhibited superior mechanical properties (maximum compressive stress 1277.98 N), enabling practical field application, while achieving cumulative urea nitrogen release of only 56.3% within 72 hours with an overall nutrient release cycle 5.5 times longer than pure urea (Wei *et al.*, 2026) ^[18]. These formulations significantly promoted wheat seedling growth in pot experiments, indicating agronomic functionality coupled with extended availability.

4.2 Phosphorus retention and bioavailability

Phosphorus (P) faces unique challenges in agriculture: rapid fixation onto soil mineral surfaces (particularly iron and aluminum oxides in acidic soils and calcium in alkaline soils) renders applied P largely unavailable to plants within days of application. Biochar's capacity to reduce P fixation while slowly releasing this nutrient could revolutionize P-limited agricultural systems, particularly in developing regions where synthetic P fertilizer remains expensive or unavailable. The mechanisms underlying biochar's P-sparing effects involve multiple pathways: direct adsorption of phosphate on biochar surfaces; competitive blocking of P fixation sites on soil minerals; enhancement of mycorrhizal colonization, which facilitates P acquisition; and in engineered biochar, deliberate incorporation of P-retaining phases like magnesium phosphates (Chiam *et al.*, 2020) ^[14]. Magnesium-enriched biochar (MBF), where phosphorus is converted to low-solubility MgP precipitates on the biochar surface, combined with the "P-trap" effect of MgO through PO_4^{3-} re-precipitation, achieved final P accumulative release ratios 6 times lower than chemical fertilizer (Luo *et al.*, 2021) ^[21]. In greenhouse trials, MBF significantly enhanced corn growth and nutrient uptake efficiency compared to conventional fertilizers. Soil column experiments with starch-coated zeolite-biochar fertilizers revealed enhanced phosphate availability at critical growth stages: during tillering, SC-ZEO/BCF provided 14.88 mg/kg available phosphate (significantly higher than

ZEO/BCF), whereas at maturity, available phosphate rebounded to 18.89 mg/kg, indicating the starch coating's success in delaying release to match late-season P demand for grain filling (Dong *et al.*, 2026) ^[17].

4.3 Potassium and micronutrient dynamics

Potassium (K), essential for turgor maintenance, photosynthesis regulation, and translocation of photoassimilates, frequently becomes limiting in intensive agriculture. Biochar-zeolite composites enhance K retention through both ion exchange on biochar surfaces and within zeolite's crystalline framework. At tillering stage, BCF demonstrated higher available potassium than NPK treatment, reflecting good K retention by biochar; however, limited supply capacity emerged in later growth stages, indicating that zeolite addition further improves mid- to late-season K availability (Dong *et al.*, 2026) ^[17]. Biochar-NPK fertilizers, optimized through central composite design experiments, achieved nutrient contents of 4.20% N, 7.57% P, and 7.01% K with particle sizes averaging 2117.2 nm, suggesting potential for controlled-release formulation development (Chiam *et al.*, 2020) ^[14].

Beyond macronutrients, biochar's rich diversity of surface functional groups and sorption capabilities extend to micronutrients (iron, zinc, manganese, copper) and rare earth elements, opening possibilities for precision micronutrient delivery to address hidden hunger in global agriculture (Djafaripetroudy *et al.*, 2025) ^[27].

4.4 Field-scale agronomic outcomes

Laboratory demonstrations of enhanced nutrient use efficiency must translate to meaningful crop yield gains under real-world field conditions. Field trials of SC-ZEO/BCF in saline-alkaline rice paddies revealed yield improvements of 22.14% (from 6.02 t/ha with conventional NPK to 7.35 t/ha with SC-ZEO/BCF) despite maintaining a 10% lower fertilizer input (Dong *et al.*, 2026). Yield components (grains per panicle, 1000-grain weight) all favored SC-ZEO/BCF, with 1000-grain weight reaching 17.09 g versus 16.22 g for conventional NPK (Dong *et al.*, 2026) ^[17]. These gains reflect not only improved nitrogen availability but also enhanced water retention and soil structural stability imparted by the biochar-zeolite core, critical in stress environments (Dong *et al.*, 2026) ^[17].

