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Advancing Sustainable Rice Production With Hydrochar And Animal-Waste Biochar Of Agronomic, Soil, And Environmental Impacts: A Systematic Review

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Abstract
Rice cultivation is a critical component of global food security, particularly in Asia, Africa, and Latin America. However, rice paddies are substantial sources of methane (CH_4), nitrous oxide (N_2O), and ammonia (NH_3), while also contributing to soil acidification from prolonged fertilizer use. To address these challenges, this systematic review evaluates the impact of biochar and hydrochar amendments on agronomic performance, soil health, and environmental outcomes in rice production systems. A comprehensive literature search was conducted using Google Scholar, Scopus, ScienceDirect, and PubMed databases, following the PRISMA guidelines. Studies published in English that assessed the application of biochar (derived from animal waste) and hydrochar in rice cultivation were included. The review synthesizes data from 41 studies, covering a range of experimental designs (soil column, pot trials, field experiments) and material types (biochar, hydrochar, and co-amended forms). Key outcomes evaluated include grain yield, biomass, plant height, tiller count, soil pH, soil organic carbon (SOC), cation exchange capacity (CEC), microbial activity, greenhouse gas emissions (GHGs), and nutrient leaching. The results show that biochar, particularly from animal waste, consistently improves yield, nutrient retention, and pH, and reduces GHG emissions. Hydrochar, though more variable, demonstrates potential for enhancing nitrogen use efficiency and mitigating methane and nitrous oxide emissions when appropriately modified. The review underscores the need for multi-season, field-scale studies, standardized material specifications, and integrated measurements to optimize the use of these amendments in sustainable rice production.
Keywords: *Agronomic performance, Soil organic carbon, Greenhouse gas mitigation, Nutrient leaching, Cation exchange capacity, Rice paddy management, Sustainable agriculture.*

1.0 INTRODUCTION

Rice (*Oryza sativa L.*) is the daily staple food for more than half of the world's people and remains foundational to food security across Asia, Africa, and Latin America, with the International Rice Research Institute (IRRI) and allied Consortium of International Agricultural Research Centres (CGIAR) materials reaffirming its central role. Globally, the Food and Agriculture Organization's *World Food and Agriculture – Statistical Yearbook 2023* documents the continued dominance of rice in cropland allocation and production, underscoring the scale at which any agronomic or environmental intervention in paddy systems matters (FAO, 2023). At the same time, flooded rice is a material source of biogenic methane (CH_4) within the anthropogenic methane budget, recent Global Methane Budget assessments attribute a substantial share of agriculture-and-waste CH_4 to rice cultivation, with sectoral breakdowns placing rice near 8% of anthropogenic CH_4 in earlier syntheses, thereby positioning paddies squarely within near-term methane-mitigation priorities reflected in the IPCC Sixth Assessment Report (IPCC, 2022). Nitrogen losses as ammonia (NH_3) volatilization are also conspicuous in paddy ecologies due to waterlogged, low-oxygen conditions; recent reviews emphasize elevated NH_3 emission factors in rice relative to upland crops and the management leverage available to reduce NH_3 while maintaining yield and nitrogen use efficiency (NUE) (Canatoy et al., 2024; Zhang et al., 2024).

Beyond gaseous losses, long-term fertilizer intensification has contributed to soil acidification in major rice regions, diminishing nutrient-retention capacity and compounding sustainability challenges; new meta-analyses and regional syntheses document significant pH declines under sustained nitrogen inputs (Zhang et al., 2022). Addressing these constraints requires strategies that rebuild soil organic carbon (SOC) and enhance cation exchange capacity for nutrient retention, targets aligned with recent evidence linking higher SOC in paddies to yield stability and with studies showing that carbonaceous amendments, most prominently biochar (the solid product of biomass pyrolysis under limited oxygen) and hydrochar (the solid product of hydrothermal carbonization, HTC, produced in hot, pressurized water) can raise cation/anion exchange capacity and curb nutrient leaching (Dey et al., 2023; Wang et al., 2024).

Pyrolytic biochars, particularly those produced from animal wastes such as poultry litter and cattle manure, are characteristically ash-rich and alkaline, with high specific surface area and persistent aromatic carbon. These properties tend to raise soil pH in acidic paddies, elevate SOC and often CEC, and improve nutrient retention, mechanistic pathways that align with frequently observed agronomic gains in rice systems (Ali et al., 2023; Babu et al., 2025; Joardar et al., 2020; Maikol et al., 2021; Kimani et al., 2021). Hydrochars, by contrast, are formed in an aqueous environment at lower temperatures and commonly contain more oxygenated surface functional groups, lower pH, and a higher fraction of labile dissolved organic matter (DOM). Hydrochar chemistry can be tuned post-production through washing, microbial aging, acid modification, or mineral templating with clays; in addition, HTC generates liquid coproducts such as the hydrothermal aqueous phase (HAP) and the hydrochar reaction-finished solution (HRFS), which can function as acidic, nutrient-bearing liquid amendments when carefully dosed (Ji et al., 2020; Hou et al., 2020; He et al., 2022b; Li et al., 2023; Yi et al., 2022; Feng et al., 2025). These material contrasts imply distinct agronomic mechanisms and environmental trade-offs in flooded paddy soils.

Decision-relevant synthesis tailored to rice systems remains incomplete. Outcomes reported in the literature vary with feedstock, production parameters (temperature, residence time), application rate, co-amendments, irrigation and drainage schedules, and experimental scale (pots, soil columns, micro-plots, or fields). Many studies are short-term and vessel-based, only partially reproducing flooded redox dynamics, rhizosphere oxygen gradients, and seasonal GHG flux patterns. Soil-physical indicators and biological endpoints (microbial biomass, enzyme activities) are often missing, limiting integration with agronomic responses. Rate sensitivity is a recurrent challenge for hydrochar: modest doses (0.5–1% w/w) often sustain or raise yield and can offset planned nitrogen reductions, whereas high doses (3% w/w) have repeatedly depressed plant height, yield, or yield components and increased global warming potential (GWP), effects linked to acidification and biochar-derived DOM (Feng et al., 2021; Wang et al., 2018; Zhou et al., 2018). Liquid derivatives such as HAP and HRFS can substitute part of mineral N at moderate doses but degrade water quality when over-applied or sourced from unsuitable feedstocks (Feng et al., 2025; Li et al., 2023; Yi et al., 2022). These mixed signals complicate guidance for researchers, agronomists, and policy makers seeking to scale carbon-based strategies in rice.

Existing narrative and scoping reviews commonly evaluate carbonaceous amendments across diverse crops, highlighting average yield gains on acidic soils, pH increases, SOC accrual, and reduced nitrogen losses. However, several gaps persist for paddy systems. While some work has been conducted on maize and other crops, systematic evidence synthesis for rice is lacking. Without a comprehensive assessment, it is difficult to draw general conclusions about optimum char production conditions, application rates and agronomic practices. This gap limits the adoption of chars in rice-based farming systems.

Iboko et al. (2023) systematically reviewed the trade-off between paddy rice yield and greenhouse gas emissions due to co-application of biochar and nitrogen fertilizer. Koizol et al. (2024) assessed biochar as a multi-action substance for soil improvement, while Chen et al. (2023) critically reviewed the characteristics and mechanisms of biochar application for the remediation of greenhouse gas emissions and nutrient loss in rice paddies. However, there is no comprehensive review on the Agronomic performance, soil health, and environmental outcomes of poultry litter hydrochar and biochar for sustainable rice production.

Sustainable rice production requires inputs that raise or maintain yield, improve soil function, and reduce environmental externalities under real-world management constraints. Carbonaceous amendments derived from animal wastes and other residues are attractive because they recycle by-products, contribute to soil carbon storage, and can complement fertilizer and water management. Nevertheless, material choice and rate can flip benefits into risks suppressing growth, increasing early-season CH_4 or NH_3, or degrading water quality. A rigorous, side-by-side assessment that distinguishes pyrochar and hydrochar families; stand-alone versus co-applied uses; and raw versus modified forms is essential. Equally important is explicit attention to soil condition (acidic versus saline–alkali; contaminated versus uncontaminated), and water and nitrogen scheduling, because these context variables frequently govern the direction and magnitude of observed effects. By integrating agronomic, soil-health, and environmental metrics, a targeted synthesis can move beyond single-discipline summaries to offer practical guidance and a clear roadmap for research and practice.

