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From Carbonaceous Residues to Engineered Fertilizers: A Performance-First Critical Review of Biochar and Hydrochar for Nutrient Recovery, Controlled Release, Agronomic Function, and Life-Cycle Climate Performance

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Abstract

Biochar and hydrochar are increasingly described as fertilizers, nutrient-recovery media, soil-carbon amendments, and climate-mitigation products, although these functions require different evidence. This structured critical narrative review reappraises a 122-source analytic corpus spanning 2019–2026 and applies the Dual-Performance Boundary Framework for Carbonaceous Fertilizers (DPB-CF), which independently tests agronomic fertilizer function and net life-cycle climate benefit. The corpus is strongly recent, with 67 sources (54.9%) published in 2024–2026 and 50 (41.0%) in 2025–2026. Evidence is synthesized from feedstock chemistry through pyrolysis, co-pyrolysis, and hydrothermal carbonization; nutrient partitioning and speciation; nutrient capture; controlled release; soil–plant response; product engineering; safety; techno-economics; life-cycle assessment; regulation; and scale-up. A three-generation author-developed framework is operationalized: amendment char, nutrient-enriched char, and engineered nutrient-recovery fertilizer. Phosphorus and potassium are often retained or concentrated in carbonaceous solids, whereas nitrogen is more vulnerable to volatilization during dry thermochemical conversion or partitioning into hydrothermal process water. Mg- and Ca-based engineering can increase phosphate capture and tailor release, but adsorption capacity or total nutrient content does not establish fertilizer value without evidence of release, plant uptake, nutrient-use efficiency, and crop response. Multi-year studies demonstrate both positive and neutral outcomes; soil dependence is therefore treated as part of product performance rather than experimental noise. For climate claims, carbon permanence must be integrated with feedstock counterfactuals, process energy, transport, co-products, avoided waste treatment, field greenhouse-gas emissions, and end-use assumptions. Evidence classification was performed as a single-reviewer interpretive synthesis and was not tested for inter-rater reliability. The central development priority is a mass-balanced pathway from nutrient recovery to crop uptake, coupled to safe product specifications, multi-season validation, and auditable techno-economic and life-cycle boundaries.

Keywords: biochar; hydrochar; nutrient recovery; controlled-release fertilizer; nutrient use efficiency; life-cycle assessment.

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Highlights

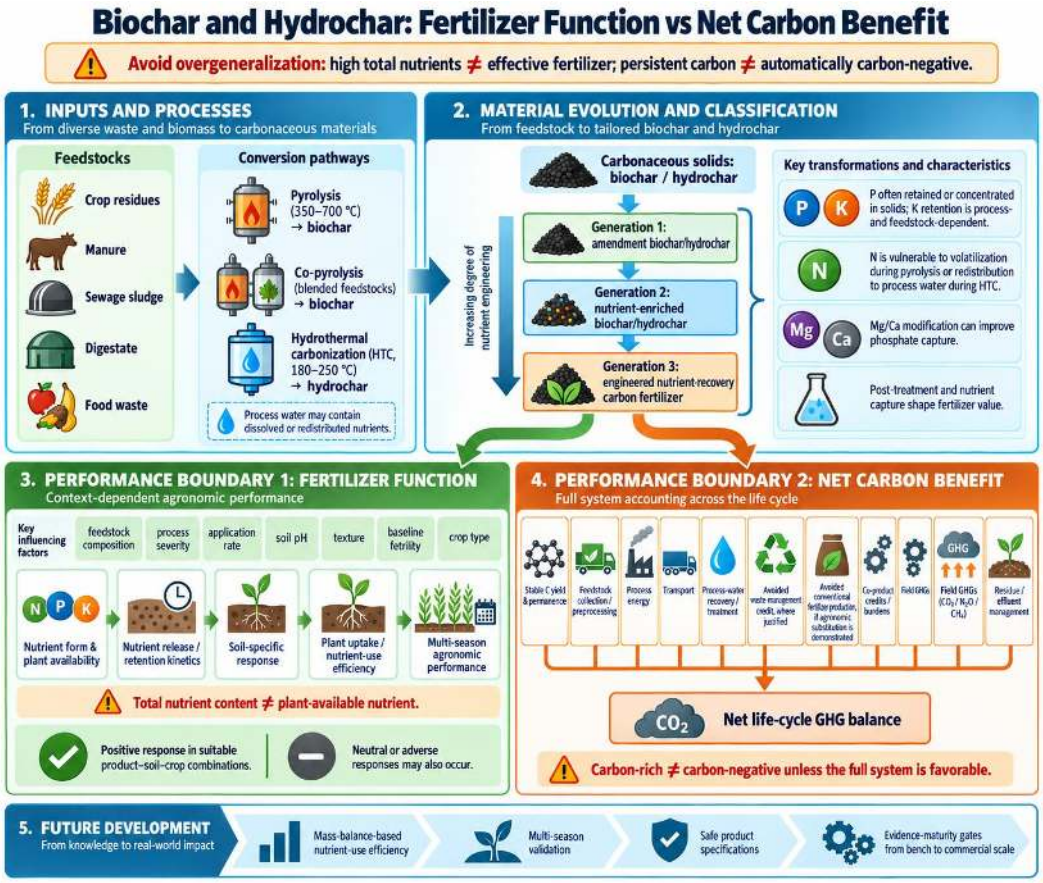
• Fertilizer function requires plant-available nutrient delivery and crop response, not high total NPK alone.

• Pyrolysis and hydrothermal carbonization create different solid–liquid–gas nutrient-recovery boundaries.

• Engineered nutrient-loaded chars require release, safety, field, and product-quality validation before fertilizer claims.

• Carbon permanence is one term in climate performance; net life-cycle GHG balance must be assessed independently.

The graphical abstract summarizes the performance-first logic of the review, linking feedstocks and conversion pathways to material classification, fertilizer-function testing, net life-cycle climate assessment, and future product development.



Graphical Abstract. Performance-first framework separating agronomic fertilizer function from net life-cycle climate performance in biochar and hydrochar systems.

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1. Introduction: separating material identity from demonstrated function

Biochar and hydrochar occupy an unusually broad conceptual space. They are described as soil amendments, sorbents, recovered-nutrient carriers, slow-release fertilizers, waste-management products, and carbon-removal materials. The problem is that these functions are not interchangeable. A material may increase soil carbon while contributing little plant nutrition, or it may deliver nutrients efficiently while having an uncertain or even unfavorable net greenhouse-gas balance. Meta-analyses and long-term field studies likewise show that crop response is conditional rather than universal: benefits depend on nutrient status, soil pH, texture, climate, crop, and the chemistry inherited from the feedstock and conversion process (Bekchanova et al., 2024; Cheng et al., 2025; Han et al., 2023; Hosseini Bai et al., 2022; Xu et al., 2021).

This review adopts a performance-first definition of fertilizer function within the Dual-Performance Boundary Framework for Carbonaceous Fertilizers (DPB-CF). A carbonaceous product is treated as a fertilizer only when it supplies one or more nutrients in agronomically relevant quantities, at rates and chemical forms plants can access without unacceptable losses or toxicity. In operational terms, a nutrient-loaded carbonaceous sorbent becomes a fertilizer only when recovered nutrients are released into plant-accessible pools under relevant soil and crop conditions. This boundary distinguishes total nutrient concentration from plant availability and places nutrient-use efficiency (NUE), phosphorus-use efficiency (PUE), potassium-use efficiency (KUE), crop uptake, and yield closer to the decision endpoint. Recent biochar-based fertilizer studies support this shift by showing that nutrient enrichment and formulation can improve efficiency, but only when nutrient release is matched to crop demand (Al-Amin et al., 2026; Banik et al., 2023; Dissanayake et al., 2026; Preza Fontes et al., 2024; Zhao et al., 2022).

A second, independent boundary is required for climate claims. Biochar carbon can persist for years to decades or longer, but permanence is only one term in a net life-cycle greenhouse-gas balance. Feedstock counterfactuals, drying, heat and electricity,

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reactor efficiency, transport, co-products, avoided waste treatment, changes in soil N_2O, CH_4 and CO_2 emissions, and the durability of stored carbon all influence the result. Avoided emissions and durable carbon removal should not be treated as interchangeable accounting categories; both may improve climate performance, but they arise from different mechanisms and require transparent system boundaries (Chiaramonti et al., 2024; European Commission, 2026; Li et al., 2024; Sanei et al., 2025; Sanei et al., 2026; Xia et al., 2024).

The framework is grounded in durable agronomic and soil-chemical principles as well as recent biochar/hydrochar evidence. Controlled-release value depends on synchronization between nutrient release and crop demand (Shaviv, 2001); nitrogen-use efficiency depends on retaining N in plant-accessible pools while limiting loss pathways (Fageria & Baligar, 2005); phosphate bioavailability reflects adsorption/desorption and precipitation/dissolution equilibria in the rhizosphere (Hinsinger, 2001); and carbon persistence depends on material chemistry and environmental context rather than on the label ‘biochar’ alone (Lehmann et al., 2006; Spokas, 2010). These five foundational sources serve as contextual anchors and are not included in the 122-source 2019–2026 analytic corpus.

External validity is deliberately bounded. Claims should be transferred only among products with comparable feedstock chemistry, conversion conditions, nutrient form, soil context, contaminant profile, and product-engineering status. Soil dependence is therefore part of the technology-performance boundary, not a nuisance variable to be averaged away.

1.1. Contribution relative to recent reviews

Recent reviews have addressed biochar-based N fertilizers, P and ammonium recovery, enrichment techniques, slow/controlled-release formulations, hydrothermal nutrient fate, soil responses, and commercialization separately. The unresolved problem is not a lack of reviews but the tendency to collapse distinct performance claims into a single label such as “sustainable biochar fertilizer.” This review therefore links nutrient

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mass balance, plant-available delivery, product engineering, safety, life-cycle climate performance, and evidence maturity within one decision architecture (Gao et al., 2022; Marcińczyk & Oleszczuk, 2022; Ngo Ndoung et al., 2021; Shakoor et al., 2021; Sim et al., 2025; dos Santos et al., 2025).

Table 1 makes the novelty test explicit: the contribution is not another catalog of feedstocks or modifications, but a set of performance boundaries that prevents adsorption, total nutrient content, or carbon concentration from being used as substitutes for fertilizer or climate performance.

Table 1. How the present review extends recent biochar/hydrochar fertilizer reviews

Reference	Primary emphasis	Remaining boundary addressed here
Ngo Ndoung et al. (2021)	Biochar fertilizer enrichment techniques and agro-environmental application	Adds explicit fertilizer-function test, product-quality gate, and life-cycle climate boundary.
Shakoor et al. (2021).	Engineered biochars for phosphate and ammonium recovery from wastewater	Extends nutrient capture to release, crop uptake, product engineering, safety, and scale-up.
Gao et al. (2022).	Biochar-based nitrogen fertilizers	Integrates N with P/K recovery, hydrochar partitioning, safety, TEA/LCA, and field evidence.
Marcińczyk & Oleszczuk (2022).	Slow- and controlled-release biochar fertilizers	Separates release behavior from verified fertilizer function and commercial readiness.
dos Santos et al. (2025).	Biochar as feedstock for sustainable fertilizers	Adds an evidence-maturity architecture and an independent net life-cycle climate test.
Sim et al. (2025).	Recent advances in slow/controlled-release fertilizers	Connects formulation to multi-season agronomy, safety, regulatory fit, TEA/LCA, and pilot evidence.
Present review	Biochar and hydrochar from feedstock to engineered fertilizer	Performance-first classification: nutrient recovery → release → uptake/NUE → product/safety → field robustness → scale/TEA/LCA, with climate performance accounted separately.

Note. Evidence-summary table comparing the scope of recent review literature with the boundaries used here.

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Figure 1 summarizes this logic as two independent tests that converge only at final product classification.

