Biochar for climate, circularity and carbon markets: technologies, integrity, deployment gaps and pathways to scale

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Highlights

- Biochar is a pathway-specific carbon-removal system whose net outcome depends on feedstock, conversion, end use and MRV.
- Recent methodology advances tighten biomass sourcing, durability and additionality requirements.
- Technology selection must balance carbon stability, energy integration, emissions control, throughput and product-market fit.
- The most material scale barriers are fragmented feedstock, inconsistent quality, evidence costs, end-use traceability and financeable offtake.
- A stage-gated model links scientific validation, operating discipline and carbon-market integrity.

Abstract

Biochar has moved from a soil-amendment niche to one of the most active durable carbon dioxide removals (CDR) pathways. Its apparent simplicity, thermochemical conversion of biomass under oxygen-limited conditions, can conceal a complex climate claim. A verified tonne of biochar removal requires sustainable and additional feedstock, controlled conversion, stable carbon characterisation, traceable long-term end use, lifecycle emission accounting and independent monitoring, reporting and verification (MRV). This review evaluates the state of the art in biochar technologies, quality enhancement, carbon-market methodologies, research gaps, market gaps, business constraints and implementation bottlenecks. It integrates recent peer-reviewed literature with current rules from Puro.earth and Verra, which now place stronger emphasis on durable storage, responsible biomass sourcing, additionality, environmental safeguards and auditable application routes. The review finds that higher pyrolysis severity can improve aromaticity and stability but may lower char yield and alter nutrient, energy and product economics; therefore, "higher temperature" is not a universal optimisation rule. Feedstock heterogeneity, moisture, logistics, process emissions and uncertainty in end-use fate are the main causes of divergence between gross char production and net credited removal. Biochar currently has a comparatively advanced carbon-removal market position. The paper proposes a Biochar

Integrity and Deployment Framework that connects feedstock qualification, process control, product characterisation, end-use routing, digital chain of custody, lifecycle netting and post-issuance monitoring. The central conclusion is that high-integrity biochar is best understood as an integrated residue-management, materials, agriculture and carbon-accounting system rather than a standalone reactor business.

Keywords: biochar; pyrolysis; carbon dioxide removal; carbon markets; MRV; circular economy; biomass residues; carbon permanence; life-cycle assessment

1. Introduction

Biochar is a carbon-rich material produced by thermochemical conversion of biomass in oxygen-limited conditions and intended for beneficial, non-combustion use. Its climate relevance stems from converting part of short-cycle biomass carbon into a more persistent form, potentially avoiding open burning or decay emissions while creating a soil amendment or functional material [1–4]. The IPCC treats biochar as one of several CDR approaches only when atmospheric carbon is removed and stored durably after full lifecycle effects are considered [5].

This definition matters. A tonne of black solid leaving a reactor is not automatically a tonne of carbon removal. The feedstock may have had another durable or high-value use; collection and drying may create material emissions; process heat may be fossil-derived; a portion of the product may oxidise; and an application route may be difficult to trace. Conversely, well-controlled systems can couple residue management, low-carbon thermal conversion, useful co-products and durable carbon storage. Biochar therefore sits at the intersection of environmental chemical engineering, agriculture, resource recovery, industrial energy integration and carbon-market governance.

The review addresses the full value chain: technology pathways; advanced process and product improvements; soil and non-soil applications; carbon accounting and methodologies; research, market, business and implementation gaps; and a disciplined scale-up sequence. The paper is positioned for the Journal of Environmental Chemical Engineering because the core questions concern feedstock chemistry, thermochemical conversion, product characterisation, environmental performance, resource circularity and evidence-based climate claims.

