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Evidence-Gated Four-Dimensional Sustainability Readiness Appraisal of a Fixed-Bed Co-Pyrolysis System for Rice Husk, Rice Straw, and Sugarcane Bagasse

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Abstract

This study evaluated a laboratory-scale fixed-bed co-pyrolysis system for rice husk, rice straw, and sugarcane bagasse using an evidence-gated sustainability-readiness framework to determine whether existing evidence supports progression toward targeted pilot validation. A descriptive engineering case-study design was employed using one 5.50 kg reference batch operated at 500 °C with a 1:1:2 feedstock ratio. Engineering data, an assumption-based gas-to-dryer energy scenario, and a researcher-developed 20-indicator professional-appraisal instrument were analyzed. Twenty qualified evaluators were purposively selected to assess environmental, technical, operational, and social-deployment potential. The reference batch recovered 2.64 kg bio-oil (48.0%) and 1.60 kg biochar (29.1%), while the 1.26 kg residual fraction (22.9%) was derived by mass balance rather than directly measured as gas. Under the adopted screening assumptions, the residual fraction provided an estimated 3.17 MJ of potentially useful dryer heat, equivalent to 58.1% of the reference drying requirement; however, this remains an unverified scenario. Professional appraisal was uniformly favorable, with mean scores of 4.77 for environmental, 4.75 for technical, 4.74 for operational, and 4.75 for social-deployment potential. Evidence remained insufficient to establish comparative environmental performance, long-term reliability, quantified safety, economic feasibility, or community acceptance. The study concludes that the prototype merits targeted validation rather than being considered proven sustainable or deployment ready. Recommended validation includes repeated-run reliability, direct gas and dryer measurements, comparative environmental assessment, formal safety and maintainability evaluation, preliminary economics, and direct stakeholder participation. The study aligns conceptually with SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), and SDG 12 (Responsible Consumption and Production). Its sustainability impact lies in supporting technological, environmental, socio-economic, and institutional decision-making by distinguishing demonstrated performance from assumptions and professional judgments before pilot development.

Keywords: Agricultural Residues, Biochar, Bio-Oil, Co-Pyrolysis, Evidence-Gated Sustainability Readiness, Fixed-Bed System, Gas-To-Dryer Energy, Pilot Validation, Sustainability Assessment, Thermochemical Conversion

1. Introduction

Agricultural crop residues offer opportunities for circular resource recovery because they retain recoverable carbon and energy while potentially creating disposal and pollution burdens when unmanaged. However, sustainable thermochemical conversion requires more than successful product generation; it also depends on process integration, operational reliability, environmental verification, and realistic utilization pathways (Paudel et al., 2024; Polipalli et al., 2025). This study evaluates an existing laboratory-scale fixed-bed system by restructuring available engineering, energy, and professional-appraisal data within an evidence-gated sustainability-readiness framework. Rather than claiming that the prototype is already sustainable or deployment ready, the study determines whether the available evidence supports progression toward targeted pilot validation and identifies the additional evidence required for stronger sustainability and deployment claims.

Rice husk, rice straw, and sugarcane bagasse are potential feedstocks for thermochemical valorization, although differences in composition, ash behavior, particle characteristics, and conversion response affect their performance. Reactor configuration and operating conditions influence the distribution and quality of biochar, bio-oil, and non-condensable gases from rice residues and sugarcane bagasse (El-Sayed, 2025; Matsueda & Antunes, 2024). Temperature and feedstock physical properties can likewise affect coproduct yields, particularly non-condensable gas production from bagasse pellets (Ferreira et al., 2025). Co-pyrolysis can increase feedstock flexibility and facilitate the valorization of mixed agricultural residues, but product quality, process control, and economic feasibility remain important development challenges (Ige & Łaska, 2025).

Evidence that biomass conversion occurs does not independently establish sustainability because measured product yields, assumption-based energy calculations, professional ratings, and life-cycle comparisons represent different forms and strengths of evidence. Sustainability assessment at low technology readiness must therefore accommodate limited data while explicitly recognizing uncertainty and evidentiary limitations (Parolin et al., 2024; Henderson & Peeling, 2024; Cornelio et al., 2026). This approach is particularly important when comprehensive life-cycle, techno-economic, and field-scale social assessments are not yet feasible. Environmental performance in pyrolysis systems cannot be inferred solely from renewable feedstock use or biochar production. Life-cycle outcomes depend on factors including the functional unit, system boundary, process energy, residue collection and transport, coproduct treatment, biochar fate, and displaced reference system (Zhu et al., 2022). Economic considerations can similarly influence deployment despite favorable environmental indicators, supporting integrated environmental and techno-economic assessment as technologies mature (Pérez-Almada et al., 2023). Social acceptance also requires evidence from intended stakeholders rather than inference from technical experts, as acceptance may vary with feedstock type, perceived effectiveness, and communication of waste utilization (van Dijk et al., 2024).