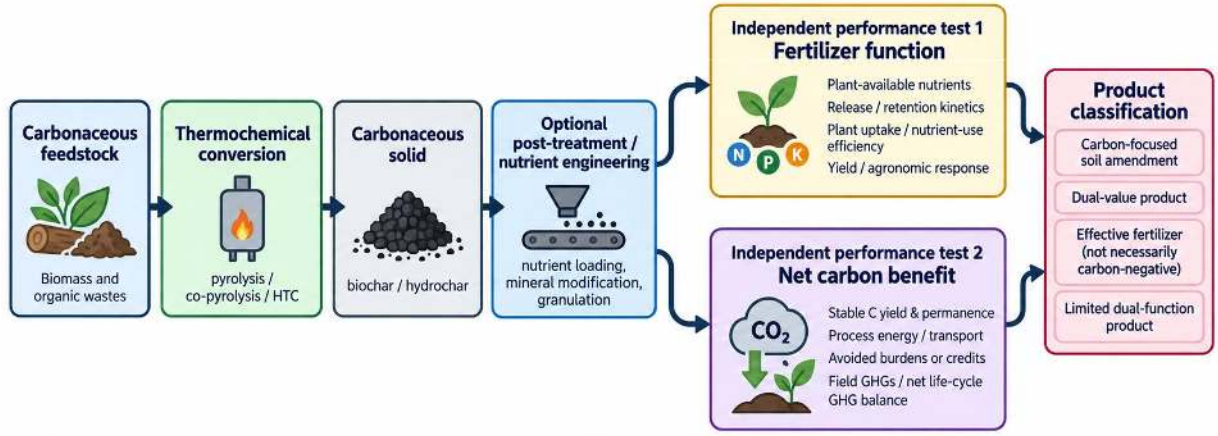

Figure 1. Sequential classification of carbonaceous materials using independent fertilizer-function and life-cycle climate tests

Note. Author-developed conceptual synthesis based on Ippolito et al. (2020), Marcińczyk and Oleszczuk (2022), Li et al. (2024), and Sanei et al. (2026). In the figures, “net carbon benefit” is used as shorthand for net life-cycle climate benefit and is not equivalent to certified carbon removal.

A single descriptor such as “biochar” therefore cannot establish performance. A nutrient-poor but persistent biochar may be best managed as a soil-carbon amendment; a nutrient-enriched product may qualify as a fertilizer only after release and agronomic validation; a nutrient-recovery sorbent may require post-loading, granulation, or blending; and a contaminated or poorly stabilized material may be unsuitable for agricultural use.

2. Review methodology and critical evidence appraisal

2.1. Review design, corpus, and eligibility

This article is a structured critical narrative review, not a systematic review or meta-analysis. The retained analytic corpus contains 122 unique references spanning 2019–2026. The scientific discovery window ran from 1 January 2020 to 4 September 2026; we retained the 2019 EU fertilizing-products regulation as an official regulatory anchor. We did not preserve the earliest Google Scholar discovery-stage retrieval totals,

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duplicate-removal counts, or article-by-article exclusion log. No retrospective PRISMA-style numbers are therefore invented. Instead, the revision makes the eligibility, coding, deduplication, update, and appraisal logic explicit and provides a source-level evidence matrix (Supplementary Table S1) and a transparent source-selection flow with unavailable historical counts identified as 'not retained' (Supplementary Table S2). Sources were eligible when they directly informed at least one decision boundary: feedstock/process chemistry, nutrient fate or recovery, fertilizer formulation and release, soil–plant performance, contaminant behavior, product engineering, techno-economics, life-cycle performance, regulation, scale-up, or data-driven prediction. Peer-reviewed experimental studies, field studies, meta-analyses/reviews, pilot or industrial demonstrations, TEA/LCA studies, and official regulatory/certification documents were retained. Studies unrelated to nutrient delivery or agricultural use were excluded, and adsorption studies were retained only when nutrient recovery, reuse, release, or fertilizer relevance could be connected to the review question.

The corpus is strongly recent: 67 of 122 sources (54.9%) were published in 2024–2026 and 50 (41.0%) in 2025–2026. Retrospective source-level coding in Supplementary Table S1 classifies the 122 records as 73 experimental/applied studies, 11 reviews, nine meta-analyses, 10 machine-learning/predictive studies, seven field studies, five TEA/LCA studies, four regulatory/certification documents, and three pilot/industrial demonstrations. These mutually exclusive source-type labels are used only to map the primary evidence role; individual studies may contribute to more than one substantive section. The small pilot/industrial subset remains an important finding because it shows how much of the literature is still below full product-scale validation.

2.2. Search architecture and update logic

We conducted discovery and structured updates in Google Scholar using the seven topic blocks reproduced verbatim in Supplementary Appendix A. Google Scholar served as the bibliographic discovery platform for this review; we used publisher pages, DOI landing pages, and official regulatory sources for record verification rather than as

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additional discovery databases. Searches covered biochar/hydrochar fertilizer and nutrient recovery; thermochemical nutrient fate; mineral-assisted capture and product engineering; plant uptake/NUE/PUE/KUE and field response; contaminant and leaching risk; TEA/LCA/carbon permanence/scale-up; and machine-learning prediction. The final scientific-literature update was completed on 4 September 2026. A publisher-level bibliographic and DOI audit of retained 2026 and advance-online records was completed on 11 September 2026. Exact search strings, date boundaries, and verification rules are reported in Supplementary Appendix A.

Duplicate and version handling used DOI as the primary identifier, followed by normalized title and author–year matching. When an advance-online record and a version of record represented the same work, we treated them as one source and retained the most stable publisher metadata. Bibliographic status for 2026 sources was checked against publisher or official-regulatory records; where a record remained advance online, that status was preserved rather than converted to an invented volume, issue, or page range. Full-text accessibility was not prospectively logged during the earliest discovery stage, so the review does not claim universal open/full-text availability; substantive synthesis was restricted to sources with sufficient article-level evidence for the specific claim used.

2.3. Evidence coding, source-level auditability, and reviewer reliability

A single reviewer/author performed all evidence classification and interpretive coding. We did not perform independent duplicate coding, a calibration sample, or an external classification audit; therefore, we do not report Cohen's kappa, Krippendorff's alpha, or percentage agreement. The classification is therefore explicitly treated as single-reviewer interpretive synthesis rather than reliability-tested coding. Supplementary Table S1 exposes the source-level coding fields used for auditability, including source type, year, feedstock, pathway, nutrient focus, fertilizer function, carbon assessment, scale, soil/crop context, safety, TEA/LCA, regulatory relevance, principal limitation, and synthesis contribution.

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The source-level matrix is a retrospective audit of the retained corpus and should not be interpreted as a reconstruction of unavailable discovery-stage logs. Evidence categories inform interpretation, not assign pooled statistical weights. Empirical studies, meta-analyses/reviews, field trials, pilot/industrial demonstrations, TEA/LCA studies, regulatory documents, and machine-learning studies are distinguished because they answer different questions and provide different levels of transferability.

2.4. Critical appraisal and synthesis rules

Table 2 summarizes the operational appraisal rules used to distinguish material characterization, nutrient recovery, fertilizer function, evidence maturity, safety, climate performance, commercial readiness, and the principal methodological limitation of the synthesis.

Table 2. Operational review protocol and evidence-maturity rules

Element	Operational rule used in the synthesis
Material characterization	Composition, ash, mineralogy, pH, surface properties, and contaminant inventory establish what the material is, not whether it is an effective fertilizer.
Nutrient recovery	Prefer mass-balanced recovery across solid, liquid and gas streams. Adsorption capacity alone is insufficient.
Fertilizer function	Requires release/availability under relevant conditions plus soil–plant evidence; crop uptake, NUE/PUE/KUE and yield are stronger endpoints than total NPK.
Evidence maturity	Bench characterization < release/soil tests < pot/mesocosm < field/multi-season < pilot/industrial + product-quality validation.
Safety	Total contaminant concentration is combined with mobility, ecotoxicity, soil exposure and crop uptake where available.
Climate performance	Carbon persistence is accounted separately from energy, transport, counterfactuals, co-products, avoided emissions and field GHG effects.
Commercial readiness	Requires physical product quality, manufacturability, storage/application behavior, TEA/LCA and regulatory fit.
Interpretive rule	A positive result at an upstream stage cannot substitute for evidence at a downstream gate; contradictory field evidence is retained rather than averaged away narratively.

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Element	Operational rule used in the synthesis
Method limitation	Because the original identification-stage log is unavailable, the review does not claim exhaustive systematic-review coverage; its contribution is transparent critical synthesis of the retained corpus.

Note. Author-developed methodological synthesis defining the appraisal rules used in this review.

The synthesis therefore distinguishes nutrient conservation from nutrient fertilizer value, adsorption from recovery-to-use, short-term response from multi-season robustness, carbon persistence from net climate performance, and material feasibility from commercial product readiness. This hierarchy is applied consistently in the following sections and culminates in the evidence-gate pathway in Figure 5. To operationalize the fertilizer-function boundary, Box 1 summarizes the minimum evidence domains that should collectively support a defensible product-level fertilizer claim.

Box 1. Minimum evidence package for a fertilizer-function claim

Minimum evidence package (performance-first decision rule)
• Total nutrient content and nutrient mass balance.
• Plant-available or potentially available nutrient fraction using a justified method.
• Release kinetics under relevant solution/soil conditions, including burst release or incomplete release.
• Crop nutrient uptake and tissue response.
• Yield and/or biomass response at comparable nutrient dose.
• Nutrient-use efficiency (e.g., NUE, PUE, KUE) where applicable.
• Leaching, volatilization, or other nutrient-loss evidence.
• Contaminant, salinity, phytotoxicity, and other safety evidence appropriate to the feedstock.
• Comparison with a conventional fertilizer and/or no-fertilizer control.
A single study need not contain every endpoint, but a defensible product-level fertilizer claim should be supported by an evidence package that collectively addresses these functions.

Note. Author-developed operational synthesis. The box defines minimum evidence domains for classification; it is not a regulatory certification checklist.

Box 1 emphasizes that no single analytical result—such as total nutrient content, adsorption capacity, or a favorable release curve—is sufficient to establish fertilizer function. Classification should instead rely on convergent evidence linking nutrient availability and release to plant uptake, agronomic response, nutrient-use efficiency, loss control, and product safety.

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3. Feedstocks, thermochemical pathways, and process severity

3.1. Feedstock chemistry as the upper performance boundary

Feedstock chemistry establishes the upper boundary of what thermochemical conversion can achieve. Reviews of feedstock and process effects consistently identify ash content, inherent mineral phases, N concentration, P speciation, alkali and alkaline-earth metals, and contaminant burden as first-order controls (Ippolito et al., 2020; Jalali et al., 2025; Qian et al., 2026).

Crop residues typically provide high organic-carbon fractions and comparatively modest nutrient concentrations, although K can be abundant in soluble or weakly bound forms. Agricultural-residue pyrolysis can also generate PAHs depending on temperature, vapor residence, and condensation conditions, so clean feedstock does not eliminate process-derived organic contaminants (Bilias et al., 2023; Devi & Dalai, 2023; Leng et al., 2022).

Manures combine carbon with substantial N, P, K, Ca, and Mg. Chicken-manure systems can produce sustained P and K release through mineral co-addition, while comparative work shows that manure-derived biochar can recover and retain nutrients more effectively than hydrochar or compost under some conditions (Leite et al., 2023; Piash et al., 2022; Piash et al., 2025).

Sewage sludge is attractive because it contains recoverable P and organic carbon, but it also faces the strongest safety and regulatory constraints. Field and extraction studies show that pyrolysis temperature strongly alters P extractability and that heavy-metal behavior can remain acceptable only within feedstock- and process-specific limits (Chagas, de Figueiredo, & Paz-Ferreiro, 2021; Chagas, de Figueiredo, da Silva, & Paz-Ferreiro, 2021; de Figueiredo et al., 2021; Hakeem et al., 2026; Mourão et al., 2026; Wei et al., 2024).