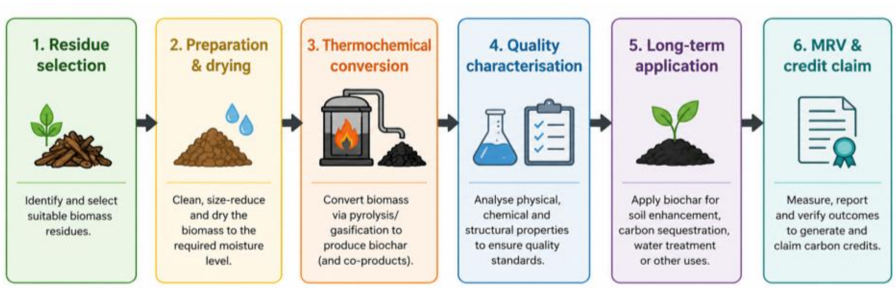

Figure 1. Integrated biochar value chain and the points at which the net climate outcome can be strengthened or lost

The climate value of biochar depends on how effectively each stage of the value chain is managed, from biomass selection to long-term carbon storage. Figure 1 illustrates the integrated biochar value chain and identifies the stages where the overall climate benefit can either be strengthened or reduced.

2. Review approach and evidence boundary

The review follows a structured evidence-mapping approach. Priority was given to authoritative synthesis reports, peer-reviewed process and field studies, recognised biochar standards, and current carbon-market methodology documents. Quantitative synthesis is descriptive because published studies use incompatible feedstocks, reactors, temperatures, residence times, particle sizes, soil conditions, application rates, functional units and lifecycle boundaries. The figures labelled "illustrative" are analytical aids built from transparent assumptions; they are not pooled market estimates.

Table 1. Evidence architecture and interpretation safeguards for this review

Evidence domain	Primary source type	Rule used in synthesis
Thermochemical performance	Peer-reviewed process studies and technical standards	Compare only after stating feedstock and reactor context.
Carbon removal and permanence	CDR assessments and methodology rules	Separate gross char carbon from net credited removal.
Market status	Registry and standard provider updates	Do not combine indicators with different dates or definitions.
Deployment feasibility	LCA, field evidence and operational logic	Use stage-specific constraints, not generic "scalability" claims.
India relevance	Project context and public biomass evidence	Treat regional feedstock and regulatory details as site-specific.

A structured evidence selection process helps ensure that conclusions are based on comparable and reliable sources rather than isolated findings. Table 1 summarizes the evidence architecture adopted in this review and explains the interpretation rules used to maintain consistency throughout the analysis.

3. Technology landscape and recent improvements

3.1 Feedstock selection and preparation

Agricultural residues, forestry residues, processing by-products, bamboo, manure-derived solids and selected organic wastes can serve as biochar feedstock. The optimal feedstock is not the most abundant material in isolation; it is the material that can be sourced without displacing a superior use, aggregated reliably, pre-processed safely, converted cleanly and routed to a traceable end use. Ash, volatile matter, fixed carbon, moisture, chlorine, sulphur, silica, nutrient content, heavy metals and particle-size distribution all influence reactor operation and product quality.

Recent improvements centre on feedstock traceability, moisture management, pre-treatment, densification, blending and contaminant screening. Mobile systems can reduce transport of low-density residues, whereas centralised facilities may enable better emissions control, laboratory quality assurance and energy integration. Neither architecture is universally superior: the correct choice depends on biomass radius, seasonality, road access, feedstock bulk density, heat demand and the need for consistent batch characterisation.

3.2 Thermochemical pathways

Slow pyrolysis is commonly selected where the aim is high char yield and relatively stable carbon. Fast pyrolysis favours liquids, whereas gasification favours combustible gas and usually leaves less char. Hydrothermal carbonisation can process wet feedstocks but creates hydrochar with distinct properties and requires careful handling of process water. Torrefaction and low-severity carbonisation can improve solid fuel properties but may not generate a product with the persistence or quality required for a removal claim. Reactor configurations include batch kilns, retorts, auger reactors, rotary kilns, screw reactors, fluidised beds and continuous industrial systems.

