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Circular Bioeconomy Pathways for High-Value Agricultural Waste Valorization: A Systematic Review

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Abstract
Agricultural intensification has increased the volume of residues and by-products generated across farming systems, while conventional disposal practices continue to create environmental burdens. This systematic literature review examines how agricultural waste is converted into higher-value products within a circular bioeconomy framework. Using a PRISMA-based approach and Scopus as the main database, the review screened the literature and synthesized 10 studies that met the final eligibility criteria. The included studies were grouped into four valorization pathways: fuels and energy carriers, biocomposites and bio-based materials, catalysts and functional carbon materials, and biomaterials produced through biotechnological processes. The evidence shows that fuel-oriented pathways, including pelletization, co-combustion, and biogas-based utilization, are the most technologically mature and currently offer the clearest route to scale. Material-based pathways, especially biocomposites and paper substitution, offer greater value addition and resource efficiency, but their industrial expansion remains constrained by processing costs and system integration. Agricultural residues also show strong potential as precursors for catalysts and functional carbon materials for environmental remediation, while fungal bioconversion offers an emerging route for producing protein-rich biomass. Across pathways, the review identifies a recurring trade-off between technological maturity, value addition, and implementation complexity. The main contribution of this review is a cross-pathway synthesis that compares agricultural waste valorization not only by product type, but also by circularity features, readiness, and evidence strength. Future research should prioritize integrated techno-economic assessment, life-cycle assessment, standardized circularity metrics, and pilot-scale validation to support large-scale implementation.

Keywords: Agricultural Waste; Bio-Based Materials; Circular Bioeconomy; Sustainable Resource Management; Waste Valorization.

Introduction

The rapid intensification of agriculture and the expansion of agro-industrial activities have substantially increased the generation of agricultural residues worldwide. In many regions, especially those with large crop and livestock sectors, residues such as rice husk, straw, bagasse, manure, and processing by-products are still managed through open burning, uncontrolled dumping, or low-efficiency disposal routes. These practices contribute to greenhouse gas emissions, air pollution, nutrient loss, and wider environmental degradation (Al-Manan et al., 2025). As residue volumes continue to grow, improving agricultural waste management is no longer only a technical issue, but also an environmental and resource-governance priority.

The circular bioeconomy offers a more productive way to frame this challenge. Within this

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perspective, agricultural waste is not treated as an end-of-life burden, but as a renewable feedstock that can re-enter production systems through conversion into fuels, materials, chemicals, and biomaterials (Hossain et al., 2025). This shift is important because it connects waste reduction with value creation. Instead of focusing only on disposal minimization, circular bioeconomy strategies seek to retain material value, reduce reliance on fossil-based inputs, and improve resource efficiency across agricultural systems.

Recent studies increasingly report promising applications of agricultural residues in bioenergy, composite materials, adsorbents, catalysts, and biotechnological products (Heredia-Martín et al., 2025; Ojo, 2023; Pandey & Sharma, 2024) However, the literature remains fragmented in three important ways. First, many studies examine only one conversion route, which limits cross-pathway comparison. Second, reported outcomes are often highly technical and product-specific, making it difficult to evaluate which pathways are more mature, more circular, or more feasible to scale. Third, claims of sustainability are often made without sufficient critical comparison of technological readiness, circularity mechanisms, and implementation barriers.

This gap is important because high-value valorization is not identical to simple recycling or low-grade energy recovery. High-value valorization refers to processes that transform agricultural residues into products with greater economic and functional value, such as engineered materials, advanced catalysts, specialty fuels, and biologically derived products (Nicastro et al., 2024; Yusuf & Ojedokun, 2024). These pathways may provide stronger returns than conventional recovery options, but they also tend to require more sophisticated processing, stronger market alignment, and better evidence of sustainability performance.

Accordingly, this review addresses the following question: How do different high-value agricultural waste valorization pathways compare in terms of performance, circularity, and implementation readiness within the circular bioeconomy? The objective is not merely to list applications, but to synthesize evidence across pathways and identify the main trade-offs that shape practical implementation.

This review makes three contributions. First, it consolidates recent evidence on four major valorization pathways. Second, it develops a comparative synthesis based on performance, circularity features, and readiness rather than on product category alone. Third, it identifies methodological and practical gaps that need to be addressed before agricultural waste valorization can be implemented more widely at scale.

Literature Review

The circular economy and the biorefinery concept are closely related, but they are not interchangeable. The circular economy provides the system-level logic: it emphasizes reducing waste, extending material use, closing loops, and regenerating natural systems. In this framework, agricultural residues are viewed as secondary resources that should be kept in productive circulation for as long as possible (McAllister, 2025). By contrast, the biorefinery concept provides the process-level logic. It focuses on how biomass can be fractionated and converted into multiple outputs, such as fuels, chemicals, materials, and energy, through physical, chemical, and biological processes (Gómez et al., 2022; Hierro-Iglesias et al., 2021).