The objectives of this systematic review are, therefore, to 1) Synthesize agronomic performance of hydrochar and animal-waste biochar in rice, quantifying effects on grain yield, biomass, plant height, and yield components (tillers, panicles, thousand-grain weight), and identifying conditions under which fertilizer savings, particularly nitrogen, are achievable without yield penalties, 2) Evaluate soil-health outcomes, including changes in soil pH, SOC, CEC, DOM/DOC quality, and reported microbial responses, with attention to material properties and post-processing, 3) Assess environmental outcomes across the production cycle composting to field application, including CH_4, N_2O, and NH_3 fluxes; nitrate and dissolved-organic losses; and trace-metal mobility and grain accumulation, while distinguishing the behaviors of biochar alone, biochar co-applied with nutrients or organics, hydrochar alone, and modified or mixed hydrochars, and 4) Develop decision-oriented insights by comparing material classes on common outcome axes, identifying rate thresholds and management contexts that flip benefits to risks, and articulating research priorities for multi-season field validation, standardized material specifications, and integrated measurements that couple functional genes with measured fluxes and crop outcomes.

Accordingly, this review systematically compares biochar and hydrochar, including modified and co-applied forms, across agronomic performance, soil-health metrics, and environmental outcomes in rice systems, with the dual aims of distilling dose- and context-specific guidance for practice and delineating research priorities for multi-season, field-scale validation.

2.0 MATERIALS AND METHODS

2.1 Inclusion and exclusion criteria

This review followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. It included only published peer-reviewed journal articles in English, without applying any restrictions on publication dates. The study selection process was governed by pre-defined eligibility criteria structured according to the PICO (Population, Intervention, Comparator, Outcomes) framework. Included were peer-reviewed primary research articles that evaluated the application of animal waste-derived biochar (pyrolyzed) or hydrochar (hydrothermally carbonized) from any material in rice cultivation systems (Population). The Intervention required the amendment of these specific chars, including studies with co-amendments if the effect of the char could be isolated. Eligible studies necessitated a relevant Comparator, such as an unamended or fertilized control. Studies were required to report on at least one quantitative outcome pertaining to agronomic performance (e.g., yield, nutrient uptake), soil health (e.g., organic carbon, nutrient availability, microbial properties), or environmental impact (e.g., greenhouse gas emissions, nutrient leaching) (Outcomes). Figure 1 gives a summary of the conceptual framework guiding the systematic review. Excluded were review articles, non-English publications, studies without empirical application or a control group, and those utilizing chars derived from feedstocks other than animal waste (for biochars) or where its specific effect could not be discerned.

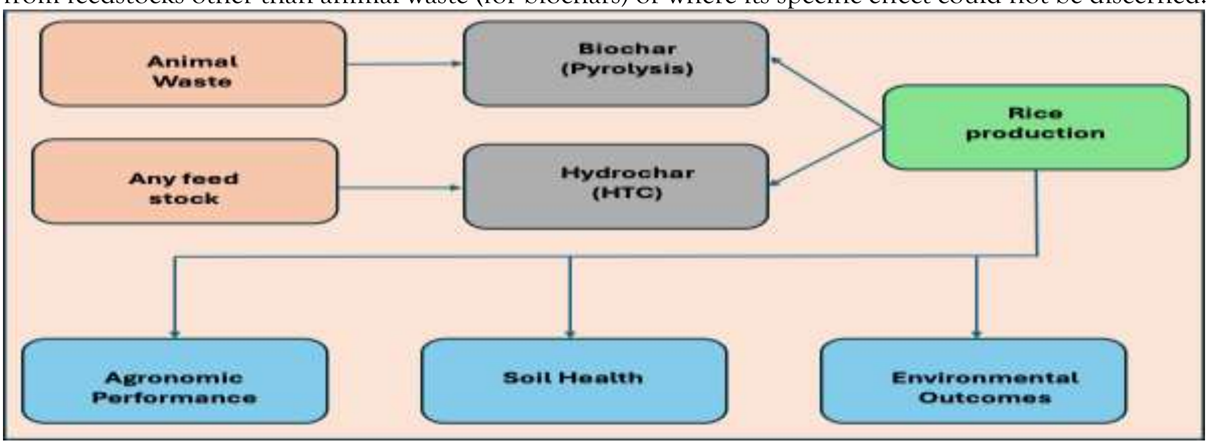

Figure 1. Summary of the conceptual framework guiding the systematic review on the application of biochar and hydrochars for sustainable rice production.

2.2 Literature search, screening and selection

The search process was performed twice using a consistent strategy across all selected databases. The initial round of searches was carried out between July 28 and August 5 2025, and a follow-up search took place from September 4th to 15th 2025 to validate and update the search results. All records retrieved during both phases underwent a rigorous screening process, including full-text and abstract reviews, to determine their eligibility based on predefined criteria.

Literature searches were conducted using Google Scholar (https://scholar.google.com/), Scopus (https://www.scopus.com), ScienceDirect (https://www.sciencedirect.com/), and PubMed (https://pubmed.ncbi.nlm.nih.gov). To enhance comprehensiveness, a snowballing approach was also applied by examining the reference lists of relevant articles identified through these databases (Saba et al., 2024; Agbam et al., 2025; Ishaq et al., 2025). Details of keywords used in carrying out comprehensive search based on PICO headings in the various databases can be found in Table 1.

The systematic search across the four electronic databases (Google Scholar, Scopus, Semantic Scholar, and PubMed) and supplemental snowballing yielded a total of 840 records. Following the removal of 224 duplicates, 616 records underwent initial title screening. During this phase, 457 records were excluded for not meeting basic eligibility criteria, resulting in 159 records proceeding to abstract screening. Application of the inclusion and exclusion criteria at the abstract level led to the exclusion of 93 records. The full texts of the remaining 66 records were sought for retrieval. Of these, 64 were successfully retrieved and subjected to a detailed eligibility assessment. Two records could not be retrieved. After a full-text review, 23 records were excluded with reasons, the most common being that the study focus was not on rice or paddy systems (n = 9). Consequently, 41 studies were deemed to satisfy all eligibility criteria and were included in the qualitative and quantitative synthesis of this systematic review. The entire selection process is summarized in Figure 2.

2.3 Identification, screening, and selection of articles

Most of the search results from each database were exported as CSV files into the Rayyan QCRI online platform (https://www.rayyan.ai/), with the exception of results obtained through snowballing. To remove duplicates, two key steps were followed: verifying the presence of relevant studies and discarding those not aligning with the inclusion criteria. Thereafter, titles and abstracts were screened using Rayyan. After completing the initial screening on Rayyan, the full texts of selected studies were retrieved for in-depth evaluation (Ouzzani et al., 2016; Saba et al., 2023). These articles were carefully reviewed, and relevant data were systematically extracted using Microsoft Excel 365 (Redmond, WA, USA). Articles not previously screened in Rayyan had their abstracts independently reviewed prior to the full-text analysis. As the comprehensive review of the full texts progressed, several studies were excluded due to failure to meet the predefined eligibility criteria.

2.4 Data extraction and synthesis

The full-text versions of all identified articles were downloaded as PDFs for further review. Relevant information was tabulated and analyzed descriptively using Microsoft Office Excel 365. General information and outcomes from the included studies was extracted including study type, methodological approach, material type, feedstock type, char production method, production temp (°C), key material properties, application rate, application method, water management, fertilizer regime grain yield, straw/biomass, plant height, tillers number, nutrient uptake (NPK), agronomic performance, effect on soil pH, effect on organic carbon/matter, nutrient availability (NPK), bulk density, microbial activity/biomass, soil health outcome, and environmental outcomes (GHG/leaching/metals).