Technology improvements are increasingly directed to continuous feeding, oxygen control, heat recovery, syngas use, flue-gas treatment, automated temperature logging, batch traceability and emissions monitoring. The engineering objective is no longer merely "produce char"; it is to generate a reproducible material while recovering energy and preventing unaccounted methane, particulate matter and volatile-organic emissions.

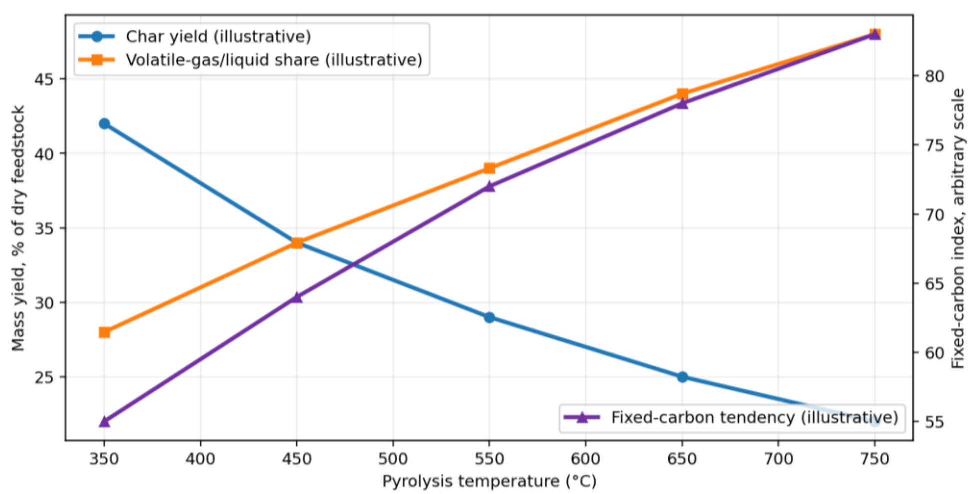

Figure 2. Directional process trade-offs with pyrolysis temperature. Lines are illustrative and must not be used as universal yield equations

Figure 2 illustrates the key design trade-off. In many lignocellulosic systems, increasing conversion severity can lower solid yield while increasing fixed-carbon content and reducing volatile components. This can improve stability indicators but may decrease mass throughput of char per tonne of feedstock. An optimum must therefore combine stable-carbon fraction, net energy, material quality, local application needs, air-emission performance and the methodology's crediting rules.

Table 2. Biochar technology pathways and the engineering conditions that determine their suitability.

Pathway	Typical operating character	Potential advantage	Critical engineering constraint	Best-suited decision context
Slow pyrolysis	Moderate temperature, longer residence; char-oriented	Higher char yield; adaptable scales	Heat balance, batch consistency, emissions control	Residue-to-char with soil or durable-material use
Fast pyrolysis	Rapid heating; liquid-oriented	Bio-oil co-product potential	Lower char fraction; product complexity	Integrated biorefinery setting
Gasification	High temperature, gas-oriented	Energy production and low tar	Lower char yield; ash/slag and gas cleaning	Energy-led facilities with char as secondary stream
Hydrothermal carbonisation	Wet-feedstock processing under pressure	Avoids extensive drying	Process-water management; hydrochar stability differs	Wet organic residues with treatment infrastructure
Retort / flame-curtain systems	Decentralised, simpler equipment	Lower entry barrier, local residue conversion	Quality variability and emissions monitoring	Small, controlled pilots with strong SOPs
Continuous reactor	Automated feeding and logging	Consistent batches, heat recovery and traceability	Capital, maintenance and reliable throughput	Commercial systems requiring uniform carbon product

Different thermochemical pathways provide distinct advantages and limitations, making technology selection highly dependent on feedstock properties and project objectives. Table 2 compares the major biochar production pathways by summarizing their operating characteristics, engineering constraints, and most suitable application scenarios.

3.3 Product improvement and functional applications

Biochar properties can be improved through controlled temperature profiles, residence time, activation, mineral or nutrient charging, compost blending, particle-size management and post-treatment. However, modification can change the carbon-accounting boundary. Adding nutrients, polymers or mineral binders may improve agronomic or material performance but also introduces upstream emissions and may alter the stability evidence required by a carbon methodology.