Digestate is a wet, nutrient-rich residue that can be carbonized directly by HTC or dried for pyrolysis. Digestate-derived biochars have been used in slow-release fertilizer

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formulations, and co-application with digestate has been tested for crop yield, NUE, and nitrate-leaching effects (Belete et al., 2021; Gamaralalage et al., 2025; Ghobadian et al., 2026; Sharma et al., 2023; Sixt et al., 2025; Yu et al., 2021).

Food waste is heterogeneous, moisture-rich, and often mineral-rich. The compositional variability of salts, fats, proteins, and packaging-derived contaminants complicates standardization, but recent work indicates that integrated food-waste/biochar systems can improve compost stability and maize performance when feedstock control is adequate (dos Santos et al., 2026; Qian et al., 2026).

3.2. Pyrolysis, co-pyrolysis, and hydrothermal carbonization

Pyrolysis converts dry biomass in limited oxygen, progressively increasing aromaticity, ash concentration, pH, and often surface area as temperature rises. Process conditions must therefore be selected against a product specification rather than a generic “high-quality biochar” target (Ippolito et al., 2020; Jalali et al., 2025; Malghani et al., 2025).

Co-pyrolysis deliberately combines feedstocks or additives so that one component compensates for another. Microwave co-pyrolysis and coating strategies illustrate how reaction and formulation steps can be integrated to create graded or sustained release rather than merely concentrating ash (An et al., 2021; Liu et al., 2021; Piash et al., 2022).

HTC operates in hot compressed water and is particularly suited to wet biomass. Reviews and experimental studies consistently show that N and P fate is highly sensitive to HTC severity and feedstock chemistry (Alhnidi et al., 2020; Aragón-Briceño et al., 2021; Belete et al., 2021; Ge et al., 2025).

Biochar and hydrochar should therefore not be compared as interchangeable solids. Figure 2 places these differences within a single nutrient-partition framework (Khosravi et al., 2024; Piash et al., 2025; Xie et al., 2025).

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HTC is conducted in hot compressed water, commonly within the approximate 180–250 °C range used in the retained literature, with pressure governed by temperature, gas generation, fill ratio, and any externally imposed pressure needed to maintain the aqueous reaction environment. Pressure should therefore not be optimized independently of the thermal and phase-equilibrium conditions. This distinction is important when comparing HTC with dry pyrolysis because HTC intentionally preserves an aqueous phase that can carry substantial nutrient value.

Figure 2 integrates these pathways and makes the phase-partition boundary explicit.

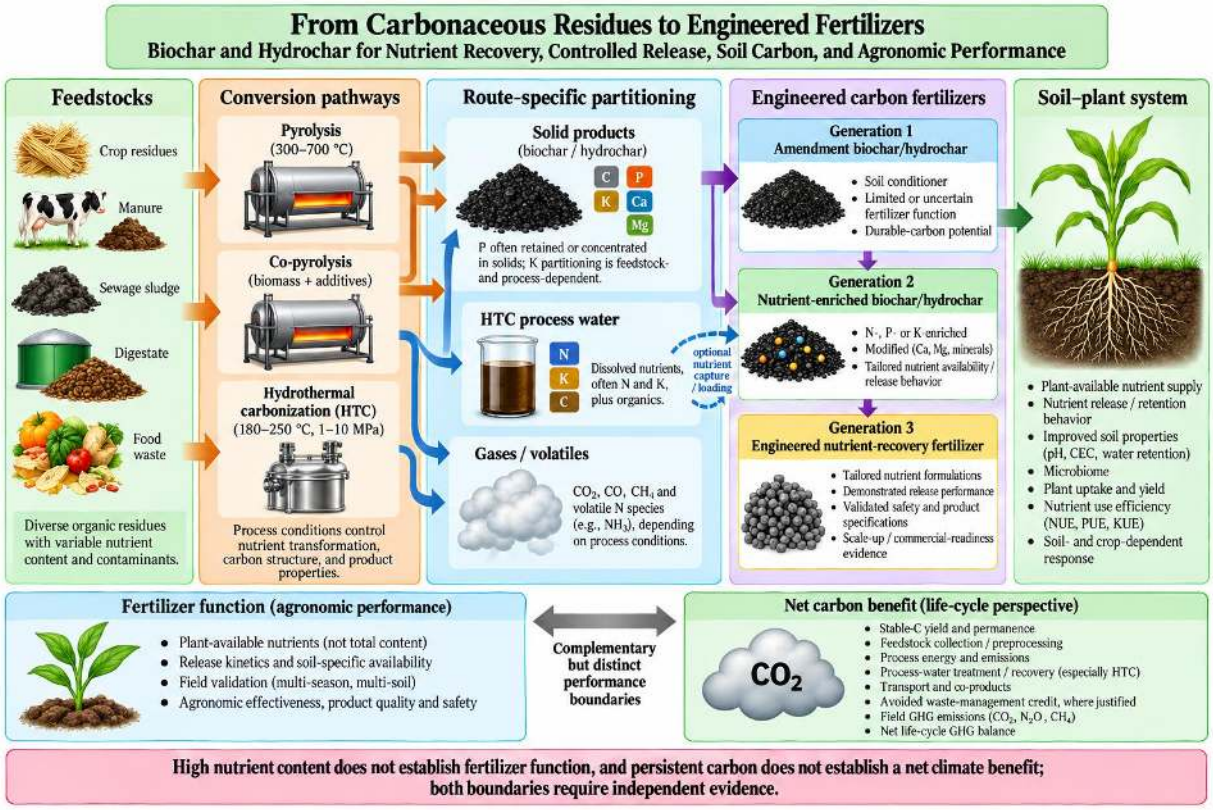

Figure 2. Feedstock–pathway–nutrient partition framework for pyrolysis, co-pyrolysis, and hydrothermal carbonization

Note. Author-developed conceptual synthesis based on Alhnidi et al. (2020), Aragón-Briceño et al. (2021), Belete et al. (2021), and Ge et al. (2025). Pyrolysis produces solid char, condensable vapors/tars, and permanent gases; HTC produces hydrochar, process water, and a gas phase. The pressure range in the schematic is indicative, not an independent variable disconnected from temperature and phase behavior.

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The framework prevents assessing recovery from the solid alone. This is especially important for HTC, where a nutrient-poor hydrochar can coexist with nutrient-rich process water containing ammonium, phosphate, potassium, dissolved organic carbon, and other soluble species that require recovery or treatment. Hydrochar also generally enters fertilizer development with a different carbon-stability profile from high-temperature biochar, and wet-feed logistics shift process burdens from drying toward pressurized aqueous reaction and process-water management. Post-treatment, dewatering, washing, aging, mineral conditioning, or blending may therefore be necessary before agronomic use. These route-specific differences justify a direct comparison rather than treating biochar and hydrochar as interchangeable carbonaceous solids.

Table 3 compares the two product families across the route-specific attributes that most strongly affect fertilizer and climate claims.

Table 3. Biochar versus hydrochar: route-specific fertilizer, carbon, and commercialization boundaries

Attribute	Biochar (dry pyrolysis)	Hydrochar (hydrothermal carbonization)
Carbon stability	Typically increases with pyrolysis severity and aromatic condensation; still needs verification for the specific product.	Often lower and more variable than high-temperature biochar because HTC produces less-condensed carbon; post-aging and stability assessment are important.
Nutrient partitioning	P, K, Ca, Mg and ash-forming elements often concentrate in the solid; N can volatilize to gas/vapor products.	N, P, K and dissolved organic species can partition strongly between hydrochar and process water; two-stream mass balance is essential.
Process-energy profile	Requires feed drying for wet residues but can recover energy from pyrolysis gas/condensables.	Accepts wet feeds and avoids complete pre-drying, but requires pressurized hot-water operation, dewatering, and often water treatment.
Liquid effluent	Condensable liquids/tars may be generated, but water is not the principal reaction phase.	Process water is an intrinsic co-stream and may contain ammonium, phosphate, dissolved organics, salts, and potentially

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Attribute	Biochar (dry pyrolysis)	Hydrochar (hydrothermal carbonization)
		inhibitory compounds.
Contaminant behavior	Thermal severity can destroy or transform some organics and immobilize some metals; volatilization/emission pathways remain relevant.	Lower temperatures can preserve more oxygenated organics; assess contaminant partitioning between solid and process water.
Agronomic evidence	Larger field and long-term evidence base, but responses remain soil-, crop-, dose-, and product-specific.	Smaller agronomic evidence base; post-treatment and process-water management are recurrent constraints on transfer to field use.
Commercialization readiness	More mature for soil amendment and emerging engineered-fertilizer products; powder handling and granulation remain important.	Generally less mature as a direct fertilizer product; wet logistics, dewatering, liquid-stream treatment, and stability qualification add development gates.

Note. Evidence-summary table synthesized from Alhnidi et al. (2020), Aragón-Briceño et al. (2021), Belete et al. (2021), Ge et al. (2025), Khosravi et al. (2024), Piash et al. (2025), and Xie et al. (2025). General tendencies do not replace product-specific measurements.

Table 4 summarizes the route-level implications of the biochar–hydrochar comparison, linking representative feedstock/pathway combinations to their dominant nutrient features, principal fertilizer opportunities, and critical limitations.

Table 4. Feedstocks and thermochemical pathways relevant to engineered carbon fertilizers

Feedstock/pathway	Dominant nutrient feature	Main opportunity	Critical limitation
Crop residues + pyrolysis	K-rich ash; modest N/P	Carbon-rich carrier for nutrient loading	Low intrinsic fertilizer value; PAH/process control
Manure + pyrolysis/co-pyrolysis	High P, K, Ca/Mg; N losses possible	Nutrient-dense slow-release fertilizer	P can become poorly soluble; salinity/ash
Sewage sludge + pyrolysis	High P and metals concentrated in ash	Recovered-P fertilizer and sorbent	PTEs, PFAS/organics, regulatory acceptance
Digestate + pyrolysis	NPK-rich mineral matrix	Granulated or blended fertilizer	Drying demand; N volatilization
Digestate/food waste + HTC	Nutrients split between hydrochar and liquor	Wet-feedstock processing and dual-stream recovery	Process-water treatment and lower carbon permanence

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Feedstock/pathway	Dominant nutrient feature	Main opportunity	Critical limitation
Bone-rich residues / bone char	Ca-phosphate dominated	P source and adsorbent platform	Low N/K; dissolution controlled by mineralogy

Note. Evidence-summary table of route-level opportunities and limitations.

Table 4 reinforces a design rule: feedstock selection should begin from the intended agronomic function. A P fertilizer, N carrier, K amendment, sorbent, and carbon-storage product impose different optimum feedstocks, mineral chemistries, and process severities.

3.3. Process severity, atmosphere, mineralogy, and ash

Thermochemical conditions translate feedstock composition into fertilizer-relevant properties. Machine-learning studies have begun to capture these interactions, but mechanistic interpretation remains essential because the same condition can improve one attribute while damaging another—for example, increasing carbon stability while lowering N retention or P solubility (Chen et al., 2023; Leng et al., 2022; Li et al., 2022; Liu et al., 2025).

Temperature is the most consistently reported control variable. Direct 33P approaches and extractant comparisons demonstrate that higher total P after pyrolysis does not guarantee higher plant-available P (de Figueiredo et al., 2021; Lustosa Filho et al., 2025; Malghani et al., 2025).

Residence time determines how completely secondary devolatilization, aromatization, mineral reactions, and gas–solid interactions proceed. Because residence time is frequently confounded with temperature and reactor type, fertilizer-oriented optimization should report severity in relation to nutrient mass balances rather than relying only on final char composition (Ippolito et al., 2020; Jalali et al., 2025).

