





REVIEW

Towards Prescriptive Deployment: A Site-Specific Optimization Framework for Biochar-Based Climate Mitigation

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ABSTRACT

Biochar is widely considered a promising negative-emission technology for soil carbon sequestration and climate change mitigation. However, its effectiveness in field conditions remains inconsistent because biochar performance depends strongly on soil characteristics, climatic conditions, and production parameters. This study aims to improve the predictability of climate mitigation outcomes from biochar application by synthesizing field-based evidence and developing a site-specific optimization framework. Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, this systematic review synthesizes 57 field-scale studies published between 2010 and 2024. Carbon persistence was evaluated using a first-order decay model, while greenhouse gas dynamics (CO₂, CH₄, and N₂O) were integrated using the Net Global Warming Potential (NGWP) metric to assess overall climate mitigation effects. The synthesis indicates that biochar application increases soil organic carbon (SOC) stocks by an average of $15.8 \pm 12.4\%$, with a carbon storage efficiency of $68.3 \pm 23.7\%$. A critical pyrolysis optimization window between 450–550 °C was identified, which enhances aromatic carbon stability and results in a mean residence time of approximately 47.2 years. Nevertheless, important trade-offs were observed in paddy systems: while CH₄ emissions decrease by 31.2%, high-ash biochars applied to alkaline soils may increase N₂O emissions by up to 21.1%. To address these trade-offs, this study operationalizes the Theory–Context–Criteria–Method (TCCM) approach into an eight-step decision framework for site-specific biochar deployment. By incorporating climate-risk screening and Measurement,

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Reporting, and Verification (MRV) considerations, the framework provides practical guidance to enhance the reliability of biochar-based climate mitigation strategies.

Keywords: Carbon Sequestration; Measurement, Reporting, and Verification; Net Global Warming Potential; Soil Organic Carbon

1. Introduction

1.1. Significance of the Topic and Current Context

Biochar is a carbon-rich material produced through the pyrolysis of biomass under oxygen-limited conditions. Inspired by the long-term fertility of Amazonian Dark Earth (terra preta), biochar has gained increasing attention as a soil amendment capable of improving soil quality while contributing to climate change mitigation^[1]. When incorporated into soils, biochar can enhance nutrient retention, improve soil structure, and stabilize organic carbon, thereby supporting both agricultural productivity and environmental sustainability.

In recent years, biochar has also been widely discussed as a negative-emission technology (NET) because of its potential to store carbon in soils while influencing greenhouse gas emissions^[2,3]. Research therefore increasingly focuses on three interconnected objectives: enhancing soil carbon storage, improving nutrient cycling, and reducing greenhouse gas emissions. However, field outcomes remain highly variable because biochar performance depends strongly on local soil properties, climatic conditions, feedstock characteristics, and land-management practices^[4]. This variability complicates the translation of experimental findings into reliable recommendations for agricultural systems.

Over the past decade, biochar research has evolved from descriptive characterization of material properties and crop responses toward more quantitative environmental assessments. Life-cycle assessment (LCA) approaches have been used to evaluate environmental trade-offs across the production and application chain^[5], while modeling studies aim to predict biochar behavior under different pedo-climatic conditions^[6]. Advances in precision agriculture and soil monitoring technologies have also improved the capacity to observe field-level soil responses to biochar

amendments^[7]. Despite these developments, methodological inconsistencies among studies still limit cross-site comparisons and hinder the development of generalized deployment strategies.

Scaling biochar to commercial agricultural systems also faces several practical constraints. Technical challenges include variability in biochar quality and inconsistent agronomic responses across regions, which can reduce confidence among farmers and industry stakeholders. These issues are compounded by the limited availability of standardized quality guidelines and certification frameworks^[1]. Economic feasibility further depends on feedstock availability, production costs, transportation logistics, and the strength of carbon-credit markets^[2]. Social factors such as farmer awareness and technology adoption also influence the potential for large-scale implementation, particularly in smallholder farming systems.

1.2. Prior Studies

Existing review literature on biochar primarily focuses on individual outcomes such as soil organic carbon (SOC) accumulation, crop productivity, or greenhouse gas emissions. Numerous syntheses evaluate the effects of biochar on SOC stocks and soil fertility, highlighting its potential to enhance soil carbon storage and agricultural productivity^[3]. However, these analyses often treat carbon sequestration as an isolated indicator without considering carbon persistence or possible trade-offs with greenhouse gas emissions.

Research on greenhouse gas mitigation has also expanded considerably, yet many studies evaluate individual gases separately. Because climate mitigation outcomes depend on the combined dynamics of multiple gases—including CO₂, CH₄, and N₂O—assessing these gases independently can obscure the overall climate impact of biochar application. Integrated climate accounting approaches are therefore needed to evaluate the net mitigation poten-

tial of biochar in complex agroecosystems.

Empirical evidence further demonstrates that biochar responses vary widely across environments. For example, Puga et al. reported substantial increases in maize yield following biochar-based fertilization in low-fertility tropical soils [8]. Similarly, Yang et al. observed improvements in soil organic carbon and irrigation efficiency in paddy systems [9]. Nevertheless, these responses are strongly influenced by local soil conditions and management practices, highlighting the need for context-specific evaluation of biochar applications.

Although the influence of feedstock type and pyrolysis conditions on biochar stability is widely recognized, existing syntheses often remain descriptive. As a result, current recommendations tend to be generalized and do not provide operational guidance linking biochar properties with specific environmental contexts.

1.3. Identification of Research Gaps

Despite extensive research on biochar applications, several structural limitations remain in the existing litera-

ture. First, many studies evaluate soil carbon storage and greenhouse gas emissions separately rather than considering the net climate impact of biochar deployment. Integrating soil organic carbon dynamics with multi-gas emissions (CO₂, CH₄, and N₂O) is essential for evaluating the overall climate mitigation potential of biochar.