For agricultural waste valorization, the circular economy answers why valorization matters, while the biorefinery model explains how value can be recovered from heterogeneous biomass streams. Their integration is therefore essential. A conversion pathway may be technically efficient from a biorefinery perspective, but still weak from a circular perspective if it creates high process burdens, limited reuse potential, or poor system fit. Conversely, a pathway may appear circular in principle, yet remain impractical without appropriate conversion technologies. this review uses

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three analytical dimensions:

1. Performance: the technical outcomes reported for each pathway, such as calorific value, tensile strength, degradation rate, or biomass productivity.
2. Circularity features: the extent to which the pathway supports waste diversion, reuse, substitution of virgin materials, recoverability, or closed-loop potential.
3. Implementation readiness: the degree to which the pathway shows evidence of scale-up potential, standardization, market relevance, or operational maturity.

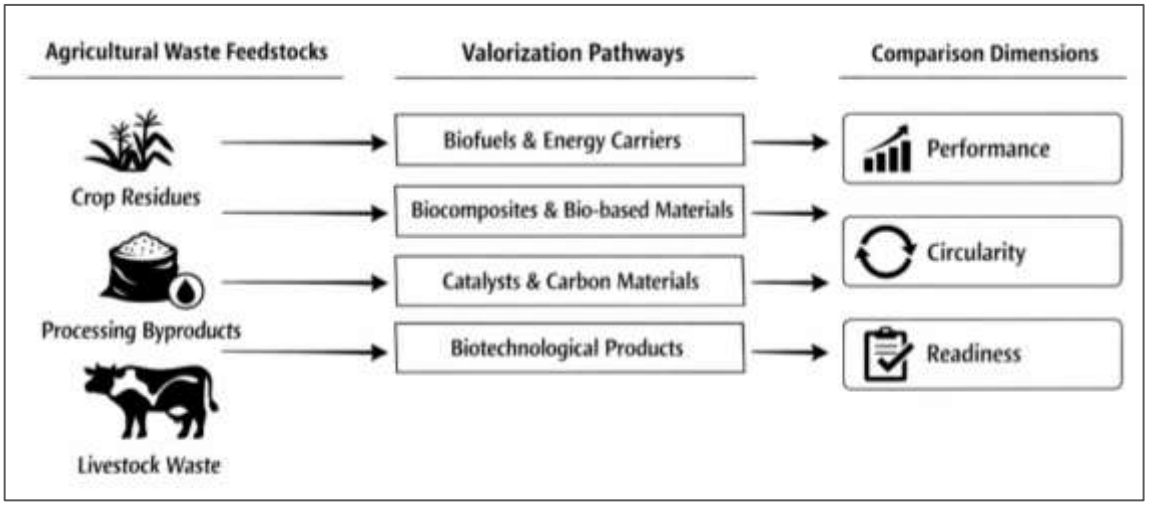


Figure 1. Conceptual framework linking agricultural waste feedstocks, valorization pathways, and comparison dimensions (performance, circularity, and readiness)

Research Method

This study used a systematic literature review (SLR) design to synthesize recent evidence on high-value agricultural waste valorization in the context of the circular bioeconomy. The review followed a PRISMA-based procedure to improve transparency, reproducibility, and consistency in study selection.

Scopus was used as the primary database because it provides broad multidisciplinary coverage across environmental science, engineering, materials science, and bioresource research. Search strings combined three concept blocks: agricultural waste feedstocks, circularity concepts, and valorization outcomes. Representative Boolean combinations included: ("agricultural waste" AND valorization), ("agricultural waste" AND "circular bioeconomy"), ("biomass waste" AND biorefinery), and ("agricultural residue" AND "high-value product"). Exclusion terms were used where necessary to reduce conceptual drift. Studies were included when they:

1. Examined agricultural waste or agro-industrial residues as the primary feedstock;
2. Reported a valorization pathway that generated energy, materials, catalysts/functional carbon materials, or biotechnological products;
3. provided empirical findings relevant to performance, circularity, or implementation; and
4. were peer-reviewed journal articles.

Studies were excluded when they focused on non-agricultural waste streams, discussed circular economy only conceptually without evidence on valorization, or lacked sufficient information on

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process outcomes.

The study selection followed the PRISMA stages of identification, screening, eligibility, and inclusión (Figure 2). Titles and abstracts were first screened for relevance, followed by full-text assessment (Table 1).