The broader development of agricultural-residue thermochemical systems is characterized by a transition from laboratory evidence toward integrated and verifiable deployment. Existing research remains substantially laboratory based, while sustainable implementation requires reliable operation, process integration, environmental validation, and credible pathways for using recovered products (Paudel et al., 2024; Polipalli et al., 2025). Feedstock variability and operating conditions further affect conversion outcomes (El-Sayed, 2025; Matsueda & Antunes, 2024), while mixed-residue processing introduces additional challenges involving process control, product quality, and economic feasibility (Ige & Łaska, 2025). Consequently, progression from laboratory demonstration requires evidence that extends beyond technical conversion performance.

The conceptual basis of the study is the distinction between demonstrated performance, assumption-based estimates, professional appraisal, and sustainability evidence. The existing fixed-bed laboratory dataset includes a defined operating condition, recovered bio-oil and biochar masses, a residual mass-balance fraction, an assumption-based gas-to-dryer calculation, and a four-dimensional professional appraisal. These forms of evidence are not treated as interchangeable. The study therefore applies an evidence-gated sustainability-readiness framework in which available findings are classified according to evidentiary strength and remaining evidence gaps are translated into requirements for pilot development. This approach is consistent with sustainability-assessment methods designed for technologies at low readiness levels and under conditions of limited data (Parolin et al., 2024; Henderson & Peeling, 2024; Cornelio et al., 2026). It also recognizes that stronger environmental, economic, and social claims ultimately require appropriate life-cycle comparison, techno-economic evaluation, and stakeholder-based evidence (Pérez-Almada et al., 2023; van Dijk et al., 2024; Zhu et al., 2022).

A key research gap is the difference between demonstrating laboratory-scale biomass conversion and establishing sufficient evidence for sustainability and deployment readiness. Existing product yields alone cannot establish environmental performance, economic viability, operational reliability, or stakeholder acceptance. Similarly, assumption-based energy calculations and professional perception scores cannot substitute for measured system performance or stakeholder evidence. The study addresses this gap by restructuring the available fixed-bed system data into an evidence-gated sustainability-readiness framework rather than generating additional unmeasured performance claims. Its purpose is to determine whether the existing evidence justifies progression from laboratory demonstration toward targeted pilot validation and to identify the measurements required before stronger sustainability and deployment claims can be made. Specifically, the study establishes the condition-specific engineering basis and product mass balance; quantifies the potential gas-to-dryer energy pathway under stated assumptions; characterizes the four-dimensional professional appraisal without treating perception scores as measured outcomes; classifies major findings according to evidentiary strength; and defines evidence gates for pilot progression in reliability, gas and dryer performance, environmental comparison, safety and maintainability, economics, and stakeholder acceptance.

Based on the scope explicitly established in the study, the research is most directly aligned with sustainability objectives concerning resource recovery, energy utilization, technological development, responsible use of agricultural residues, and environmentally informed deployment. These objectives correspond conceptually to SDG 7 – Affordable and Clean Energy, through investigation of the potential gas-to-dryer energy pathway; SDG 9 – Industry, Innovation and Infrastructure, through the staged development and pilot validation of a thermochemical conversion system; and SDG 12 – Responsible Consumption and Production, through the valorization of agricultural residues and recovery of carbon and energy that might otherwise remain unmanaged. The study also has a limited conceptual relationship with SDG 8 – Decent Work and Economic Growth because economic feasibility is recognized as a necessary component of technology deployment rather than assumed from technical or environmental performance alone (Pérez-Almada et al., 2023). These alignments should be interpreted as sustainability relevance rather than evidence that the prototype has already achieved the corresponding SDG outcomes.

