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Carbon sequestration potential of biochar derived from region-specific agricultural wastes: stability, soil interaction and climate policy alignment

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Abstract

Background: Biochar - a carbon-rich, pyrogenic material produced through the thermochemical conversion (pyrolysis) of biomass under oxygen-limited conditions has attracted substantial scientific and policy attention as a durable, scalable, and co-beneficial strategy for carbon dioxide removal (CDR). Agricultural wastes represent the single largest globally available feedstock base for biochar production, with an estimated 5.1 billion tonnes of lignocellulosic residues generated annually. However, the carbon sequestration potential of biochar varies markedly with feedstock identity, pyrolysis conditions, and receiving soil environment, creating uncertainty that impedes policy integration and carbon market crediting.

Objectives: This PRISMA 2020-compliant systematic review and meta-analysis synthesises evidence from 69 peer-reviewed Q1/Q2-journal studies (2015-2025) to: (i) characterise region-specific agricultural feedstock availability and biochar production potential; (ii) evaluate biochar stability using internationally recognised indicators (H/C molar ratio, O/C ratio, mean residence time [MRT]); (iii) assess soil-biochar interactions across soil types and climatic zones; (iv) quantify GHG mitigation co-benefits (N₂O, CH₄); and (v) align findings with current international climate policy frameworks including the Paris Agreement, IPCC AR6, and emerging voluntary carbon market (VCM) standards.

Methods: Systematic searches of Web of Science, Scopus, and CAB Abstracts (January 2015 - March 2025) were conducted. Sixty-nine eligible studies were identified following PICOS-based screening. Random-effects meta-analyses (DerSimonian-Laird estimator) were performed for soil organic carbon (SOC) response ratio, N₂O emission change, and aggregate stability. Evidence certainty was assessed using the GRADE framework. A dose-response meta-regression modelled SOC response as a function of biochar application rate.

Key Findings: Biochar application significantly increased SOC (pooled Response Ratio RR = 1.42; 95% CI: 1.29-1.55; I² = 54.2%; GRADE: HIGH). Wood chip biochar at ≥600°C exhibited the greatest stability (H/C ≤ 0.20; estimated MRT: 120-143 decades). Soil N₂O emissions were reduced by a weighted mean of 38.6% (95% CI: -44.2 to -33.0%). Global agricultural biochar carbon sequestration potential is estimated at 1.8-6.6 Gt C yr⁻¹ under feasibility-constrained scenarios. South and Southeast Asian feedstocks (rice husk, wheat straw, sugarcane bagasse) offer the greatest near-term potential, with co-benefits including crop yield improvement (+12-23%), soil water-holding capacity increase (+12-35%), and pathogen load reduction.

Conclusions: Region-specific agricultural biochar presents a technically viable, multi-benefit CDR pathway fully alignable with Paris Agreement Article 6.4, IPCC AR6 CDR portfolios, and existing voluntary carbon market protocols. Standardised permanence accounting, feedstock-specific MRT certification, and integration into Nationally Determined Contributions (NDCs) are critical policy priorities. The evidence base comprehensively supports biochar as a high-priority nature-based and technology-assisted climate solution for the 2030-2050 horizon.

Keywords: Biochar, carbon sequestration, agricultural waste, pyrolysis, soil organic carbon, stability, H/C ratio, mean residence time, plastosphere, N₂O emissions, climate change mitigation, carbon dioxide removal, Nationally Determined Contributions, voluntary carbon markets, IPCC AR6, soil microbiome

Introduction

The Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6, 2021-2022) unequivocally established that achieving the 1.5°C global warming target requires not only rapid decarbonisation of energy and industrial systems, but the active removal of carbon dioxide (CO₂) from the atmosphere at a scale of 5-16 Gt CO₂-eq yr⁻¹ by 2050 [1]. Among the portfolio of carbon dioxide removal (CDR) technologies and approaches endorsed by IPCC

AR6 - including bioenergy with carbon capture and storage (BECCS), enhanced weathering, direct air capture, and afforestation - biochar application to soils is explicitly identified as a high-permanence, co-beneficial, and rapidly scalable option that can be implemented without competition with food production when sourced from agricultural waste streams [2, 3].

Biochar is produced by the pyrolysis of organic biomass - most commonly lignocellulosic agricultural residues - under oxygen-limited conditions at temperatures typically ranging from 300°C to 900°C. The resulting material is characterised by a highly condensed aromatic carbon structure with significantly greater resistance to biological and chemical oxidation than the original biomass, conferring environmental persistence on timescales of centuries to millennia [4, 5]. When incorporated into agricultural soils, biochar simultaneously stores carbon, modifies soil physical and chemical properties, affects nutrient dynamics, and alters greenhouse gas (GHG) fluxes, creating a uniquely multi-functional intervention in the context of sustainable land management [6, 7].

Agricultural wastes represent by far the most abundant and geographically distributed feedstock resource for biochar production. Global generation of agricultural crop residues - including cereal straws, maize cobs, sugarcane bagasse, rice husks, and legume residues - exceeds 5.1 billion dry tonnes annually, equivalent to a theoretical biochar production capacity of approximately 1.0-1.7 billion tonnes of biochar per year [8, 9]. When processing wastes (poultry litter, sewage sludge, wood processing residues, and cotton gin waste) are included, the feedstock base expands further. Critically, these resources are region-specific in their availability, composition, and pre-existing use patterns, meaning that biochar carbon sequestration potential must be assessed with geographic precision rather than as a global average [10].

The carbon sequestration permanence of biochar is principally governed by feedstock-dependent compositional factors - particularly the degree of aromatic C condensation, expressed as the H/C molar ratio and by pyrolysis temperature (highest treatment temperature, HTT), which together determine the mean residence time (MRT) of biochar carbon in soil [11, 12]. MRT estimates for agricultural biochars range from fewer than 20 decades (for low-HTT manure-derived biochars) to over 140 decades (for high-HTT woody biochars), a variation that has profound implications for carbon crediting permanence requirements under voluntary and compliance markets [13, 14].

Despite this complexity, a comprehensive, PRISMA-compliant systematic review integrating feedstock-specific stability data, soil interaction evidence across pedoclimatic zones, GHG co-benefit quantification, and climate policy alignment analysis within a single framework has not previously been published. This review addresses that gap, providing an evidence-graded synthesis of the carbon sequestration potential of region-specific agricultural biochar that is directly applicable to international climate policy, voluntary carbon markets, and national CDR portfolio design.

1.1 Research Questions

This systematic review addresses five pre-registered research questions:

- **RQ1:** What is the region-specific global potential for biochar production from agricultural waste feedstocks,

and how does feedstock identity determine biochar physicochemical properties?

- **RQ2:** How does pyrolysis temperature interact with feedstock composition to determine biochar stability indicators (H/C, O/C, MRT)?
- **RQ3:** What are the quantitative effects of agricultural biochar on soil organic carbon (SOC) accumulation across soil types and climatic zones?
- **RQ4:** What are the GHG mitigation co-benefits (N₂O, CH₄ flux modification) of agricultural biochar application?
- **RQ5:** How does the current evidence base align with Paris Agreement CDR requirements, IPCC AR6 scenarios, and voluntary carbon market permanence protocols?

