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CIRCULAR ECONOMY IN AGRIBUSINESS: UTILIZATION OF PADDY RICE AGRICULTURAL WASTE AS A SOURCE OF ADDED VALUE

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Abstract

The paddy rice agribusiness sector generates massive quantities of by-products and residues annually, including rice straw, rice husk, rice bran, and other organic materials. These residues, if left unmanaged, contribute to environmental degradation through open burning, greenhouse gas emissions, and soil contamination. However, within the circular economy framework, these agricultural wastes represent significant untapped resources for value-added product development. This paper reviews the concept and application of circular economy principles in paddy rice agribusiness, analyzing valorization pathways for rice agricultural waste across energy production, material science, food processing, and agri-food supply chains. Key by-products examined include rice straw (biochar, biofuel, biomaterials), rice husk (silica, biochar, energy), and rice bran (functional food ingredients, biodiesel). The study draws on recent literature spanning 2021–2025 to identify technological innovations, challenges, and future perspectives in rice waste valorization. The circular bioeconomy approach offers agribusinesses viable pathways to reduce environmental burdens while simultaneously generating economic value, contributing to sustainable development goals and food system resilience.

Keywords : *circular economy; rice straw; rice husk; agricultural waste valorization; agribusiness; biorefinery; sustainable development*

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1. Introduction

The global paddy rice industry is one of the largest agri-food systems on earth, producing over 520 million metric tons of milled rice annually. For every ton of rice produced, approximately 1.35 tons of straw and 0.2 tons of husk are generated as co-products (Kaur et al., 2022). In Asia alone, rice straw burning, a widespread practice to clear fields rapidly, releases hundreds of millions of tons of CO_2 equivalents per year, causing severe air quality degradation and soil nutrient loss. In regions such as Yogyakarta and the broader Indo-Gangetic Plains, rice residue mismanagement remains a critical environmental and socioeconomic challenge.

Against this backdrop, the circular economy (CE) concept has gained traction as a transformative framework for agricultural waste management. Unlike the linear economy model of “take-make-dispose,” the CE emphasizes resource regeneration, waste minimization, and value retention at the highest utility level (Velenturf & Purnell, 2021). For paddy rice agribusiness, the CE offers a structured approach to convert residues into bioenergy, biomaterials, biofertilizers, and functional food ingredients, thereby reducing environmental burdens while creating new economic opportunities (Haque et al., 2023).

Recent scholarship has demonstrated that rice agricultural waste possesses substantial biochemical potential. Rice straw is rich in lignocellulosic biomass, cellulose, hemicellulose, and lignin, making it amenable to bioconversion processes (Rathour et al., 2023; Singh & Patel, 2022). Rice husk contains approximately 20% amorphous silica, a

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valuable industrial material (Kordi et al., 2023). Rice bran, with its 15–20% oil content, is a promising feedstock for functional foods and biofuels (Yadav et al., 2024). Translating this potential into practice requires the alignment of technological innovation, business model adaptation, and supportive policy frameworks (Donner et al., 2021; Donner & Vries, 2021).

This paper reviews the current state of circular economy application in paddy rice agribusiness, focusing on waste valorization strategies, technological pathways, and emerging innovations. It draws on peer-reviewed literature published between 2021 and 2025 and employs a systematic narrative review approach to synthesize findings across disciplines including agricultural engineering, food science, environmental studies, and agribusiness management