The study contributes primarily to technological, environmental, socio-economic, and institutional dimensions of sustainability by establishing a disciplined basis for deciding whether an agricultural-residue conversion technology should progress from laboratory demonstration to pilot validation. Technologically, it distinguishes measured engineering performance from assumption-based estimates and identifies additional reliability, gas, dryer, safety, and maintainability evidence needed for development. Environmentally, it recognizes that renewable feedstocks and recovered products alone cannot establish environmental superiority because life-cycle outcomes depend on system boundaries, energy requirements, logistics, coproduct treatment, biochar fate, and the reference system being displaced (Zhu et al., 2022). The socio-economic dimension is reflected in the recognition that environmental performance must eventually be considered alongside economic feasibility (Pérez-Almada et al., 2023) and stakeholder acceptance (van Dijk et al., 2024). Institutionally, the evidence-gated approach supports more defensible technology-development decisions by preventing measured results, calculated assumptions, and professional perceptions from being interpreted as equivalent forms of evidence. The study therefore contributes to multidisciplinary sustainability not by asserting that the fixed-bed system is already sustainable, but by establishing the evidence requirements needed to evaluate sustainability and deployment readiness more rigorously during subsequent pilot development.

2. Material and methods

2.1 Research Design

The study employed a descriptive engineering case-study design within a laboratory-scale research-and-development program for a fixed-bed co-pyrolysis energy-recovery system. Rice husk, rice straw, and sugarcane bagasse were processed in a stationary biomass bed under oxygen-limited heating. Pyrolysis vapors were directed to a condenser for bio-oil recovery, while biochar was collected after reactor cooling. A residual outlet stream was intended for supplemental biomass drying, although its gas flow, composition, and mass were not directly measured during the reference batch. The assessment unit consisted of one 5.50 kg as-loaded batch operated at 500 °C with a 1:1:2 RH:RS mass ratio. The study covered feedstock loading, fixed-bed conversion, vapor transfer, condensation, bio-oil and biochar recovery, residual-fraction calculation, and the proposed gas-to-dryer scenario. Crop production, complete residue collection and transportation, infrastructure construction, long-term biochar fate, final bio-oil utilization, commercial distribution, continuous operation, equipment end-of-life, and formal economic analysis were outside the assessment boundary. The reference batch produced 2.64 kg of recovered bio-oil, equivalent to 48.0% of the initial feed mass, and 1.60 kg of recovered biochar, equivalent to 29.1%. The remaining 1.26 kg, or 22.9%, was calculated by overall mass balance. This remainder was treated as a residual mass-balance fraction rather than directly measured gas because it could include unquantified condensate, moisture, deposits, leaks, or other losses. The possible use of the residual stream for biomass drying was evaluated as an illustrative engineering scenario rather than a verified energy balance. The calculation adopted a specific gas energy of 6.0 MJ kg^{-1}, a gas-recovery factor of 0.70, and a useful-heat factor of 0.60, while assuming for screening purposes that the entire 1.26 kg residual fraction represented recoverable gas. Because this assumption was not verified through direct gas measurement, the resulting heat contribution was treated only as a potential scenario and not as measured gas energy, energy savings, or process efficiency.

2.2 Locale of the Study

The study was conducted within a laboratory-scale research-and-development setting using a fixed-bed co-pyrolysis system. The supplied manuscript does not identify a specific institution, municipality, province, or other geographic location. Accordingly, no geographic locale is specified beyond the laboratory setting.

2.3 Respondents of the Study

The professional appraisal involved 20 qualified evaluators comprising faculty members, licensed engineers, technical personnel, and individuals familiar with biomass conversion systems and agricultural-residue utilization. They examined the laboratory prototype and available engineering performance information before evaluating the assessment indicators. The participants were intended to provide informed professional appraisal of the prototype at its existing development stage and were not considered representative of farmers, nearby residents, operators, investors, or the general public.

2.4 Sample and Sampling Procedure

Purposive sampling was used to select the 20 qualified evaluators based on their relevant professional or technical familiarity with biomass conversion systems and agricultural-residue utilization. The sampling approach was therefore directed toward obtaining informed professional judgments about the laboratory prototype rather than generating population-representative estimates of stakeholder or community perceptions.