Heating rate affects volatile release, pore development, secondary char formation, and the thermal history mineral phases experience. From a fertilizer perspective, treat heating rate as a controllable variable only when you measure the associated nutrient

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retention, contaminant profile, and product handling properties (Devi & Dalai, 2023; Leng et al., 2022).

The gas atmosphere changes redox conditions and heat transfer and can alter mineral phases, surface functionality, and gaseous N species. Scale-up therefore requires confirmation that the product formed under laboratory inert gas remains chemically and physically comparable under commercial reactor hydrodynamics (Hakeem et al., 2026; Wei et al., 2024).

HTC severity combines temperature and time in an aqueous reaction environment. Data-driven models can predict hydrochar properties and phosphorus fate, but the fertilizer optimum must include both phases and any downstream concentration or recovery step (Chen et al., 2023; Ge et al., 2025; Xie et al., 2025).

Mineralogy governs nutrient immobilization and release. Mineral-engineered biochars show that these interactions can be used deliberately, but they can also unintentionally reduce nutrient availability if the resulting phases dissolve too slowly under field pH conditions (Leite et al., 2023; Sornhiran et al., 2022; Zhao et al., 2025).

Ash is not simply an inert residue. Product specifications should therefore report nutrient and contaminant mass per unit product together with plant-availability metrics (Albert et al., 2021; Bilias et al., 2023; Ippolito et al., 2020; Wei et al., 2024).

Practically, process optimization cannot be reduced to char yield or surface area. A fertilizer-oriented objective function should maximize recoverable nutrient value and safe agronomic performance subject to carbon, energy, and manufacturability constraints.

Process optimization should therefore maximize recoverable nutrient value and safe agronomic performance subject to carbon stability, energy demand, contaminant behavior, and manufacturability constraints, rather than maximizing char yield, surface area, or total nutrient concentration in isolation.

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4. Nutrient transformation and whole-process partitioning

Nutrient transformation is the mechanistic core of fertilizer performance because carbonization changes chemical form as well as concentration. Table 5 summarizes the dominant behavior of major nutrients.

Table 5. Dominant nutrient transformations during pyrolysis and hydrothermal carbonization

Nutrient	Typical transformation	Potential agronomic consequence	Preferred evidence
N	Volatilization during pyrolysis; ammonium/organic N partitioning in HTC	Total N may decrease; remaining N can be poorly available	N mass balance, mineral N release, plant N uptake
P	Organic P → inorganic phosphates; Ca/Mg/Fe/Al association	Higher total P may coexist with lower solubility	P speciation, isotopic dilution, crop P uptake
K	Concentration in ash; often present as soluble/exchangeable salts	Rapid K release can be beneficial but prone to leaching	Sequential extraction, release kinetics, plant K uptake
Ca/Mg	Concentrated mineral phases; can precipitate phosphate	Supports liming and P capture but can reduce P dissolution	Mineralogy, dissolution vs pH, plant availability
Si	Concentrated in phytolith/silicate phases	Potential Si fertilizer/corrective value	Soluble Si and crop-specific response
Micronutrients/PTEs	Concentration by mass loss; variable stabilization	Deficiency correction or toxicity risk	Speciation, leaching, tissue accumulation

Note. Evidence-summary table of nutrient transformation pathways and preferred evidence.

Table 5 shows why total-element assays are insufficient for fertilizer classification. Nutrient form, solubility, desorption, mineral dissolution, and soil interaction determine the fraction that can enter the plant-available pool.

4.1. Nitrogen: the least conservative macronutrient

Nitrogen is the nutrient most likely to be lost during dry thermochemical conversion. Biochar-based N fertilizers overcome this limitation by post-loading mineral N,

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embedding fertilizers, or using coatings that regulate release (Banik et al., 2023; Gao et al., 2022; Mustaffa et al., 2024; Rasse et al., 2022).

4.2. Phosphorus: retention does not equal plant availability

Phosphorus usually remains in the condensed phase during pyrolysis but undergoes substantial speciation change. Depending on soil pH and mineralogy, this can either provide gradual release or create recalcitrant P that contributes little to crop nutrition (de Figueiredo et al., 2021; Kooij et al., 2024; Lustosa Filho et al., 2025; Tesfaye et al., 2021).

The organic-to-inorganic P transition is especially important because conventional fertilizer analyses may interpret increased mineral P as improved value even when the resulting mineral is sparingly soluble. Meta-analysis confirms that pyrolysis can shift the relative agronomic performance of sewage-sludge biochar compared with conventional P fertilizers (Lustosa Filho et al., 2025; Malghani et al., 2025).

4.3. Potassium, Ca, Mg, Si, and micronutrients

Potassium is frequently enriched because it is retained in the ash while carbon and volatiles are lost. Field evidence confirms that biochar can increase soil K availability and maize K uptake, but the response is soil-specific (Bao et al., 2024; Bilias et al., 2023; Fachini et al., 2022; Xiu et al., 2023).

Ca and Mg have dual roles as nutrients and as mineral modifiers that control phosphate capture and dissolution. Mineralogy, not bulk Ca/Mg/Si content, therefore determines fertilizer function (Leite et al., 2023; Liang et al., 2025; Sornhiran et al., 2022; Zhao et al., 2025).

Micronutrients such as Fe, Mn, Zn, Cu, and B may concentrate, but the same mechanism applies to potentially toxic elements. High pH and mineral stabilization can reduce metal mobility, yet total concentrations increase on a dry-mass basis, and long-term field monitoring remains essential for sludge-derived products (Albert et al., 2021; Chagas et al., 2021; Wei et al., 2024).

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4.4. HTC process water and the need for complete mass balances

HTC requires a two-stream nutrient balance. Ignoring this stream can lead to a misleading conclusion that hydrochar production destroyed nutrient value when it actually transferred the value to a recoverable liquid phase (Alhnidi et al., 2020; Aragón-Briceño et al., 2021; Belete et al., 2021; Ge et al., 2025).

The critical distinction in Section 4 is thus between nutrient conservation and nutrient fertilizer value: retention in a char is useful only when the nutrient remains accessible on the time scale of crop demand.

The critical distinction is therefore between nutrient conservation and nutrient fertilizer value: a nutrient retained in a char contributes to fertilizer function only if its release, dissolution, desorption, microbial transformation, or rhizosphere mobilization occurs on a time scale compatible with crop demand.

5. Nutrient recovery and mineral engineering

Biochar and hydrochar can act as intermediate nutrient-recovery media before functioning as fertilizers. Figure 3 expresses this capture–release duality.

Figure 3 places adsorption or precipitation at the beginning—not the end—of a fertilizer-development pathway.

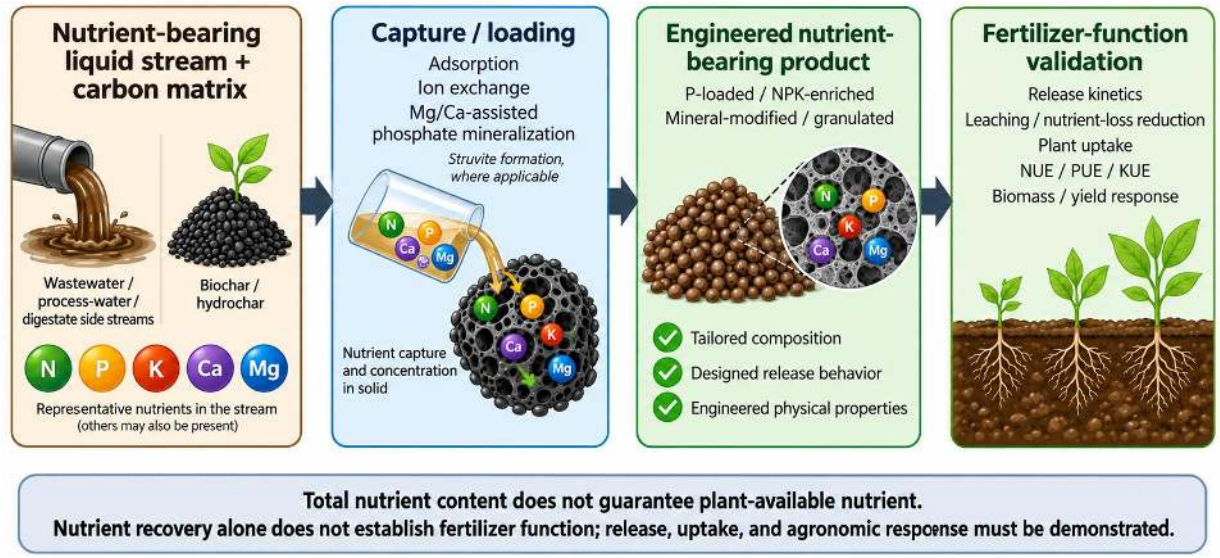

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Figure 3. Nutrient capture, product engineering, and agronomic release in carbonaceous fertilizer systems

Note. Author-developed conceptual synthesis based on Dai et al. (2020), Shakoor et al. (2021), Marcińczyk et al. (2022), and Shin et al. (2023).

The sequence in Figure 3 prevents interpreting adsorption studies as complete fertilizer demonstrations. Desorption, dissolution, soil competition, microbial transformations, and plant uptake remain necessary downstream tests.

5.1. Ammonium and phosphate capture

Ammonium recovery relies on cation-exchange sites, surface oxygen groups, mineral phases, and electrostatic interactions. Engineering with clays or Mg-bearing phases can improve simultaneous N and P recovery, while urine-derived systems can recover NH_4^+-N directly onto sludge biochar for subsequent fertilizer use (Dai et al., 2020; Shakoor et al., 2021; Xi et al., 2022; Yu, 2022).

Phosphate adsorption is generally weak on negatively charged pristine carbon surfaces unless mineral sites are present. Bentonite-modified and Mg-modified biochars have therefore been investigated as P-recovery media with subsequent slow-release behavior (An et al., 2020; He et al., 2022; Shin et al., 2020; Shin et al., 2023).

5.2. Mg-, Ca-, clay-, and mineral-assisted recovery

Magnesium modification is one of the most developed strategies because Mg can both increase phosphate affinity and create agronomically useful Mg–P phases. Yet excessive Mg can convert P into phases whose dissolution depends strongly on soil acidity, so the optimum is not necessarily the maximum Mg loading (Leite et al., 2023; Li et al., 2023; Luo et al., 2021; Xi et al., 2022).

Calcium modification follows a similar logic but creates different phosphate mineralogy. Fertilizer behavior is dominated by dissolution and soil pH rather than desorption alone (Liang et al., 2025; Pereira et al., 2025; Pereira & Marçal, 2025).

Struvite formation links N and P recovery by precipitating $MgNH4PO_4 \cdot 6H2O$. Combined sewage-sludge ash, food wastewater, and Mg-biochar systems demonstrate

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the feasibility of this route, but product purity, competing ions, and release behavior must be validated for agricultural use (Zin & Kim, 2021).

5.3. Wastewater recovery, direct application, and regeneration

Wastewater applications broaden the feedstock boundary beyond the char itself. Reviews of phosphate and ammonium recovery show the technical potential, while pilot-scale phosphate recovery on biosolids biochar begins to address the evidence gap between batch adsorption and real wastewater operation (Marcińczyk et al., 2022; Pap et al., 2026; Pathy et al., 2021; Sagar et al., 2024; Shakoor et al., 2021).

After nutrient loading, two options exist: regenerate the sorbent and recover a separate fertilizer, or apply the loaded carbon directly. The choice should be based on whole-process recovery, product specification, and crop response rather than adsorption capacity alone (He et al., 2022; Li et al., 2023; Sagar et al., 2024).

A useful performance metric for these systems is therefore nutrient recovery to plant uptake: the fraction of nutrient removed from the waste stream that ultimately enters crop biomass without unacceptable leaching or accumulation.

For these systems, the most decision-relevant metric is nutrient recovery to plant uptake: the fraction of nutrient removed from the source stream that is ultimately delivered to crop biomass without unacceptable leaching, toxicity, or residual accumulation.