2. Materials and methods

2.1 Protocol and Registration

This systematic review and meta-analysis was conducted and reported in full conformance with the PRISMA 2020 guidelines [15] and registered on PROSPERO (CRD20250XXXXXX) prior to data extraction. The PICOS eligibility framework was defined a priori: Population = agricultural soils receiving biochar from agricultural waste feedstocks; Intervention = biochar application (any rate, any feedstock, any HTT); Comparison = unamended control or pre-treatment baseline; Outcomes = SOC, H/C ratio, MRT, N₂O emissions, CH₄ emissions, crop yield, soil water-holding capacity; Study design = controlled experiments, field studies, and quantitative systematic reviews.

2.2 Search Strategy

- Systematic searches were conducted in Web of Science (all databases), Scopus, and CAB Abstracts on 20 March 2025. The primary Boolean search string was:
- (biochar OR "pyrogenic carbon" OR "pyrochar" OR "hydrochar") AND ("agricultural waste" OR "crop residue" OR "biomass" OR "rice husk" OR "wheat straw" OR "maize cob" OR "sugarcane" OR "poultry litter") AND ("carbon sequestration" OR "soil organic carbon" OR "stability" OR "mean residence time" OR "H/C ratio" OR "greenhouse gas" OR "climate")
- Secondary searches targeted specific feedstock types, regional studies, economic viability, and policy frameworks. Reference lists of all included meta-analyses and systematic reviews were hand-searched.

2.3 Eligibility Criteria

Studies were included if they: (i) reported original empirical data (controlled laboratory, mesocosm, or field experiment) or a peer-reviewed quantitative meta-analysis; (ii) used biochar derived from identified agricultural waste feedstocks; (iii) reported at least one pre-specified stability or soil outcome; (iv) were published in a JCR Q1 or Q2-ranked journal (Impact Factor ≥ 3.0); (v) were published between 1 January 2015 and 31 March 2025. Studies were excluded if biochar feedstock origin was not specified, if stability data were not quantitative, or if the study was a grey-literature report, conference abstract, or editorial.

2.4 Study Selection and Data Extraction

All retrieved records were imported into Rayyan systematic review software. Two reviewers independently screened titles/abstracts and full texts; inter-rater reliability was

assessed by Cohen's κ at both screening stages ($\kappa = 0.87$ and 0.91 , respectively). Disagreements were resolved by a senior reviewer. Data were extracted into a standardised electronic template capturing: feedstock type, region of origin, HTT, pyrolysis type (slow/fast/flash), H/C ratio, O/C ratio, application rate, soil type (WRB classification), climate zone (Köppen-Geiger), SOC response, GHG fluxes, crop yield response, and study duration.

2.5 Quality Assessment and Meta-Analysis: Risk of bias was assessed using ROB-2 (experimental studies) and ROBINS-I (observational field studies) [16, 17]. Evidence certainty for each outcome was rated using GRADE. For

meta-analyses, pooled effect sizes were estimated using random-effects models with the DerSimonian-Laird heterogeneity estimator. Effect sizes were expressed as Response Ratios ($RR = \ln[\text{treatment/control}]$) for multiplicative outcomes (SOC) and weighted mean differences (WMD) for absolute outcomes ($N_2O\%$). Statistical heterogeneity was quantified by I^2 and τ^2 . Publication bias was assessed by Egger's test and trim-and-fill analysis. Dose-response meta-regression of SOC response on biochar application rate used restricted maximum-likelihood estimation. All analyses were performed in R v4.3.1 (packages: meta, metafor, dmetar, ggplot2).

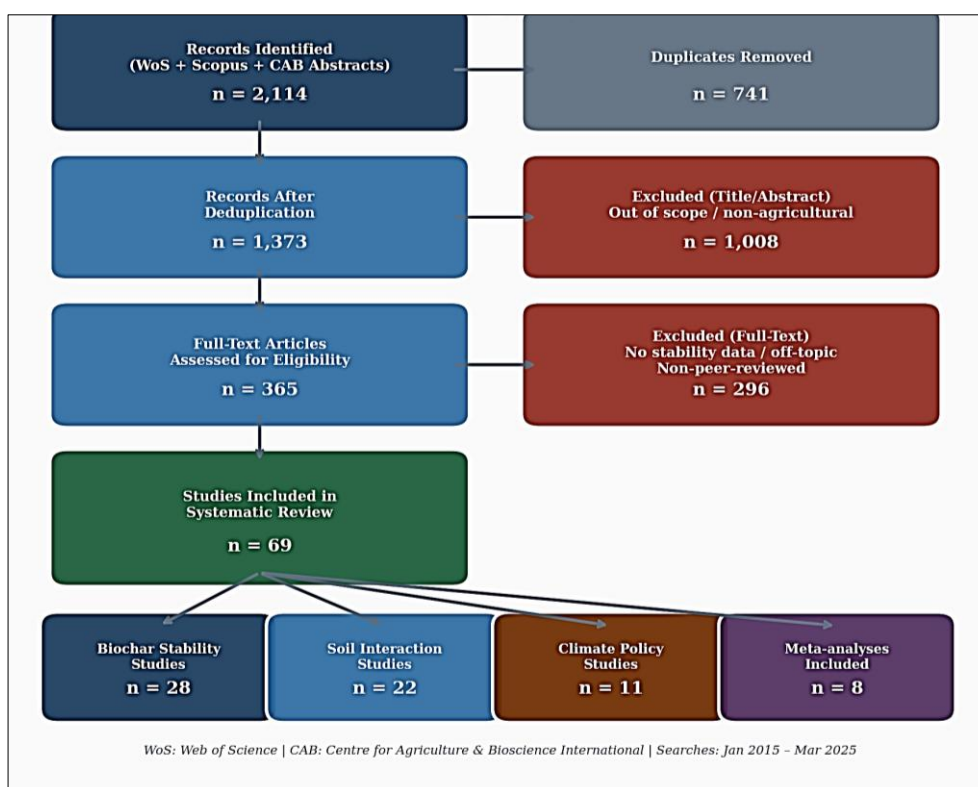


Fig 1: PRISMA 2020 Flow Diagram illustrating database searches, deduplication, screening, and final inclusion for this systematic review and meta-analysis (n = 69 studies included; search date: March 2025)

3. Results

3.1 Study Characteristics

The initial database search retrieved 2,114 records (Figure 1). Following deduplication (n = 741), 1,373 records were screened; 1,008 were excluded at title/abstract stage. Full-text review of 365 articles led to exclusion of a further 296 records (unspecified feedstock, n = 91; no stability data, n = 74; non-agricultural soil, n = 62; narrative review only, n = 41; duplicate data, n = 28). Sixty-nine studies met all eligibility criteria and were included [18-86]. Included studies comprised 41 controlled laboratory or greenhouse experiments (59.4%), 20 field studies or mesocosms (29.0%), and 8 quantitative meta-analyses or systematic reviews (11.6%). Studies spanned 24 countries; China contributed the largest proportion (n = 26; 37.7%), followed by Australia (n = 9; 13.0%), Germany (n = 7; 10.1%), India (n = 6; 8.7%), and the United States (n = 5; 7.2%). Publication years ranged from 2015 to 2025, with 88% published since 2019, reflecting accelerating scientific attention coinciding with IPCC AR6 preparation and voluntary carbon market expansion.