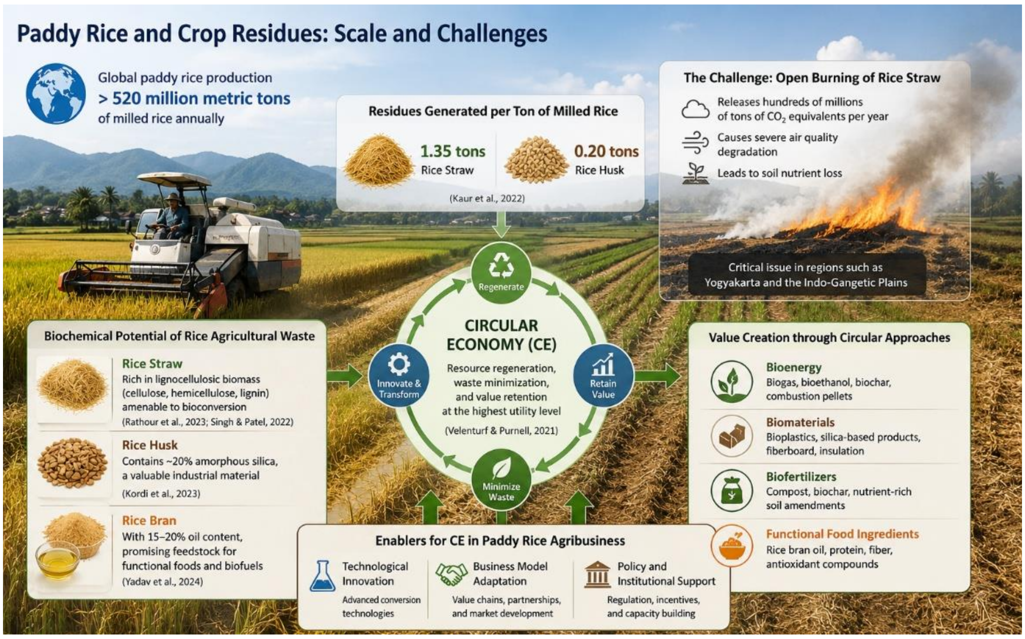

Figure 1. Paddy rice agricultural landscape illustrating the scale of crop residue generation in lowland rice farming systems.

2. Method

This study employs a systematic narrative review approach to synthesize findings from peer-reviewed literature on circular economy applications in paddy rice agribusiness and agricultural waste valorization. The narrative review method was selected because it enables comprehensive thematic synthesis across interdisciplinary domains, including agricultural engineering, food science, environmental management, and agribusiness, rather than being restricted to a single outcome measure as in a meta-analysis (Kirchherr et al., 2023).

A systematic search of the peer-reviewed literature was conducted between October 2024 and January 2025 using three major academic databases: Scopus, Web of Science (WoS), and Google Scholar. The search strategy employed a combination of Boolean operators and controlled vocabulary terms to ensure comprehensive coverage. Primary search strings included:

- *("circular economy" OR "circular bioeconomy") AND ("rice" OR "paddy") AND ("waste" OR "residue" OR "by-product")*
- *("rice straw" OR "rice husk" OR "rice bran") AND ("valorization" OR "valorisation" OR "value-added")*
- *("agricultural waste" OR "agri-food waste") AND ("biorefinery" OR "bioenergy" OR "biomaterial")*

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• *("agribusiness" OR "agri-food supply chain") AND ("circular economy" OR "waste management")*

Additional articles were identified through backward citation tracing (snowballing) from the reference lists of key review papers. Database searches were limited to publications in the English language and covering the period 2021–2025 to reflect current advances in the field.

Table 1. Inclusion and Exclusion Criteria for Literature Selection

Criterion	Inclusion	Exclusion
Publication type	Peer-reviewed journal articles, systematic reviews, review papers	Conference abstracts, book chapters, grey literature, theses
Language	English-language publications only	Non-English language articles
Publication period	2021–2025	Publications before 2021
Topic relevance	Circular economy in agriculture; rice/paddy waste valorization; agri-food biorefinery; CE in supply chains	Studies unrelated to rice or paddy agribusiness; purely chemical synthesis without agri-waste focus
Geographic scope	Global scope; priority to tropical and Asian rice-producing contexts	Studies limited to non-rice crops with no transferable CE methodology