Agronomic nitrogen use efficiency (ANUE, reflecting the amount of grain produced per unit of applied N) reached 14.08 kg/kg under SC-ZEO/BCF dramatically exceeding conventional fertilizers and validating the synergistic design of the composite carrier. When combined with smart drone-enabled variable-rate application, net field-scale profits increased by 597 \$/ha compared to conventional uniform application, demonstrating both agronomic and economic viability (Dong *et al.*, 2026) ^[17].

5. Environmental risk mitigation through biochar-based agrochemical carriers

5.1 Heavy-metal immobilization and reduced plant uptake

Heavy metal contamination in agricultural soils poses severe risks to food safety and ecosystem integrity. Iron-modified biochar (FeBC), particularly goethite-modified variants (GBC), substantially reduced soil cadmium (Cd) bioavailability (by 80.4% for rice grains) while simultaneously reducing CH₄ emissions (26.3% reduction) and suppressing methane-related genes (22.7% reduction in *mcrA* gene relative abundance) (Wang *et al.*, 2025) ^[19]. The mechanism involves enhanced iron plaque [FeO(OH)] formation on root surfaces, creating a barrier to metal uptake. A field demonstration of biochar amendment

(20 t/ha) combined with calcium superphosphate (2 t/ha) in mining-contaminated soil reduced available Cd and Pb by 70% and 85%, respectively, within one year, enabling safe cultivation of vegetables with hazard quotients below threshold values (Wang *et al.*, 2019) ^[33]. The cost of this comprehensive remediation (\$3885 ha⁻¹) proved economically feasible relative to the value of reclaimed agricultural land.

Cadmium-contaminated rice paddies treated with biochar demonstrated consistent reductions in grain Cd concentration, with mechanisms including direct sorption onto biochar, formation of stable Cd-biochar surface complexes, and reduced microbial mobilization of Cd (Sarraf *et al.*, 2024) ^[9]. Biochar's abundant functional groups (carboxyl, phenolic hydroxyl) form inner-sphere complexes with heavy metals, rendering them kinetically inert and thermodynamically immobilized (Sashidhar *et al.*, 2020) ^[4].

5.2 Pesticide and herbicide retention

Global pesticide consumption exceeds 4 billion pounds annually, with a substantial fraction reaching non-target environments through leaching, runoff, and volatilization, causing aquatic ecosystem contamination and triggering endocrine disruption in non-target organisms (Sun and Liang, 2026) ^[8]. Biochar's exceptional capacity to adsorb organic agrochemicals offers a powerful tool for reducing agrochemical environmental fate and enhancing utilization efficiency. Biochar prepared at 600 °C demonstrated maximum adsorption capacities for triazine herbicides (prometryn, atrazine, simazine) of 120–180 mg/g, with adsorption following Freundlich kinetics ($n < 1$), indicating saturation of high-affinity sites at elevated concentrations (Liu *et al.*, 2023) ^[24]. Importantly, biochar addition to soil significantly accelerated herbicide degradation: half-lives for atrazine decreased from 5.2–8.1 days in unamended soil to 3–5 days with biochar, suggesting biochar-facilitated interactions with soil microorganisms (Liu *et al.*, 2023) ^[24].

A pH-responsive biochar carrier (280CPFe) engineered for quinclorac herbicide exhibited 153.59 mg/g adsorption capacity and pH-dependent release: 21% release at pH 3, 56% at pH 5, and 90% at pH 11 (Chen *et al.*, 2024) ^[2]. This pH-tuning creates microenvironments in the rhizosphere and bulk soil where herbicide release can be modulated, reducing leaching losses in neutral soils while enabling release under acidic stress conditions. Field trials confirmed herbicidal efficacy (weed control against Barnyard grass) comparable to direct herbicide application without phytotoxic effects on rice, validating practical agronomic utility.

Triazine herbicide-contaminated soils amended with biochar exhibited reduced herbicide mobility, with partition coefficients (*K_d*) increasing from 1.14–1.91 in unamended soil to 30.92–50.74 with 10% biochar amendment, representing >20-fold increases in herbicide retention (Stojanov *et al.*, 2021) ^[29]. This retention persists sufficiently long for soil microbes to degrade herbicides, reducing long-term environmental residues while maintaining pesticide efficacy during the growing season.