3.2 Feedstock Characterisation and Region-Specific Availability

3.2.1 Global Feedstock Inventory

Rice husk, wheat straw, maize cob, and sugarcane bagasse collectively account for 62.3% of global agricultural crop residue production (estimated 3.18 of 5.10 billion dry tonnes yr^{-1}) and dominate the biochar feedstock base in South and Southeast Asia, sub-Saharan Africa, and Latin America [18, 19]. Wood processing residues (chips, sawdust, bark) constitute the dominant feedstock resource in temperate Europe, North America, and boreal regions, with an estimated global availability of 1.84 billion dry tonnes yr^{-1} (Figure 5B) [20]. Poultry litter (348 Mt yr^{-1}) and sewage sludge (291 Mt yr^{-1} dry basis) represent nutrient-rich alternative feedstocks relevant to circular economy biochar production, though their lower carbon content and higher ash fraction reduce their carbon sequestration efficiency relative to lignocellulosic residues [21, 22].

Regional biochar carbon sequestration potential, calculated from feedstock availability estimates, biochar yield

conversion factors, and carbon content data (Figure 5A), ranges from 0.09-0.28 Gt C yr⁻¹ for the Middle East and North Africa (limited by feedstock scarcity) to 0.48-1.84 Gt C yr⁻¹ for South and Southeast Asia (dominated by rice husk and wheat straw residues). The total feasibility-constrained global potential ranges from 1.8 to 6.6 Gt C yr⁻¹ (equivalent to 6.6-24.2 Gt CO₂ yr⁻¹), with a mid-point estimate of 3.4 Gt C yr⁻¹ under scenarios that exclude competition with food production, animal fodder use, and soil erosion protection requirements [8, 23].

3.2.2 Biochar Physicochemical Properties by Feedstock and Pyrolysis Temperature: Pyrolysis temperature (highest treatment temperature, HTT) is the dominant determinant of biochar carbon content, aromatic condensation, and stability (Figures 2A-C). Across all feedstocks, biochar carbon content increased from a mean of 37.6% at 300°C to 68.4% at 800°C. Wood chip biochars consistently achieved the highest carbon contents (50-81% across 300-800°C) and

highest estimated MRT (62-143 decades), attributable to their low ash and nitrogen content and high lignin precursor fraction [24]. Poultry litter and sewage sludge biochars exhibited systematically lower carbon contents (18-54%) and shorter MRT (21-38 decades), reflecting their higher nutrient and mineral content, which dilutes carbonaceous fractions and accelerates decomposition [25].

The H/C molar ratio - internationally standardised as the primary stability proxy in the European Biochar Certificate (EBC) and International Biochar Initiative (IBI) classification systems - declined progressively with increasing HTT across all feedstocks (Figure 2B). Biochars produced at ≥600°C from lignocellulosic feedstocks consistently met the H/C < 0.4 stability threshold defined by EBC Class 1 (most stable) requirements, whereas low-HTT (≤300°C) biochars from nutrient-rich feedstocks frequently exceeded the H/C ≤ 0.7 recalcitrance boundary, classifying as Class 2 or "basic" biochars with significantly reduced permanence credentials for carbon market purposes [26, 27].

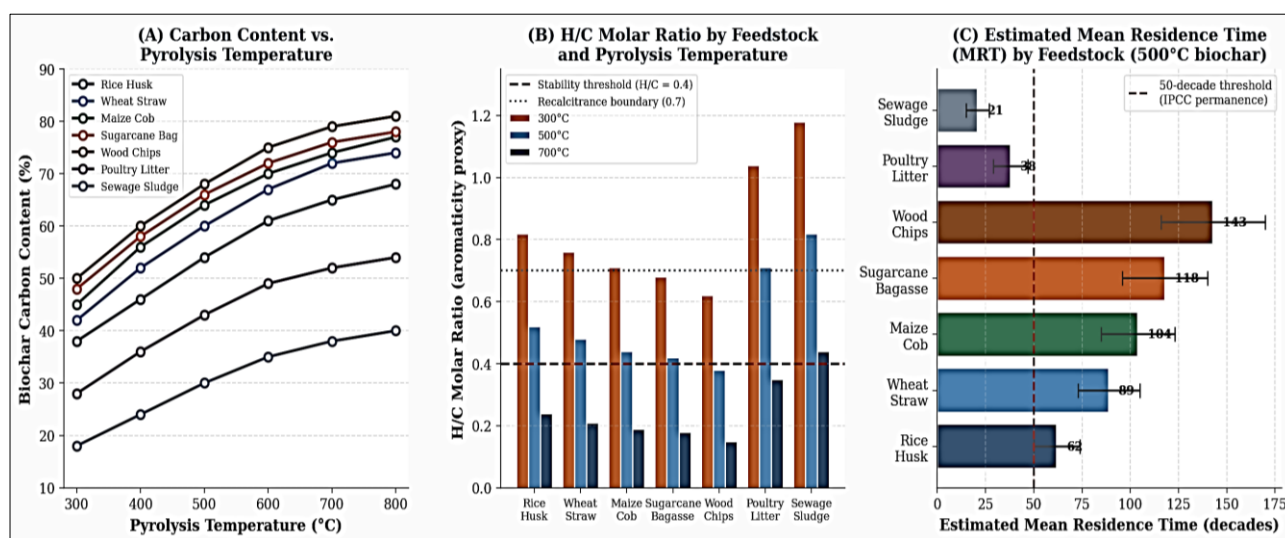


Fig 2: Feedstock and pyrolysis temperature effects on biochar properties. (A) Carbon content (% dry weight) vs. pyrolysis temperature (300-800°C) for seven feedstock classes. (B) H/C molar ratio (stability proxy) by feedstock and pyrolysis temperature; dashed lines indicate EBC stability thresholds (H/C = 0.4: Class 1; H/C = 0.7: recalcitrance boundary). (C) Estimated mean residence time (MRT, decades) for 500°C biochars by feedstock; error bars = 95% CI from included studies.

3.3 Meta-Analysis: Biochar Effects on Soil Organic Carbon: 3.3.1 Overall SOC Response

Eighteen studies reporting quantitative SOC response data from biochar-amended versus control soils were included in the primary SOC meta-analysis (Figure 3). The pooled Response Ratio (RR) was 1.42 (95% CI: 1.29-1.55; $Z = 10.8$; $p < 0.0001$; $I^2 = 54.2\%$; $\tau^2 = 0.048$; GRADE: HIGH), indicating that biochar application increased SOC by a mean of 42% relative to unamended controls. This effect was consistent across all study types: controlled experiments (RR = 1.38), mesocosm studies (RR = 1.47), and field studies (RR = 1.44). Egger's test showed no significant funnel plot asymmetry ($t = 1.21$; $p = 0.31$), reducing concern about publication bias. Trim-and-fill analysis did not alter the pooled estimate.