Table 1. Search keywords from different databases based on PICO headings

PICO Element	Core Concepts and Keywords	Synonyms and Related Terms
P (Population)	rice, paddy, Oryza sativa	"rice field", *"paddy field"*, "rice crop*", "rice cultivation", "rice production"
I (Intervention)	**Hydrochar:** hydrochar, HTC, "hydrothermal carbonization"	"hydrothermal charcoal", "hydrochar amendment"
	Biochar: biochar, "bio-char"	"biochar amendment", "soil amendment"

	Source: "animal waste", manure, slurry, dung, "livestock waste", "poultry litter", "chicken manure", "swine manure", "cattle manure"	"animal by-product*", "farmyard manure", feces, faecal, excreta
C (Comparison)	control, "business as usual", conventional, fertilizer, compost, "organic amendment"	(Often implied in the study design. These terms help find comparative studies) "no amendment", "chemical fertilizer", NPK, urea, "mineral fertilizer"
	Agronomic: yield, "grain yield", "crop yield", "plant growth", biomass, "nutrient uptake", "nitrogen use efficiency"	"agronomy", "crop performance", "productivity"
	Soil Health: "soil health", "soil quality", "soil fertility", "soil organic carbon", CEC, "cation exchange capacity", "microbial biomass", "enzyme activity", "soil structure", aggregation, porosity, WHC, "water holding capacity"	"soil property", *"soil chemical property"*, "soil physical property", *"soil biological property"*, "microbial community", "soil respiration"
O (Outcomes)	**Environmental:** "greenhouse gas", GHG, emissions, methane, CH_4, nitrous oxide, N_2O, "nitrogen leaching", "phosphate leaching", "carbon sequestration", "carbon storage", "heavy metal" immobilization, bioavailability	"climate change", "global warming potential", "nutrient leaching", "pollutant", "environmental impact"

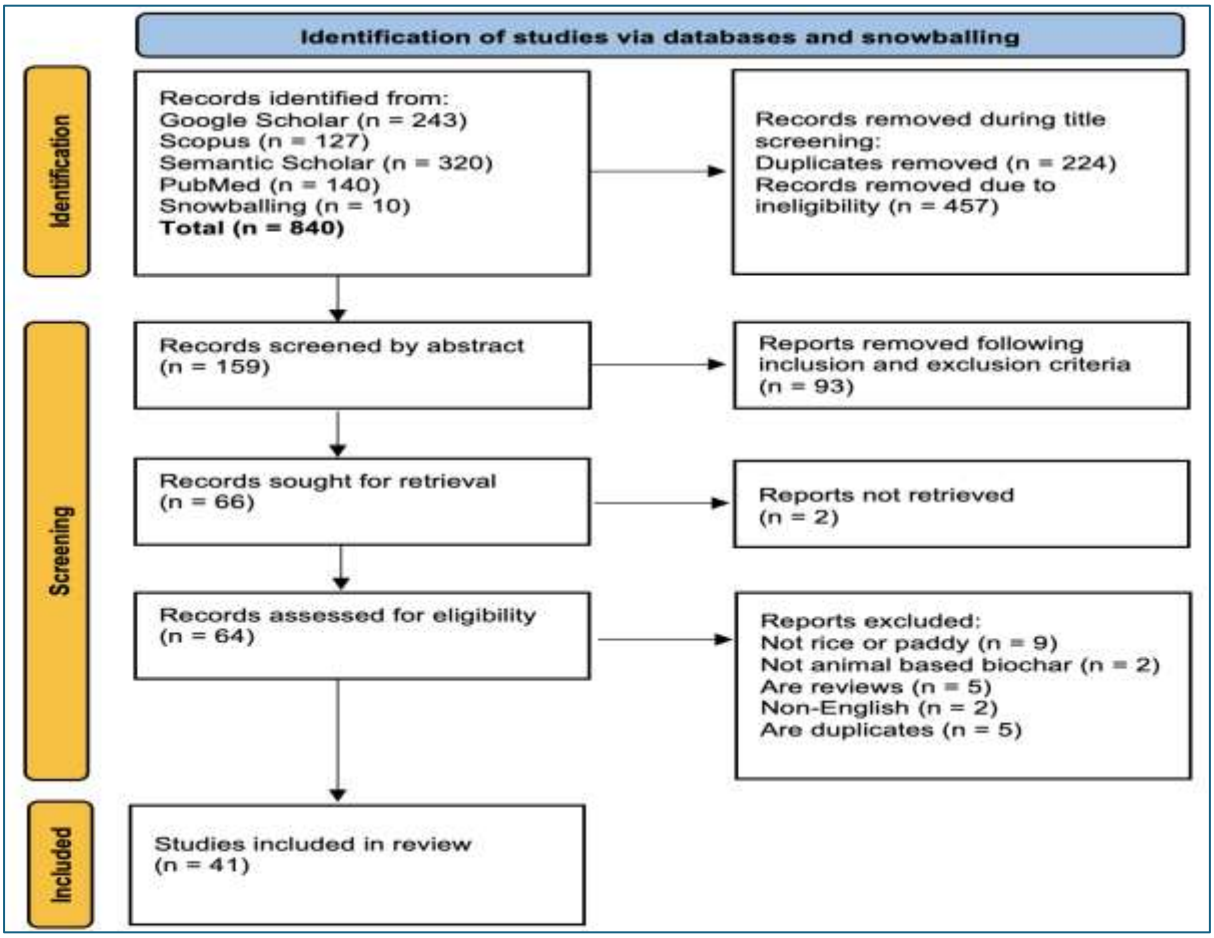

Figure 2. PRISMA flow chart of literature search, screening and selection process.

3.0 RESULTS AND DISCUSSION

3.1 Study Characteristics

There is a notable trend in the distribution of research on animal waste biochar and hydrochar in rice systems, with the majority of studies published in recent years. Specifically, 2020 emerged as the most active year for research, accounting for 9 studies (28%) of the total. This was followed by 2021 to 2023 with 6 (15%) studies each, reflecting growing interest in the application of animal waste biochar and hydrochar in sustainable rice cultivation (Figure 3).

The trend suggests a surge in interest beginning in 2020, coinciding with a global push for sustainability in agricultural practices and heightened awareness of the environmental challenges associated with conventional rice production, particularly related to greenhouse gas emissions and soil degradation. The relatively high number of studies from 2023 indicates a continued commitment to advancing this field, likely spurred by ongoing global research funding and the increasing focus on mitigating climate change impacts. In the near future, the frequency of studies in 2024 and 2025 is expected to increase, reflecting the growing body of evidence supporting the efficacy of these amendments in improving both agronomic performance and environmental sustainability in rice farming systems.

Across the included studies, most experiments were conducted in Asia, with a strong concentration in China with 26 studies (63%), followed by Malaysia with 4 studies (10%) (Figure 4). There is a significant representation of studies from diverse geographical regions, with a concentration in Asia, particularly China, where rice is a major crop. This geographic focus highlights the region's central role in advancing sustainable rice practices through the use of carbon-based amendments such as biochar and hydrochar.

Designs were predominantly soil-column/pot CRD trials with triplicate replication, supplemented by a smaller number of fields RCBD studies (typically three–four blocks). Hydrochar (HC) was generally produced via hydrothermal carbonization at about 180–260 °C**,** while animal-waste biochar (AWB; e.g., chicken-litter biochar) were mainly pyrolyzed at about 500 °C (Table 2)**.**

More so, interventions cluster into pyrolytic biochar (often from animal wastes), biochar co-applied or co-composted with other inputs, hydrochar produced by hydrothermal carbonization, and hydrochar that is modified or delivered as liquid derivatives. Outcomes vary with feedstock, production temperature, application rate, soil chemistry, nitrogen management, and whether materials are washed, clay-composited, aged, or acid-tuned. For clarity, acronyms are expanded at first mention and then used thereafter: greenhouse gases (GHG: methane, CH_4; nitrous oxide, N_2O; ammonia, NH_3), global warming potential (GWP), greenhouse gas intensity (GHGI), dissolved organic matter (DOM), dissolved organic carbon (DOC), soil organic carbon (SOC), cation exchange capacity (CEC), nitrogen use efficiency (NUE), hydrothermal carbonization (HTC) producing hydrochar (HC), hydrothermal aqueous phase (HAP), hydrochar reaction-finished solution (HRFS), clay-modified hydrochar (CHC), normalized difference vegetation index (NDVI), soil and plant analyzer development chlorophyll index (SPAD), thousand-grain weight (TGW), and controlled irrigation (CI). Several studies also track functional genes linked to GHG pathways, including nitrite reductases (nirK, nirS), nitrous oxide reductase (nosZ), particulate methane monooxygenase (pmoA), and methyl coenzyme M reductase A (mcrA).