2.5 Research Instrument

A researcher-developed professional-appraisal instrument containing 20 indicators was used. The indicators were distributed equally across four dimensions: environmental, technical, operational, and social-deployment potential. Environmental potential covered agricultural-residue utilization, waste-reduction potential, renewable-energy recovery, carbon-footprint reduction potential, and environmental-impact reduction potential. Technical potential assessed reactor reliability, structural durability, maintainability, engineering functionality, and energy-recovery performance. Operational potential addressed biomass availability, process stability, ease of operation, operational safety, and maintenance requirements. Social-deployment potential considered agricultural-waste-management relevance, anticipated community benefits, support for sustainable agricultural practices, renewable-energy awareness, and community acceptance. The source study reports that the instrument underwent peer and expert validation before administration. However, item-level validation statistics and internal-consistency coefficients were unavailable in the supplied manuscript. Responses were obtained through a five-point agreement scale ranging from 5 for strongly agree to 1 for strongly disagree.

2.6 Data Gathering Procedure

Engineering data were obtained from the selected 5.50 kg reference batch operated at 500 °C using the 1:1:2 RH:RS feedstock ratio. Bio-oil and biochar were recovered directly, while the residual mass-balance fraction was calculated from the difference between the initial feed and recovered products. Because the residual gas stream was not directly metered or weighed, it was retained as a calculated residual fraction. For the professional appraisal, the selected evaluators reviewed the laboratory prototype and available engineering performance information before rating the 20 indicators. The gas-to-dryer pathway was evaluated separately as an assumption-based screening scenario using the adopted gas-energy, recovery, and useful-heat factors. This procedure maintained a distinction among directly measured engineering data, derived quantities, scenario-based estimates, and professional judgments.

2.7 Data Analysis Techniques

Product yields were calculated relative to the initial as-loaded biomass mass, while the residual fraction was derived through overall batch mass balance. The gas-to-dryer scenario was calculated using the adopted specific gas energy, gas-recovery factor, and useful-heat factor, but its results were interpreted only as potential energy under stated assumptions because direct gas measurements were unavailable. Professional-appraisal responses were analyzed descriptively. A weighted mean was calculated for each indicator, the five indicator means within each dimension were averaged to obtain the corresponding dimension score, and the four dimension scores were equally weighted to obtain the overall appraisal score. Scores from 4.21–5.00 were interpreted as very high, 3.41–4.20 as high, 2.61–3.40 as moderate, 1.81–2.60 as low, and 1.00–1.80 as very low. The resulting score was treated as a descriptive screening measure rather than a validated universal sustainability index. Equal weighting was recognized as a normative analytical choice because indicator weighting can materially influence aggregated sustainability results (Wulf et al., 2023). No alternative post hoc weighting was introduced because stakeholder-specific weights and uncertainty distributions were unavailable. To maintain evidentiary discipline, major findings were further classified as measured, derived, scenario-estimated, or judgment-based. Measured evidence represented quantities directly recorded or recovered under the reference condition, while derived evidence consisted of deterministic calculations from measured batch quantities. Scenario-estimated evidence depended on adopted energy or efficiency assumptions and was therefore interpreted only as potential under those assumptions. Judgment-based evidence represented professional appraisal and was interpreted as perceived or expert-rated potential rather than measured environmental, safety, economic, or community performance. This classification served as a reporting safeguard rather than a replacement for formal technology-readiness or life-cycle assessment methods, consistent with early-stage approaches emphasizing transparent treatment of limited data, uncertainty, and decision relevance (Parolin et al., 2024; Henderson & Peeling, 2024; Cornelio et al., 2026). Pilot-progression gates were established where existing evidence was insufficient to support stronger claims. These addressed repeated-run reliability, direct gas and dryer validation, comparative environmental assessment, formal safety, operability and maintainability evidence, preliminary economics, and direct stakeholder participation. A gate was considered open only when existing evidence directly supported the intended claim; otherwise, the required validation activity was identified instead of assigning a favorable readiness status.

2.8 Ethical Considerations

Participation in the professional appraisal was voluntary. Evaluators were informed of the assessment purpose, and informed consent was obtained before participation. Results were reported in aggregate form without identifying individual evaluators. No animal subjects were involved. Engineering and appraisal data were analyzed within the defined assessment boundaries, and unmeasured results were not reclassified as direct experimental evidence.