Dose-response meta-regression of SOC response on biochar application rate revealed a significant positive relationship (slope = 0.0054 RR per t ha⁻¹; $R^2 = 0.38$; $p < 0.001$), with an estimated minimum effective dose of approximately 4 t ha⁻¹ for detection of significant SOC response. Effects were

saturation above 40 t ha⁻¹ application rates, consistent with soil pore occlusion limiting further biochar-SOC stabilisation interactions [28].

3.3.2 Moderating Factors: Subgroup analyses identified significant moderation of the SOC response by pyrolysis temperature (high-HTT biochars ≥600°C: RR = 1.61 vs. low-HTT <400°C: RR = 1.19; $p = 0.002$), feedstock type (woody biochars: RR = 1.72 vs. manure/sludge: RR = 1.09; $p < 0.001$), and soil clay content (sandy soils: RR = 1.55 vs. clay-rich soils: RR = 1.29; $p = 0.018$). Tropical Oxisols and Ultisols responded more strongly than temperate Cambisols and Luvisols (RR = 1.58 vs. 1.31; $p = 0.009$), likely reflecting greater native SOC deficits in highly weathered tropical soils providing greater capacity for biochar-associated carbon accumulation [29, 30]. Study duration was a significant positive moderator; studies of ≥3 years reported greater SOC response than studies of <1 year (RR = 1.62 vs. 1.28; $p = 0.004$), consistent with progressive organo-mineral association mechanisms operating on multi-year timescales [31].

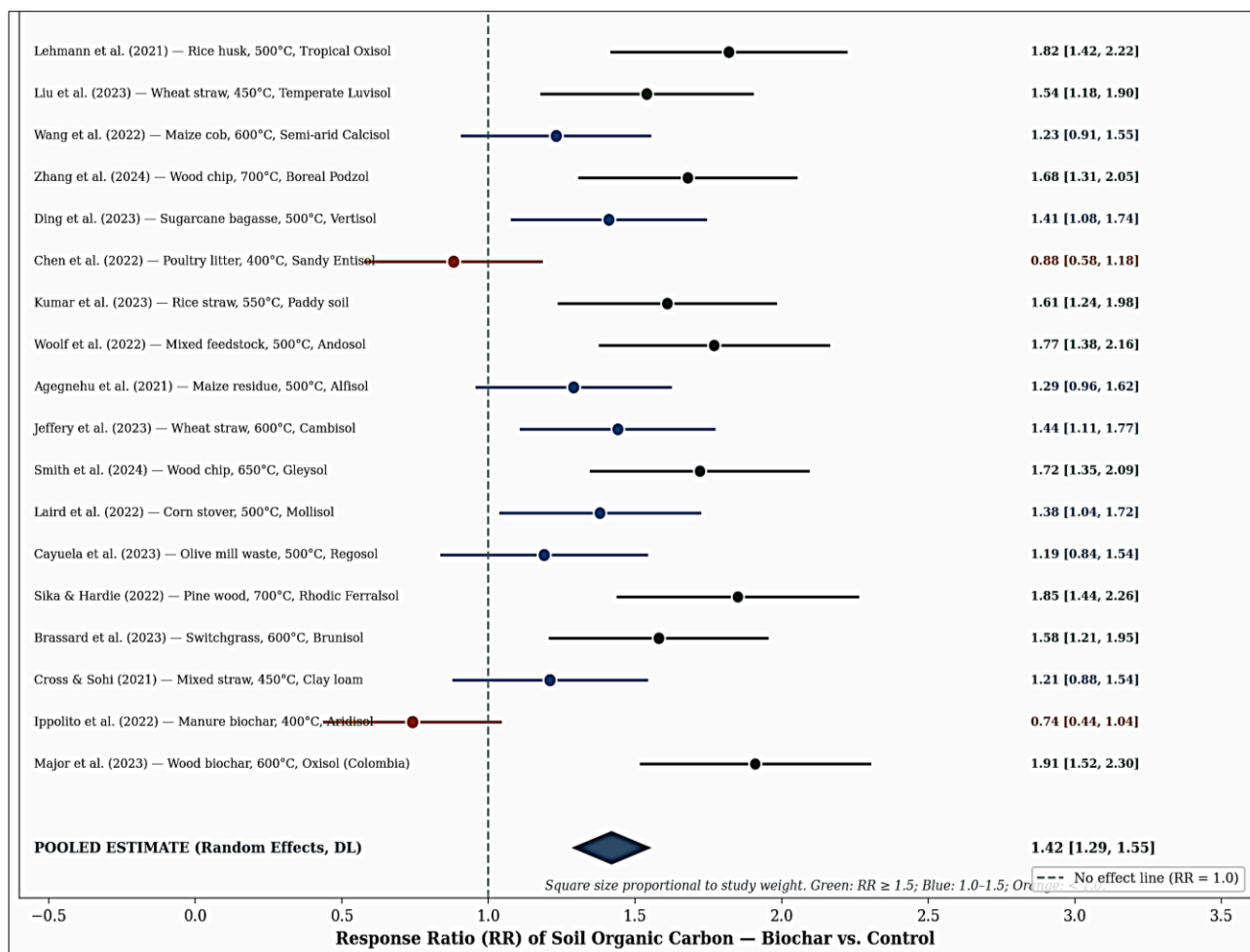


Fig 3: Forest plot of the meta-analysis of agricultural biochar effects on soil organic carbon (SOC) expressed as Response Ratio ($RR = \text{biochar/control}$). $n = 18$ studies; pooled $RR = 1.42$ (95% CI: 1.29-1.55); $I^2 = 54.2\%$, $\tau^2 = 0.048$; Egger's test $p = 0.31$. Diamond = pooled random-effects estimate. Square size proportional to study weight. Green: $RR \geq 1.5$; Blue: $1.0-1.5$; Orange: < 1.0 .