5.3 Nitrogen leaching reduction and greenhouse-gas mitigation

Nitrogen losses from agricultural soils occur through multiple pathways: leaching of nitrate-nitrogen into groundwater, volatilization of ammonia to the atmosphere, and denitrification of nitrate to N₂O (a potent greenhouse gas) and N₂. Each pathway carries environmental consequences ranging from eutrophication to climate change acceleration. Biochar-based

slow-release nitrogen fertilizers substantially reduce all three loss pathways. Soil column leaching experiments demonstrated that conventional NPK fertilizer released 84.61% of applied nitrogen within 7 days with continued rapid release, whereas starch-coated biochar-zeolite composites released only 61.84% in the same timeframe (Dong *et al.*, 2026) ^[17]. Cumulative nitrate leaching from MgFe-LDH@BC composites was 198–224% higher than control at 30–80% soil moisture, demonstrating moisture-responsive slow-release that matches soil water availability (Gao *et al.*, 2025) ^[25].

Critically, biochar amendment reduces denitrification losses and associated N₂O emissions. Goethite-modified biochar (GBC) suppressed relative N₂O emissions by reducing the *mcrA* gene (methane monooxygenase oxidoreductase, involved in N₂O production pathways) abundance by 22.7%, ultimately achieving 26.3% reduction in CH₄ emissions (Wang *et al.*, 2025) ^[19]. The mechanistic basis involves biochar's capacity to stabilize reactive nitrogen species and inhibit dissimilatory nitrate reduction-associated pathways in soil microbiota (Cheng *et al.*, 2026) ^[20].

5.4 Microplastic and emerging-contaminant mitigation

Microplastics (MPs) fragments of degraded plastics and microbeads from consumer products have emerged as ubiquitous environmental contaminants accumulating in soils at concentrations reaching 10⁶ particles kg⁻¹ (Upadhyay, 2026) ^[30]. Beyond direct physical effects, MPs act as vectors for sorbed contaminants including heavy metals and organic pollutants, creating combined exposure risks. Biochar's multifunctional pore structure and large surface area enable comprehensive MP removal: adsorption through π - π interactions and hydrophobic partitioning, physical filtration through pore interception, and biodegradation facilitation through biofilm development on biochar surfaces (Luo *et al.*, 2026) ^[31]. Reported MP removal efficiency by biochar exceeds 90%, with biochar simultaneously mitigating greenhouse gas emissions (CO₂, N₂O) generated by MP-induced microbial processes (Li *et al.*, 2024) ^[32].

Coexistence of MPs and heavy metals in soil environments generates complex pollution scenarios. Polystyrene microplastics (PS) coexisting with biochar paradoxically enhanced Cd adsorption at smaller particle sizes (10–20 μ m), attributed to increased interfacial area and electrostatic heterogeneity, whereas larger PS particles (30 μ m) inhibited Cd adsorption (Wang *et al.*, 2024) ^[33]. This particle size-dependent behaviour underscores the need for tailored biochar designs accommodating real-world mixed contamination scenarios.

Beyond legacy pollutants, biochar effectively removes emerging contaminants including antibiotics, per- and polyfluoroalkyl substances (PFAS), and brominated flame retardants. Biochar-supported nanoscale zero-valent iron (BC-nZVI) reduced intracellular antibiotic resistance genes (iARGs) by 30.58–16.69% and extracellular ARGs (eARGs) by 95.09–3.65%, preventing horizontal gene transfer and reducing antibiotic resistance dissemination in food waste anaerobic digestion (Chen *et al.*, 2025) ^[34]. PFAS adsorption by biochar-zeolite-iron oxide amendments in stormwater infiltration basins significantly improved attenuation compared to native soils, with mechanisms involving electrostatic interactions and hydrophobic partitioning (Barua, 2024) ^[35].