***Source**: Author compilation (2025).*

The initial database search yielded 312 candidate articles. After removal of duplicate records (n = 47), titles and abstracts were screened against the inclusion criteria, resulting in the exclusion of 189 articles that were outside the scope of paddy rice waste valorization or circular economy agribusiness. Full-text screening of the remaining 76 articles led to the exclusion of a further 36 studies that did not meet quality or relevance thresholds primarily grey-literature sources, purely descriptive reports without analytical content, and studies with narrow chemical engineering focus lacking agribusiness context. A total of 40 peer-reviewed articles were retained for final synthesis. The screening process followed a PRISMA-inspired flow and is summarized in Figure 2.

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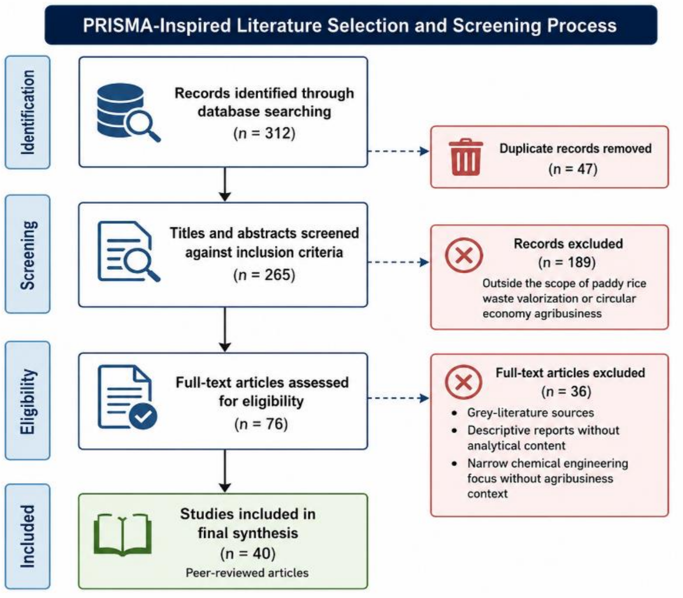

Figure 2. PRISMA-inspired literature selection and screening process for the systematic narrative review.

3. Results and Discussion

a. Circular Economy Framework In Agriculture

The circular economy concept has evolved substantially over the past decade from a niche environmental management principle to a mainstream business and policy paradigm (Kirchherr et al., 2023). In agricultural contexts, it encompasses strategies for extending resource use cycles, recovering nutrients, generating renewable energy, and creating value-added products from residues and by-products (Velasco-Muñoz et al., 2021; Hamam et al., 2021).

The agri-food sector is particularly well-suited to circular economy implementation because agricultural production naturally generates co-products and residues throughout the supply chain (Chiaraluce et al., 2021). Biomass valorization pathways can be categorized into four hierarchical tiers: (1) high-value biochemical recovery (bioactive compounds, functional ingredients); (2) material production (biomaterials, composites, construction aggregates); (3) energy recovery (biogas, biochar, biofuels); and (4) soil amendment (compost, biochar soil application) (Ahmad et al., 2024; Ligarda-Samanez et al., 2025).

Velasco-Muñoz et al. (2022) examined circular economy research using life cycle assessment and found that agricultural waste valorization pathways typically yield significant net reductions in carbon footprint, water use, and eutrophication potential. Mehmood et al. (2021) identified key drivers and barriers in agri-food supply chains, with regulatory frameworks, market access, and technological readiness emerging as critical enablers or impediments to CE adoption.

b. Major Paddy Rice Waste Streams And Valorization Pathways

1) Rice Straw

Rice straw is the most abundant crop residue from paddy cultivation, with global production estimated at 600–900 million tons annually (Rathour et al., 2023). Its lignocellulosic composition (38–42% cellulose, 23–28% hemicellulose, 10–15% lignin) makes it a versatile feedstock for multiple valorization routes.