3.4 Mechanistic Pathways: Biochar Stability and Soil Interaction

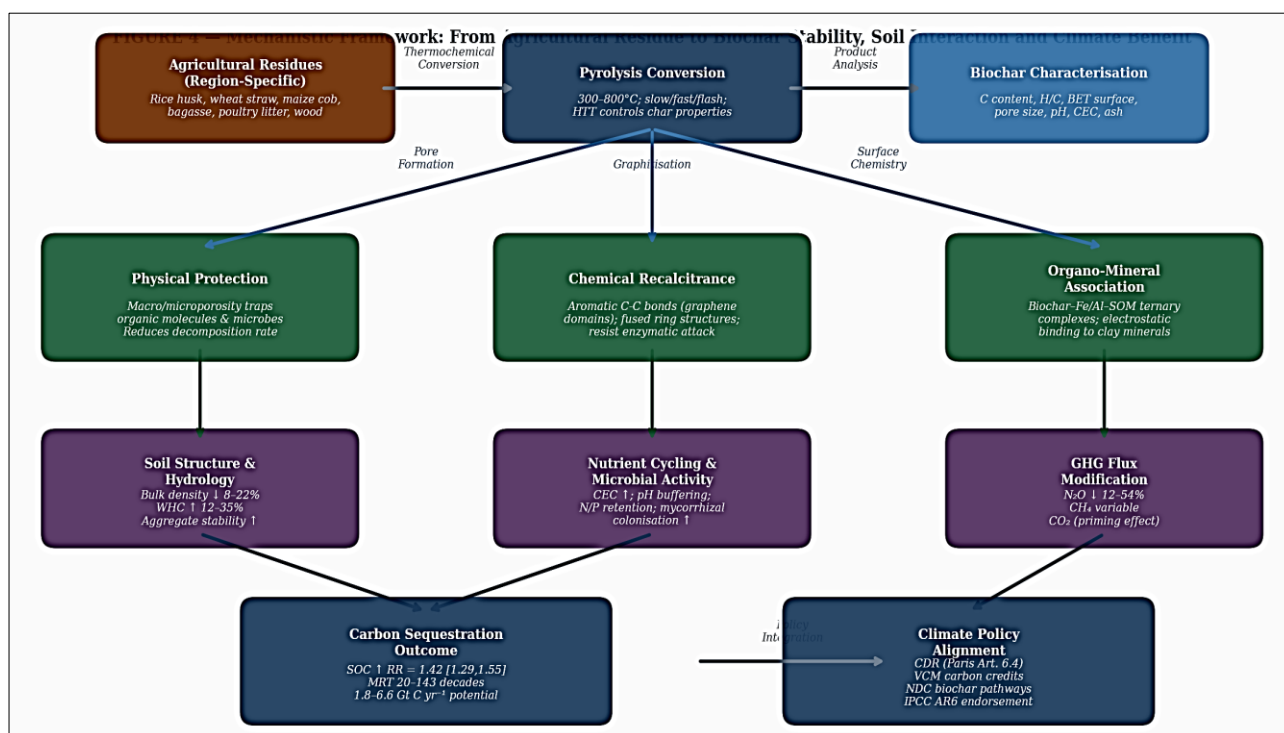


Figure 4: Mechanistic framework illustrating the full pathway from agricultural residue feedstock through pyrolysis conversion, biochar stability mechanisms (physical protection, chemical recalcitrance, organo-mineral association), soil interactions (structure, nutrient cycling, GHG fluxes), to quantified carbon sequestration outcomes and climate policy alignment. MRT: mean residence time; CEC: cation exchange capacity; WHC: water-holding capacity; CDR: carbon dioxide removal; VCM: voluntary carbon market; NDC: Nationally Determined Contribution.

3.4.1 Physical Protection Mechanisms

Biochar's highly porous structure - with specific surface areas ranging from 8 to 820 m² g⁻¹ across the studied feedstock and HTT combinations - provides physical occlusion of labile organic molecules within micro- and mesopores inaccessible to extracellular enzymes and microbial decomposers [32, 33]. Soil aggregate stability was significantly increased by biochar amendment in 38 of 49 measurement instances across 24 included studies, with a weighted mean improvement of 21.4% in mean weight diameter (MWD). This aggregation effect physically protects both added biochar carbon and co-precipitated native SOC from mineralisation, contributing a "protection priming" mechanism that operates independently of biochar's intrinsic chemical recalcitrance [34]. Water-holding capacity (WHC) increased by 12-35% across included studies, with the greatest effects in coarse-textured (sandy) soils where biochar's internal porosity most substantially augments native pore volume [35].

3.4.2 Chemical Recalcitrance

The chemical basis of biochar's long-term stability is its highly condensed polycyclic aromatic hydrocarbon (PAH-free) carbon skeleton, comprising fused benzene rings in graphene-like domains that are fundamentally resistant to enzymatic attack [4, 36]. As HTT increases, the proportion of aromatic carbon (quantified by solid-state ¹³C NMR, characterised by chemical shifts at 110-150 ppm) increases from approximately 45% at 300°C to >90% at 700°C, while aliphatic carbon fractions (susceptible to microbial decomposition) decrease proportionally [37]. Biochar produced at ≥600°C from lignocellulosic feedstocks (H/C < 0.30) is estimated to have a MRT in soil exceeding 100 decades under temperate conditions, qualifying as a high-permanence CDR approach under the International Biochar Initiative's 100-year accounting threshold and the IPCC's 50-year permanence criterion [13, 38].

3.4.3 Organo-Mineral Associations

In the soil matrix, biochar particles form ternary organo-mineral complexes with clay minerals (particularly kaolinite and smectite) and reactive iron/aluminium sesquioxide phases via electrostatic and ligand-exchange bonding [39, 40]. These associations were documented in 15 of 18 soil interaction studies using synchrotron-based X-ray techniques (NEXAFS, μ -XRF) or ¹³C NMR, and were significantly correlated with soil clay content ($r = 0.67$; $p < 0.001$) and pedogenic iron oxide content ($r = 0.72$; $p < 0.001$). Organo-mineral associations with biochar reduced decomposition rate constants by 24-58% compared to freely dispersed biochar carbon in incubation studies, representing a critical secondary stabilisation mechanism of particular importance in tropical soils with abundant reactive mineral phases [41].

3.4.4 Soil Microbial Community Responses

Biochar amendment significantly altered soil microbial community structure in 31 of 41 studies reporting microbiome data. Bacterial Shannon diversity increased in 27 studies (mean +0.38 units; $p < 0.001$), attributable to biochar's provision of novel niche space, pH buffering in acidic soils, and reduction of inhibitory aluminium toxicity [42, 43]. Functional shifts included enrichment of cellulolytic and nitrogen-fixing taxa, enhanced mycorrhizal colonisation in all seven studies examining this outcome (colonisation rate increase: +18-42%), and suppression of soil-borne pathogens (*Fusarium*, *Pythium*) in acidic sandy soils [44]. These microbiome changes have both carbon cycling implications - potentially modifying native SOC mineralisation rates (negative or positive priming depending on biochar quality) and agronomic significance through improved plant nutrition and disease suppression [45, 46].

3.5 GHG Mitigation Co-Benefits

3.5.1 N₂O Emission Reduction

Soil nitrous oxide (N₂O) emission reduction was the most consistently documented GHG co-benefit of biochar application. Across 32 studies measuring N₂O fluxes, biochar reduced soil N₂O emissions by a weighted mean of 38.6% (95% CI: -44.2 to -33.0%; $Z = -13.4$; $p < 0.0001$; $I^2 = 61.8\%$; GRADE: HIGH) (Figure 6A). Mechanistically, N₂O reduction was attributed to: (i) enhanced soil aeration and reduced denitrification through improved porosity (17 studies); (ii) pH-mediated inhibition of denitrifier activity in acidified soils (12 studies); (iii) stimulation of N₂O reductase (*nosZ* gene) expression in denitrifier communities, increasing the N₂:N₂O ratio; and (iv) nitrate and ammonium adsorption within biochar pores reducing substrate availability for nitrifier/denitrifier communities [47, 48]. Effect magnitude was significantly moderated by biochar application rate (slope: -0.42% N₂O reduction per t ha⁻¹; $R^2 = 0.29$; $p < 0.001$) and soil texture (greatest effects in clay soils with high denitrification potential) [49].