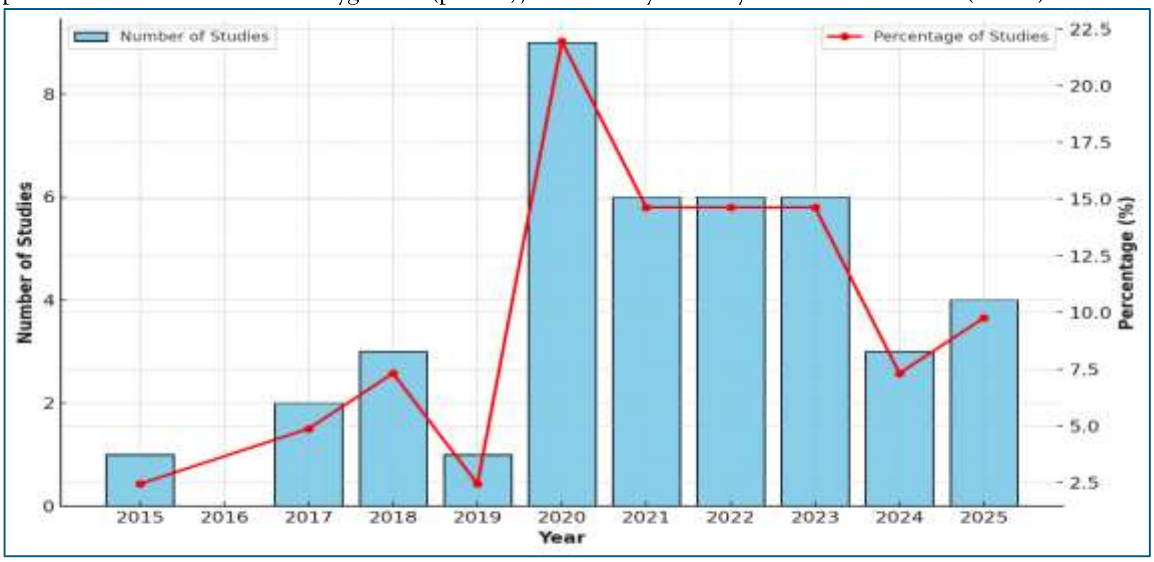

Figure 3. Frequency and percentage of included studies by year

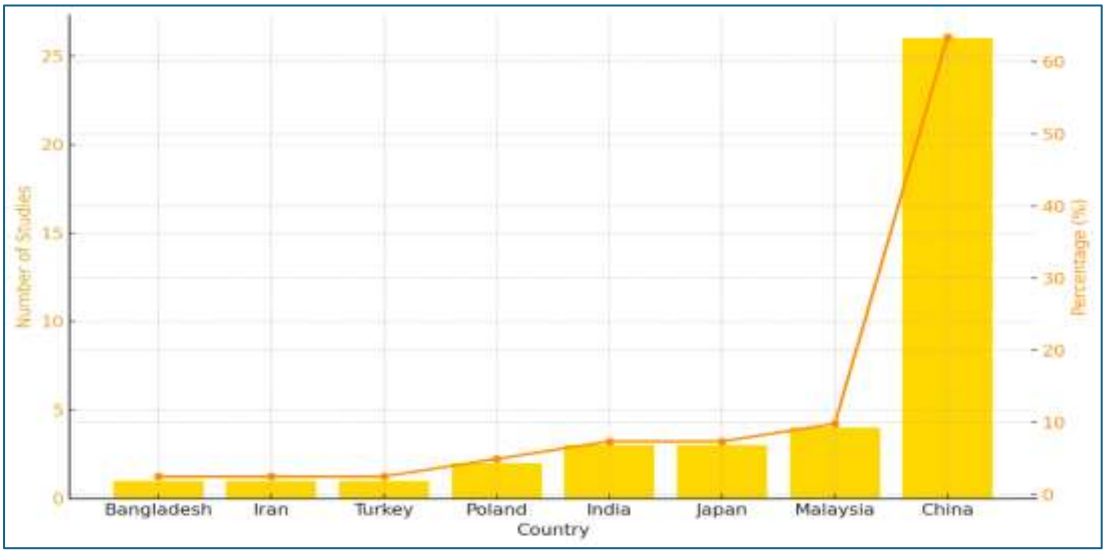

Figure 4. Frequency and percentage of included studies by country

Table 2. Study characteristics

Experimental setting	Experimental design	Treatment	Feedstock type	Production temp (°C)	References
Soil column	CRD, 4 treatments, 3 replicates	Biochar	Poultry litter; Rice husk biochar	500	Alarefee et al. (2023)
Field	RCBD, treatments NR, replicates NR	Biochar	Chicken litter biochar co-composted with broiler litter; chicken litter; cow dung; Leucaena; or Leucaena+chicken litter	NR	Ali et al. (2023)
Field	RCBD, treatments NR, replicates NR	Biochar	Poultry Litter (PL)	250°C for 30 min (PLB250-30); 300°C for 60 min (PLB300-60); 350°C for 30 min (PLB350-30)	Babu et al. (2025)
Soil column	CRD, treatments NR, replicates NR	Biochar	NR for biochar (likely crop residue or wood based given context)	NR	Behera et al. (2020)
Field	CRD, treatments NR, 2 replicates	Biochar	Chicken manure	402, 449, 528	Ishimori et al. (2017)
Soil column	CRD, 7 treatments, 6 replicates	Biochar	Eggshells, blend of eggshells and corn stover	550	Islam et al. (2024)
Field	CRD, treatments NR, 3 replicates	Biochar	Poultry litter	300	Jarosz et al. (2022)
Soil column	CRD, treatments NR, replicates NR	Biochar	Poultry litter	400	Joardar et al. (2020)

Soil column	CRD, 8 treatments, 4 replicates	Biochar	Poultry litter	450-500	Kimani et al. (2021)
Field	RCBD, treatments NR, 4 replicates	Biochar	Chicken litter	NR	Maikol et al. (2021)
Field	Factorial/Combined, treatments NR, replicates NR	Biochar	Chicken litter	NR	Maru et al. (2015)
Field	RCBD, treatments NR, 3 replicates	Biochar	Poultry litter	300	Mierzwa-Hersztek et al. (2018)
Soil column	CRD, treatments NR, replicates NR	Biochar	Neem (*Azadirachta indica*) wood+Vermicompost	NR; slow pyrolysis for ~1 hr	Mondal et al. (2021)
Greenhouse	CRD, treatments NR, 4 replicates	Biochar	Poultry manure	300	Sahin et al. (2017)
Soil column	Factorial, 4 treatments, replicates NR	Biochar	Poultry litter; Azolla (*A. filiculoides*)	450–500	Kimani et al. (2020)
Soil column	CRD, 6 treatments, 3 replicates	Hydrochar	Wheat straw	260	Feng et al. (2021)
Soil column	Factorial, 35 treatments, replicates NR	Hydrochar	Rice straw	200	Maghsoodi et al. (2025)
Soil column	CRD, treatments NR, replicates NR	Hydrochar	Rice straw	250; 300	Liu et al. (2022)
Soil column	CRD, treatments NR, replicates NR	Hydrochar	Wheat straw; Sawdust	260	Liu et al. (2020)
Soil column	Factorial, 6 treatments, 3 replicates	Hydrochar	Sawdust	260	Wang et al. (2018)
Soil column	CRD, 5 treatments, 3 replicates	Hydrochar	Rice straw	220	Yu et al. (2023)
Soil column	Factorial, 10 treatments, replicates NR	Hydrochar	Wheat straw and sawdust	260	Zhou et al. (2018)
Soil column	CRD, 3 treatments, replicates NR	Hydrochar	*Chlorella vulgaris* biomass	260	Chu et al. (2020a)
Soil column	CRD, 4 treatments, replicates NR	Hydrochar	Sewage sludge (secondary treatment after anaerobic digestion)	260	Chu et al. (2020b)
Soil column	CRD, 4 treatments, replicates NR	Hydrochar	Cattle manure	180, 260	Ding et al. (2022)
Soil column	CRD, 4 treatments, replicates NR	Hydrochar	Pig manure	180, 260	Ding et al. (2024)
Soil column	CRD, 5 treatments, 3 replicates	Hydrochar	Sewage sludge; Kitchen waste	NR	Feng et al. (2025)
Soil column	CRD, treatments NR, 3 replicates	Hydrochar	Sewage Sludge, Pig Manure	180, 260	He et al. (2022b)
Soil column	Factorial, 4 treatments, 3 replicates	Hydrochar	Sawdust	260	Hou et al. (2020)