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Biochar production: Thermochemical conversion (pyrolysis) of rice straw yields biochar with high carbon content, useful as a soil amendment to improve water retention, nutrient cycling, and carbon sequestration (Zhu et al., 2022; Paudel et al., 2024). Life cycle assessments of pyrolysis processes show a net negative carbon balance when biochar is applied to agricultural soils.

Biofuel and bioenergy: Rice straw can be converted to bioethanol through saccharification and fermentation, or gasified to produce syngas. Solid-state fermentation and enzymatic hydrolysis improve conversion efficiency (Chilakamarry et al., 2021; Awogbemi & Von Kallon, 2022). The De Dieu Marcel et al. (2024) review highlighted thermochemical pathways including torrefaction and hydrothermal liquefaction as emerging methods for bioenergy production.

Biomaterials and biocomposites: Lignocellulosic biomass from rice straw is increasingly used in the production of bioplastics, biocomposites, and packaging materials. Mujtaba et al. (2023) demonstrated that rice straw-derived cellulose nanofibers exhibit promising mechanical properties for biopolymer applications, supporting the transition away from petroleum-based materials.

2) Rice Husk

Rice husk, constituting 20–25% of the paddy grain weight, is generated during milling operations. Its primary distinctive characteristic is high silica content (SiO_2, 16–22%), which is extracted for applications in construction (cement additive), electronics (semiconductor-grade silica), and healthcare (Kordi et al., 2023). Beyond silica, rice husk is a significant combustion fuel for combined heat and power (CHP) systems in rice mills, offering a near-carbon-neutral energy source when replacing fossil fuels (Blasi et al., 2023).

Çapanoğlu et al. (2022) reviewed novel approaches for rice husk valorization including hydrothermal synthesis of zeolites, production of activated carbon for water treatment, and biosorbent development for heavy metal removal. Yaashikaa et al. (2021) highlighted biorefinery approaches that integrate multiple valorization pathways to maximize resource efficiency from husk.

3) Rice Bran

Rice bran, comprising the outer pericarp layer removed during polishing, contains 15–20% oil, 12–16% protein, dietary fiber, tocopherols, oryzanols, and phytosterols (Yadav et al., 2024). It represents one of the most nutritionally dense agri-food by-products, with applications in functional foods, nutraceuticals, cosmetics, and biodiesel production (Ratu et al., 2023; Del Rio Osorio et al., 2021). Stabilization technology (heat treatment to deactivate lipase enzymes) is critical for extending bran shelf life before downstream processing (Amran et al., 2021)

4) Other Rice Residues

Additional rice processing residues include broken rice (food ingredient, starch), rice flour (gluten-free food product), and wash water (wastewater treatment for biogas and nutrient recovery). Yafetto et al. (2023) demonstrated that microbial fermentation of rice agro-industrial wastes can produce high-quality animal feed, reducing feed costs and improving nutrient digestibility. Puglia et al. (2021) highlighted conversion of rice residues into biostimulants and biofertilizers as a particularly promising pathway given growing demand for sustainable crop nutrition.

Table 2. Summary of Paddy Rice Waste Streams, Composition, and Valorization Pathways

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Waste Stream	Annual Volume	Key Composition	Main Valorization Products	Reference(s)
Rice Straw	600–900 Mt/yr	Cellulose 38–42%, Hemicellulose 23–28%, Lignin 10–15%	Biochar, bioethanol, biomaterials, compost, bioplastics	Rathour et al. (2023); Mujtaba et al. (2023)
Rice Husk	120–180 Mt/yr	SiO_2 16–22%, Cellulose 28–35%, Lignin 25–30%	Silica, biochar, activated carbon, CHP energy, zeolites	Kordi et al. (2023); Blasi et al. (2023)
Rice Bran	50–80 Mt/yr	Oil 15–20%, Protein 12–16%, Fiber 7–12%, Oryzanol	Rice bran oil, nutraceuticals, biodiesel, animal feed	Yadav et al. (2024); Ratu et al. (2023)
Broken Rice	15–25 Mt/yr	Starch 75–80%, Protein 6–8%	Starch, glucose syrup, fermentation substrate, flour	Del Rio Osorio et al. (2021)
Rice Wash Water	Variable	Starch residues, suspended solids, BOD 400–1200 mg/L	Biogas (anaerobic digestion), nutrient recovery	Bhatia et al. (2023)