Soil application remains the principal use route, but non-soil applications are expanding: composting, livestock bedding, filtration media, anaerobic digestion support, construction materials, asphalt, concrete and polymer composites. Verra's VM0044 explicitly includes long-term soil and non-soil applications, including biochar-amended concrete and building materials, subject to methodology requirements [6]. Product design should begin with the end-use route because it determines the required specification, chain-of-custody evidence, storage duration and market economics.

4. Carbon removal, MRV and carbon-market integrity

A conservative biochar-removal calculation begins with sustainable biomass carbon and ends with carbon remaining out of the atmosphere in an eligible use route. A simplified expression is: Net CDR = stable biochar carbon stored − feedstock sourcing emissions − transport and drying emissions − conversion and auxiliary energy emissions − application/logistics emissions − leakage/displacement − uncertainty deduction. Methodologies specify their own parameters, eligibility tests, emission factors and durability approaches; the equation is a conceptual structure rather than a substitute for an approved calculation.

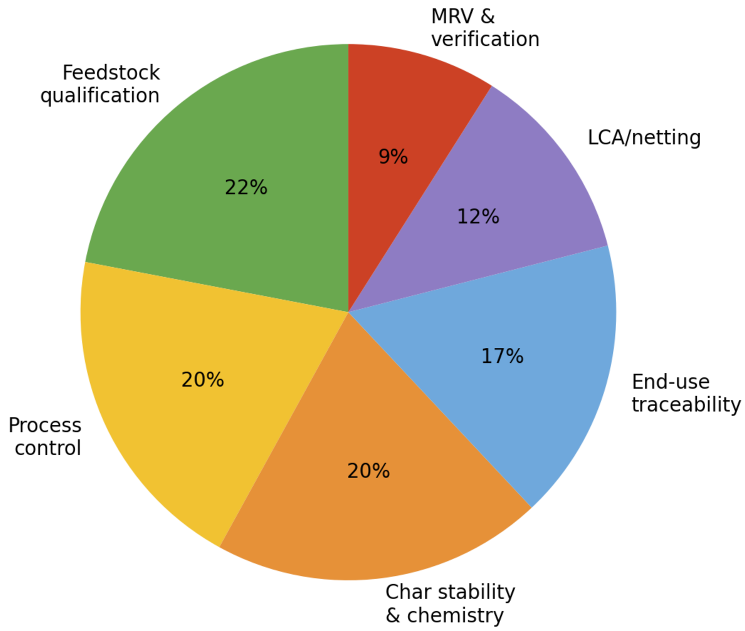

Figure 3. Analytical allocation of the evidence burdens in a high-integrity biochar carbon-removal claim

Figure 3 makes an important practical point: a laboratory certificate alone cannot establish a credit. The claim depends on an evidence chain spanning feedstock eligibility, process operation, product stability, application, lifecycle netting and verification. Digital MRV can strengthen mass-balance records, geo-tagging, batch certificates, transport logs and application evidence, but independent review remains necessary.

4.1 Methodology developments

Puro.earth's Biochar Methodology Edition 2025 introduced a CORC200+ durability label, stronger responsible-biomass and production guidance, and updated treatment of persistence. Puro.earth describes the label as representing several centuries of durability under its standard [7,8]. Verra's VM0044 v1.2 applies globally to eligible waste biomass converted in new facilities and applied to long-term soil and non-soil applications; it includes an investment-analysis requirement for additionality [6,9]. These developments show the market moving toward more explicit eligibility, durability and evidence requirements.

Methodology choice should be made early. It affects feedstock contracts, plant data logging, laboratory programme, application records, financial additionality evidence, validation schedule and buyer communication. Retrofitting the evidence chain after production is costly and can make otherwise useful biochar ineligible for crediting.