6. Challenges, future directions and recommendations

6.1 Standardization and long-term field validation

Despite substantial laboratory and greenhouse evidence supporting biochar-based agrochemical carriers, several

significant challenges impede commercial deployment and regulatory acceptance. Lack of standardization remains a primary obstacle: biochar production parameters vary widely (feedstock type, pyrolysis temperature, heating rate, residence time), generating materials with highly heterogeneous properties from nominally identical source materials (Ayaz *et al.*, 2025) ^[36]. This variability necessitates either strict feedstock and process standardization economically challenging for decentralized biochar production or flexible specification of functional properties rather than production parameters.

Long-term field validation is critical but logistically demanding. Most published trials span single growing seasons; multi-year field data accounting for biochar aging (physical, chemical, and biological degradation), changes in soil conditions, and variation in climate are largely lacking (Yang *et al.*, 2024) ^[37]. Biochar aging can reduce its adsorption capacity for agrochemicals over time: hydrophobic aging (loss of surface functional groups) and chemical aging (oxidation of reactive carbon sites) both reduce nutrient retention and slow-release capacity. Biological aging, driven by microbial colonization and metabolism within biochar pores, can either enhance (through formation of stabilized organic matter) or impair (through microbial mobilization of sorbed species) functionality depending on environmental context (Yang *et al.*, 2024) ^[37]. Rigorous multi-year trials across diverse agroecological zones and soil types would substantiate recommendations for biochar carrier application under real-world variability.

6.2 Economic feasibility and scalability

While biochar-based fertilizers typically exhibit improved nutrient use efficiency and reduced environmental impact per unit applied, their capital and operational costs must be competitive with incumbent fertilizer formulations for market adoption (Dong *et al.*, 2026) ^[17]. The SC-ZEO/BCF composite fertilizer, despite demonstrating superior agronomic and environmental performance, adds measurable cost due to zeolite procurement, starch coating application, and granulation infrastructure. Field economic analysis showed that smart drone-enabled variable-rate application of SC-ZEO/BCF (reducing application rates by 10% while maintaining yield) recovered costs through reduced fertilizer expenditure (\$112.04 ha⁻¹ savings) and labor cost reduction (\$387.11 ha⁻¹), yielding net profit of 597 \$/ha versus losses with conventional application (Dong *et al.*, 2026) ^[17]. However, this economic viability depends on relatively high crop values (rice in industrialized systems) and access to precision application technology conditions not universally available in developing agricultural regions where nutrient efficiency gains are most critical.

Scalability presents another barrier: current biochar production occurs primarily at small to medium scales (<10,000 t year⁻¹), insufficient to supply global demand if biochar-based fertilizers were to achieve even modest market penetration (>5% of fertilizer consumption). Scaling biochar production to utility-scale operations (millions of tons annually) while maintaining quality control and avoiding unintended environmental consequences of large-scale biomass mobilization requires substantial research and infrastructure investment. Co-location of biochar production with agricultural and industrial biomass utilization sites, district-scale pyrolysis infrastructure, and integration with existing fertilizer manufacturing facilities offer potential scalability pathways.

6.3 Regulatory and policy framework development

Regulatory pathways for biochar-based fertilizers remain

uncertain in most jurisdictions. While biochar itself is increasingly recognized as a safe soil amendment (EU Fertilizing Products Regulation recognizes biochar as a constituent material), the specific requirements for slow-release fertilizer registration vary by country and are sometimes contradictory. Some regulatory bodies require extensive ecotoxicity data; others demand proof of consistent nutrient release; still others impose restrictions on polymer coatings or additive contents. Harmonization of international standards for slow-release biochar-based fertilizers would facilitate market development and ensure environmental safety across borders. Policy incentives driving biochar adoption remain limited. While some jurisdictions (e.g., EU under its circular economy action plan, some US states) offer incentive payments for biochar production and application as a climate change mitigation strategy (carbon sequestration), most agricultural policies provide no support for biochar-based fertilizers relative to conventional alternatives. Incorporation of biochar-based slow-release fertilizers into subsidy structures, particularly in developing countries, could accelerate adoption where nutrient use efficiency is most critical for food security (Neogi *et al.*, 2022) ^[10].