6. From nutrient-containing chars to engineered fertilizers

Engineering converts a generic carbon matrix into a product with defined nutrient content, release profile, strength, size distribution, and handling behavior. To clarify this progression, Table 6 proposes three generations of carbonaceous fertilizer.

Table 6. Three generations of biochar/hydrochar-based agricultural products

Generation	Primary design objective	Typical product	Minimum evidence for classification

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Generation	Primary design objective	Typical product	Minimum evidence for classification
Generation 1 — amendment biochar	Modify soil pH, CEC, water retention, carbon stock	Pristine biochar/hydrochar	Material quality + soil amendment response; nutrient claims secondary
Generation 2 — nutrient-enriched biochar	Increase nutrient content and reduce nutrient loss	N-, P-, K-, or NPK-enriched char; co-pyrolyzed blend	Release kinetics + soil nutrient availability + crop uptake
Generation 3 — engineered nutrient-recovery fertilizer	Recover nutrients from residues/liquids and deliver them predictably	Mineral-biochar composite, coated granule, loaded sorbent, smart fertilizer	Mass-balanced recovery + product engineering + multi-condition agronomy + safety + TEA/LCA

Note. Author-developed conceptual synthesis informed by Ngo Ndoung et al. (2021), Marcińczyk and Oleszczuk (2022), dos Santos et al. (2025), and Sim et al. (2025). The three-generation classification is an evidence-informed framework proposed for research design and product assessment; it is not an externally validated regulatory, industry, or certification category.

The classification in Table 6 avoids labeling every nutrient-containing char as a fertilizer. Generation 2 and Generation 3 require demonstrated nutrient delivery, while Generation 3 additionally requires an auditable recovery boundary and engineered product quality.

6.1. Generation 2 and 3 nutrient formulations

Because thermal conversion can reduce N availability, post-loading is often the most rational route to an N fertilizer. Slow-release N studies show improved N recovery efficiency and reduced losses in some maize and rice systems, while reviews caution that sorption alone may not synchronize release with plant demand (Banik et al., 2023; Gao et al., 2022; Mustaffa et al., 2024; Rasse et al., 2022).

P-loaded biochars are produced by sorbing phosphate from wastewater or by adding P-rich minerals before or after carbonization. Modified biochars can improve P-use efficiency, but comparisons with soluble fertilizers remain necessary to determine

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whether a slower release is beneficial or simply incomplete (An et al., 2020; Frene et al., 2025; Sagar et al., 2024; Shin et al., 2020; Tesfaye et al., 2021).

K-enriched products can exploit naturally K-rich feedstocks or combine biochar with K-bearing minerals. Because K is highly mobile and not strongly incorporated into organic structures, formulation should aim to reduce early leaching without creating diffusion limitations that delay crop uptake (Bao et al., 2024; Fachini et al., 2022; Xiu et al., 2023).

NPK formulations treat the char as a matrix for multiple nutrient species rather than a single-nutrient carrier. Data-driven models predicting NPK composition and experimental Mg-enriched compound fertilizers illustrate the move toward formulation rather than feedstock-determined composition (Li et al., 2026; Liu et al., 2025).

Co-pyrolysis enables in-situ synthesis of nutrient-mineral phases. This approach can reduce post-processing steps, but it increases the need for feed-mixing control and process reproducibility because local mineral ratios determine final release behavior (An et al., 2021; Liu et al., 2021; Piash et al., 2022).

Mineral–biochar composites broaden the design space by introducing bentonite, Mg/Ca compounds, layered double hydroxides, or other phases that enhance capture and regulate release. Their benefit should therefore be expressed per unit nutrient delivered, not per unit char produced (An et al., 2020; Shin et al., 2023; Sornhiran et al., 2022; Xi et al., 2022).

Nano- and fine-mineral additives can increase reactive surface area and create highly selective nutrient-binding sites, but they also raise manufacturing and safety questions. Urban biosolids-to-nanobiochar research illustrates the opportunity while also highlighting the need for stronger field and risk evidence (Mourão et al., 2026).

Hybrid smart fertilizers combine chemical loading with coatings, binders, microbial functions, or responsive matrices. The engineering challenge is to achieve a release profile that responds to soil moisture, pH, and biological activity without sacrificing

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mechanical integrity or storage stability (Chen et al., 2025; Liu et al., 2023; Rubel & Wei, 2022; Sim et al., 2021).

The most mature engineered products increasingly resemble conventional fertilizer products in their need for controlled granule size, crushing strength, storage stability, nutrient guarantees, and predictable field response. The carbon matrix becomes a design component rather than the product's entire identity.

6.2. Controlled-release mechanisms and failure modes

Controlled release is the point at which nutrient enrichment becomes agronomically meaningful. Table 7 summarizes the dominant mechanisms.

Table 7. Mechanisms controlling nutrient release from biochar- and hydrochar-based fertilizers

Mechanism	Dominant control	Typical nutrient/product	Failure mode
Desorption/ion exchange	Surface charge, competing ions, pH	NH_4^+, K+, weakly bound phosphate	Burst release or displacement in saline soils
Diffusion through matrix/coating	Porosity, coating thickness, water ingress	Coated NPK and encapsulated products	Release too slow or coating failure
Mineral dissolution	Mineral phase, saturation, rhizosphere pH	Ca/Mg phosphates, bone char, ash-rich char	High total P but low plant availability
Surface precipitation dissolution	Mg/Ca/Al/Fe phase chemistry	Recovered phosphate products	Strong fixation under neutral/alkaline conditions
Microbial mediation	Carbon availability, microbes, enzymes	Organic N/P, microbial-assisted fertilizers	Inconsistent response across soils
Particle/granule disintegration	Binder, strength, wetting–drying	Pellets and granules	Dust, segregation, uncontrolled release

Note. Evidence-summary table of controlled-release mechanisms and failure modes.

Table 7 shows that “slow release” is not one mechanism. Identical release curves can arise from diffusion, mineral dissolution, desorption, or particle breakdown, and

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these mechanisms respond differently to soil pH, moisture, ionic strength, and biological activity.

The broader controlled-release literature confirms that engineering must couple nutrient-release kinetics with environmental co-functions. Reviews of engineered biochar fertilizers emphasize release control as a design problem, while recent rice-husk formulations demonstrate that nutrient release can be combined with cadmium immobilization rather than optimized in isolation (Marcińczyk & Oleszczuk, 2022; Tan et al., 2024; Wang et al., 2022).

Diffusion dominates when nutrients are embedded in a porous matrix or isolated by a coating. Coated biochar fertilizers can therefore regulate the initial burst and extend release, but performance depends on coating continuity, thickness, biodegradation, and temperature (An et al., 2021; Rubel & Wei, 2022; Sim et al., 2021).

Desorption is important for ammonium, K, and weakly bound phosphate. Mg-biochar and nutrient-loaded sorbents should be evaluated in soil solution or representative electrolytes to quantify competitive release (Li et al., 2023; Shin et al., 2020).

Mineral dissolution controls many P-rich biochars and hydrochars. This explains why total P and even conventional extractable P may not consistently predict crop response (Khosravi et al., 2024; Malghani et al., 2025; Sornhiran et al., 2022; Zhao et al., 2025).

Ion exchange couples release to soil chemistry. The effect can reduce leaching in coarse soils but may be modest where native CEC is already high (Knoblauch et al., 2021; Rasse et al., 2022).

pH is a master variable because it controls surface charge, phosphate mineral solubility, ammonium–ammonia equilibrium, and soil microbial activity. Consequently, a product can improve soil chemistry while simultaneously reducing the immediate availability of part of its P inventory (Carneiro et al., 2021; Zhang et al., 2025).

Reduced nutrient leaching is often presented as evidence of slow-release performance. Granulation studies and digestate–biochar field evaluations indicate that

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lower losses can coexist with sustained crop performance, but this balance is formulation- and soil-dependent (Costa et al., 2026; Grafmüller et al., 2024; Sixt et al., 2025).

Common kinetic models can describe release curves but do not by themselves establish mechanism. Product development benefits from fitting multiple models across temperature, moisture, and pH conditions rather than reporting a single best-fit coefficient from water extraction (Chen et al., 2025; Luo et al., 2021; Luo et al., 2024; Wang et al., 2025).

A critical reporting improvement would be to express release as both percentage of product nutrient and absolute nutrient mass per unit fertilizer dose, then link those values to crop demand and uptake.

Release should be reported both as percentage of nutrient inventory and as absolute nutrient mass per unit product or area, then compared with crop demand and uptake. A slow release curve is not automatically desirable if it represents incomplete nutrient delivery within the agronomic time window.

7. Soil–plant performance: the decisive fertilizer test

The soil–plant system is the decisive test of fertilizer function. Evidence across meta-analyses and long-term trials shows both positive and neutral outcomes, underscoring that biochar-based fertilizer performance is conditional rather than intrinsic (Cheng et al., 2025; Han et al., 2023; Hosseini Bai et al., 2022; Jiao et al., 2025; Y. Zhai et al., 2026).

7.1. Soil controls on response

Biochar commonly increases soil pH when ash and alkaline minerals are abundant. Application rate must therefore be calibrated to soil buffering capacity rather than transferred directly between soils (Jin et al., 2024; Zhang et al., 2026).

Surface oxidation and functional groups can increase effective CEC over time, particularly in weathered or sandy soils. The agronomic benefit is strongest when

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nutrient retention is a limiting process rather than when soil fertility is already high (Knoblauch et al., 2021; Xu et al., 2021).

Improved water retention can indirectly increase nutrient-use efficiency by maintaining root–soil contact and reducing drought stress. It should not be generalized to fine-textured soils, where hydrological changes may be small and crop response driven mainly by nutrient or pH effects (Han et al., 2023; Knoblauch et al., 2021).

The microbiome mediates nutrient mineralization, immobilization, P solubilization, and N transformations. The resulting response is context-dependent because microbial communities, substrate availability, and soil moisture differ strongly among sites (Liu et al., 2023; Rong et al., 2023).

Nutrient availability bridges material chemistry and crop response. Soil-specific testing is therefore essential before making broad fertilizer claims (Carneiro et al., 2021; Cheng et al., 2025; Zhang et al., 2026; Zhang et al., 2025).

7.2. Uptake, nutrient-use efficiency, and yield

Crop uptake provides stronger evidence than extractable soil nutrients because it integrates root access over time. Localized placement may further improve uptake by concentrating nutrient and carbon near roots while reducing the total application rate (Bao et al., 2024; Frene et al., 2025; Loginova et al., 2026; Y. L. Zhai et al., 2026).

Efficiency metrics are particularly useful because they separate crop production from nutrient input. PUE and KUE remain less consistently reported and should be standardized because they directly test whether the carbon matrix converts recovered nutrient into plant biomass (Al-Amin et al., 2026; Banik et al., 2023; Dissanayake et al., 2026; Mustaffa et al., 2024; Preza Fontes et al., 2024; Zhao et al., 2022).

Yield remains the most policy- and farmer-relevant endpoint, but it can mask nutrient inefficiency at high fertilizer rates. Conversely, a seven-year field study found no crop-growth or yield improvement from biochar in a semi-humid region, providing an

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important counterexample to claims of universal benefit (Cheng et al., 2025; Dissanayake et al., 2026; Omidvar et al., 2026).

7.3. Context dependence and contradictory field evidence

Soil dependence is not experimental noise; it is part of the technology. Multi-soil experiments and explainable machine learning increasingly identify pH, texture, application rate, and baseline fertility as key moderators (Jin et al., 2024; Wang et al., 2026; Xu et al., 2025; Y. Zhai et al., 2026; Zhang et al., 2026).