Table 3. Evidence chain required to transform a biochar production event into a defensible removal claim

Integrity element	Evidence needed	Frequent weak practice	High-integrity control
Feedstock eligibility	Source, prior use, rights, sustainability, moisture and contaminant records	Assuming all "waste" biomass is additional	Signed sourcing records and counterfactual assessment
Production traceability	Mass in/out, temperature logs, energy, batch ID, emissions control	Monthly estimates without reconciled mass balance	Continuous or batch-level records plus calibrated weighing
Stability / carbon content	Representative laboratory analysis and methodology-required parameters	Using one historical analysis for heterogeneous feedstocks	Sampling plan tied to batch and feedstock variability
End-use and storage	Application location, quantity, recipient or product route	Untracked retail resale or unverifiable disposal	Chain of custody, geo-tagging and approved application records
Net lifecycle result	All material emissions and leakage terms	Reporting gross char carbon as removal	Transparent LCA boundary and conservative deductions
Additionality	Investment, regulatory and common-practice evidence	Assuming carbon revenue is automatically additional	Methodology-aligned additionality assessment

The strength of a biochar carbon credit depends on demonstrating traceability and transparency throughout the production and application process. Table 3 outlines the essential evidence required for each integrity element while identifying common weaknesses and the controls needed to support a reliable removal claim

4.2 Market signals and interpretation

Biochar has become an important durable-CDR market pathway because it combines familiar conversion technology with relatively measurable production batches and a physical storage product. Puro.earth reported more than 408,000 issued biochar CORCs by June 2025 and described biochar as delivering 43% of market-verified durable removal volumes to buyers in that update [10]. Its January 2026 update reported 658,000 tCO_2e of biochar removals delivered since the start of 2022 and 302,000 tCO_2e retired by the end of Q2 2025 [11]. These numbers are evidence of activity and demand, not a direct price benchmark or a complete global market inventory.

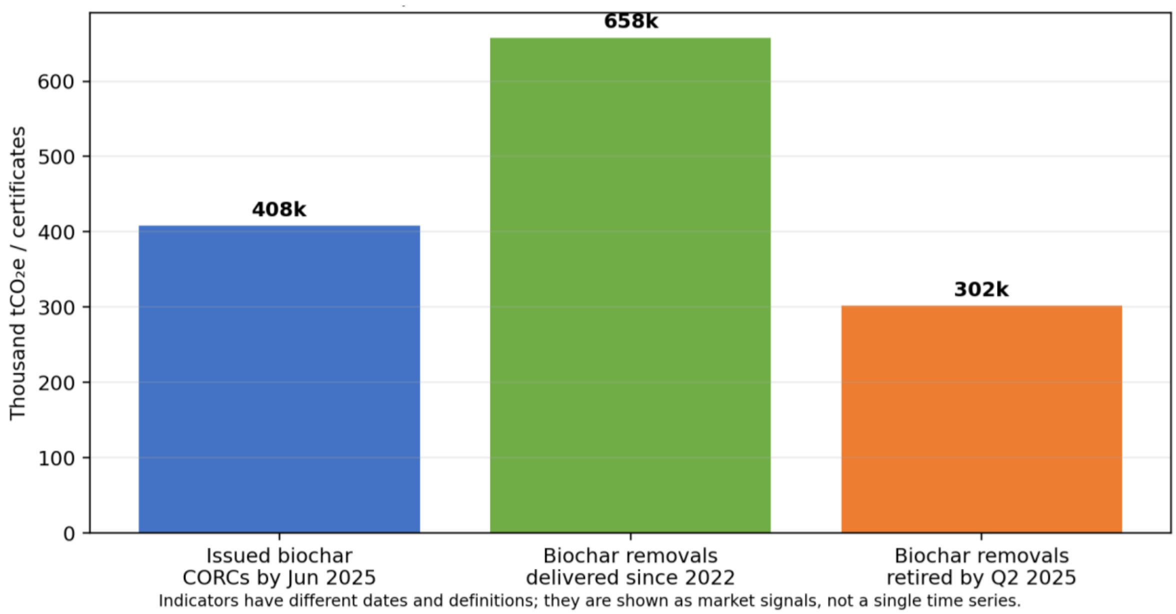

Figure 4. Selected reported market indicators for biochar carbon removal. Metrics have differing scopes and dates and must not be aggregated