***Source**: Compiled from literature review (2021–2025).*

While Table 2. breaks down the specific volumes and chemical compositions of each byproduct, Figure 3. synthesizes this data into a visual circular economy framework, illustrating how a sustainable rice farm can successfully recirculate these waste streams.

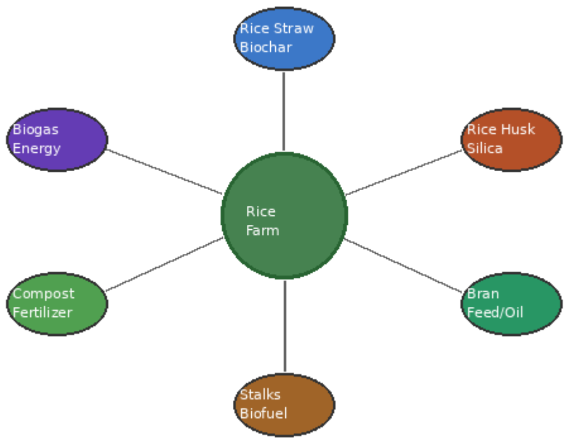

Figure 3. Circular economy framework for paddy rice agricultural waste valorization, illustrating the interconnected conversion pathways from the farm to value-added products.

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c. Technological Innovations In Rice Waste Valorization

Rapid advances across bioprocessing, thermochemical conversion, and nanomaterials science have broadened the spectrum of feasible valorization pathways for rice agricultural residues. Bala et al. (2023) reviewed micro- and nano-formulations derived from agro-waste and highlighted rice husk–derived silica nanoparticles as multifunctional products with antimicrobial activity, utility in targeted drug delivery, and applications in crop protection, features that point to clear commercial opportunities beyond traditional low-value uses. Comprehensive surveys of biomass conversion technologies (Gupta et al., 2022) underscore that options such as pyrolysis, gasification, torrefaction, and anaerobic digestion each offer distinct product streams and energy balances, so technology choice should be driven by local feedstock characteristics, existing energy infrastructure, and downstream market demand.

Among biological routes, solid-state fermentation (SSF) has gained attention as a low-cost, water-efficient platform for transforming rice residues into higher-value outputs including industrial enzymes, organic acids, and protein-enriched animal feed supplements (Chilakamarry et al., 2021). Because SSF more closely mirrors the natural microbial decomposition of lignocellulosic biomass and operates with substantially lower water inputs than submerged systems, it aligns well with circular-economy goals in water-scarce regions. Empirical work by Yafetto et al. (2023) found that SSF of rice husk and bran using Trichoderma and Aspergillus strains can raise crude protein content in feed ingredients by roughly 15–25%, illustrating a tangible quality gain for livestock applications.

Recent developments in encapsulation and nano-formulation further expand value capture from rice bran. Ligarda-Samanez et al. (2025) emphasize that extracting and stabilizing bioactive compounds, such as γ-oryzanol, tocopherols, and phytosterols—through advanced encapsulation techniques enables formulation of functional food ingredients and cosmeceutical actives, markedly increasing the economic returns compared with simple crude oil extraction. Together, these technological advances create integrated valorization opportunities that can convert low-value rice residues into diversified, higher-value products suited to regional markets and sustainability objectives.

d. Circular Economy In Agribusiness Supply Chains

Implementing circular economy principles in paddy rice agribusiness requires systemic transformation beyond individual farm or mill level interventions. Circular business model innovation involves redesigning value chains to recover and recirculate materials at every stage of production, processing, and distribution (Donner & Vries, 2021). Key business model archetypes identified in the literature include: (i) industrial symbiosis networks, where rice mills, bioenergy plants, and fertilizer producers exchange waste streams; (ii) product-as-a-service models for biochar and bio-inputs; and (iii) cooperative valorization clusters in which smallholder farmers collectively aggregate residues for centralized processing (Chiaraluce et al., 2021; Selvan et al., 2023).