Second, the lack of standardized analytical frameworks limits the comparability of results across studies conducted under different pedo-climatic conditions. This issue is particularly relevant in methane-sensitive agroecosystems such as paddy soils, where increases in soil carbon stocks may be offset by changes in methane emissions.

Third, many existing syntheses provide limited guidance for translating experimental findings into operational field practices. Without decision-oriented frameworks that link biochar properties with site-specific environmental conditions, the practical implementation of biochar-based mitigation strategies remains uncertain. **Table 1** summarizes the key differences between previous biochar reviews and the approach adopted in this study.

Table 1. Comparison between previous biochar reviews and the present study.

Aspect	Previous Biochar Reviews	This Study
Primary focus	Effects of biochar on soil organic carbon (SOC), fertility, or crop yield	Integrated climate mitigation focus using net global warming potential (NGWP) combining SOC and multi-gas emissions (CO ₂ , CH ₄ , N ₂ O)
Greenhouse gas coverage	Often single-gas or partial (mostly CO ₂ or N ₂ O)	Explicit synthesis of CO ₂ , CH ₄ , and N ₂ O fluxes, including methane-dominated systems (e.g., paddy soils)
Treatment of carbon permanence	Frequently inferred from SOC increase	Explicit discussion of long-term carbon persistence, trade-offs, and uncertainty
Pyrolysis parameters	Qualitative discussion of temperature and feedstock	Identification of an optimization window linking pyrolysis temperature (450–550 °C), residence time, and carbon stability
Application rate guidance	Broad or inconsistent recommendations	Context-dependent dosage ranges (e.g., 10–30 t ha ⁻¹) tied to soil type, pH, and management system
System differentiation	Limited separation between land-use types	Explicit differentiation between paddy and upland systems, accounting for contrasting methane and nitrous oxide dynamics
Methodological synthesis	Narrative review or meta-analysis focused on single outcomes	Systematic review integrating climate, agronomic, and environmental outcomes
Decision-support output	Conceptual discussion	Rule-based, site-specific decision framework for biochar deployment
Practical implementation	Limited operational guidance	Actionable framework suitable for field trials, MRV design, and policy-relevant carbon accounting

1.4. Novelty and Scientific Contribution

This study addresses the limitations identified above

by synthesizing field-scale evidence on biochar applications within an integrated climate-mitigation framework. The main scientific contributions are summarized as follows:

1. Integrated Climate Accounting

The study evaluates biochar impacts using a Net Global Warming Potential (NGWP) perspective that integrates soil organic carbon dynamics with multi-gas emissions (CO₂, CH₄, and N₂O).

2. System-Level Evidence Synthesis

Field studies from diverse pedo-climatic contexts are systematically analyzed to identify patterns influencing the climate mitigation performance of biochar.

3. Decision-Oriented Framework Development

Empirical findings are translated into a structured decision framework designed to support site-specific biochar deployment strategies.

4. Linkage with Monitoring Frameworks

The synthesis incorporates considerations relevant to Measurement, Reporting, and Verification (MRV), enhancing the applicability of the results for climate mitigation initiatives and carbon accounting.

2. Methods

2.1. Protocol and Registration

This study follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines^[10]. PRISMA is selected because it has been shown to improve reporting quality and methodological rigor for systematic reviews across disciplines^[11–13]. The method is structured so that the review process is transparent and replicable by other researchers, and the findings are trustworthy when synthesizing studies on biochar for carbon sequestration.

2.2. Information Sources and Search Strategy

A systematic literature search was conducted across four electronic databases: Scopus, Web of Science Core Collection, ScienceDirect, and Google Scholar. The search was restricted to peer-reviewed journal articles published in English between 2010 and 2024, consistent with the scope of field-based biochar research synthesized in this study.

The search strategy used Boolean operators and key-

word combinations based on three main concepts:

1. Biochar material terms: “biochar”, “bio-char”, “pyrolyzed biomass”, “char”, “pyrolysis”, “carbonized biomass”;
2. Soil carbon and permanence terms: “soil organic carbon”, “SOC”, “carbon sequestration”, “carbon storage”, “carbon permanence”, “mean residence time”, “decay”, “stability”, “recalcitrance”, “aromaticity”, “H/C”, “O/C”;
3. Greenhouse gas and climate metric terms: “greenhouse gas”, “GHG”, “CO₂”, “N₂O”, “CH₄”, “methane”, “nitrous oxide”, “net global warming potential”, “NGWP”, “CO₂-equivalent”.

These keyword groups were combined using the AND operator to ensure retrieved studies covered biochar, soil-carbon outcomes, and/or greenhouse-gas/climate outcomes. The search strategy for Scopus utilized the following string: (TITLE-ABS-KEY("biochar" OR "bio-char") AND TITLE-ABS-KEY("carbon sequestration" OR "soil organic carbon") AND TITLE-ABS-KEY("methane" OR "nitrous oxide" OR "climate mitigation")). In addition, the reference lists of included articles and relevant review papers were manually screened to identify further eligible studies (backward citation tracking).

2.3. Eligibility Criteria

Eligibility criteria were defined to ensure operational relevance for site-specific deployment and climate accounting. Studies were included if they met all of the following criteria:

- Study type: original research articles (excluding reviews, editorials, conference abstracts, book chapters, and non-peer-reviewed reports);
- Experimental setting: field-scale experiments (excluding laboratory-only incubation and pot-only studies unless explicitly field-validated);
- Intervention: soil amendment with biochar (any feedstock) with reported application rate and/or production parameters;
- Outcomes: reported at least one climate-mitigation component, including SOC change/stock, and/or CO₂, CH₄, N₂O fluxes, and/or variables enabling

- Technical reporting: provided information on at least one key production attribute (e.g., pyrolysis temperature, feedstock, or residence time), and sufficient site/context information (e.g., soil pH/texture, land-use system).