The market is increasingly shaped by long-term offtake agreements, buyer scrutiny of durability and methods, and the demand for traceable supply. At the same time, it remains fragmented: project eligibility differs across standards; credit delivery depends on validation and verification timing; and high-quality buyers often require data access, technical diligence and contractual certainty beyond registry issuance. Market maturity is therefore a combination of physical capacity, evidence quality, contractual structure and credible demand, not simply the number of reactors.

5. Research gaps, market gaps and deployment gaps

5.1 Research gaps

The scientific literature is extensive but uneven. Major gaps include multi-year field evidence across soil classes and climates; harmonised measures of biochar persistence; robust treatment of priming effects and non-CO_2 emissions; fate of engineered or charged biochars; field-scale contaminant monitoring; and comparability of LCA boundaries. Much of the published performance evidence is derived from short-duration pot studies or specific feedstock–soil combinations. Extrapolation to a commercial, multi-feedstock operation should therefore be cautious.

5.2 Market and business gaps

The main market gap is the separation between a physical product market and a carbon-credit market. Soil users may value water retention, nutrient management or resilience, whereas carbon buyers value durable tonnes with rigorous evidence. These markets have different procurement cycles, quality specifications, payment terms and risk tolerances. A project that relies on only one revenue stream is more exposed to price or demand changes. Co-product heat, waste-treatment services, material applications and agronomic products can improve utilisation of the same physical system, but each must be accounted for carefully to avoid double claiming.

The main operational business gap is reliability at the interface between dispersed residues and controlled industrial process. Agricultural residues can be seasonal, bulky, wet and heterogeneous. Facilities need a defensible procurement radius, storage strategy, moisture specification, sampling regime, working-capital plan, operator training, downtime response and clear ownership of carbon attributes. High-quality output requires quality systems and records that are often absent from informal charcoal supply chains.