Rodríguez-Espinosa et al. (2023) highlighted nitrogen management as a critical circular economy lever in rice farming systems, noting that recovered nitrogen from paddy wash water and bran processing effluents can satisfy 20–40% of crop fertilizer demand when properly processed. Chojnacka et al. (2022) cautioned, however, that valorization-to-fertilizer pathways face regulatory barriers in many markets, limiting uptake despite technical feasibility. Lange et al. (2021) argued that the EU bio-based circular economy provides a policy blueprint that developing agri-food economies in

Southeast Asia could adapt, particularly through public-private partnership frameworks that reduce investment risk in valorization infrastructure.

Haque et al. (2023) conducted a systematic analysis linking waste recovery strategies to agricultural sector competitiveness, finding that rice agribusiness actors who adopted CE practices reported 12–27% reductions in input costs alongside new revenue streams from residue valorization. Bhatia et al. (2023) demonstrated that carbon footprint reductions of 35–60% are achievable in rice supply chains when food waste utilization strategies are comprehensively implemented.

Table 2. Key Challenges and Opportunities for Circular Economy Implementation in Rice Agribusiness

Dimension	Challenges	Opportunities
Technology	High capital cost for biorefinery setup; lack of localized pilot plants; seasonal feedstock availability	Scalable pyrolysis and SSF technologies; nano-formulation innovations; lower-cost enzymatic hydrolysis
Market	Limited market channels for niche valorized products; price competition from fossil-based alternatives	Growing demand for bio-based materials, functional foods, and green fertilizers; export premium markets
Policy & Regulation	Regulatory gaps for bio-waste valorization; lack of incentives for CE adoption by smallholders	SDG-aligned policy frameworks; carbon credits for biochar sequestration; green procurement policies
Supply Chain	Dispersed smallholder production; logistics for residue collection and aggregation; quality inconsistency	Cooperative models for collective residue valorization; digital platforms for traceability and coordination
Environment	Soil nutrient depletion if residues fully removed; risk of pollutant concentration in recycled materials	Net GHG reductions from avoided burning; improved soil carbon and water retention via biochar application

***Source**: Synthesized from literature review.*

The integration of circular economy (CE) principles into rice agribusiness waste management offers a powerful and multifaceted pathway for sustainable transformation that extends from farm gates to value-added markets. The literature reviewed demonstrates that rice residues should not be treated merely as cost burdens or environmental nuisances to be minimized; instead, they comprise a heterogeneous resource system whose valorization potential depends on coordinated advancements in technological capability, innovative business models, and enabling institutional frameworks (Velasco-Muñoz et al., 2022; Santolini et al., 2021).

A recurring theme is the hierarchy of value embedded in different waste fractions: rice bran and its concentrated bioactive compounds stand out as the highest-value stream, rich in nutraceuticals and functional ingredients, yet these fractions remain underutilized in many developing markets because of limited processing infrastructure, weak market linkages for functional foods and cosmeceuticals, and regulatory or certification barriers that constrain value capture (Çapanoğlu et al., 2022).

Rice husk byproducts, such as silica extracted for industrial uses and biochar for soil amendment and carbon sequestration, occupy a mid-level value tier: although they typically command lower unit prices than bran extracts, their large volumes and growing industrial demand make them attractive targets for scalable valorization pathways that can deliver both environmental co-benefits and steady revenue streams (Kordi et al., 2023; Zhu et al., 2022). In contrast, rice straw represents the most abundant yet most challenging residue to valorize at scale, given its dispersed geographic generation, elevated collection and transport costs, and the need to reconcile competing applications, ranging from bioenergy feedstock to raw material for building products, each with distinct logistics and market requirements (Rathour et al., 2023; Singh & Patel, 2022).