Soil column	CRD, treatments NR, replicates NR	Hydrochar	Rice straw	200, 250, 300	Ji et al. (2020)
Soil column	CRD, 4 treatments, 3 replicates	Hydrochar	Poplar sawdust; Composites: Hydrochar co-pyrolyzed with Bentonite (BTHC), Montmorillonite (MTHC), or Kaolinite (KTHC)	220, 300	Li et al. (2021)
Field	RCBD, treatments NR, replicates NR	Hydrochar	Cattle manure; Kitchen waste (vegetables)	220, 260	Li et al. (2023)
Soil column	CRD, 4 treatments, replicates NR	Hydrochar	Rice straw (RH); Corn straw (CH); Poplar wood (PH); Enteromorpha (EH)	300	Miao et al. (2023)
Soil column	CRD, treatments NR, 3 replicates	Hydrochar	Wood dust (HWD) and wheat straw (HWS)	260	Sun et al. (2020)
Soil column	CRD, 6 treatments, replicates NR	Hydrochar	Rice straw	200	Wang et al. (2024)
Soil column	CRD, 5 treatments, replicates NR	Hydrochar	Sawdust	220	Wu et al. (2023)
Soil column	CRD, 9 treatments, 3 replicates	Hydrochar	Cellulose (CL), Skeleton (SK), Protein (PT), Starch (ST) kitchen waste	260	Xu et al. (2025)
Soil column	RCBD, 8 treatments, 3 replicates	Hydrochar	Chinese fir (*Cunninghamia lanceolata*) leaf litter	200	Yi et al. (2022)
Soil column	Factorial, 6 treatments, replicates NR	Hydrochar	Sawdust	260	Yu et al. (2019)
Soil column	CRD, 4 treatments, 3 replicates	Hydrochar	Sawdust	180-260	Chen et al. (2021)
Soil column	CRD, 5 treatments, 3 replicates	Hydrochar	Wheat straw, Clay	220 co-pyrolysis of hydrochar +clay at 300 °C	He et al. (2022a)

3.2 Agronomic performance

The use of biochar and hydrochar as amendments in rice production has demonstrated positive effects on yield, plant growth, soil health, and environmental outcomes across various studies. Animal-waste biochar, particularly poultry-litter blends, has shown substantial improvements in grain yield, with increases ranging from 9 to 13 t ha^{-1}, depending on the application. Along with yield benefits, biochar also increased plant height and tiller number, with some studies reporting significant improvements in soil organic carbon (SOC) and total organic carbon (TOC). For example, poultry-litter biochar led to increased SOC and organic matter in the soil, while also improving soil pH, which was buffered and prevented excessive alkalinization (Babu et al., 2025; Ali et al., 2023). Similarly, composted cattle manure biochar, when combined with mineral nitrogen, restored plant growth to levels comparable to traditional NPK fertilization, but biochar alone caused a decrease in plant height (Ishimori et al., 2017).

Hydrochar amendments, though more variable, showed potential benefits in reducing nitrogen leaching and improving nitrogen use efficiency (NUE). For instance, hydrochar with reduced nitrogen applications increased grain yield by approximately 7-8%, comparable to conventional nitrogen rates, and showed improvements in spike number. While hydrochar's effect on soil health and microbial activity was less consistent compared to biochar, certain modifications, such as washing or microbial aging, improved its performance, especially in controlling methane and nitrous oxide emissions (Chu et al., 2020b). Mixed amendments, including biochar combined with organic inputs like vermicompost, also enhanced root and shoot biomass, with some studies noting a positive impact on tiller growth, though the specific effects of biochar were less clear (Mondal et al., 2021). In some cases, biochar helped alleviate arsenic-induced biomass loss, highlighting its potential for mitigating environmental stressors in contaminated soils (Sahin et al., 2017). Overall, these studies indicate that biochar, particularly animal-waste-derived variants, is highly effective for improving agronomic performance and soil health, while hydrochar, with appropriate modifications, can complement these benefits by enhancing nitrogen retention and mitigating greenhouse gas emissions. However, further research is needed to standardize the use of these materials and assess their long-term impacts in field conditions.

Pyrolytic biochar, particularly animal-waste biochar from poultry litter provides the most reliable improvements in grain yield, biomass, and growth components. Gains coincide with higher soil pH, greater SOC, and often increased CEC, consistent with liming from ash minerals and large specific surface areas (Babu et al., 2025; Ali et al., 2023; Maikol et al., 2021; Kimani et al., 2021; Joardar et al., 2020). Stress-mitigation benefits extend to remediation contexts, with biochar alleviating chromium toxicity relative to farmyard manure or sewage sludge, reducing arsenic accumulation while enhancing antioxidant status, and when iron magnesium modified, simultaneously lowering grain arsenic and cadmium while improving microbial attributes (Behera et al., 2020; Sahin et al., 2017; Islam et al., 2024). Co-application with fertilizers or organic inputs typically magnifies nutrient-management benefits. Animal-waste biochar combined with mineral nitrogen improves NUE and enables fertilizer savings without yield penalties; several pot and field studies maintained or increased yield despite approximately 25% reductions in urea inputs (Maru et al., 2015; Maikol et al., 2021; Kimani et al., 2021). Pairing biochar with Azolla increased yield and reduced nitrous oxide without raising seasonal methane, indicating potential to lower GHGI while supporting agronomy, although clear interaction effects beyond additivity are not universal in short-term pots (Kimani et al., 2021; Kimani et al., 2020). In degraded paddies, composted cattle manure alone depressed growth due to nitrogen limitation, whereas mineral-nitrogen supplementation restored performance, underscoring nitrogen supply as a first-order control where carbon inputs are high (Ishimori et al., 2017).

Hydrochar alone is more variable and strongly conditioned by dose and chemistry. Modest rates of 0.5-1% by mass maintain or modestly increase yield and spikes or panicle number and can offset planned nitrogen reductions of about 40% without yield loss, highlighting potential for input substitution when carefully dosed (Zhou et al., 2018). High rates near 3% repeatedly suppress plant height and yield, effects linked to transient acidification and inhibitory biochar-derived organic matter within the HC-DOM pool (Feng et al., 2021; Wang et al., 2018; Zhou et al., 2018). Beyond plant responses, hydrochar commonly increases DOC and shifts SOC toward more aromatic, higher-molecular-weight, and microbially resistant fractions while altering microbial communities-changes consistent with longer-term carbon stabilization but not guaranteed to deliver near-term yield gains (Li et al., 2023; Miao et al., 2023; Liu et al., 2022; Sun et al., 2020).

3.3 Soil chemical and biological health

Animal-waste biochars consistently improved microbial activity, soil fertility, and nutrient retention across various studies. These amendments enhanced soil properties such as total organic carbon, cation exchange capacity, and nitrogen-use efficiency, while reducing exchangeable acidity and metals like arsenic and cadmium. Agronomically, biochar co-applied with fertilizers reduced mineral nitrogen inputs by approximately 25% without affecting yields. Environmental benefits included reduced ammonia volatilization and increased methane oxidation. Biochar's role in managing contaminants, especially heavy metals, was a key outcome, with several studies showing significant reductions in bioavailable arsenic and cadmium in rice grains. Pyrolytic biochar in acidic soils raises pH, increases SOC, and often elevates CEC alongside higher yields and nutrient uptake; multi-year observations indicate slower mineralization of organic matter and expansion of persistent carbon pools under poultry-litter biochar at agronomic rates (Ali et al., 2023; Jarosz et al., 2022; Maikol et al., 2021; Mierzwa-Hersztek et al., 2018).