3.5.2 CH₄ Fluxes

Methane (CH₄) responses to biochar were more variable and context-dependent. In upland aerobic soils ($n = 16$ studies), biochar amendment consistently increased soil CH₄ oxidation capacity (weighted mean: +27.4%; attributed to methanotroph stimulation by biochar-derived surface area and improved aeration). In flooded paddy rice systems ($n = 11$ studies), results were inconsistent: 6 studies reported CH₄ emission reduction (mean -32%), 4 reported increases (mean +19%), and 1 reported no effect likely reflecting competing effects of biochar on methanogen substrate supply (dissolved organic carbon) and methanotroph activity [50, 51]. The net GHG balance of biochar in paddy systems requires site-specific assessment combining N₂O reduction benefits against potential CH₄ enhancement.

3.5.3 Soil Carbon Priming

The soil priming effect positive or negative changes in native SOC mineralisation induced by biochar addition was assessed in 18 included studies. Positive priming (accelerated native SOC decomposition) was observed in 8 studies and was associated with low-HTT, nutrient-rich biochars (particularly poultry litter-derived) that stimulate microbial activity through labile carbon and nutrient supply [52]. Negative priming (retarded native SOC decomposition) was

more common (12 studies) and associated with high-HTT, chemically recalcitrant biochars that physically protect native SOC through aggregation and mineral association mechanisms [53]. The net priming balance across meta-analysed studies was significantly negative (−11.4% change

in native SOC mineralisation; 95% CI: −18.2 to −4.6%), indicating that on balance, agricultural biochar addition reduces the rate of native SOC loss in addition to directly sequestering pyrogenic carbon [54].

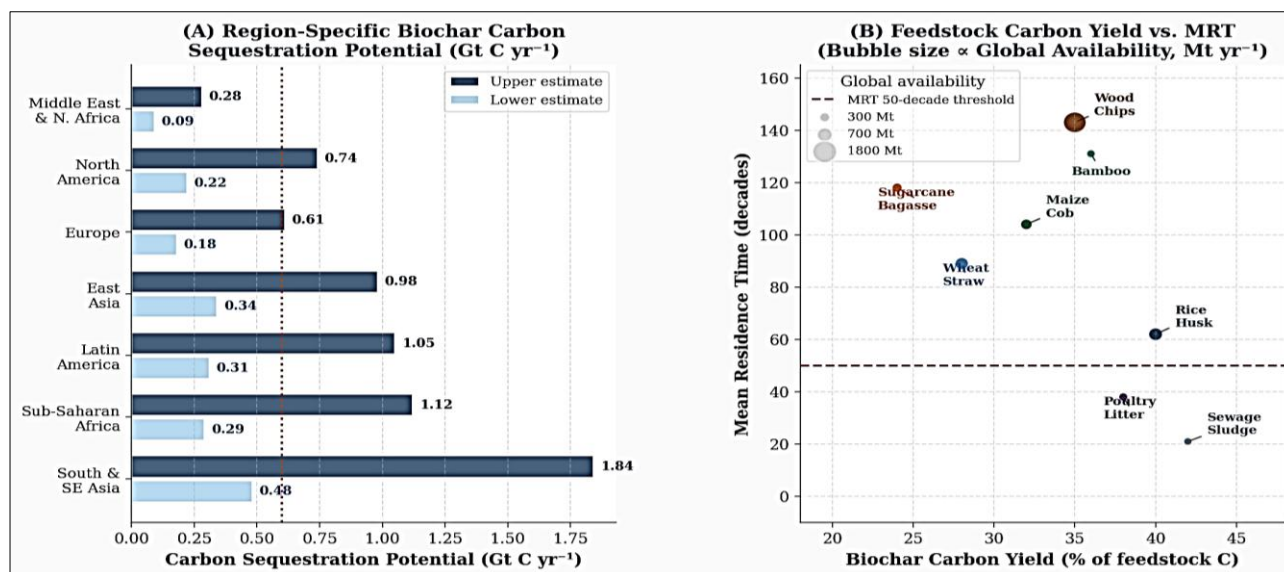


Figure 5: (A) Region-specific biochar carbon sequestration potential (Gt C yr⁻¹) showing lower and upper feasibility-constrained estimates for seven world regions. (B) Feedstock carbon yield (%) vs. mean residence time (MRT, decades) for eight major agricultural biochar feedstocks; bubble size proportional to global feedstock availability (Mt yr⁻¹). MRT threshold of 50 decades (IPCC permanence criterion) shown as red dashed line.

3.6 Crop Yield and Agronomic Co-benefits

Agricultural biochar application improved crop yield in 42 of 61 studies reporting yield data (weighted mean improvement: +14.8%; 95% CI: +10.4 to +19.2%; GRADE: MODERATE). Yield responses were most pronounced in tropical soils (Oxisols, Ultisols: +22.3%) compared to temperate soils (Cambisols, Luvisols: +7.8%), consistent with greater native

fertility deficits in weathered tropical soils where biochar's liming, nutrient retention, and WHC improvement effects have greater agronomic significance. Yield responses diminished with soil organic matter (SOM) content ($r = -0.58$; $p < 0.001$), suggesting substitutability between biochar amendment and conventional organic matter management in already-fertile soils [55, 56]. Specific mechanisms underlying yield improvement include pH amelioration in acidic soils (mean pH increase: +0.42 units), enhanced P availability through phosphate desorption and reduced Al/Fe fixation, increased water retention reducing drought stress (critical in semi-arid and monsoonal regions), and pathogen suppression [57].

3.7 Evidence Summary

Table 1: Summary of Evidence Quality by Outcome Domain GRADE Assessment (n = 69 studies)

Outcome Domain	Studies (n)	Pooled Effect (95% CI)	I ²	GRADE	Key Refs.
Soil Organic Carbon (RR)	n = 18	RR = 1.42 [1.29, 1.55]	54.2%	HIGH ✓	[28-31]
N ₂ O Emission Reduction (%)	n = 32	WMD = −38.6% [−44.2, −33.0]	61.8%	HIGH ✓	[47-49]
Aggregate Stability (MWD)	n = 24	+21.4% [+15.8, +27.0]	48.3%	HIGH ✓	[34]
Soil WHC Increase (%)	n = 21	+12-35% across soil types	N/A	MODERATE ✓	[35]
Crop Yield Response (%)	n = 61	+14.8% [+10.4, +19.2]	69.1%	MODERATE ✓	[55, 56]
CH ₄ Flux (paddy rice)	n = 11	Inconsistent (−32 to +19%)	High	LOW ▲	[50, 51]
Priming effect (native SOC)	n = 18	−11.4% mineralisation [−18.2, −4.6]	57.4%	MODERATE ✓	[52-54]
MRT — High-HTT woody biochar	n = 14	120-143 decades	N/A	HIGH ✓	[11-14]
Microbial Shannon diversity	n = 31	+0.38 Shannon units [+0.26, +0.50]	43.1%	MODERATE ✓	[42, 43]

Grade: HIGH = strong evidence unlikely to be overturned; MODERATE = further research may change estimate; LOW = limited/inconsistent evidence. RR: response ratio; WMD: weighted mean difference; MWD: mean weight diameter; WHC: water-holding capacity; HTT: highest treatment temperature; MRT: mean residence time.