Studies were excluded if they: (i) Were not in English; (ii) were not peer-reviewed journal articles; (iii) focused on biochar production only without field soil application; or (iv) lacked baseline/control comparisons or lacked the minimum reporting needed to interpret climate outcomes.

2.4. Selection Process and Screening

All retrieved records were imported into a reference

manager, and duplicates were removed automatically and verified manually. The study selection followed the PRISMA stages: identification, screening, eligibility, and inclusion.

A total of 624 records were identified through database searching. After duplicate removal and initial filtering, records were screened by title and abstract to exclude studies not relevant to field-scale biochar application or climate mitigation outcomes. The remaining articles were assessed by full-text eligibility using the predefined criteria described above. After full-text evaluation, 57 field studies were included in the final synthesis. The complete screening process is illustrated in the PRISMA flow diagram (**Figure 1**).

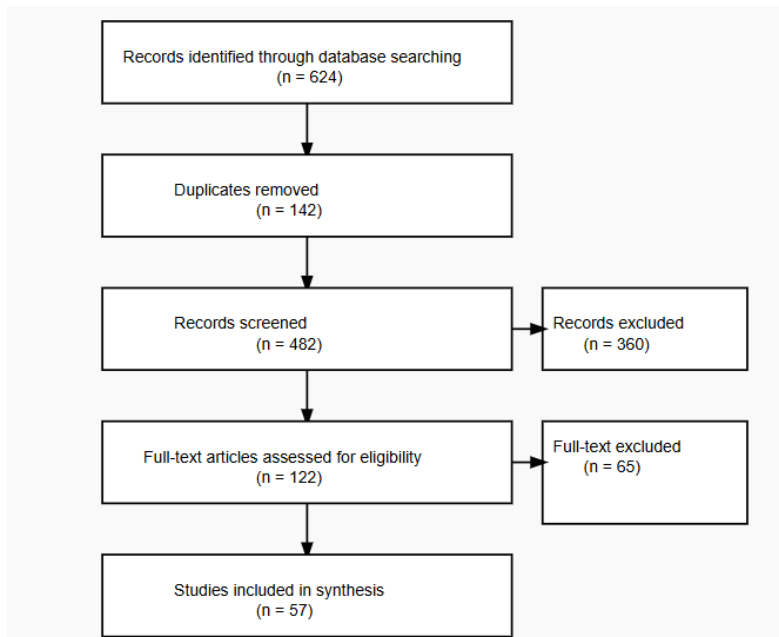


Figure 1. PRISMA flow diagram illustrating the literature search, screening, eligibility, and inclusion process.

2.5. Data Extraction

A standardized data extraction form was developed (Microsoft Excel) to capture the following variables from each included study:

- Bibliographic information (author, year, journal, country/region);
- Site and system context (land-use system: paddy vs. upland; climate zone if reported; baseline soil pH; soil texture; baseline SOC/SOM);
- Biochar characteristics (feedstock type; pyrolysis temperature; residence time if available; ash content where reported; proxies of stability such as H/C or O/C when available);
- Application protocol (application rate; incorporation method; co-amendments/fertilizer; irrigation regime such as continuous flooding vs. AWD for paddy);
- Carbon outcomes (SOC concentration and/or SOC stock; reporting basis and depth; storage efficiency when derivable);

- GHG outcomes (CO₂, CH₄, N₂O fluxes; measurement period; units; seasonal coverage);
- Climate accounting variables enabling NGWP synthesis (time horizon assumptions if reported; CO₂-eq conversions when derivable).

Data extraction was performed by one reviewer and cross-checked for consistency in units and definitions.

2.6. Methodological Quality and Risk-of-Bias Appraisal

To evaluate the reliability of evidence used to derive decision thresholds, each included study was assessed for methodological quality and reporting completeness using a structured appraisal adapted for field agronomic experiments. Key appraisal domains included:

1. Clarity of experimental design and objectives;
2. Presence of control/baseline comparisons;
3. Adequacy of replication and duration;
4. Transparency of site description (soil pH/texture/SOC baseline);
5. Completeness of biochar production reporting (feedstock, pyrolysis temperature, residence time if available);
6. Transparency of measurement protocols for SOC and/or GHG fluxes;
7. Reporting of uncertainty/variability (SD/SE, range, or replicate statistics);
8. Potential short-termism bias (study duration insufficient relative to carbon permanence questions);

Quality appraisal results were used to guide interpretation and to flag high-uncertainty contexts in the framework's risk-screening step.

2.7. Data Synthesis Method and Operationalization of TCCM

Given substantial heterogeneity across studies—arising from differences in feedstock, pyrolysis conditions, soils, climates, land-use systems, management practices, and measurement protocols—a fully pooled meta-analysis was not applied as the primary synthesis approach. Instead, a structured synthesis was adopted, combining descriptive statistics and rule-based evidence mapping.

Where sufficient data were available, treatment effects were standardized using the log response ratio (ln *RR*) to support cross-study comparison:

$$\ln RR = \ln \left(\frac{X_t}{X_c} \right)$$

where X_t is the treatment mean (biochar-amended) and X_c is the control mean. Effects were synthesized for core outcomes (SOC and CO₂/CH₄/N₂O where reported) and interpreted alongside dispersion patterns across context variables (soil pH, texture, land-use type, pyrolysis temperature, and application rate). Positive lnRR values indicate increases following biochar application, whereas negative values indicate reductions relative to control treatments.