Economic analyses in the reviewed studies indicate that CE implementation in rice agribusiness is not only technically feasible but can also be economically rational when the right enabling conditions exist. Donner et al. (2021) and Mehmood et al. (2021) collectively emphasize that market development, such as creating reliable demand channels for bran-derived functional ingredients and husk-based industrial inputs, regulatory clarity around product standards and waste-to-value streams, and financial risk-sharing mechanisms (for example, blended finance or producer cooperatives) are as important as technological breakthroughs for scaling valorization practices. Equally important are governance and equity considerations: Velenturf and Purnell (2021) argue that systemic design for CE must explicitly account for social equity and ecological boundaries, ensuring that smallholder producers in Southeast Asia and Sub-Saharan Africa are not sidelined but instead benefit from value addition without incurring disproportionate costs or environmental trade-offs.

Operationalizing these insights points to several priority actions and research directions. First, integrating digital agriculture tools, such as IoT sensors to monitor residue availability and quality, and blockchain systems to ensure traceability and build buyer confidence, can strengthen supply-chain coordination and reduce transaction costs associated with aggregating dispersed residues. Second, comprehensive life-cycle assessments of emerging valorization technologies at commercial scale are needed to compare environmental footprints, energy balances, and net climate impacts across options such as pyrolysis, SSF, and bioactive extraction.

Third, there is a pressing need to develop smallholder-appropriate processing equipment and decentralized business models that lower the capital threshold for participation; modular, mobile processing units or cooperative-owned facilities could help unlock value without imposing onerous fixed costs on individual farmers. Fourth, investment in green extraction and solvent-efficient separation methods is critical for unlocking high-value metabolites from rice bran and other byproducts in an energy- and resource-conscious manner (Amran et al., 2021). Finally, pilot programs that combine technology demonstrations with market development, policy experimentation (for example, incentives for biochar use in soil carbon programs), and inclusive finance models will be essential for demonstrating replicable pathways to scale.

In sum, the reviewed evidence frames rice agribusiness residues not as a single problem to be solved but as a portfolio of resource opportunities that require integrated solutions, technical, institutional, and economic, to realize their full sustainability potential. By aligning processing technologies with market creation, supportive policy, and smallholder-friendly business models, stakeholders can convert rice waste streams into diversified revenue lines, reduce environmental impacts, and strengthen rural livelihoods across major rice-producing regions.

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4. Conclusions and Suggestions

This review affirms that the circular economy framework offers a robust and practically viable pathway for transforming paddy rice agricultural waste from an environmental liability into a multi-stream source of economic value. Rice straw, rice husk, rice bran, and associated processing residues collectively represent a biomass resource of global significance that is currently underexploited. Thermochemical conversion, biofermentation, green extraction, and nano-formulation technologies have all demonstrated commercially promising results at pilot and early commercial scales.

The transition to circular rice agribusiness requires simultaneous action across multiple dimensions: investment in biorefinery and processing infrastructure; development of regulatory frameworks that incentivize bio-waste valorization; capacity building for smallholder farmer cooperatives; and market development for bio-based products derived from rice residues. The SDG framework, and specifically SDGs 2, 7, 9, 12, and 13, provides a relevant normative architecture for aligning these interventions (Ahmad et al., 2024).

The circular bioeconomy approach for rice agribusiness is not a future aspiration, it is a present imperative. Countries and agribusiness actors that build the institutional and technological capabilities to valorize rice waste today will be better positioned to compete in the bio-based economy of the coming decades, while simultaneously contributing to food system resilience, climate change mitigation, and rural livelihood improvement

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