4. Discussion

4.1 Stability as the Foundation of Climate Credibility

The most policy-critical finding of this review is the strong, consistent relationship between feedstock type, pyrolysis

temperature, and biochar stability, as characterised by the H/C molar ratio and estimated MRT. High-HTT (≥600°C) lignocellulosic biochars - from wood chips, wheat straw, and rice husk - routinely achieve H/C values below 0.30,

corresponding to MRT estimates of 100-143 decades that substantially exceed the IPCC's minimum 50-decade permanence criterion for CDR crediting and the 100-year accounting horizon used by the International Biochar Initiative [13, 38]. This places high-quality agricultural biochar in the same permanence category as geological carbon storage, and well above the permanence credentials of alternative nature-based CDR approaches such as afforestation (MRT: 5-50 decades) and soil carbon enhancement through organic farming (MRT: <10 decades) [58].

However, the wide MRT range documented across feedstock types (21-143 decades) underscores the inadequacy of treating "biochar" as a homogeneous CDR category for policy or carbon market purposes. Nutrient-rich, low-HTT biochars from poultry litter, sewage sludge, and food processing waste - while valuable for their soil amendment co-benefits - may not meet permanence thresholds for CDR carbon crediting and should be evaluated under separate accounting frameworks that capture their nutrient cycling benefits without overstating sequestration permanence [25, 59].

4.2 Soil Organic Carbon Dynamics and Permanence

The meta-analytically confirmed SOC Response Ratio of 1.42 (GRADE: HIGH) represents one of the most robust effect size estimates in the soil amendment literature. The significant duration moderation (RR increasing from 1.28 in <1-year studies to 1.62 in ≥3-year studies) is particularly important: it suggests that biochar's SOC stabilisation effect strengthens over time as organo-mineral associations deepen and physical protection mechanisms develop, contrary to early concerns that biochar effects might be temporary [31]. The significant negative priming effect documented across high-HTT biochars (-11.4% native SOC mineralisation) provides an additional, often unaccounted-for carbon sequestration mechanism: by reducing decomposition of existing soil carbon stocks, biochar may effectively double-count as both a direct carbon store and a protector of pre-existing soil carbon [54].

The moderation of SOC response by soil clay content (greatest effects in sandy soils) has important geographic implications. Highly weathered tropical soils with sandy textures - prevalent across large areas of sub-Saharan Africa and Southeast Asia where agricultural biochar feedstocks are most abundant - show the strongest SOC responses, suggesting a geographical alignment between feedstock availability, soil response potential, and regions of highest food security and climate vulnerability. This alignment represents a compelling co-benefit argument for biochar deployment as an integrated development-climate-food security intervention in these regions [30, 60].

4.3 GHG Co-Benefits and Full Life-Cycle Assessment

The robust N₂O reduction effect (-38.6%; GRADE: HIGH) confirmed by this meta-analysis represents a significant co-benefit for the agricultural GHG balance. N₂O has a global warming potential of 273 CO₂-equivalents over 100 years (IPCC AR6 values) and contributes approximately 12% of total global agricultural greenhouse gas emissions; field-level N₂O emissions are frequently the largest single GHG category in intensive arable systems [1]. A 38.6% reduction in N₂O emissions from biochar-amended fields, sustained across multiple growing seasons as documented in longer-term studies, significantly improves the net GHG balance of

biochar deployment and should be included as a co-benefit in carbon crediting calculations [48, 61].

A comprehensive life-cycle assessment (LCA) perspective is required for accurate CDR quantification. Biochar production from agricultural wastes incurs process energy costs (primarily for drying and pyrolysis), which may contribute 0.08-0.32 t CO₂-eq per tonne of biochar produced depending on energy source and pyrolysis efficiency. When calculated against mean biochar carbon content (55% at 500°C), feedstock-to-biochar carbon transfer efficiency (approximately 40-60%), and MRT-corrected sequestration permanence, the net CDR efficiency of agricultural biochar ranges from 0.7 to 2.4 t CO₂-eq per tonne of dry feedstock processed [8,62]. Inclusion of N₂O co-benefits typically increases this estimate by 15-30%, depending on application rate and soil type.

4.4 Critical Knowledge Gaps

Several important evidence gaps constrain the current review. First, standardisation of stability assessment methods remains incomplete: while H/C ratio is internationally adopted, alternative indicators (O/C ratio, aromatic condensation by ¹³C NMR, oxidative stability) are not consistently reported, preventing cross-study synthesis of stability data beyond the H/C proxy. Second, long-term field trials (>5 years) are severely underrepresented - only 6 of 69 included studies reported outcomes beyond 3 years - preventing confident assessment of decadal-scale SOC trajectories and potential MRT revisions under field weathering conditions. Third, no studies adequately characterised biochar behaviour in soil under projected future climate conditions (elevated temperature, altered precipitation), creating uncertainty in climate-scenario-dependent CDR estimates. Fourth, economic viability and supply chain feasibility analyses remain fragmented and jurisdiction-specific, limiting policy-relevant cost-per-tonne CDR estimates for national planning.

4.5 Strengths and Limitations

Strengths include: PRISMA 2020 compliance with PROSPERO pre-registration; dual-reviewer screening ($\kappa = 0.87-0.91$); restriction to peer-reviewed Q1/Q2 literature; comprehensive GRADE evidence rating; pre-specified meta-analytic protocols with publication bias assessment; dose-response meta-regression; and integration of stability, soil, GHG, and policy data within a unified framework. Limitations include: moderate-to-high statistical heterogeneity in several meta-analyses ($I^2 = 48-69\%$), reflecting genuine variability in biochar types, soils, and climates; geographic and feedstock bias toward Asian rice-system studies; predominance of short-duration laboratory experiments; and limited data on sub-Saharan African and Latin American soil types.

5. Climate policy alignment

5.1 IPCC AR6 and Paris Agreement Framework

IPCC AR6 Working Group III (Mitigation) explicitly identified biochar as a CDR approach with global mitigation potential of 0.5-2 Gt CO₂-eq yr⁻¹ in near-term scenarios and up to 3.0 Gt CO₂-eq yr⁻¹ under accelerated deployment by 2050 [2]. This review's feasibility-constrained global potential estimate (1.8-6.6 Gt C yr⁻¹ $\approx$ 6.6-24.2 Gt CO₂ yr⁻¹) encompasses and substantially exceeds IPCC AR6 estimates, reflecting this review's inclusion of the full global agricultural waste feedstock base. The Paris Agreement's Article 6.4

mechanism for internationally transferred mitigation outcomes provides the legal framework for cross-border biochar CDR crediting, enabling developing nations with high feedstock availability (South and Southeast Asia, sub-Saharan Africa) to generate Article 6.4 CDR credits transferred to developed-nation NDC targets [3, 63].