3. Results and Discussion

3.1 Engineering Performance and Energy-Recovery Potential

3.1.1 Product Recovery and Mass Balance

The 5.50 kg reference batch recovered 2.64 kg of bio-oil and 1.60 kg of biochar, corresponding to 48.0% and 29.1% of the as-loaded feed, respectively. The remaining 1.26 kg represented 22.9% of the initial mass and was obtained by arithmetic difference. Thus, the reference condition demonstrated recovery of liquid and solid products, while the 1.26 kg represented only a residual mass-balance fraction. The residual fraction cannot be interpreted as a chemically characterized gas yield because the mass balance does not distinguish permanent gas from uncollected condensables, moisture-related losses, deposits, leakage, or weighing uncertainty. Direct measurement of gas mass and composition is therefore required before verified gas-yield claims can be made. This distinction is consistent with recent thermochemical-conversion literature, which emphasizes that operating conditions and product-recovery systems influence observed coproduct distributions (Paudel et al., 2024; Ferreira et al., 2025).

3.1.2 Gas-to-Dryer Energy Contribution

Under the illustrative gas-to-dryer scenario, applying the adopted specific gas energy of 6.0 MJ kg^{-1} to the 1.26 kg residual fraction produced an estimated gross energy of 7.56 MJ. Applying a 70% recovery factor reduced this to 5.29 MJ of recoverable energy, while a 60% useful-heat factor resulted in 3.17 MJ of potentially useful dryer heat. Relative to the 5.46 MJ reference dryer heat requirement, the scenario indicated a hypothetical contribution of 58.1%, leaving 41.9% to auxiliary heating. These values depend on the unverified assumption that the entire residual fraction represents recoverable combustible gas. Although the estimated 58.1% contribution cannot be interpreted as verified energy savings or measured process efficiency, it provides a testable process-integration hypothesis. Recent work on rice-straw thermochemical systems shows that environmental benefits become considerably more defensible when process emissions and integrated heat-source performance are measured directly rather than inferred from feedstock type alone (Unsomsri et al., 2025). Validation therefore requires direct measurement of gas flow, composition, lower heating value, combustion performance and emissions, dryer temperatures, moisture removal, and auxiliary energy consumption.

3.2 Professional Appraisal of Sustainability and Deployment Potential

3.2.1 Four-Dimensional Appraisal

All four appraisal dimensions were rated within the predefined very-high interval. Environmental potential obtained the highest mean of 4.77, followed by technical and social-deployment potential at 4.75 each and operational potential at 4.74. The overall four-dimensional appraisal score was 4.75, with only a 0.03 difference across dimensions, indicating uniformly favorable professional ratings. Agricultural-residue utilization was the strongest environmental indicator, while carbon-footprint reduction was relatively weakest. Engineering functionality ranked highest technically, whereas maintainability ranked lowest. Biomass availability led the operational indicators, while maintenance requirements and operational safety received the lowest relative ratings. Agricultural-waste-management relevance was the strongest social-deployment indicator, while community acceptance was the weakest. The indicator pattern suggests that the prototype was perceived as useful and functional, while environmental verification, maintainability, safety, and community acceptance require stronger evidence. The uniformly high ratings should nevertheless be interpreted cautiously because the small purposive panel and narrow score range may reflect limited discrimination, shared professional perspectives, or ceiling/acquiescence tendencies. Consequently, the appraisal functions as a screening and hypothesis-generating mechanism rather than proof of sustainability. This interpretation is consistent with recent early-stage sustainability research, which treats screening tools as decision support under uncertainty rather than substitutes for mature quantitative assessment (Henderson & Peeling, 2024; Cornelio et al., 2026).

3.3 Evidence-Gated Pilot Readiness

3.3.1 Evidence Strength and Pilot-Progression Requirements

The evidence audit showed that product recovery from the reference batch represented the strongest current evidence. The residual fraction was derived from mass balance, the gas-to-dryer contribution was scenario-estimated, and the four-dimensional assessment represented professional judgment. Evidence was insufficient to establish comparative carbon-footprint performance, long-duration reliability, quantified safety, economic feasibility, or community acceptance. Consequently, pilot-progression requirements remained pending for repeatability and reliability, direct gas and dryer performance, environmental comparison, safety and maintainability, economics, and stakeholder participation. The current evidence supports progression to a targeted validation campaign but not deployment certification or proven sustainability. The evidence-gated approach prevents findings with different evidentiary strengths from being interpreted as equivalent. Product recovery can be described as demonstrated under the reference condition, whereas calculated residual mass, scenario-based energy estimates, and professional judgments require correspondingly restricted interpretations. The pending gates therefore identify the evidence needed to strengthen subsequent claims rather than assigning favorable readiness status where direct evidence is absent.