The literature contains both positive and neutral responses, and this heterogeneity should be treated as mechanistic information rather than noise. The seven-year neutral-yield result reported by Cheng et al. (2025), alongside positive nutrient-efficiency and crop-response studies, shows why baseline fertility, soil buffering, crop demand, rate, placement, and product chemistry must be reported before a fertilizer claim is generalized (Al-Amin et al., 2026; Dissanayake et al., 2026; Omidvar et al., 2026; Zhao et al., 2022).

To make soil dependence operational rather than treating it as experimental noise, Table 8 summarizes the main soil–plant modifiers and the response variables that should accompany agronomic validation of carbonaceous fertilizers.

Table 8. Soil–plant factors that control agronomic response to carbonaceous fertilizers

Modifier	Why it matters	Recommended response variable
Soil pH/buffering	Controls P mineral dissolution, surface charge, micronutrient availability	pH change + nutrient availability + tissue concentration
Texture / CEC	Controls nutrient retention, water storage, transport	Leaching + exchangeable nutrients + uptake
Baseline fertility	Determines probability of crop response	Yield response per unit nutrient added
Salinity / EC	May increase with ash-rich products	EC + emergence + ion balance
Crop nutrient demand	Controls timing and magnitude of required release	NUE/PUE/KUE + yield

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Modifier	Why it matters	Recommended response variable
Application rate/placement	Controls pH, salinity, nutrient concentration, economics	Dose-response + localized vs broadcast efficiency
Trial duration	Captures residual and legacy effects	Multi-season yield, SOC, nutrient balance

Note. Evidence-summary table of soil–plant response modifiers.

The table supports a shift from single-soil proof-of-concept experiments toward factorial validation across contrasting soils, because a fertilizer claim that only holds under one favorable soil chemistry is a niche product rather than a general fertilizer platform.

8. Carbon permanence and net life-cycle climate performance

Fertilizer function and climate performance can coexist, but they must be accounted for independently. Carbon permanence is evidence about storage durability; it is not, by itself, a complete greenhouse-gas balance or a certificate of carbon removal.

8.1. Stable carbon, priming, and soil organic carbon

Pyrolysis generally produces more aromatic and persistent carbon than HTC, although stability varies with feedstock and temperature. Field recovery of aged biochar provides valuable validation of persistence beyond short incubation studies (Chiaramonti et al., 2024; Sanei et al., 2025; Sanei et al., 2026).

Biochar can alter the decomposition of native soil organic matter through positive or negative priming. Consequently, adding stable char does not guarantee an equivalent increase in net SOC; responses must account for interactions with pre-existing soil carbon (Bekchanova et al., 2024).

SOC response reflects both the carbon added in biochar and changes in native SOC. Predictive models now attempt to estimate SOC response from site and product properties, though independent validation remains important (Xu et al., 2021; Xu et al., 2025).

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8.2. Field GHGs, energy, transport, and counterfactuals

N_2O can materially change the climate balance because of its high global-warming potency. N_2O should therefore be measured in field systems where N fertilizers are reduced or reformulated rather than assumed from generic biochar effects (L. L. Zhai et al., 2026).

CO_2 emissions arise during feedstock decomposition, thermal conversion, energy generation, transport, and soil processes. Carbon-removal claims require the persistent fraction of char carbon to exceed upstream and downstream fossil and non-CO_2 greenhouse-gas burdens over the chosen accounting horizon (Gamaralalage et al., 2025; Li et al., 2024; Xia et al., 2024).

Methane effects are most important when the feedstock would otherwise decompose anaerobically or when biochar changes emissions from flooded soils or waste management. A biochar system based on residue that would otherwise be efficiently utilized cannot automatically claim the same avoided-emission benefit (Gamaralalage et al., 2025; Qian et al., 2026).

Transport matters because biochar can have low bulk density and long hauling distances. Carbon accounting should include feedstock collection, centralized versus distributed processing, product transport, and field application logistics (Furuhashi et al., 2024; Senadheera et al., 2025).

Process energy depends on feedstock moisture, reactor integration, heat recovery, and co-product use. LCA results are therefore technology-specific, and process integration can be as important as carbon yield (Gamaralalage et al., 2025; Li et al., 2024; Xia et al., 2024).

8.3. Permanence, avoided emissions, and carbon-removal claims

Permanence is the fraction of stored carbon expected to remain outside the atmosphere over the accounting period. Regulations for certified permanent carbon removal are also evolving, increasing the need to connect analytical indicators with

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recognized certification methodologies (European Commission, 2026; Sanei et al., 2025; Sanei et al., 2026).

A persistent carbon fraction can coexist with an unfavorable life-cycle GHG result if processing energy is fossil-intensive, transport is excessive, the char is insufficiently stable, process-water treatment is burdensome, or the feedstock counterfactual already avoids emissions. Conversely, avoided methane or displaced waste treatment can improve the project GHG balance without equaling durable atmospheric carbon removal. Report these categories separately before aggregation (Gamaralalage et al., 2025; Li et al., 2024; Sun et al., 2025; Xia et al., 2024).

Figure 4 converts the two performance boundaries into a final outcome space rather than repeating the sequential decision logic of Figure 1.

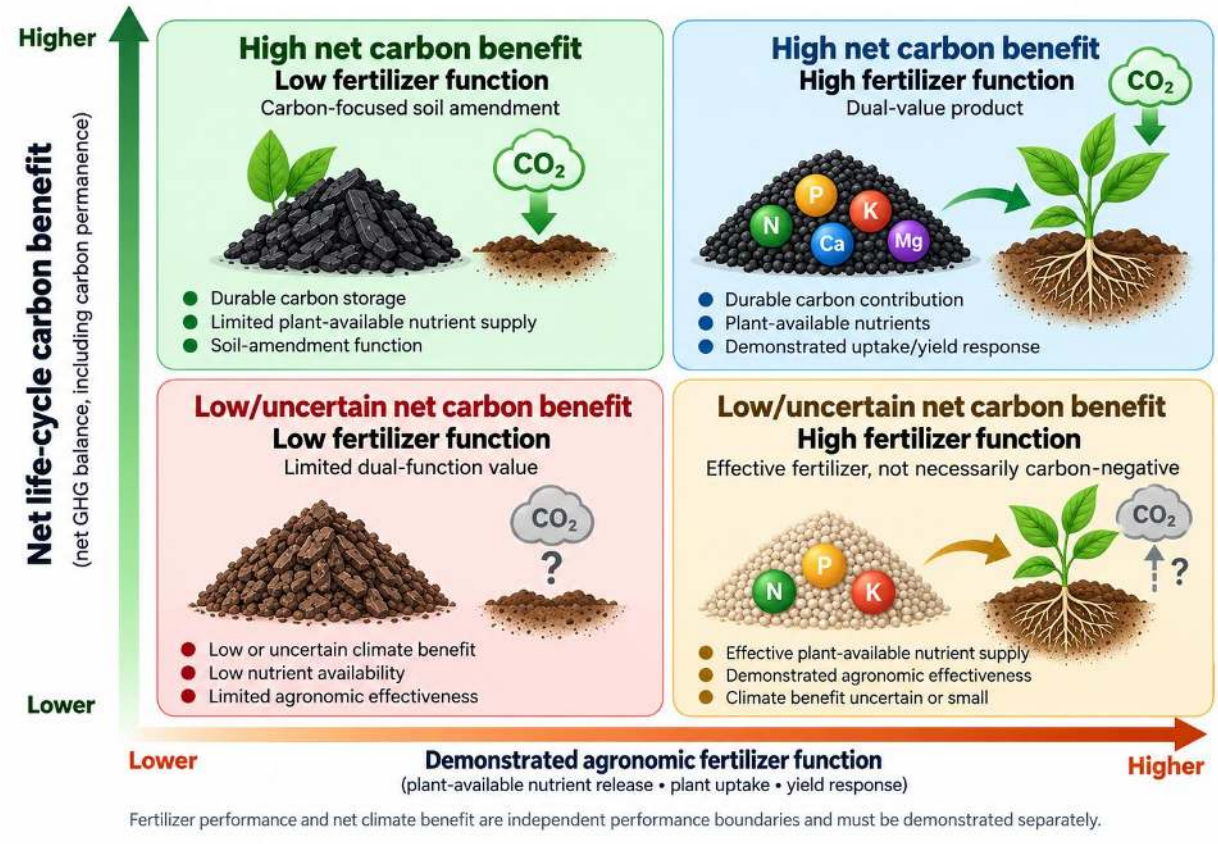

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Figure 4. Two-dimensional outcome space separating demonstrated agronomic fertilizer function from net life-cycle climate benefit

Note. Author-developed conceptual synthesis based on Bekchanova et al. (2024), Li et al. (2024), Sanei et al. (2025, 2026), and Xia et al. (2024). High climate benefit does not necessarily imply certified carbon removal, and strong fertilizer performance does not establish a net-negative GHG balance.

The strongest dual-purpose products are therefore not simply those with the highest carbon or nutrient concentration, but those that combine plant-available delivery, durable carbon, low process burden, safe composition, and marketable physical quality within auditable system boundaries.

9. Contaminants, safety, and environmental risk

Agricultural use moves carbonaceous materials from a waste-management system into soils and food-production chains, making contaminant control a non-negotiable gate. Safety assessment must therefore combine product analysis with realistic soil exposure and crop uptake (Albert et al., 2021; Coelho et al., 2025; Dong et al., 2025).

9.1. Potentially toxic elements and metal mobility

Many mineral-associated metals tend to become concentrated on a dry-mass basis as organic matter is removed during pyrolysis, but volatility and phase partitioning are element-, species-, temperature-, atmosphere-, and matrix-dependent; the blanket assumption that all PTEs are nonvolatile is not defensible. Long-term field work indicates that bioavailability can remain limited for some sludge-derived chars, but this cannot be generalized across feedstocks or process conditions (Albert et al., 2021; Chagas, de Figueiredo, da Silva, & Paz-Ferreiro, 2021; Wei et al., 2024).

Pyrolysis can stabilize metals through mineral encapsulation, precipitation, and changes in surface sorption, often reducing short-term leachability. The appropriate claim is therefore reduced mobility under tested conditions rather than permanent immobilization (Chagas, de Figueiredo, da Silva, & Paz-Ferreiro, 2021; Dong et al., 2025).

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9.2. PAHs, PFAS, dioxins, and PCBs

PAHs may form during incomplete pyrolysis or condense from vapors onto char. Agricultural products should be produced under controlled conditions that minimize condensation of tars and should be tested using standardized PAH methods rather than assuming that thermal treatment eliminates organic contaminants (Devi & Dalai, 2023; European Biochar Certificate, 2025).

PFAS have become a critical issue for biosolids-derived biochar. Pilot work and co-pyrolysis studies are beginning to quantify destruction, transformation, and emission pathways, while techno-economic analysis indicates that PFAS treatment can materially affect system cost (Hakeem et al., 2026; Keller et al., 2024; Rathnayake et al., 2025; Sørmo et al., 2023).

Dioxins and PCBs require targeted verification when chlorine, catalytic metals, or contaminated feedstocks are present. Product certification should therefore adopt feedstock risk screening and process-specific contaminant panels appropriate to the residue class, with particular attention to sewage sludge and mixed municipal feedstocks (Dong et al., 2025; European Biochar Certificate, 2025).

9.3. Sewage-sludge products, leaching, and ecotoxicity

Sewage-sludge biochar sits at the intersection of nutrient recovery and contaminant risk. Industrial-scale pyrolysis studies and pilot phosphate-recovery work show increasing technical maturity, yet agricultural acceptance depends on consistent feed quality and regulatory compliance (de Figueiredo et al., 2021; Hakeem et al., 2026; Pap et al., 2026; Wei et al., 2024).

Leaching tests should address both nutrients and contaminants. Multiple extraction conditions, soil column tests, and crop uptake are therefore preferable to a single standardized leach test when assessing agricultural performance (Chagas, de Figueiredo, da Silva, & Paz-Ferreiro, 2021; Coelho et al., 2025; Costa et al., 2026).