To translate evidence into actionable deployment guidance, this study operationalized the Theory–Context–Criteria–Method (TCCM) approach into an eight-step decision logic. Specifically:

- **Theory:** Mechanistic insights from the literature were synthesized to identify processes controlling carbon stability and greenhouse gas responses following biochar application.
- **Context:** Studies were categorized according to key environmental and management contexts, including soil pH, soil texture, climatic zone, and land-use system (paddy versus upland).
- **Criteria:** Empirical thresholds and recurring response patterns were identified across studies, including indicators related to carbon storage efficiency, greenhouse gas trade-offs, and biochar stability.
- **Method:** These criteria were translated into rule-based decision logic designed to guide site-specific biochar deployment and climate mitigation assessment.

This operationalization allowed the synthesis to move beyond descriptive reporting toward the development of a structured framework for interpreting biochar performance across diverse agroecosystems.

2.8. Weighting of Effect Sizes

To account for differences in study reliability and experimental design, effect sizes were weighted during syn-

thesis using information on sample size and experimental duration when available. Studies with larger replication or longer observation periods were considered more robust and therefore given greater analytical weight in the qualitative synthesis.

When variance statistics such as standard deviation (SD) or standard error (SE) were reported, these values were used to assess the reliability of reported outcomes. In cases where variance information was not available, studies were treated with equal weighting but were flagged during interpretation as having lower methodological transparency.

This weighting strategy allowed heterogeneous field experiments to be integrated while minimizing bias arising from uneven study representation.

2.9. Assessment of Heterogeneity

Given the diversity of environmental conditions and experimental designs across the included studies, heterogeneity was expected. Variability among studies was therefore evaluated using both qualitative and descriptive statistical approaches.

Study outcomes were compared across several contextual variables, including:

- Soil type and texture;
- Baseline soil organic carbon levels;
- Biochar feedstock type;
- Pyrolysis temperature;
- Land-use system (paddy vs. upland).

Where comparable datasets were available, heterogeneity was examined through the dispersion of calculated effect sizes. This approach allowed identification of recurring patterns and context-dependent responses while avoiding inappropriate pooling of results from highly heterogeneous systems.

3. Results

Based on the 57 studies reviewed, publications on biochar for carbon sequestration increased substantially after 2018 and peaked during the 2020–2023 period, accounting for 34 studies (59.6%) of the dataset. This trend reflects the rapidly growing scientific interest in biochar as a potential negative-emissions technology for climate change mitigation. The distribution of feedstock types across the reviewed studies reveals a predominance of woody biomass and crop residues, accounting for a significant portion of the data (Figure 2).

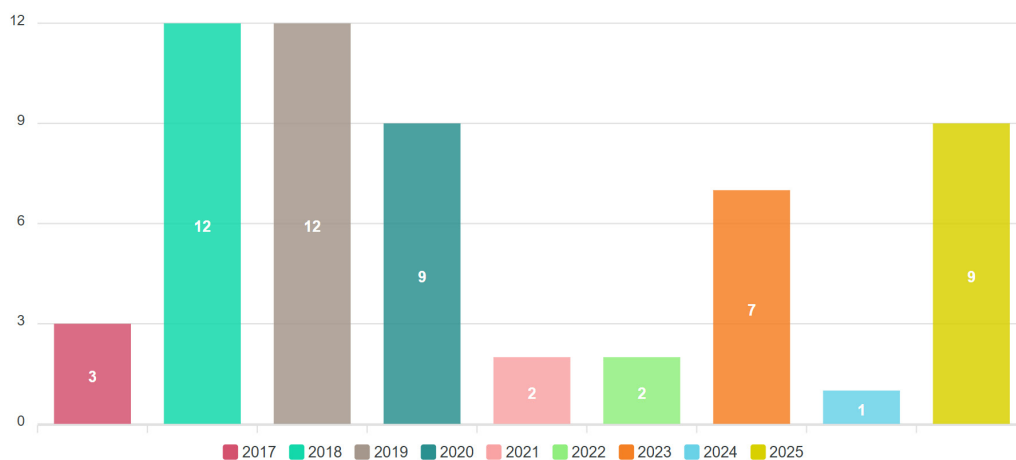


Figure 2. Year publication trends.

Most biochar research was conducted in the Asia–Pacific (n = 32), especially China (n = 18) and India (n = 8) [9,14–16]. By environment, tropical–subtropical locations dominate (n = 41) and paddy systems are a major focus (n = 28) because flooded rice fields are large sources of

methane (CH₄), so biochar is often tested there. In contrast, Africa (n = 6) and Latin America (n = 4) remain underrepresented, so findings may not fully transfer to the many smallholder systems in those regions. The dataset is geographically uneven, with a concentration of studies in the

Asia-Pacific region; this imbalance is acknowledged as a limitation and considered during interpretation of synthesis results. As shown in **Figure 3**, the geographic distribution of biochar research is heavily concentrated in specific regions, with China contributing nearly half of the analyzed datasets.

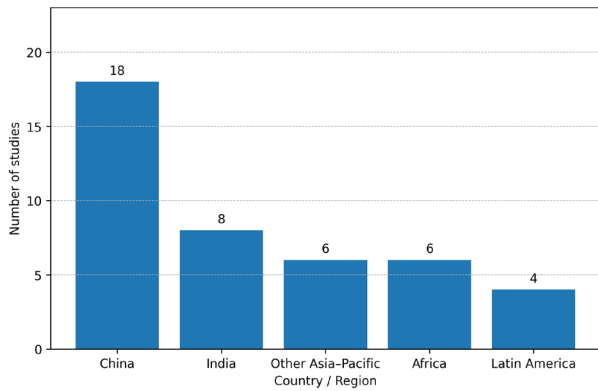


Figure 3. Geographic distribution of field-scale biochar studies included in the systematic review.