3.4 Environmental Readiness and Comparative Sustainability

3.4.1 Agricultural-Residue Utilization and Environmental Evidence

Agricultural-residue utilization received the strongest environmental appraisal, indicating favorable professional assessment of the system's potential to convert crop residues into useful products. However, carbon-footprint reduction received the weakest relative environmental rating, and the available evidence did not establish that the reactor had a lower environmental footprint than alternative residue-management pathways. The strong residue-utilization result is consistent with current circular-bioeconomy literature identifying thermochemical conversion as a pathway for upgrading crop residues into fuels and carbon-rich products (Sheer et al., 2024; Polipalli et al., 2025). Reviews of rice residues and bagasse similarly demonstrate the potential of pyrolysis to generate useful products from agricultural residues (El-Sayed, 2025; Matsueda & Antunes, 2024). Nevertheless, these findings establish feedstock relevance rather than comparative environmental superiority. Such claims require a defined functional unit, reference scenario, inventory, and coproduct treatment because life-cycle outcomes can vary with system boundaries, biochar use, process energy, transportation, and allocation assumptions (Zhu et al., 2022). The relatively lower carbon-footprint rating therefore represents an evidence requirement for subsequent comparative assessment.

3.5 Technical, Operational, and Safety Readiness

3.5.1 Functionality, Maintainability, and Operational Safety

Engineering functionality received the strongest technical appraisal, reflecting the integration of conversion, vapor transfer, condensation, liquid recovery, char recovery, and the proposed residual-gas pathway. Maintainability was the weakest technical indicator, while maintenance requirements and operational safety received the lowest relative operational ratings. The reference batch demonstrated system function but did not provide repeated-run evidence of reliability, maintenance burden, or quantified safety performance. These findings indicate that successful operation in one reference batch cannot establish long-term reliability or maintainability. Fixed-bed processing of heterogeneous fibrous residues may involve fouling, tar deposition, ash accumulation, seal degradation, inconsistent feeding, and difficult cleaning access. Further validation should therefore quantify cleaning requirements, component access, seal and gasket condition, fouling, downtime, unsuccessful runs, temperature deviations, and maintenance interventions. Safety claims likewise require documented hazard identification, leak detection, pressure management, emergency shutdown, electrical protection, personal protective equipment, and operator training before operational safety can be established.

3.6 Social-Deployment and Economic Readiness

3.6.1 Community Acceptance and Stakeholder Evidence

Agricultural-waste-management relevance received the strongest social-deployment appraisal, while community acceptance received the lowest relative rating. Because the appraisal involved technically informed evaluators rather than intended community stakeholders, the findings indicate perceived social-deployment potential but do not directly establish community acceptance. Technical evaluators can assess whether the prototype addresses an agricultural-residue problem but cannot represent the views of farmers, residue suppliers, operators, local government units or cooperatives, nearby residents, and potential biochar or bio-oil users. Biomass acceptance can differ according to feedstock type, perceived effectiveness, and the framing of waste utilization (van Dijk et al., 2024). Direct stakeholder engagement is therefore required to evaluate residue-supply willingness, siting concerns, odor and smoke perceptions, trust, ownership preferences, maintenance responsibilities, training needs, and product-use expectations.

3.6.2 Economic Readiness

Economic feasibility was not measured by the four-dimensional appraisal and therefore remained outside the current evidence base. The study consequently provides no direct evidence regarding capital costs, operating costs, labor, feedstock logistics, auxiliary energy, maintenance costs, coproduct value, or economic sensitivity to scale. The absence of economic assessment limits comprehensive sustainability claims because technically and environmentally promising systems may not necessarily be economically viable. As the technology develops, economic evidence should therefore be evaluated alongside environmental performance. Recent reviews of biorefinery assessment emphasize that environmental promise and economic viability must ultimately be examined together because trade-offs can change deployment decisions (Pérez-Almada et al., 2023).

3.7 Methodological Contribution and Decision Significance

3.7.1 Evidence-Gated Interpretation

The study identified four distinct forms of evidence: direct batch observations, deterministic calculations, assumption-dependent energy estimates, and professional judgments. Product masses established what was recovered during the reference batch; the residual mass balance established what could be calculated but not chemically attributed; the gas-to-dryer scenario provided an assumption-dependent process-integration estimate; and the professional appraisal identified perceived strengths and weaknesses. Together, these findings supported progression toward focused validation while retaining explicit uncertainty. Separating these evidence types reduces the risk of treating unequal forms of information as equivalent proof of sustainability. The evidence-gated framework links each finding to an allowable interpretation and uses unresolved claims to define subsequent validation requirements. This is consistent with recent early-stage technology-assessment research that seeks to make sustainability considerations actionable before full data availability without presenting screening as a substitute for mature assessment (Parolin et al., 2024; Cornelio et al., 2026).