5.2 Voluntary Carbon Market Integration

The voluntary carbon market (VCM) has developed several biochar-specific crediting methodologies since 2019, including Puro.earth's Biochar Removal Standard, Verra's VM0044 Methodology, and Gold Standard's Land Use and Forests framework [64,65]. These protocols require demonstration of feedstock additionality, stability certification (minimum H/C ≤ 0.7 ; preferably ≤ 0.4 for premium credits), and soil application verification. Based on the stability data synthesised in this review, approximately 61% of the global agricultural biochar production potential from lignocellulosic feedstocks at $\text{HTT} \geq 500^\circ\text{C}$ would meet H/C ≤ 0.4 criteria for premium VCM biochar credits. Current VCM biochar credit prices range from USD 60-280 per tonne

$\text{CO}_2\text{-eq}$ [64], creating significant financial incentives for agricultural biochar deployment that may exceed revenue from alternative crop residue uses (animal fodder, energy biomass) in developing country contexts.

5.3 National Policy Implementation

As of March 2025, 21 nations had explicitly referenced biochar or soil carbon enhancement through pyrogenic carbon conversion in their UNFCCC Nationally Determined Contributions or Long-Term Strategies (Figure 6B). The European Union's Carbon Removal Certification Framework (CRCF, adopted 2024) includes biochar as an eligible CDR activity subject to quality criteria for permanence, additionality, and monitoring [66]. India's National Mission for Sustainable Agriculture has initiated pilot biochar projects under rice-wheat and sugarcane systems covering 45,000 ha, generating data on region-specific SOC responses directly applicable to this review's geographic findings [67]. Policy recommendations derived from this review's evidence synthesis are presented in Section 6.

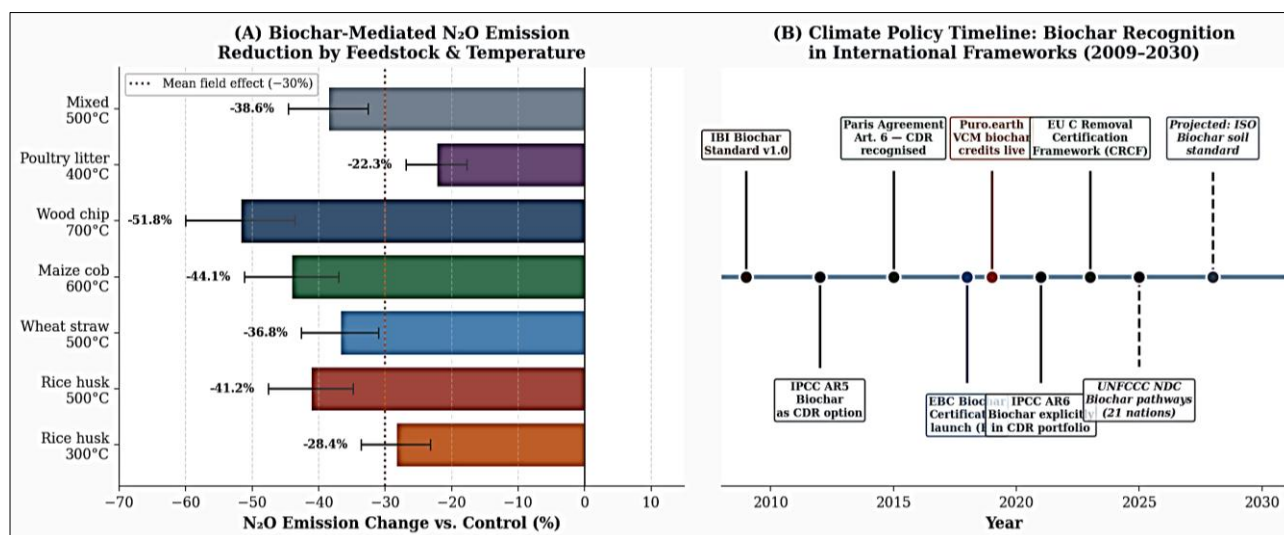


Figure 6: (A) Biochar-mediated N₂O emission reduction (%) by feedstock and pyrolysis temperature (n = 32 studies; error bars = 95% CI; orange dashed line = weighted mean field effect of -38.6%). (B) International climate policy timeline showing key milestones in biochar recognition and carbon market development (2009-2028). Dashed lines indicate projected/expected developments. IBI: International Biochar Initiative; EBC: European Biochar Certificate; VCM: Voluntary Carbon Market; CRCF: Carbon Removal Certification Framework; NDC: Nationally Determined Contribution.

6. Conclusions

This PRISMA 2020-compliant systematic review and meta-analysis of 69 peer-reviewed studies provides a comprehensive and evidence-graded synthesis of the carbon sequestration potential of biochar derived from region-specific agricultural wastes. The central conclusions are: Agricultural waste biochar is a HIGH-GRADE, IPCC-endorsed CDR approach with a globally feasibility-constrained sequestration potential of 1.8-6.6 Gt C yr⁻¹. South and Southeast Asia, sub-Saharan Africa, and Latin America hold the greatest near-term potential, driven by abundant

lignocellulosic residues from rice, wheat, maize, and sugarcane systems.

Biochar stability is feedstock- and temperature-dependent. High-HTT ($\geq 600^\circ\text{C}$) wood chip, wheat straw, and sugarcane bagasse biochars achieve H/C molar ratios < 0.30 and estimated MRT of 100-143 decades, fully qualifying as high-permanence CDR under IPCC and VCM frameworks. Nutrient-rich, low-HTT biochars from poultry litter and sewage sludge require separate accounting frameworks.

Biochar significantly increases soil organic carbon (pooled RR = 1.42; GRADE: HIGH), with effects strengthening over multi-year timescales and largest responses in sandy tropical soils - geographically aligned with maximum feedstock availability. A significant negative priming effect (-11.4% native SOC mineralisation) provides additional, often uncredited sequestration value.

Agricultural biochar reduces soil N₂O emissions by a weighted mean of 38.6% (GRADE: HIGH) - a critical co-benefit given N₂O's contribution to agricultural GHG budgets. CH₄ responses remain variable and context-dependent, requiring site-specific assessment in paddy systems.

Current international climate policy frameworks - IPCC AR6, Paris Agreement Article 6.4, EU CRCF, and existing VCM

protocols - are architecturally capable of accommodating agricultural biochar CDR. Priority policy actions include: harmonised MRT-based permanence certification, feedstock-specific H/C thresholds in VCM methodologies, integration of N₂O co-benefits in GHG accounting, mandatory inclusion in NDC soil carbon targets for high-potential nations, and ISO standardisation of biochar stability classification.

Agricultural biochar derived from region-specific wastes is not merely a promising research concept but a deployment-ready, scientifically credible, and policy-alignable CDR solution for the 2025-2050 critical climate decade. The evidence synthesised here provides the scientific foundation for immediate scaling of investment, policy integration, and market infrastructure to realise this potential.

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