3.1. Biochar Characterization and Material Variability

Across the reviewed studies, biochar feedstock and production conditions were key determinants of carbon stability and soil responses. Rice-residue biochar dominated

the dataset ($n = 38$ studies), followed by tropical hardwood biochar ($n = 15$), with smaller numbers of coconut-based ($n = 3$) and palm-residue biochar ($n = 1$).

Material characteristics varied substantially with pyrolysis conditions. In particular, the H/Corg ratio, commonly used as a proxy for aromaticity and carbon stability, declined sharply at pyrolysis temperatures above approximately 500 °C, indicating increased carbon recalcitrance. These findings suggest that feedstock selection and thermal conversion conditions strongly influence the carbon sequestration potential of biochar materials [16,17].

Land-management practices also influenced outcomes. Conservation systems such as no-till management tended to preserve soil carbon more effectively by reducing soil disturbance. In paddy systems, Alternate Wetting and Drying (AWD) irrigation strategies reduced methane emissions while maintaining soil carbon stocks, whereas continuous flooding generally limited methane mitigation potential. Interactions with fertilizer management were also observed: biochar frequently showed synergistic effects with organic amendments, while excessive mineral nitrogen inputs sometimes reduced soil-carbon stabilization benefits [8,18,19]. The types of feedstock used for biochar production vary significantly, with woody biomass and crop residues being the most prevalent (**Table 2**).

Table 2. Distribution of biochar feedstock types across reviewed field studies.

No.	Tropical Feedstock-Based	Count	Authors
1	Rice Waste Biochar	38	Cai et al., 2017 [14]; He et al., 2018 [20]; Wang et al., 2018 [15]; Zhou et al., 2019 [16]; Billa et al., 2019 [21]; Qi et al., 2018 [22]; Xu et al., 2019 [23]; Huang et al., 2018 [24]; Ji et al., 2018 [5]; Sheng and Zhu, 2018 [25]; Grutzmacher et al., 2018 [26]; Roobroeck et al., 2019 [2]; Alam et al., 2019 [27]; Yang et al., 2019 [9]; Tao et al., 2019 [28]; Yi et al., 2019 [29]; Liu et al., 2019 [30]; Singh et al., 2019 [31]; Shin et al., 2019 [32]; Bi et al., 2020 [33]; Rehman et al., 2020 [34]; Mohammadi et al., 2020 [35]; Irshad et al., 2020 [36]; Puga et al., 2020 [8]; Yang et al., 2021 [6]; Thao et al., 2022 [37]; Basak et al., 2022 [1]; Latawiec et al., 2023 [18]; Nan et al., 2023 [38]; Singh et al., 2023 [39]; Li et al., 2025 [40]; Wang et al., 2025 [41]; Shi et al., 2025 [42]; Chang et al., 2025 [43]; Gabetto et al., 2025 [44]; Haider et al., 2025 [45]; Lyu et al., 2025 [46]; Nogueira et al., 2025 [17]
2	Tropical Hardwood Biochar	15	Ramlow and Cotrufo, 2018 [47]; Qadeer et al., 2017 [48]; Polifka et al., 2018 [49]; Ascough et al., 2018 [50]; Greenberg et al., 2019 [51]; Arfaoui et al., 2019 [52]; Bramble et al., 2019 [53]; Ramlow et al., 2019 [54]; Blanco-Canqui, 2020 [4]; Dumortier et al., 2020 [55]; Vijay et al., 2021 [19]; Mishra et al., 2023 [7]; Wang et al., 2023 [56]; Shrestha et al., 2023 [3]; Bednik et al., 2023 [57]
3	Coconut-Based Biochar	3	Chin-Pampillo et al., 2020 [58]; Jeanne-Rose et al., 2024 [59]; Gurau et al., 2025 [60]
4	Palm Residue Biochar	1	Karananidi et al., 2020 [61]

3.2. Changes in Soil Physicochemical Properties

Biochar application consistently modified soil phys-

icochemical properties across multiple studies. Soil bulk density decreased by $8.7 \pm 6.2\%$ ($k \approx 25$ studies; range: 1–21%), indicating increased soil porosity and improved structure [8]. Water-holding capacity increased by $23.4 \pm$

18.9% ($k \approx 27$ studies; range: 4–61%), and this improvement was positively correlated with biochar application rate ($r = 0.73$; $p < 0.001$)^[8,34].

Soil pH in acidic soils increased by approximately 0.8 ± 0.4 units ($k \approx 30$ studies) due to the liming effect of alkaline ash fractions. In contrast, pH responses were minimal in already alkaline soils. Similarly, Cation Exchange Capacity (CEC) increased by $18.6 \pm 14.7\%$ ($k \approx 22$ studies), reflecting improved nutrient retention and reduced leaching losses.

Nutrient availability responses were more variable. Approximately 68% of studies reported increases in available phosphorus, with an average increase of $24.7 \pm 31.2\%$, primarily due to reduced P fixation and pH-mediated mobilization^[16,25,26]. Nitrogen responses were more heterogeneous: 52% of studies reported increased available nitrogen, whereas 48% observed neutral or negative responses, indicating competing processes such as ammonium sorption and microbial immobilization.

3.3. Soil Carbon Sequestration Performance

To standardize comparisons across studies, relative changes in soil organic carbon (SOC) stocks were quantified using a response-ratio approach (Equation (1))^[33,40].

$$\Delta \text{SOC (\%)} = \frac{\text{SOC}_{\text{biochar}} - \text{SOC}_{\text{control}}}{\text{SOC}_{\text{control}}} \times 100\% \quad (1)$$

Across approximately 41 studies reporting SOC outcomes, biochar application increased SOC stocks by $15.8 \pm 12.4\%$ (range: 2.1–47.3%). However, responses varied substantially depending on initial soil carbon levels and pedo-climatic conditions.