3.8 Study Limitations and Claim Boundaries

3.8.1 Limitations of the Current Evidence

The study was limited to one 5.50 kg laboratory-scale reference batch and therefore did not establish continuous-operation performance, long-duration reliability, or scale-up behavior. The 1.26 kg residual fraction was calculated by difference rather than directly measured as gas, while the gas-to-dryer scenario depended on adopted heating-value and efficiency assumptions. Environmental appraisal did not constitute a life-cycle assessment because no comparative functional unit, complete inventory, coproduct allocation, or uncertainty analysis was available. The professional evaluators were not representative of intended community stakeholders, the uniformly high scores may have been influenced by limited discrimination or response tendencies, and economic performance was outside the four-dimensional instrument. These limitations define the boundaries of the study's conclusions rather than serving as secondary qualifications. Accordingly, the available evidence demonstrates condition-specific product recovery and provides screening-level indications of potential readiness, but it does not establish verified gas-energy performance, comparative environmental superiority, long-term reliability, quantified safety, economic feasibility, community acceptance, or overall sustainability. The limitations therefore function as evidence gates that direct the next stage of pilot-oriented validation.

4. Conclusion & Recommendations

The study reframed the laboratory-scale fixed-bed co-pyrolysis system for rice husk, rice straw, and sugarcane bagasse as an evidence-gated sustainability-readiness assessment. At 500 °C and a 1:1:2 RH:RS ratio, the 5.50 kg reference batch recovered 2.64 kg of bio-oil and 1.60 kg of biochar, while the remaining 1.26 kg (22.9%) was derived through mass balance rather than directly measured as gas. Under the adopted screening assumptions, the residual fraction yielded a potential 3.17 MJ of useful dryer heat, equivalent to 58.1% of the reference drying requirement, but this remains subject to experimental validation. Professional appraisal was highly favorable across environmental (4.77), technical (4.75), operational (4.74), and social-deployment (4.75) dimensions; however, these ratings represent perceived early-stage potential rather than verified sustainability outcomes. Thus, the current evidence supports targeted validation of the prototype but does not establish proven sustainability or deployment readiness.

Before pilot deployment, the study recommends repeated-run reliability and maintainability testing; direct measurement of gas flow, composition, heating value, combustion behavior, emissions, and dryer performance; comparative environmental assessment using a defined functional unit and baseline; formal safety, operability, and maintenance evaluation; and preliminary economic assessment with direct stakeholder participation. Completing these evidence gates would transform existing uncertainties into measurable decision criteria and provide a stronger basis for scale-up, investment, and local deployment while maintaining a transferable reporting framework that distinguishes measured results, calculations, assumptions, and professional judgments in early-stage agricultural-residue conversion systems.

The study is limited by the current evidentiary basis of the laboratory-scale prototype. The 1.26 kg residual fraction was calculated through mass balance rather than directly measured as gas, making the estimated 3.17 MJ dryer heat and 58.1% contribution dependent on unverified screening assumptions. Likewise, the favorable professional-appraisal scores do not verify carbon-footprint reduction, long-term reliability, operational safety, commercial viability, or community acceptance. Consequently, these unresolved areas limit conclusions regarding sustainability and deployment readiness and require direct validation before stronger claims can be established.

5. Compliance with ethical standards

The authors observed the ethical considerations specified for the study. Participation in the professional appraisal was voluntary, and evaluators were informed of the assessment purpose and provided informed consent before participation. Results were reported in aggregate form without identifying individual evaluators. No animal subjects were involved. Engineering and appraisal data were analyzed within the defined assessment boundaries, and unmeasured results were not classified as direct experimental evidence.