Hydrochar, on the other hand, showed more variable results depending on feedstock, modification, and application rate. Modified hydrochars (e.g., washed, clay-composited, or acid-tuned) generally improved nitrogen retention, soil organic carbon quality, and reduced greenhouse gas emissions like nitrous oxide. However, unmodified hydrochar or high application rates often led to reduced yield and increased methane emissions. Hydrothermal liquids offered partial nitrogen substitution but required careful control to avoid negative water-quality impacts. Overall, biochar was more reliable for agronomic benefits, while modified hydrochar showed potential for environmental mitigation when applied at low doses and with careful management.

Hydrochar presents a more nuanced soil-health profile. Short-term acidification is common, DOC rises markedly, and SOC quality shifts toward more stable fractions, but these benefits sometimes coincide with near-term growth penalties or microbial shifts that do not immediately favor productivity; soil-health gains from hydrochar therefore remain promising for carbon stabilization yet contingent on modification, rate, and background soil chemistry (Sun et al., 2020; Li et al., 2023; Miao et al., 2023; Liu et al., 2022). A trade-off appears in some clay–hydrochar field observations where total organic carbon increases while soil CEC decreases, implying that not all newly sequestered carbon surfaces contribute equivalently to nutrient-retention capacity and that material design must match dual goals (Li et al., 2021).

3.4 Environmental outcomes (GHG, nitrogen losses, leaching, metals)

Upstream use of biochar during composting reduces ammonia and carbon dioxide emissions; a rice-husk biochar at carbon-to-nitrogen ratio near 25 was operationally effective under greenhouse conditions, though methane and nitrous oxide were not measured and field-scale composting trials remain necessary (Alarefee et al., 2023). In flooded production phases, dose and chemistry dominate the greenhouse-gas ledger. Low-rate hydrochar can reduce methane and nitrous oxide relative to controls, whereas high-rate hydrochar increases GWP and GHGI; washing and aging shift responses favorably by removing labile compounds and altering surface functionality (Ji et al., 2020; Hou et al., 2020; Zhou et al., 2018). Modified hydrochars, including water-washed hydrochar and clay composites, reduce methane and nitrous oxide and shift functional genes toward lower net emissions, while acid-modified sludge-derived hydrochar reduces ammonia volatilization and nitrogen runoff within conventional split-fertilizer regimes (Chen et al., 2021; Li et al., 2021; Chu et al., 2020b). Systems-level gains appear when hydrochar is paired with controlled irrigation; net ecosystem carbon budget and SOC sequestration rise, and the controlled-irrigation-hydrochar combination helps offset energy and carbon embedded in organic inputs, although current evidence is primarily short-term and pot-based (Wang et al., 2024). Regarding metals and water quality, clay-modified hydrochar lowers grain cadmium while sustaining yield, and low-dose sewage-sludge HAP improves water-quality metrics and nutrient status; high-dose kitchen-waste HAP increases total nitrogen and chemical oxygen demand and reduces dissolved oxygen, indicating the need for strict rate control and feedstock screening for liquid carbon amendments (Feng et al., 2025; Li et al., 2023; He et al., 2022a).

Biochar alone provides the most dependable route to higher yields and improved soil chemical status in rice, particularly on acidic soils, with frequent possibilities for reducing mineral nitrogen inputs without yield penalties. Co-application or co-composting of biochar with fertilizers or organic inputs often improves NUE and can maintain or increase yield at reduced nitrogen rates, though clear interaction effects beyond additivity are not guaranteed in short-term pots (Ali et al., 2023; Kimani et al., 2021; Maru et al., 2015). Hydrochar alone is performance-sensitive, with modest rates functioning well and high rates producing agronomic penalties and unfavorable greenhouse-gas profiles; however, hydrochar that is washed, clay-composited, microbially aged, or acid-modified shows consistent improvements in both agronomic and environmental dimensions, including lower methane, nitrous oxide, and ammonia, higher nitrogen use efficiency, and reduced grain cadmium in contaminated systems (Chen et al., 2021; Li et al., 2021; He et al., 2022a; Chu et al., 2020b; Hou et al., 2020; Yu et al., 2019). Liquid derivatives such as hydrothermal aqueous phase and hydrochar reaction-finished solution can substitute a portion of mineral nitrogen and improve yield and nitrogen use efficiency at moderate doses but require strict control of feedstock choice and application rate to avoid adverse water-quality effects (Feng et al., 2025; Li et al., 2023; He et al., 2022b; Yi et al., 2022;).

Rate sensitivity is a cross-cutting driver of outcomes, especially for hydrochar. High-rate applications around 3% by mass are repeatedly associated with growth inhibition and higher global warming potential, whereas modest rates in the range of approximately 0.5-1% by mass tend to maintain or improve yield and can support planned nitrogen reductions when paired with optimized nitrogen splits (Feng et al., 2021; Maikol et al., 2021; Yu et al., 2019; Zhou et al., 2018; Maru et al., 2015). For liquid derivatives, mid-range, feedstock-specific optima emerge, with steep penalties at higher doses; sewage-sludge hydrothermal aqueous phase generally performs better than kitchen-waste hydrothermal aqueous phase at comparable volumes, but both require explicit drainage scheduling to safeguard water quality (Feng et al., 2025; Li et al., 2023; He et al., 2022b; Yi et al., 2022). In contaminated paddies, clay-modified hydrochar at approximately 1% by mass offers a pragmatic starting point for lowering grain cadmium while sustaining yield (He et al., 2022a).