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Ecotoxicity integrates effects that chemical analysis can miss. Germination, soil-organism, aquatic, and longer-term plant tests provide an additional safety layer, especially for engineered or waste-derived products (Coelho et al., 2025; Dong et al., 2025).

Safety should therefore be treated as a gate rather than a co-benefit. A product that performs agronomically but fails contaminant, ecotoxicity, or exposure requirements should not advance to agricultural commercialization.

10. Product engineering, commercial quality, and regulatory fit

A scientifically effective powder is not automatically a commercial fertilizer. Product engineering therefore deserves equal status with nutrient chemistry in scale-up decisions (Chen et al., 2025; Furuhashi et al., 2024; Grafmüller et al., 2024; Senadheera et al., 2025; Wang et al., 2025).

10.1. Density, dust, granulation, and mechanical integrity

Fine biochar powders have low bulk density, create dust, segregate during blending, and can be difficult to meter uniformly. Densification is therefore not only a convenience; it changes the economic and environmental performance of the product (Furuhashi et al., 2024; Senadheera et al., 2025).

Dust loss reduces the applied nutrient and carbon dose while creating nuisance and inhalation concerns. Pelletization, granulation, binders, or slurry-based products can reduce dust, but each adds cost and can alter release kinetics (Chen et al., 2025; Rubel et al., 2026).

Low bulk density increases storage and transport volume per unit nutrient. Economic comparisons should therefore use cost per kilogram of delivered nutrient and, where relevant, per tonne of durable carbon rather than cost per tonne of product (Rubel & Wei, 2025; Trollip & Merckel, 2025).

Granulation can produce fertilizer-sized particles compatible with conventional spreaders and can integrate binders and mineral nutrients. Granule engineering should

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optimize strength without sealing nutrients too effectively (Chen et al., 2025; Grafmüller et al., 2024).

Pelletization is particularly relevant for manure compost and low-density biochar. In biofertilizers, pelletization conditions can also reduce microbial viability, creating a trade-off between physical quality and biological function (Furuhashi et al., 2024; Rubel et al., 2026).

Crushing strength must be high enough for transport and handling but low enough to disintegrate when release depends on particle breakdown. Report mechanical testing alongside nutrient-release curves because a formulation that performs in intact laboratory granules may behave differently after real logistics and field spreading (Chen et al., 2025; Wang et al., 2025).

10.2. Hygroscopicity, blending, and storage

Hygroscopic fertilizer cakes deform and change release behavior during storage. Packaging and storage studies are rarely reported but become necessary once hygroscopic mineral nutrients are incorporated into carbon matrices (Sim et al., 2021; Sim et al., 2025).

Blending biochar with conventional fertilizer is attractive because it uses existing nutrient products, but differences in particle size and density can cause segregation during transport and spreading. Blending studies should therefore assess physical homogeneity after realistic handling, not just initial laboratory mixing (Grafmüller et al., 2024; Li et al., 2026).

Storage stability includes moisture uptake, nutrient migration, coating integrity, microbial survival, and mechanical durability. Commercial product specifications should therefore include shelf-life testing under relevant temperature and humidity conditions (Rubel & Wei, 2022; Rubel et al., 2026; Sim et al., 2021).

The product-engineering literature suggests that the future market will favor carbonaceous fertilizers that can be treated as standard fertilizer products—with defined

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granule size, nutrient grade, storage stability, and application behavior—rather than as variable bulk chars.

10.3. Safety and regulatory gates

To translate contaminant, product-quality, and compliance concerns into development decisions, Table 9 summarizes the principal safety, regulatory, and commercialization gates to examine before advancing fertilizer or climate-related market claims.

Table 9. Safety, regulatory, and commercialization gates for biochar/hydrochar fertilizer products

Gate	Minimum question	Example evidence/criterion
Feedstock acceptance	Is the incoming residue suitable and traceable?	Source control; contaminant screening; batch traceability
Thermal process control	Does processing consistently achieve target conversion?	Temperature–time records; emissions control; product QA
PTEs and organics	Are contaminants below applicable thresholds and acceptably mobile?	Total + leachable PTEs; PAHs; PFAS where relevant
Agronomic safety	Does the product avoid phytotoxicity/salinity problems?	EC, pH, germination, soil/crop testing
Fertilizer compliance	Can nutrient claims be guaranteed?	Declared nutrient content + availability/release evidence
Carbon claim	Is permanence and net removal auditable?	Recognized carbon accounting and certification method
Market quality	Can the product be stored, transported, and applied?	Granule size, dust, bulk density, strength, hygroscopicity

Note. Regulatory-synthesis table; criteria are conceptual decision gates and do not constitute universal compliance requirements.

Fertilizer and carbon markets impose overlapping but non-identical compliance systems. A product can satisfy contaminant limits yet fail nutrient-label or release requirements, and it can satisfy fertilizer rules without providing the monitoring, additionality, durability, or life-cycle evidence needed for a carbon-removal claim.

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Regulatory constraints are especially important for sewage-sludge products because fertilizing-product rules, pyrolysis material categories, contaminant limits, waste-derived product status, and carbon-removal certification can overlap. Regulatory acceptance should therefore be designed into feedstock selection and process monitoring rather than addressed after product development (European Biochar Certificate, 2025; European Commission, 2021; European Commission, 2026; European Parliament & Council of the European Union, 2019).

This review provides a conceptual regulatory map, not a universal compliance determination. Agricultural use must be assessed under jurisdiction-specific rules for fertilizer, waste, biosolids, contaminants, labeling, product status, and carbon credits. Compliance with one framework cannot automatically transfer to another jurisdiction, and carbon-removal certification does not establish fertilizer-market compliance. Regulatory acceptance should therefore be designed into feedstock selection, traceability, process monitoring, quality assurance, and product specification rather than treated as an end-of-pipe documentation exercise (European Biochar Certificate, 2025; European Commission, 2021; European Commission, 2026; European Parliament & Council of the European Union, 2019).

11. Long-term evidence, techno-economics, life-cycle assessment, and scale-up

Scale-up requires evidence that persists beyond a successful batch test, and that remains valid after product engineering, storage, transport, application, and field exposure. Figure 5 operationalizes this requirement as a proposed evidence-maturity pathway.

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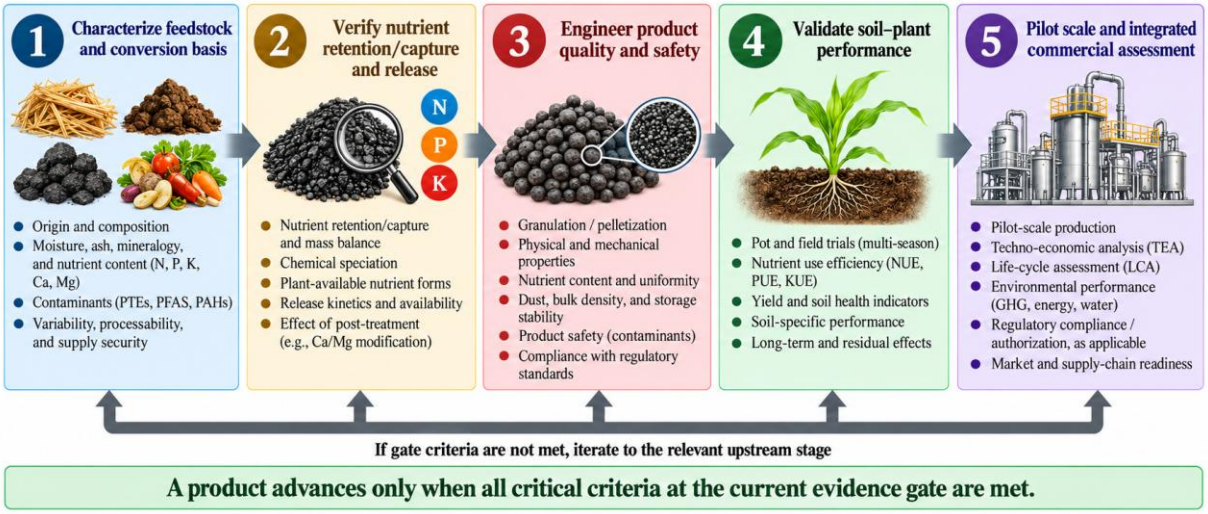

Figure 5. Proposed evidence-maturity and decision-gate pathway for engineered carbonaceous fertilizers

Note. Author-developed conceptual synthesis based on Keller et al. (2024), Rubel and Wei (2025), Gamaralalage et al. (2025), Pap et al. (2026), and Senadheera et al. (2025). The gates are a decision framework proposed in this review, not an established regulatory standard.

The decision structure in Figure 5 also allows a project to exit rationally at an earlier stage—for example, as a soil amendment or wastewater sorbent—rather than forcing every carbonaceous product into a fertilizer category.

11.1. Multi-year agronomy and persistence

Multi-year evidence is essential because pH, nutrient pools, carbon oxidation, contaminant mobility, and crop response change over time. These contrasting results are among the strongest evidence that context must be treated as part of product performance (Chagas et al., 2021; Cheng et al., 2025; Jin et al., 2024; Rong et al., 2023; Zhang et al., 2026).

Carbon persistence and agronomic persistence are different. Long-term studies should therefore track carbon stocks and nutrient budgets separately (Carneiro et al., 2021; Chiaramonti et al., 2024; Rong et al., 2023).

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11.2. Techno-economic assessment and functional units

TEA converts laboratory formulation into a cost per unit product and, more importantly, cost per unit nutrient delivered. Revenue from carbon credits or avoided waste treatment can improve economics but should be treated as scenario-dependent (Dissanayake et al., 2026; Keller et al., 2024; Rubel & Wei, 2025; Trollip & Merckel, 2025).

Drying is a dominant burden for wet residues, whereas HTC trades drying energy for pressurized aqueous processing and downstream water treatment. Energy integration with pyrolysis gas or local waste heat can materially change both OPEX and LCA, making site configuration a first-order design variable (Belete et al., 2021; Gamaralalage et al., 2025; Rubel & Wei, 2025).

Cost per kilogram of nutrient is particularly useful for comparing engineered carbon fertilizers with conventional fertilizers. TEA should therefore use effective nutrient content rather than total nutrient content whenever possible (Dissanayake et al., 2026; Rubel & Wei, 2025; Trollip & Merckel, 2025).

11.3. Life-cycle assessment, pilot evidence, and technology readiness

LCA results depend on the functional unit and system boundary. Reviews and feedstock-specific LCAs show that no single functional unit suits all claims (Gamaralalage et al., 2025; Li et al., 2024; Xia et al., 2024).

Table 10 standardizes functional units by claim so mass-based, agronomic, and climate comparisons are not conflated.

Table 10. Recommended functional units for TEA, LCA, and carbon-accounting comparisons

Decision question	Recommended functional unit	Interpretive use
Feedstock conversion efficiency	Per tonne dry feedstock processed	Compares mass/energy recovery and process burdens before differences in product yield are hidden.
Product manufacture	Per tonne finished product	Useful for plant throughput, storage,

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Decision question	Recommended functional unit	Interpretive use
		transport, and manufacturing cost; insufficient alone for fertilizer value.
Fertilizer delivery	Per kilogram plant-available nutrient delivered	Compares products with different total nutrient contents, release fractions, and recovery efficiencies.
Agronomic performance	Per hectare per crop season	Links product dose, soil/crop response, field GHGs, nutrient losses, and management.
Yield-normalized performance	Per unit yield maintained or increased	Tests whether apparent benefits persist when productivity is the service provided.
Durable carbon-removal claim	Per tonne CO_2-equivalent durably removed	Requires explicit permanence, leakage, process emissions, counterfactuals, and allocation rules.
Waste-management service	Per tonne residue managed	Appropriate for avoided-treatment comparisons; should not be presented as equivalent to durable carbon removal.