6.4 Emerging frontiers: nanotechnology and AI-driven optimization

Nano-biochar and nanocomposite biochar platforms represent emerging directions that could overcome current performance limitations. Nano-sized biochar particles (10–100 nm) exhibit dramatically increased specific surface area, enhanced diffusion kinetics, and potential for targeted delivery to specific soil compartments or plant root zones (Pathak *et al.*, 2024) ^[38]. However, nano-biochar introduces novel environmental risk questions: potential for atmospheric mobility, accumulation in non-target organisms, and interaction with soil colloids require comprehensive ecotoxicological assessment before large-scale deployment (Virú-Vásquez *et al.*, 2025) ^[39].

Artificial intelligence and machine learning offer transformative potential for accelerating biochar design optimization. Quantitative structure-activity relationship (QSAR) models trained on existing biochar performance data could predict optimal feedstock-temperature-modification combinations for specific agrochemicals without exhaustive experimentation (Mu'azu and Abubakar, 2025) ^[40]. AI-driven inverse design could identify novel surface modifications or coating materials achieving desired release kinetics. Integration of AI-based optimization with high-throughput experimental platforms could dramatically compress development timelines from years to months, enabling rapid iteration toward commercially viable formulations.

Multi-functional biochar systems engineered to simultaneously deliver multiple agrochemicals (N, P, K, micronutrients, plant growth regulators, biocontrol agents) represent a promising integrated approach, reducing application frequency and improving farmer acceptance (Bauer *et al.*, 2025) ^[41]. Metal-organic frameworks (MOFs) assembled on biochar surfaces could provide highly selective delivery of specific species while maintaining the agronomic soil amendment benefits of the biochar carrier (Bauer *et al.*, 2025) ^[41].

6.5 Recommendations for stakeholders

For researchers: Priority should be given to multi-year field trials across diverse agroecologies and soil types, emphasizing biochar aging dynamics and long-term performance under real-world variability. Integration of biochar-based carriers with

precision agriculture technologies (drones, variable-rate applicators, remote sensing) and AI-driven optimization warrants substantial investment. Comprehensive life-cycle assessment (LCA) and techno-economic analysis frameworks comparing biochar-based systems with conventional alternatives on a standardized basis would facilitate peer comparison and regulatory advancement.

For policymakers: Development of harmonized international standards for biochar-based slow-release fertilizers, with aligned regulatory pathways across major agricultural trading blocs, would substantially reduce commercialization barriers. Integration of biochar-based fertilizer incentives into agricultural subsidy structures, carbon pricing schemes, and circular economy support programs would accelerate farmer adoption. Support for establishment of district-scale biochar production and formulation infrastructure, particularly in developing countries, would address scalability barriers while creating rural employment.

For agricultural industry: Investment in demonstration farms and farmer training programs illustrating biochar-based carrier functionality under real-world conditions would build confidence and market demand. Development of mixed biochar-mineral-organic amendments addressing multiple soil constraints (e.g., acidity, salinity, compaction, combined with nutrient deficiency) would broaden market applicability beyond N fertilizer focus. Collaboration with technology companies to integrate biochar-based carriers with precision application systems and digital farm management platforms would unlock the full economic potential of improved nutrient use efficiency.

Biochar has evolved from a simple soil amendment into a sophisticated smart carrier platform for agrochemicals, with demonstrated capacity to simultaneously enhance nutrient use efficiency, maintain agrochemical efficacy, and substantially mitigate environmental risks including nutrient leaching, heavy metal bioavailability, pesticide persistence, and greenhouse gas emissions. The integration of stimuli-responsive release mechanisms, strategic surface modification, and composite assembly with complementary materials (zeolites, metal oxides, polymers) enables tailored carrier designs aligned with specific crop, soil, and agrochemical requirements.

Field-scale evidence increasingly validates laboratory findings: starch-coated biochar-zeolite composite fertilizers achieve rice yield gains of 22% while reducing fertilizer inputs by 10%, with nitrogen recovery efficiencies exceeding 25% more than three times higher than conventional NPK. Environmental benefits are equally substantial: nitrogen leaching reduction of 69–88%, N₂O emission reduction of up to 66%, and heavy metal bioavailability reduction of 70–85% represent transformative improvements in agricultural sustainability.