The carbon storage efficiency (η)—representing the fraction of applied biochar carbon retained in soil—averaged $68.3 \pm 23.7\%$ ($k \approx 28$ studies). This suggests that roughly two-thirds of the applied carbon remained stabilized within soil systems over medium-term timescales. Using a first-order decay model to approximate long-term persistence:

$$C(t) = C_0 e^{-kt} \quad (2)$$

The mean residence time of biochar-derived carbon was estimated at 47.2 ± 28.9 years ($k \approx 24$ studies), indicating substantially greater stability than most labile organic amendments.

3.4. Greenhouse Gas Dynamics

Greenhouse gas responses varied across studies but generally indicated a net mitigation potential.

- CO₂ emissions declined in 67% of the evaluated studies ($k \approx 27$), with a mean change of $-18.7 \pm 24.3\%$ (range: -55 to +12%). Short-term emission increases were occasionally observed, particularly for low-temperature biochars with higher volatile carbon fractions.
- N₂O emissions were reduced in 78% of studies ($k \approx 32$), with an average change of $-23.4 \pm 18.9\%$ (range: -61 to +21%), likely due to improved soil aeration and nitrogen immobilization processes. However, several studies reported increased emissions when high-ash biochars were applied to alkaline soils^[3].
- In paddy systems, CH₄ emissions declined in 82% of studies ($k \approx 22$) with an average reduction of $-31.2 \pm 22.8\%$ (range: -68 to +14%), indicating that biochar can significantly suppress methane production under anaerobic conditions^[15,23].

3.5. Crop Yield and Net Global Warming Potential (NGWP)

Crop productivity responses were generally positive. Across approximately 29 studies reporting yield outcomes, crop yields increased by $18.3 \pm 22.7\%$ (range: -12 to +61%), with the strongest improvements observed in acidic, nutrient-limited soils. When both carbon storage and greenhouse gas responses were considered together, NGWP declined in approximately 73% of studies ($k \approx 17$), with an average reduction of $-28.6 \pm 31.4\%$. These findings indicate that biochar can generate simultaneous climate-mitigation and productivity benefits, although outcomes remain highly dependent on site-specific soil and management conditions.

3.6. Summary of Key Outcomes

To improve interpretability across heterogeneous studies, **Table 3** summarizes the principal outcomes reported in the reviewed literature. Values represent mean changes relative to control treatments with standard devia-

tion (SD) and observed ranges. The column *k* indicates the number of contributing studies for each outcome, reflect-

ing variability across pedo-climatic conditions and management systems.

Table 3. Summary statistics of key soil, greenhouse gas, and agronomic outcomes reported in the reviewed biochar field studies.

Outcome	Studies (<i>k</i>)	Mean Change	Standard Deviation (SD)	95% Confidence Interval (CI)	Range
SOC change (%)	41	15.8	12.4	12.0–19.6	2.1–47.3
Storage efficiency (%)	28	68.3	23.7	59.5–77.1	21–94
CO ₂ emissions (%)	27	–18.7	24.3	–27.9 to –9.5	–55–12
N ₂ O emissions (%)	32	–23.4	18.9	–29.9 to –16.9	–61–21
CH ₄ emissions (%)	22	–31.2	22.8	–40.7 to –21.7	–68–14
Crop yield (%)	29	18.3	22.7	10.0–26.6	–12–61
NGWP (%)	17	–28.6	31.4	–43.5 to –13.7	–82–15

The wide ranges observed across several outcomes indicate substantial between-study heterogeneity, reflecting differences in soil properties, climatic conditions, biochar feedstocks, and land-management practices.

4. Discussion

4.1. Determinants of Biochar Recalcitrance and Carbon Persistence

The long-term sequestration potential of biochar is primarily governed by its chemical recalcitrance, often quantified through the H/C_{org} and O/C ratios. Unlike earlier descriptive studies, recent evidence suggests that the 'half-life' of biochar carbon is not a fixed attribute but a function of the interaction between pyrolysis intensity and soil mineralogy^[16,33]. High-temperature pyrolysis (>550 °C) typically enhances the aromaticity of the carbon matrix, yet the actual persistence in field conditions is heavily modulated by the soil's native organic matter and microbial activity. This section synthesizes the critical thresholds of pyrolysis temperature and residence time that dictate the formation of fused aromatic rings, which serve as practical indicators of carbon stability frequently reported across the reviewed studies.

4.2. Mechanistic Trade-Offs in Greenhouse Gas Mitigation

The efficacy of biochar in mitigating non-CO₂ greenhouse gases (CH₄ and N₂O) is characterized by significant site-specific variability. In aerobic upland soils, biochar typically suppresses N₂O emissions by improving soil aer-

ation and altering the nitrification-denitrification pathways. However, in anaerobic systems such as paddy fields, the application of biochar can paradoxically stimulate methanogenesis if the biochar contains high levels of labile carbon or if it significantly alters the soil redox potential^[1,4,8]. Understanding these mechanistic trade-offs is essential for moving beyond generalities. This review identifies the pedo-climatic 'tipping points' where biochar transitions from a mitigation tool to a potential source of net positive emissions, providing the necessary risk-screening criteria for field deployment.

These contrasting outcomes highlight that the climate benefits of biochar cannot be assumed universally. Instead, mitigation effects are strongly conditioned by soil redox status, microbial activity, and the chemical composition of the applied biochar. Such variability underscores the need for context-sensitive evaluation when interpreting reported emission reductions.