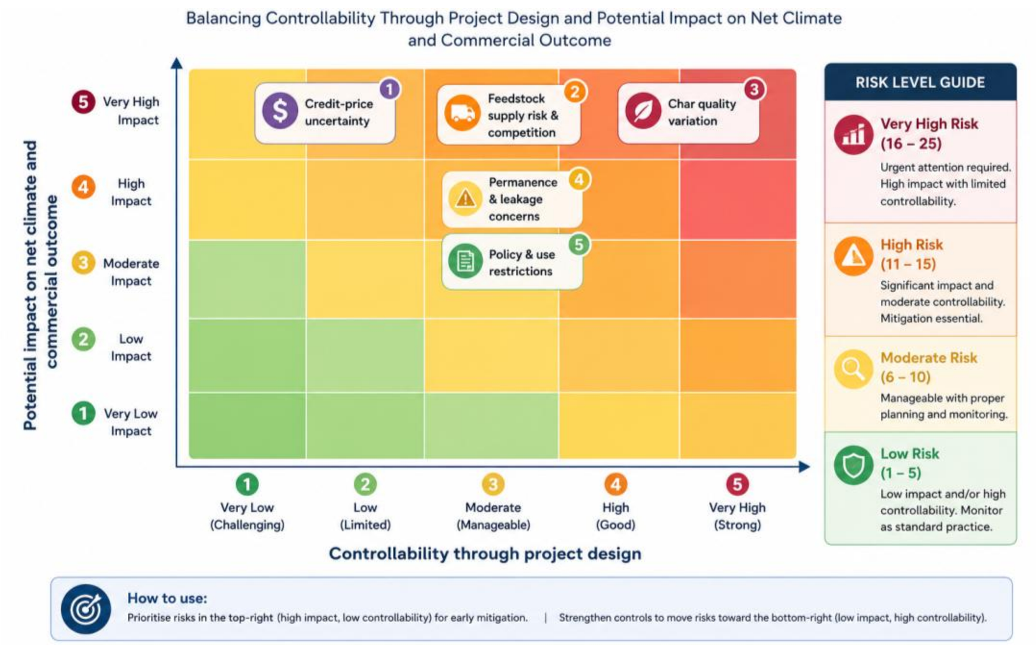

Figure 5. Illustrative deployment risk map. Positions guide prioritisation of controls; they do not represent measured probabilities

Successful deployment requires early identification of the factors that can delay implementation or reduce project reliability. Figure 5 presents an illustrative deployment risk map that helps prioritize technical, operational, and market-related control measures during project planning.

Table 4. The gaps that most often prevent a technically feasible biochar concept from becoming a reliable, scalable system.

Gap category	Why it matters	Evidence-led response
Research gap: persistence across uses	Credit durability depends on actual oxidation and use route	Long-term field monitoring, representative characterisation and uncertainty discounting
Research gap:	Yield and nutrient	Stratified field trials with controls and

agronomic variability	outcomes vary by soil, crop and char	transparent null results
Market gap: non-comparable credits	Different methodologies and durability labels complicate buyer comparison	Disclose method, storage period, uncertainty and lifecycle boundary
Market gap: validation/verification latency	Revenue may lag production and application	Plan working capital, data completeness and verification calendar early
Business gap: feedstock aggregation	Low-density seasonal residues can dominate delivered cost and risk	Secure supply contracts, moisture specs, storage and traceable logistics
Business gap: quality consistency	Batch variation can affect application and credit eligibility	Feedstock segregation, SOPs, laboratory plan and reject/rework rules
Implementation gap: local permissions	Air emissions, waste handling, land and product regulation are site-specific	Early permitting matrix, monitoring plan and regulator engagement

Many technically feasible biochar projects encounter practical challenges before reaching commercial deployment, particularly in feedstock management, verification, and financing. Table 4 summarizes the major research, market, business, and implementation gaps together with evidence-based responses that can improve project scalability.

6. State-of-the-art implementation framework

The evidence suggests that biochar systems scale successfully when development is staged. A site should first be screened for residue availability and competing uses; a pilot should establish product quality, emissions, logistics and application evidence; the carbon methodology and MRV plan should then be aligned before commercial production; and scale-up should proceed only after the key evidence and offtake risks are controlled. This sequence is particularly important for systems combining agricultural residues, farmer-facing applications and carbon-market revenue.

Figure 6. Stage-gated implementation path that connects process development, end-use evidence and carbon-market assurance

A phased implementation strategy reduces uncertainty by ensuring that technical performance and evidence quality are established before commercial expansion. Figure 6 illustrates the proposed stage-gated implementation pathway linking process development, end-use validation, and carbon-market assurance

6.1 India-oriented deployment insight

India has large and diverse agricultural-residue resources, but this potential is not a guarantee of low-cost sustainable feedstock. Residue availability varies by crop, district, harvest window, competing fodder and fuel uses, collection infrastructure and moisture. For the AP–Telangana context previously assessed by Zenith, a combined surplus estimate of approximately 28.34 million tonnes per year provides a strategic starting point, but project-level procurement must be based on a narrower, verified supply radius and explicit counterfactual uses. The initial commercial design should be driven by assured daily throughput rather than regional theoretical potential.

Biochar projects serving agricultural land should couple a clear product specification with local soil baselines, demonstration plots, farmer training, logistics records, application evidence and a defined carbon-rights arrangement. This is not merely a social-addition step: it improves product performance, end-use traceability and the quality of the eventual climate claim. A field programme should measure soil pH, organic carbon, bulk density, water-holding characteristics, nutrient status, salinity/sodicity and relevant contaminants before interpreting agronomic results.