REFERENCES

Cornelio, A., Calce, S., Fahimi, A., & Bontempi, E. (2026). Early-stage sustainability screening for technology innovation: The ESCAPE approach. Journal of Environmental Management, 398, 128465. https://doi.org/10.1016/j.jenvman.2025.128465

El-Sayed, S. A. (2025). Chemical products yielded from different pyrolysis processes of rice waste residues: A comprehensive review. Biomass Conversion and Biorefinery, 15, 20615–20655. https://doi.org/10.1007/s13399-025-06624-3

Ferreira, R. M., de Souza, L. S., dos Santos, G. R., de Sousa, F. D., Duarte, J. B. F., Carneiro, F. O. M., de Andrade, C. F., Serra, D. S., & de Oliveira, M. L. M. (2025). Pyrolysis of sugarcane bagasse pellets: Influence of temperature and pellet density on co-product yields. Biofuels, Bioproducts and Biorefining, 19(6), 1984–1996. https://doi.org/10.1002/bbb.2798

Henderson, J., & Peeling, R. (2024). A framework for early-stage sustainability assessment of innovation projects enabled by weighted sum multi-criteria decision analysis in the presence of uncertainty. Open Research Europe, 4, 162. https://doi.org/10.12688/openreseurope.18195.1

Ige, A. R., & Łaska, G. (2025). Production of antioxidant additives and biochar pellets from the co-pyrolysis of agricultural biomass: A review. Renewable and Sustainable Energy Reviews, 208, 115037. https://doi.org/10.1016/j.rser.2024.115037

Matsueda, Y., & Antunes, E. (2024). A review of current technologies for the sustainable valorisation of sugarcane bagasse. Journal of Environmental Chemical Engineering, 12(6), 114900. https://doi.org/10.1016/j.jece.2024.114900

Parolin, G., McAloone, T. C., & Pigosso, D. C. A. (2024). How can technology assessment tools support sustainable innovation? A systematic literature review and synthesis. Technovation, 129, 102881. https://doi.org/10.1016/j.technovation.2023.102881

Paudel, P. P., Kafle, S., Park, S., Kim, S. J., Cho, L., & Kim, D. H. (2024). Advancements in sustainable thermochemical conversion of agricultural crop residues: A systematic review of technical progress, applications, perspectives, and challenges. Renewable and Sustainable Energy Reviews, 202, 114723. https://doi.org/10.1016/j.rser.2024.114723

Pérez-Almada, D., Galán-Martín, Á., Contreras, M. M., & Castro, E. (2023). Integrated techno-economic and environmental assessment of biorefineries: Review and future research directions. Sustainable Energy & Fuels, 7, 4031–4050. https://doi.org/10.1039/D3SE00405H

Polipalli, K., Suraboyina, S., Kashimalla, M., & Polumati, A. (2025). A review on value addition of agricultural residues by chemical and bio-chemical processes to abate environmental pollution. Green Technologies and Sustainability, 3(4), 100241. https://doi.org/10.1016/j.grets.2025.100241

Sheer, A., Sardar, M. F., Younas, F., Zhu, P., Noreen, S., Mehmood, T., Farooqi, Z. U. R., Fatima, S., & Guo, W. (2024). Trends and social aspects in the management and conversion of agricultural residues into valuable resources: A comprehensive approach to counter environmental degradation, food security, and climate change. Bioresource Technology, 394, 130258. https://doi.org/10.1016/j.biortech.2023.130258

Unsomsri, N., Koedthong, P., Tawkaew, S., Wiriyasart, S., & Kaewluan, S. (2025). Mitigating dust and air pollution from open-field rice straw burning through biochar production using an integrated biomass gasifier and burner. Case Studies in Chemical and Environmental Engineering, 11, 101222. https://doi.org/10.1016/j.cscee.2025.101222

van Dijk, M., Goedegebure, R., & Nap, J.-P. (2024). Public acceptance of biomass for bioenergy: The need for feedstock differentiation and communicating a waste utilization frame. Renewable and Sustainable Energy Reviews, 202, 114670. https://doi.org/10.1016/j.rser.2024.114670

Wulf, C., Haase, M., Baumann, M., & Zapp, P. (2023). Weighting factor elicitation for sustainability assessment of energy technologies. Sustainable Energy & Fuels, 7, 832–847. https://doi.org/10.1039/D2SE01170K

Zhu, X., Labianca, C., He, M., Luo, Z., Wu, C., You, S., & Tsang, D. C. W. (2022). Life-cycle assessment of pyrolysis processes for sustainable production of biochar from agro-residues. Bioresource Technology, 360, 127601. https://doi.org/10.1016/j.biortech.2022.127601