4.3. Operational Constraints and Sustainability Trade-Offs

The transition from theoretical sequestration potential to operational deployment faces critical trade-offs that are often overlooked in descriptive reviews. A primary challenge is the 'Carbon-Nutrient Trade-off': while high-temperature pyrolysis (>550 °C) maximizes carbon recalcitrance, it often results in biochar with lower nutrient availability, potentially requiring supplemental fertilization that can offset GHG mitigation gains through upstream emissions^[2,18].

Furthermore, the sustainability of biochar systems is

inextricably linked to their 'Bankability' within voluntary carbon markets. Our analysis indicates that without a standardized MRV (Measurement, Reporting, and Verification) protocol—as proposed in our framework—the high initial capital expenditure for pyrolysis units remains a significant barrier for small-to-medium scale applications. This section identifies the 'Economic-Climatic Tipping Points' where site-specific optimization becomes essential, particularly because economic feasibility varies substantially depending on feedstock availability, production infrastructure, and carbon-credit incentives.

4.4. Interpretation of Heterogeneity across Field Studies

The wide variability observed across the reviewed studies highlights the complex interaction between biochar properties, soil characteristics, and management practices. Differences in pyrolysis temperature, feedstock composition, application rate, and experimental duration introduce substantial heterogeneity that complicates direct cross-study comparisons. For instance, application rates reported in the literature range from 5 to 80 t ha⁻¹, while pyrolysis temperatures vary from 350 to over 700 °C.

Such methodological diversity partially explains the broad ranges observed in SOC change, greenhouse gas responses, and crop yields. These findings suggest that average effect sizes should be interpreted cautiously, as they may mask important context-specific dynamics. Recognizing this heterogeneity is essential for translating experimental evidence into practical deployment strategies.

4.5. Site-Specific Optimization Framework

The profound variability observed across the 57 field studies reviewed here highlights a critical gap in biochar research: the absence of operational protocols for field deployment. While previous syntheses^[3,4,40] have established average effects on soil carbon, they stop short of providing a decision logic for practitioners. This study moves beyond simple outcome-reporting to introduce a prescriptive paradigm. By identifying specific 'pedo-climatic tipping points,' this study offers a rule-based logic that helps reduce the reliance on trial-and-error approaches and provides a structured decision-support tool intended to guide

context-specific deployment.

However, the framework should be interpreted as a heuristic synthesis rather than a definitive operational protocol. Because the underlying evidence base is heterogeneous and often short-term, the proposed decision logic should be tested and refined through long-term field trials before large-scale implementation. Therefore, the framework should be considered a conceptual synthesis of current evidence rather than a universally applicable protocol, and its practical performance requires validation through long-term field experiments across diverse agroecological conditions. To address these complexities, we propose an integrated site-specific optimization framework. As shown in **Figure 4**, this eight-step decision logic guides practitioners from initial site assessment and feedstock selection to long-term monitoring and MRV readiness.

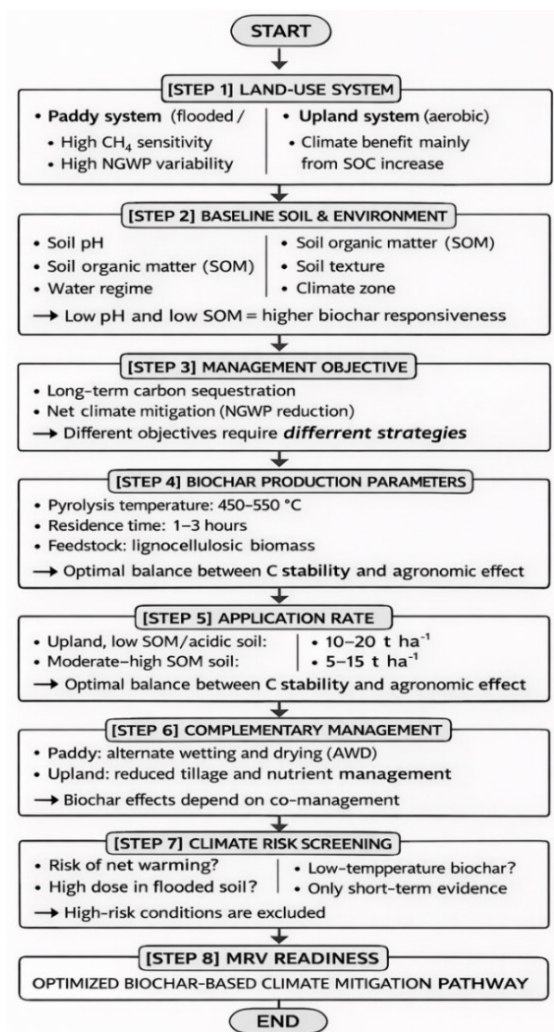


Figure 4. Decision framework for biochar-based climate mitigation.

4.6. Methodological and Data Limitations

Despite the breadth of evidence synthesized, several limitations must be acknowledged. In addition, potential publication bias cannot be entirely excluded, as studies reporting positive biochar effects may be more likely to be published than those showing neutral or negative outcomes. First, a large proportion of field trials remain short-term. Approximately 72% of studies reviewed were conducted for less than two years, whereas the estimated residence time of biochar carbon extends over several decades. As a result, current evidence primarily captures early-stage soil responses rather than long-term stabilization dynamics.

Second, substantial methodological heterogeneity exists across studies. Experimental designs vary widely in terms of application rate (5–80 t ha⁻¹), pyrolysis temperature, feedstock composition, and measurement protocols. Such variability limits the comparability of results and constrains the application of formal meta-analytical synthesis.

Third, geographic representation remains uneven. More than half of the available field studies originate from the Asia–Pacific region, while Africa and Latin America remain comparatively underrepresented. This regional bias raises questions about the generalizability of current findings to smallholder farming systems and other agroecological contexts.