Table 5. Practical stage gates and evidence outputs for a high-integrity biochar programme

Stage	Minimum output	Decision criterion	Evidence pack
Screen	Verified feedstock map and competing-	Assured supply supports target throughput	Supplier list, seasonal quantities, route and moisture data

	use assessment	without displacing priority use	
Pilot	Representative char and application trial	Product passes safety/quality specification; operations are stable	Batch analysis, emissions/energy log, plot records, user feedback
Method alignmen t	Applicable standard and conservative net-removal model	Eligibility and additionality evidence are feasible	Methodology assessment, draft PDD, MRV plan, LCA workbook
Commer cial integratio n	Reliable production and end-use routing	Operational, financial and data controls are repeatable	SOPs, contracts, QA/QC plan, traceability system
Verificati on readiness	Complete monitoring period evidence	Verifier can reproduce claimed result from raw records	Monitoring report, data room, batch/application ledger

Developing a high-integrity biochar project requires clear decision points supported by measurable technical and operational evidence. Table 5 presents the recommended implementation stages together with their expected outputs, decision criteria, and supporting evidence required before progressing to the next phase.

7. Discussion: what constitutes a high-value biochar system?

The state of the art is not defined by reactor temperature alone or by the maximum theoretical carbon content. It is defined by how well the system controls the interfaces: feedstock to reactor, reactor to quality product, product to durable use, and physical activity to credible climate claim. Continuous reactors, heat recovery and digital logging can strengthen these interfaces, but only if they are matched to secure feedstock, appropriate end use and an organisation capable of maintaining calibration, quality assurance and record discipline.

Biochar's strongest strategic characteristic is its modularity. Residue handling, process heat, product development, soil improvement, materials applications and carbon removal can be integrated in different combinations. Its main vulnerability is that each combination changes the system boundary. Developers and researchers should therefore report complete mass and energy balances, specify the counterfactual fate of residues, describe the application route and disclose uncertainties. This makes results comparable and prevents the most attractive element of a system from being presented as if it represents the entire lifecycle.

For carbon buyers, the practical due-diligence question is: can the claimed tonne be traced from eligible biomass through a controlled process to a durable and verified end use, after all material emissions and uncertainty have been deducted? For product users, the question is different: does this char meet the required agronomic, environmental or material specification? A mature biochar system answers both questions without conflating them.

8. Conclusions

Biochar is one of the most implementable durable carbon-removal pathways, but it is not a generic commodity and it is not equivalent to charcoal. Its climate value arises only when an eligible biomass feedstock is converted under controlled conditions, characterised for stability and safety, applied to an approved durable use, and accounted for conservatively across its lifecycle. Recent market-methodology updates by Puro.earth and Verra show increasing discipline around durability, responsible sourcing, additionality and traceability.

The principal technology direction is toward reliable, energy-integrated and traceable conversion: improved feedstock preparation, continuous operation where scale justifies it, heat and syngas utilisation, emissions controls, batch-level quality systems and digital MRV. The principal research direction is toward longer-term field evidence, harmonised persistence science, rigorous non-CO_2 accounting, field-scale safety evidence and transparent LCA. The principal deployment direction is stage-gated: secure feedstock and end use, demonstrate quality and operations, establish methodology and MRV feasibility, then scale with evidence and offtake discipline.

The most credible opportunity lies in systems that treat carbon removal as the result of sound environmental chemical engineering and transparent governance. Biochar's appeal is not a single number; it is the possibility of linking residue management, circular materials, agriculture, energy recovery and measurable climate outcomes in one auditable system.

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Author’s evidence note

This manuscript is an original, evidence-led review drafted in JECE-style structure. The charts showing process trade-offs, evidence allocation and deployment risks are explicitly illustrative analytical syntheses; they do not claim universal empirical values. Before a journal submission, the authors should conduct a formal database search, expand the peer-reviewed corpus, verify every bibliographic record and adapt the title page, declaration statements, reference style and highlights to the journal’s current Guide for Authors.