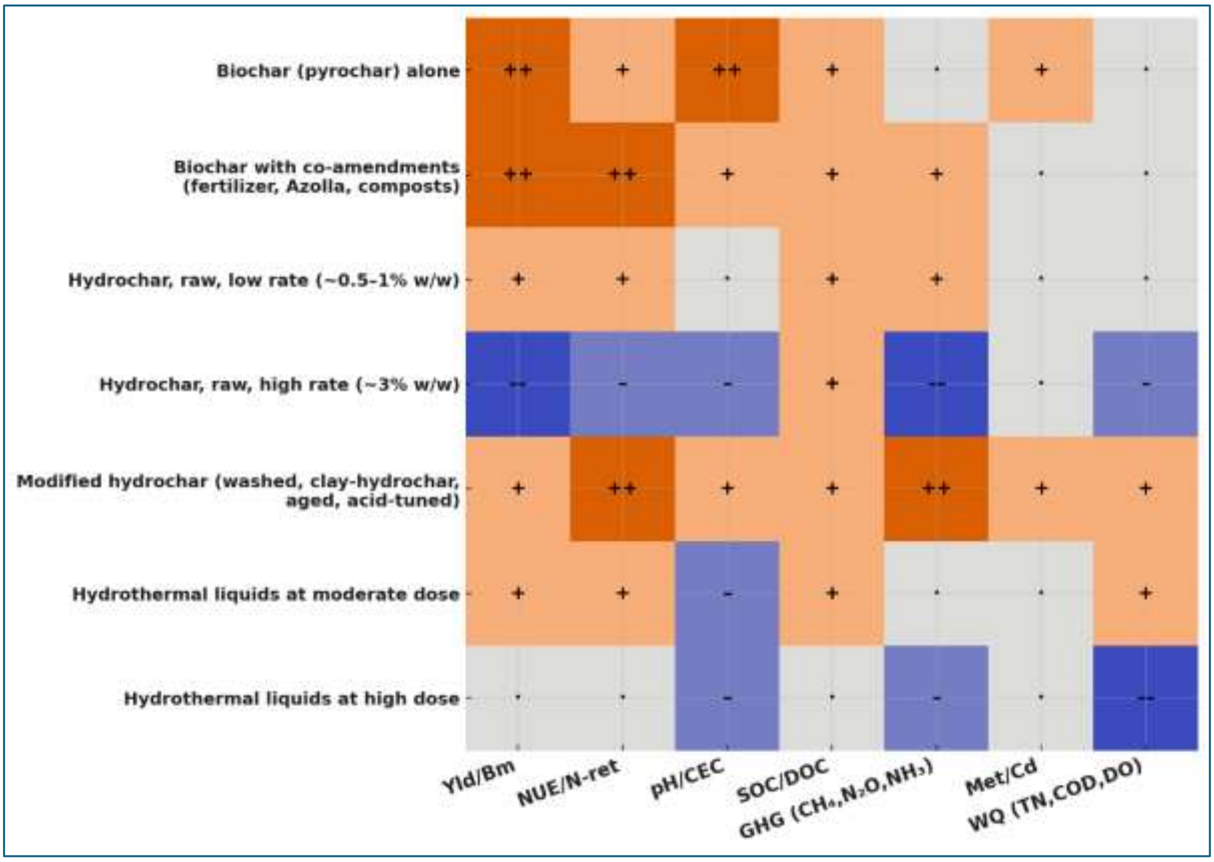

Figure 4. Direction and strength of effects across seven outcome domains: agronomy (yield and biomass), nitrogen efficiency and retention, soil pH and cation exchange capacity, carbon quality (soil organic carbon and dissolved organic carbon), greenhouse-gas balance (methane, nitrous oxide, ammonia), metal risk and grain cadmium, and water quality (total nitrogen, chemical oxygen demand, dissolved oxygen). Symbols indicate magnitude (++ strong positive; + positive; · neutral/mixed; – negative; –– strong negative). Color gradients reinforce the same scale for rapid visual appraisal. HC = hydrochar; CHC = clay-modified hydrochar; HAP = hydrothermal aqueous phase; HRFS = hydrochar reaction-finished solution; SOC = soil organic carbon; DOC = dissolved organic carbon; CEC = cation exchange capacity; NUE = nitrogen use efficiency; GHG = greenhouse gases; CH_4 = methane; N_2O = nitrous oxide; NH_3 = ammonia; GWP = global warming potential; GHGI = greenhouse gas intensity; TGW = thousand-grain weight; TN = total nitrogen; COD = chemical oxygen demand; DO = dissolved oxygen. Yld/Bm = yield and biomass; NUE/N-ret = nitrogen use efficiency and nitrogen retention; pH/CEC = soil pH and cation exchange capacity; SOC/DOC = soil organic carbon and dissolved organic carbon; GHG (CH_4,N_2O,NH_3) = greenhouse-gas balance (methane, nitrous oxide, ammonia); Met/Cd = metal risk and grain cadmium; WQ (TN,COD,DO) = water quality (total nitrogen, chemical oxygen demand, dissolved oxygen)

Recommendations for future research and practice in sustainable rice systems

Sustainable rice systems research must begin with field-scale, multi-season trials that directly quantify methane, nitrous oxide, ammonia fluxes, nitrate leaching, and trace-metal behaviors under realistic irrigation and nitrogen management regimes. Trials like these generate robust longitudinal datasets essential for understanding amendment impacts over time. Harmonized and comprehensive reporting of biochar and hydrochar properties, including feedstock, production conditions, ash composition, pH, functional chemistry, and pore structure, is critical for enabling meta-analyses and building transferable dose-response guidelines (Figure 5). Integration of soil-physical indicators (bulk density, structure) and microbial functional endpoints (enzyme activity, biomass, gene-flux linkages) with agronomic outcomes, especially for modified hydrochars such as water-washed, clay-composited, microbially aged, or acid-tuned forms, allows a fuller understanding of system function and sustainability (Figure 6). Additionally, rigorous safety testing, full life-cycle assessments, and economic evaluations for sludge-derived materials are needed to ensure responsible adoption and public trust (Figure 7).

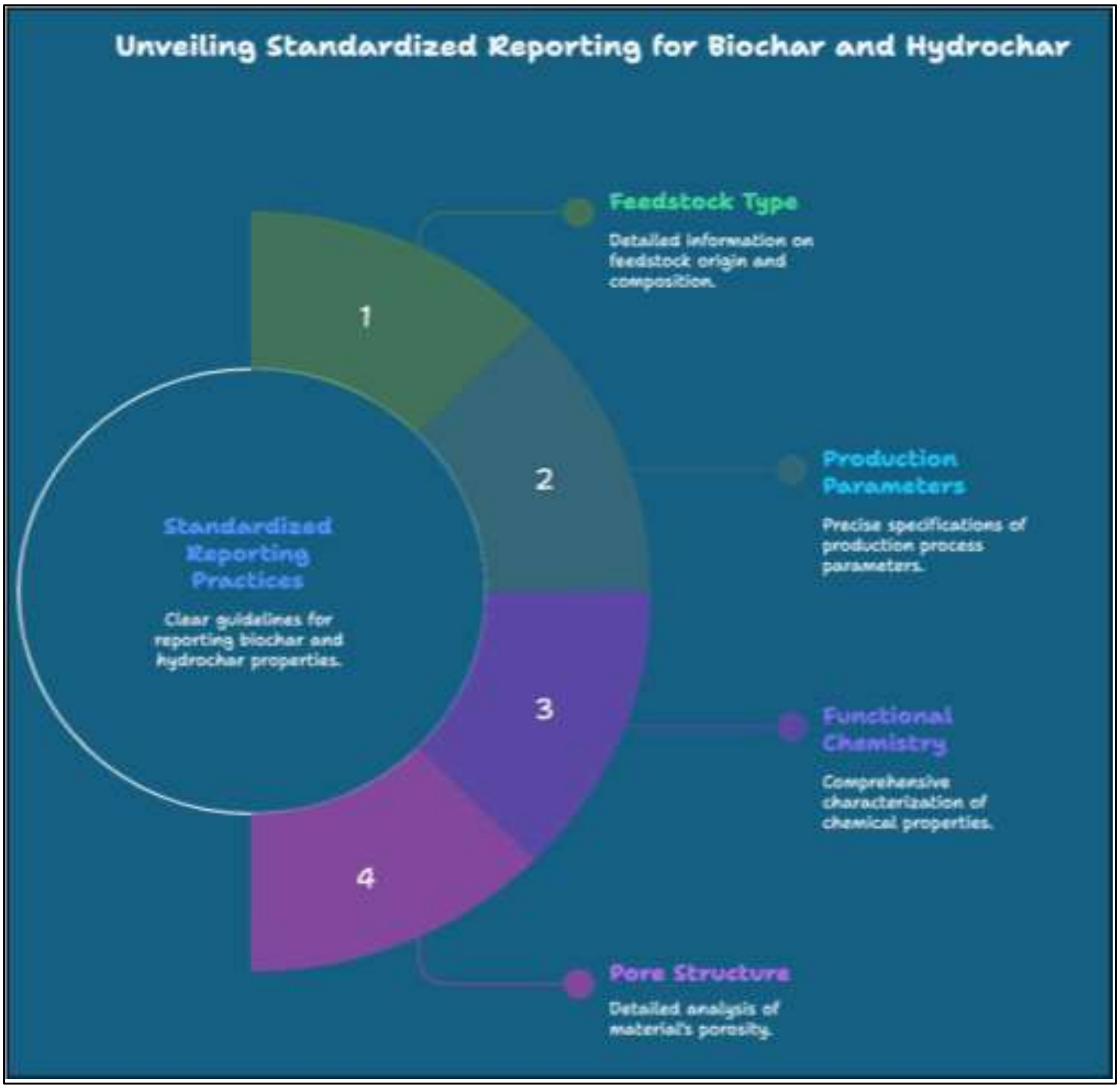

Figure 5. Imperatives for standardized reporting in biochar and hydrochar research for sustainable rice production

Figure 6. Comprehensive integration of soil physical, biological, agronomic, and microbial parameters in biochar and hydrochar research for sustainable rice production