Finally, differences in reporting standards for biochar characterization and greenhouse gas measurements further complicate cross-study comparisons. The lack of standardized protocols highlights the need for internationally harmonized reporting guidelines to improve reproducibility and enable stronger quantitative synthesis^[56].

4.7. Theoretical and Practical Implications

Beyond the empirical findings, this synthesis has broader implications for both biochar research and climate mitigation policy. Findings point to non-linear responses and thresholds; purely linear dose–response models are insufficient. A complex-systems lens is needed to capture interacting physical, chemical, and biological effects that occur simultaneously (i.e., not merely additive). Because biochar C persistence ranges from tens to hundreds of

years, carbon accounting should avoid a single fixed persistence value; probabilistic approaches with explicit uncertainty bands are more appropriate. This has major implications for carbon crediting methodologies (how much CO₂ is truly stored, and for how long) and for climate policy: schemes should accommodate thresholds, interactions, and uncertainties to assess biochar fairly and accurately.

Implementation must be precise and site-specific—match biochar type, dose, and application method to local soils, crops, and climate to maximize climate benefits and cost-effectiveness. For producers, a practical technical range is 450–550 °C pyrolysis with 1–3 h residence, which tends to balance carbon stability and production costs.

Decision-making should adopt a risk-based NGWP lens (CO₂, CH₄, N₂O), enabling policymakers and land managers to test whether a scenario delivers net mitigation (or risks net warming). We recommend staged deployment: start with pilots, then scale while strengthening technology transfer, quality standards, and supply chains—so technical/economic risks are controlled and adoption rates improve. These considerations highlight the need for a more robust empirical basis to evaluate the long-term climate and agronomic impacts of biochar deployment.

4.8. Future Research Directions

Future research should prioritize long-term field experiments that extend beyond typical agronomic trial durations. Integrating standardized reporting protocols for biochar properties, soil characteristics, and greenhouse gas measurements will also be essential for improving cross-study comparability. In addition, expanding field trials to underrepresented regions such as Africa and Latin America will be necessary to ensure that biochar deployment strategies are globally applicable.

5. Conclusions

This systematic review synthesizes evidence from 57 field-scale studies to clarify the conditions under which biochar contributes to soil carbon sequestration and climate mitigation. The findings confirm that biochar can increase soil carbon stocks, with a mean storage efficiency of approximately 68.3%. However, the magnitude and direction of climate outcomes vary substantially across studies, re-

flecting interactions among pyrolysis conditions, soil properties, land-use systems, and management practices. These results highlight that the climatic performance of biochar is not an intrinsic property of the material itself but rather an outcome shaped by pedo-climatic context and production parameters. In this synthesis, a thermal “optimization window” of approximately 450–550 °C emerged as a recurrent range associated with improved carbon stability, while certain contexts—such as high-pH paddy soils—may present a potential “mitigation paradox” where greenhouse-gas responses offset carbon gains.

To interpret these heterogeneous outcomes, this study proposes an eight-step, site-specific optimization framework derived from the Theory–Context–Criteria–Method (TCCM) approach. Rather than serving as a definitive operational protocol, the framework should be considered a structured decision-support tool intended to guide context-sensitive biochar deployment and to connect material-level insights with climate-accounting practices, including measurement, reporting, and verification (MRV) requirements.

Despite the expanding evidence base, several critical knowledge gaps remain. Most notably, a large proportion of field trials remain short-term, with approximately 72% lasting less than two years, whereas the persistence of biochar-derived carbon may extend over multiple decades. Long-term monitoring is therefore essential to verify carbon permanence and to evaluate delayed soil and greenhouse-gas responses. In addition, the geographical distribution of studies remains uneven, with a strong concentration in the Asia–Pacific region and relatively limited empirical data from Africa and Latin America. Addressing this imbalance will require regional calibration of biochar application strategies, particularly for smallholder farming systems in the Global South, where agroecological conditions and resource constraints differ substantially from those represented in the current literature.

Future research should therefore prioritize decadal-scale field experiments, harmonized reporting standards for biochar characterization and greenhouse-gas measurements, and improved monitoring frameworks that can support credible climate accounting. Expanding empirical studies across underrepresented regions will also be essential for evaluating the scalability and socio-economic feasi-

bility of biochar deployment.

Overall, biochar represents a potentially valuable component of integrated climate mitigation strategies. However, its effectiveness depends on careful alignment between biochar properties, site-specific conditions, and management practices. Continued long-term experimentation and regional calibration will be crucial to ensure that biochar-based interventions deliver reliable climate and agronomic benefits across diverse agroecosystems.

Author Contributions

A.D.S. led the conceptualization, designed the study, conducted the formal analysis, and drafted the original manuscript. J.H., A.F.A., and A.F. contributed to supervision, provided critical review and editing, and supported interpretation of the findings. M.F. developed the methodology, supported study selection and data synthesis, and contributed to writing and revision. T.D.I. contributed to data curation and assisted in synthesis and manuscript preparation. A.A.O. contributed to data extraction and validation and supported visualization and manuscript editing. All authors read and approved the final manuscript.

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Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data supporting the findings of this study are derived from publicly available academic literature. All data-

sets analyzed and the references to the original studies are included within the article.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

During the preparation of this manuscript, the authors utilized generative AI and AI-assisted technologies to support the research and writing process. Specifically, Qwen AI and a Black-box AI system were employed to assist in the extraction and classification of relevant articles during the systematic literature review (SLR). Furthermore, ChatGPT was used to enhance the readability, grammar, and structural coherence of the initial draft.

The authors emphasize that these tools were used solely to improve language quality and clarity, and were not utilized to generate core research content or draw scientific conclusions. Meaningful human oversight and editorial authority were maintained throughout the process. All AI-generated outputs were critically reviewed, edited, and validated by the authors to ensure the accuracy, originality, and integrity of the work.

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