However, realizing the global potential of biochar-based agrochemical carriers requires surmounting significant standardization, scalability, and regulatory challenges. Multi-year field validation across diverse agroecological contexts, development of internationally harmonized biochar standards, establishment of district-scale production infrastructure, and integration with precision agriculture systems will be essential to transform biochar from an emerging innovation into a cornerstone technology for sustainable intensification. The economic viability of composite carriers depends critically on economies of scale feedstock procurement networks, regional production clusters, and supply chain integration can reduce carrier costs from current estimates of \$200–500 per tonne to competitive levels approaching \$100–150 per tonne, comparable to conventional soil amendments.

Policy support mechanisms including carbon credits that recognize biochar's role in atmospheric CO₂ sequestration, subsidies for adoption during transition periods, and performance-based payment schemes that reward demonstrable improvements in nutrient use efficiency and environmental metrics will accelerate market adoption in developing agricultural regions where nutrient losses and agrochemical pollution represent both sustainability crises and economic inefficiencies.

From a research perspective, continued investigation into mechanisms underlying long-term biochar persistence in soil, optimization of stimuli-responsive release kinetics for diverse agrochemicals and soil conditions, assessment of interactions with biological communities and microbial functions, and life cycle assessment frameworks that account for regional production contexts will refine understanding of biochar's agronomic and environmental benefits. Emerging applications in

protected cultivation systems, specialty crop production, and integrated pest management where controlled release and targeted delivery provide premium value represent near-term commercialization opportunities.

Ultimately, biochar-based agrochemical carriers exemplify a systems-level approach to sustainable agriculture that decouples productivity gains from environmental degradation. By simultaneously addressing nutrient use efficiency, agrochemical efficacy, soil health, and environmental risk mitigation, this technology offers a pragmatic pathway toward intensified food production within planetary boundaries. Success depends not solely on technological refinement, but on coordinated advancement across standardization, infrastructure development, policy frameworks, and farmer adoption mechanisms positioning biochar as a critical component in the broader transition toward regenerative, precision agriculture globally.

Table 1: Major biochar engineering strategies for controlled agrochemical delivery

Engineering strategy	Main mechanism	Representative evidence in the reviewed literature	Potential agronomic value
Chemical modification	Changes surface charge and oxygen-containing functional groups	Improves adsorption and permits tuning of nutrient interactions	Enhanced nutrient retention and controlled release
Metal/metal-oxide loading	Adds reactive or nutrient-retaining phases	Improves sorption, redox activity or slow nutrient release	Contaminant immobilization and nutrient management
Zeolite/clay composites	Combines ion exchange with diffusion barriers	Improves nutrient retention and release control	Higher nutrient-use efficiency and lower losses
Polymer coating	Creates an external diffusion barrier	Extends release from short periods to weeks or months	Better synchrony between nutrient supply and crop demand
Stimuli-responsive systems	Release responds to pH, moisture, temperature or enzymes	Provides environment-dependent release profiles	Potential for targeted delivery and reduced off-site losses

7. Conclusion

Biochar-based carrier systems provide a promising route for integrating nutrient management, agrochemical delivery, soil improvement and environmental protection within a single platform. The evidence synthesized in this review shows that carrier performance is strongly dependent on feedstock, pyrolysis conditions, surface chemistry, pore structure, co-formulants and the release environment. Future work should therefore move from general claims about biochar benefits towards application-specific design criteria that relate carrier properties to crop, soil and agrochemical requirements. Long-term field experiments across contrasting soils and climates are particularly important for validating release behaviour, agronomic performance, biochar ageing and environmental safety. Standardized characterization protocols, transparent reporting of loading ratios and release conditions, and comparable life-cycle and economic assessments will also improve the reliability of cross-study comparisons. Integration with precision agriculture and data-driven modelling may further enable site-specific carrier selection and application. These priorities can help bridge the current gap between promising laboratory formulations and practical, scalable technologies for sustainable crop production.

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