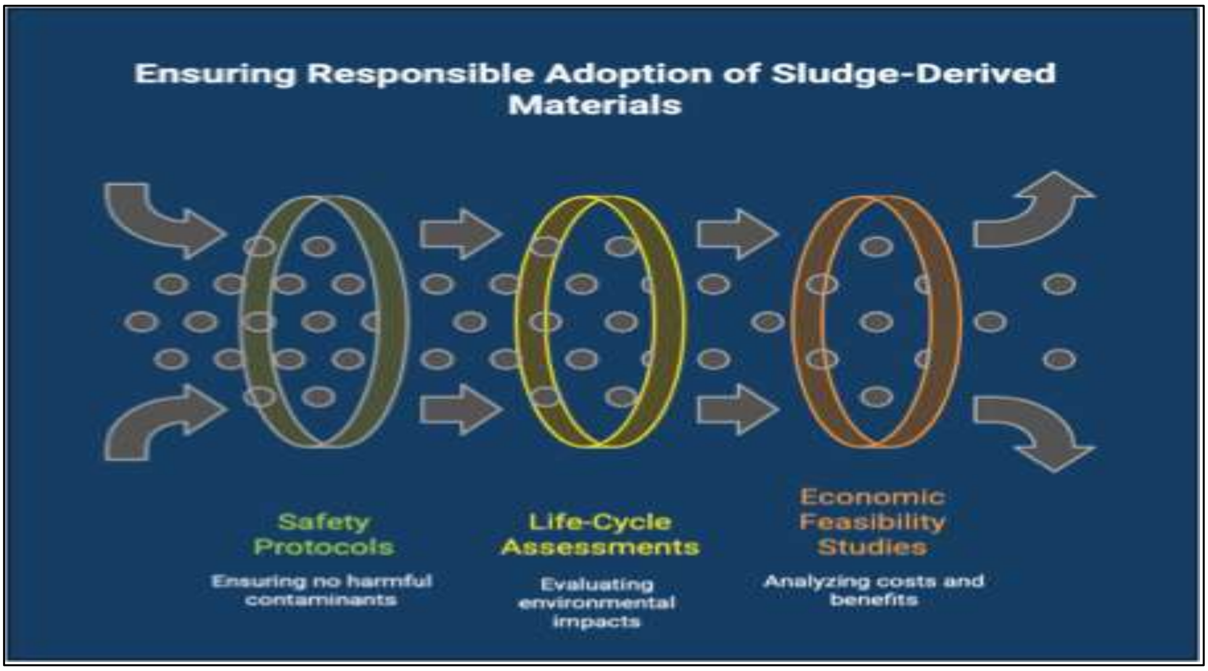

Figure 7. Responsible adoption of safety protocols and life cycle assessment of waste-derived materials in biochar and hydrochar research for sustainable rice production

In practice, the use of animal-waste biochar is consistently beneficial for improving agronomic and soil chemical properties in acidic soils. When co-applied with fertilizer or organic amendments, animal-waste biochar can support up to 25% reduction in urea fertilizer application without yield penalties (Maru et al., 2015; Maikol et al., 2021; Kimani et al., 2021; Ali et al., 2023). Hydrochar, although more variable in effect, gains environmental and agronomic value when modified by washing, clay composition, ageing or acid tuning, and applied at modest rates, with documented reductions in methane, nitrous oxide, and ammonia emissions, improved nitrogen use efficiency, and reduced grain cadmium in contaminated systems. Liquid derivatives from hydrothermal processes can partially substitute for mineral nitrogen and improve crop yield and nutrient efficiency in moderate doses, though strict feedstock selection and careful rate management are critical to avoid water-quality pitfalls. The development and routine use of decision-support tools aligning amendment type, modification, and application rate to site-specific soil condition and crop management practices would further enhance confident, targeted implementation of sustainable solutions (Figure 8).

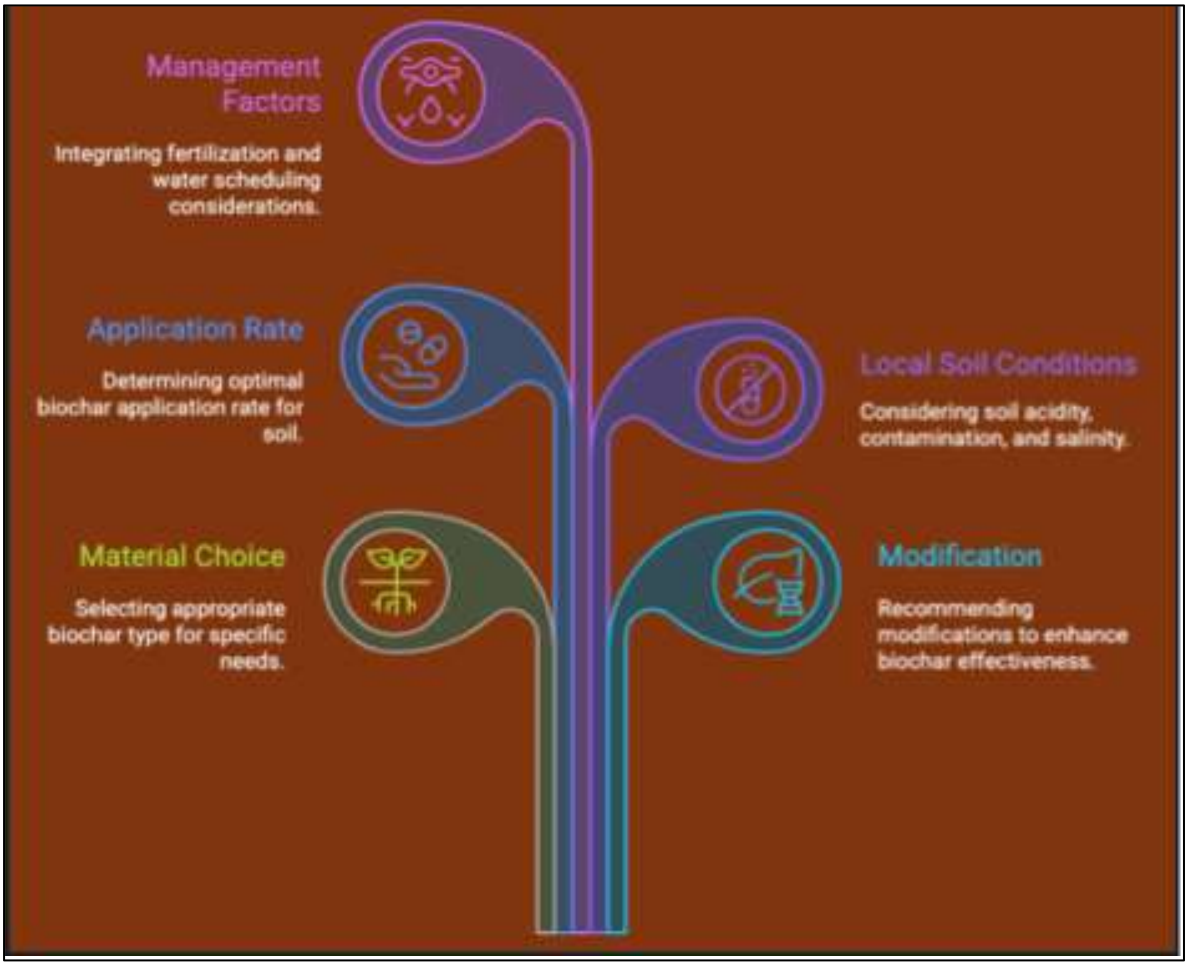

Figure 8. Decision supports tools for biochar and hydrochar use.

CONCLUSION

This review highlights the significant potential of biochar and hydrochar to enhance sustainable rice production by improving agronomic performance, soil health, and reducing environmental externalities. Biochar, particularly derived from animal waste, consistently improves soil fertility and crop yield by increasing soil pH, organic carbon content, and nutrient retention. It also plays a vital role in mitigating greenhouse gas emissions, particularly ammonia and methane, while offering a pathway to reduced nitrogen fertilizer inputs. Notably, animal-waste biochar co-applied with mineral fertilizers or organic inputs has demonstrated the ability to maintain or increase rice yields with reduced nitrogen use, offering a viable strategy for mitigating both agronomic and environmental challenges.

Hydrochar, while more variable, offers promising environmental benefits, particularly in reducing nitrous oxide and methane emissions. Its effectiveness in enhancing nitrogen use efficiency and improving soil

organic carbon quality is influenced by its modification. Modified hydrochars, such as those washed, microbial-aged, or clay-composited, demonstrate consistent benefits across multiple environmental and agronomic parameters. However, unmodified hydrochar or high application rates (above 3%) often lead to negative outcomes, such as suppressed plant growth and increased global warming potential (GWP).
The integration of biochar and hydrochar into rice farming systems depends on careful management of application rates and material modification, particularly in relation to soil condition and nutrient management practices. Further research should focus on long-term, field-scale trials to better understand the trade-offs and synergies between these carbon-rich amendments. The development of decision-support tools that align material properties with site-specific conditions, nitrogen management, and irrigation practices will be essential for the successful implementation of biochar and hydrochar in sustainable rice production systems. Future studies should also focus on standardized material specifications, environmental impact assessments, and life-cycle analyses to support the wider adoption of these materials in rice farming, ensuring that the full environmental and agronomic benefits are realized without unintended consequences.

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