Note. Author-developed analytical synthesis based on the functional-unit and system-boundary issues discussed by Gamaralalage et al. (2025), Li et al. (2024), Rubel and Wei (2025), Trollip and Merckel (2025), and Xia et al. (2024). Select functional units to match the asserted service or claim.

Pilot-scale evidence remains limited but is increasing. Pilot results should include mass and energy balances, not only product samples (Hakeem et al., 2026; Pap et al., 2026).

Assign technology readiness based on the weakest critical subsystem. Conversely, a conventional granulation process can reduce development risk when coupled to a novel but well-characterized nutrient-loaded char (Senadheera et al., 2025; Sim et al., 2025).

The combined evidence suggests that scale-up decisions should be based on a multi-criteria boundary: agronomic effectiveness, safe nutrient and contaminant behavior, physical product quality, manufacturing economics, life-cycle performance, and regulatory fit.

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Table 11 places representative techno-economic and life-cycle studies against the decisions they can support, highlighting how economic and environmental evidence should be interpreted within functionally relevant product and system boundaries.

Table 11. Representative techno-economic and life-cycle evidence and its decision relevance

Study	Assessment emphasis	Decision-relevant lesson
Keller et al. (2024)	Feasibility and TEA of biosolids pyrolysis for removal of microplastics, PFAS, and PPCPs	Contaminant-control requirements can materially influence process configuration and economics.
Li et al. (2024).	Review of agricultural biochar LCA	Functional unit, system boundary, feedstock counterfactual, and co-product treatment strongly influence conclusions.
Xia et al. (2024).	Feedstock-specific GHG LCA for biochar soil amendment	No single feedstock or carbon concentration guarantees the best GHG outcome.
Gamaralalage et al. (2025).	Integrated TEA/LCA for food-waste digestate to biochar and field use	Consider site energy integration, wet-feedstock handling, field application, and avoided treatment together.
Rubel & Wei (2025)	Economic assessment of controlled-release N fertilizer at industrial scales	Compare scale, formulation, and product manufacturing costs per unit effective nutrient delivered, not just per tonne of product.
Trollip & Merckel (2025).	Techno-economic feasibility of nutrient-enriched biochar	Nutrient enrichment can create value but depends on feedstock, processing, product specification, and market assumptions.
Dissanayake et al. (2026).	Agronomic and economic performance of biochar-based fertilizer	Economic value strengthens when reduced nutrient input is demonstrated without a yield penalty.

Note. Evidence-summary table of representative TEA/LCA evidence and decision relevance.

Table 11 shows why TEA and LCA should be linked to functionally relevant outputs. For fertilizer claims, cost per kilogram plant-available or crop-recovered nutrient is more informative than cost per tonne of char. For climate claims, the functional unit should match the assertion, such as per hectare-year, per tonne residue managed, or per tonne CO_2-equivalent durably removed, while avoided emissions are reported separately when appropriate.

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12. Predictive design and priority research gaps

The next phase of research is moving from descriptive characterization toward predictive product design. Machine learning can integrate feedstock composition, process severity, material properties, soil conditions, and crop response, but only if datasets contain consistent outputs that reflect fertilizer function. Models trained only on char yield, surface area, or total NPK risk optimizing variables that are weakly connected to crop performance (Chen et al., 2023; Leng et al., 2022; Li et al., 2022; Liu et al., 2025; Xie et al., 2025).

12.1. Machine learning as decision support, not a substitute for validation

Machine-learning models have already predicted hydrochar characteristics, biochar yield and composition, P fate, crop yield, and soil organic carbon. Explainable approaches are particularly valuable because they can identify threshold effects and interactions among pH, application rate, feedstock, and process temperature. The strongest use case is decision support that narrows experimental space, not replacement of field validation (Chen et al., 2023; Ge et al., 2025; Jiao et al., 2025; Leng et al., 2022; Li et al., 2022; Liu et al., 2025; Xu et al., 2025; Y. Y. Zhai et al., 2026).

Minimum reporting standards for machine-learning applications should include, at minimum, feedstock composition and provenance; process temperature, residence time, heating mode and/or HTC severity; nutrient speciation and analytical method; nutrient-loading and release-test method; initial soil pH, texture, CEC, organic carbon, salinity and baseline fertility; crop species and growth conditions; trial duration; contaminant and safety results where relevant; and field-validation status. Model studies should additionally report sample size, missing-data treatment, feature definition, train/validation/test splitting, performance metrics, uncertainty, applicability domain, and external validation when available. Without these fields, model accuracy can reflect data-set regularities while remaining weakly transferable to fertilizer performance.

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12.2. Soil-specific and feedstock–process–property models

Soil-specific recommendations are necessary because the same product can be beneficial, neutral, or potentially harmful across contrasting soils. Predictive tools should therefore use initial soil pH, texture, CEC, organic carbon, salinity, available N/P/K, climate, crop, and placement as input variables. Machine-learning approaches for P availability and crop growth demonstrate the feasibility of this direction, but independent datasets are still limited (Wang et al., 2026; Y. Zhai et al., 2026; Zhang et al., 2026).

Feedstock–process–property models should be extended from generic char properties to nutrient speciation, release, contaminant behavior, and physical product quality. For pyrolysis, key outputs include N retention, P mineralogy, K release, stable carbon, and PAHs; for HTC, they should include nutrient partition to process water and hydrochar stability. Data augmentation can help sparse datasets but cannot compensate for inconsistent analytical definitions (Ge et al., 2025; Liu et al., 2025; Xie et al., 2025).

12.3. Crop-response prediction and evidence balance

Crop-response models should predict yield and nutrient uptake relative to a defined fertilizer control, not absolute yield alone. This requires comparable nutrient doses and baseline fertility data. Current models show that crop response can be predicted from biochar and soil features, but they must explicitly handle the class imbalance between positive and neutral/negative outcomes to avoid optimistic recommendations (Jiao et al., 2025; Xu et al., 2025; Y. Y. Zhai et al., 2026).

12.4. Priority research gaps

Five research gaps are most consequential. First, whole-process nutrient mass balances are needed for pyrolysis and especially HTC, including liquid and gas streams. Second, nutrient-release tests should be calibrated against plant uptake and multi-season field response. Third, safety studies must integrate PTEs, PAHs, PFAS, salinity, and ecotoxicity for waste-derived products. Fourth, product engineering should be reported alongside agronomy so granules, pellets, coatings, and microbial formulations

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are evaluated after realistic storage and handling. Fifth, TEA and LCA should use functionally relevant units such as cost per kilogram plant-available nutrient and net greenhouse-gas balance per hectare or tonne CO_2-equivalent removed (Costa et al., 2026; Dong et al., 2025; Keller et al., 2024; Pap et al., 2026; Rubel & Wei, 2025; Senadheera et al., 2025; Sim et al., 2025; Trollip & Merckel, 2025).

A sixth cross-cutting gap follows from the evidence-maturity appraisal: future studies should report negative and neutral outcomes with the same detail as positive outcomes. Models and reviews trained on selectively successful formulations risk inflating expected performance and obscuring the soil, crop, or process conditions under which a product should not be recommended.

12.5. Limitations of the review method and evidence base

This review has methodological limitations that constrain the strength of inference. First, it is a structured critical narrative review, not a systematic review: we did not preserve the earliest Google Scholar retrieval counts, intermediate duplicate-removal totals, or article-by-article full-text exclusion reasons, and we did not fabricate retrospective counts. Second, a single reviewer/author classified evidence without independent coding or inter-rater reliability testing. Supplementary Table S1 improves source-level auditability, but it is a retrospective evidence map of the retained corpus rather than an independent validation exercise. Third, the evidence base is heterogeneous across laboratory experiments, pot studies, field trials, reviews/meta-analyses, pilot demonstrations, TEA/LCA studies, regulatory documents, and machine-learning analyses, so the synthesis does not imply pooled effect estimates or common statistical weights. Fourth, full-text accessibility status was not prospectively logged during initial discovery, and bibliographic metadata for fast-moving 2026 literature may continue to evolve even after the 11 September 2026 verification audit.

External validity is similarly bounded. A sewage-sludge biochar, manure-derived biochar, crop-residue biochar, digestate hydrochar, mineral-engineered phosphate sorbent, and coated NPK granule should not be treated as interchangeable products.

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Claims should be transferred only among products with comparable feedstock chemistry, conversion conditions, nutrient form, soil context, contaminant profile, and product-engineering status. Regulatory conclusions are jurisdiction-specific, and soil dependence is a component of product performance. These boundaries are especially important for hydrochar because process-water management, dissolved-organic species, wet logistics, and generally lower carbon permanence relative to high-temperature biochar can shift both agronomic and life-cycle outcomes.

13. Conclusions

Biochar and hydrochar are not inherently fertilizers, and persistent carbon does not inherently establish a net-negative life-cycle greenhouse-gas balance. The Dual-Performance Boundary Framework for Carbonaceous Fertilizers (DPB-CF) separates these two claims and requires fit-for-purpose evidence for each. Fertilizer value emerges from a chain that begins with feedstock composition and thermochemical partitioning, continues through nutrient speciation, recovery, formulation, and release, and is ultimately tested by plant-available delivery, crop uptake, nutrient-use efficiency, yield, safety, and product quality under relevant soil conditions. Soil dependence is therefore part of the technology, not experimental noise. Hydrothermal carbonization requires explicit accounting of process water and post-treatment, whereas dry pyrolysis requires attention to volatile and gaseous nutrient losses as well as the condensed solid. The three-generation classification—amendment char, nutrient-enriched char, and engineered nutrient-recovery fertilizer—is an author-developed evidence framework, not a certification system. For climate claims, permanence must be embedded in a complete life-cycle boundary that includes counterfactual feedstock fate, energy, transport, co-products, field greenhouse-gas fluxes, and end use. The most credible development pathway is consequently not maximum char yield, total NPK, sorption capacity, or carbon concentration, but auditable recovery to crop uptake, multi-season validation, consistent product quality, contaminant control, appropriate functional units, and transparent scale-up and regulatory gates.

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Declarations

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Conflict of Interest

No conflict of interest was reported.

Data Availability

No new experimental datasets were generated. The analytic synthesis is based on the 122-source corpus cited in the manuscript; source-level coding is provided in Supplementary Table S1.

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Supplementary material

To make the literature-selection pathway auditable without reconstructing unavailable historical counts, Supplementary Table S2 summarizes each source-selection stage, the documented count or status, and the decision rule applied during the retained-corpus audit.

Supplementary Table S2. Source-selection flow for the retained analytic corpus

Stage	Documented count/status	Decision rule / audit statement
Google Scholar discovery and structured update (2020–4 Sep 2026)	Original retrieval count not retained	Seven Boolean blocks plus citation chaining; no retrospective hit count invented.
Official regulatory/context retrieval	Targeted; intermediate count not retained	Official EU fertilising-product, pyrolysis-material, biochar-certification, and carbon-removal sources retained when directly relevant.
Duplicate/version resolution	Intermediate count not retained	DOI → normalized title → author–year; one retained source per work; stable version preferred.
Title/abstract relevance screening	Intermediate count not retained	Required direct connection to at least one manuscript decision boundary.
Article-level eligibility assessment	Article-by-article exclusion log not retained	Eligibility/exclusion criteria reported in Appendix A3; no reconstructed exclusion reasons.
Final analytic corpus	122 unique sources	All 122 are mapped in Supplementary Table S1.
Contextual foundational anchors added at revision	5; outside analytic corpus	Used only for durable agronomic/soil-chemistry/carbon principles; excluded from S1 and corpus counts.
2026/advance-online bibliographic audit	19 journal sources + 1 EU regulatory record in the analytic corpus	Publisher or official-source metadata checked on 11 Sep 2026; status preserved as version of record or advance online as applicable.

Note. Narrative source-selection flow. The table deliberately distinguishes documented final counts from unavailable historical intermediate counts and is not presented as a PRISMA flow diagram.