Table 1. Summary characteristics of the studies

No.	Reference	Pathway	Feedstock	Main product/ output	Evidence type	Readiness indication
1	Ali et al. (2025)	Fuel and energy	Crop residues and manure	Energy potential and biogas/power projections	National-level estimation	Strategic/ planning level
2	Suriyakumar et al. (2025)	Fuel and energy	Rice husk and de-oiled cashew nut shell cake	Pellets	Experimental optimization	Market-relevant standardization
3	Liu et al. (2025)	Fuel and energy	Bamboo scraps with sewage sludge	Co-combustion system	Laboratory combustion analysis	Process optimization stage
4	Toptaş & Toptaş (2025)	Fuel and energy	Apricot residues	Specialty solid fuel	Proof of concept	Early-stage application
5	Vinodh et al. (2025)	Biocomposites	Oil cake filler and natural fibers	Hybrid biocomposite	Laboratory material test	Prototype-level potential
6	Sustainable paper production study	Bio-based materials	Rice straw	Paper pulp substitution	Supply-chain optimization	Industrial relevance indicated
7	Li et al. (2025)	Catalyst/ functional material	Lignin nanoparticles from residues	Magnetic catalytic nanocomposite	Laboratory catalytic test	Promising but cost-sensitive
8	Chen et al. (2025)	Catalyst/ functional material	Spent mushroom substrate	Fe-doped biomass carbon catalyst	Laboratory degradation study	Scale-up claimed, not demonstrated
9	Feng et al. (2025)	Catalyst/ functional material	Wood flour-derived biochar	g-C3N4-based photocatalyst	Laboratory removal study	Early-stage validation
10	Sumarriva-Bustinza et al. (2025)	Biotechnological product	Sugarcane bagasse, tomato pomace	Protein-rich fungal biomass	Biological conversion study	Emerging pathway

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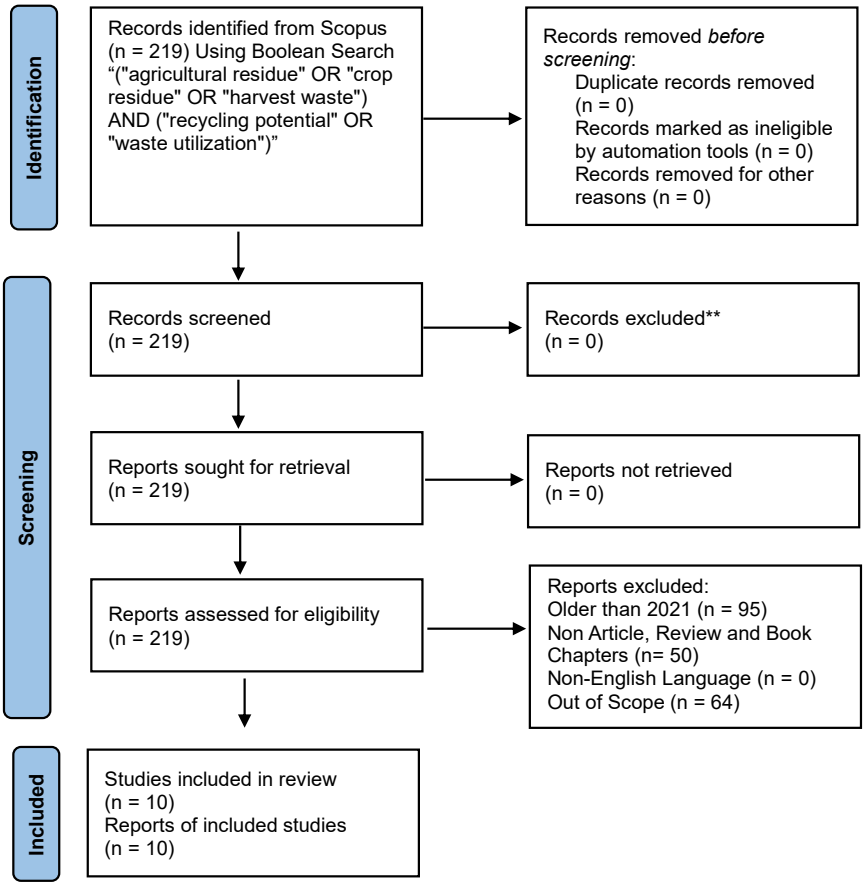


Figure 2. The PRISMA flow diagram detailing the screening and selection process of literature.

Results

Fuels and Energy Carriers

Fuel and energy pathways remain the most mature valorization route in the reviewed literature. Their main strength lies in handling relatively large residue volumes while using process metrics that are already familiar to industry and policy. Ali et al. (2025) estimated substantial national bioenergy potential from crop residues and animal manure, showing that agricultural waste can contribute directly to renewable energy planning. Suriyakumar et al. (2025) also demonstrated that rice husk and de-oiled cashew nut shell cake can be converted into ISO-aligned pellets with good density, durability, and calorific value. These findings indicate that energy pathways already have a clearer route to practical deployment than most higher-value alternatives.

However, technological maturity should not be confused with comprehensive superiority. Fuel pathways often maximize waste diversion, but they do not always maximize value addition. For example, the use of apricot residues for specialty fuel (Toptaş & Toptaş, 2025) shows that energy-related valorization can move beyond conventional combustion products, yet most energy routes still direct biomass toward one-time conversion rather than longer material retention. Similarly, co-combustion studies reveal important operational concerns such as no emissions, ash behavior, and slagging risk, which complicate claims of simple sustainability.

From a circularity perspective, energy pathways perform well in residue utilization and fossil fuel substitution, but less strongly in reuse, recoverability, and long-loop material retention. Their main comparative advantage is therefore readiness, not necessarily highest value creation.

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Biocomposites and Bio-based Materials from Agricultural Waste

Biocomposites and bio-based materials represent a stronger form of value addition because agricultural residues are used as functional inputs rather than simply as combustible biomass. Vinodh et al. (2025) reported that agricultural-waste-derived filler and natural fibers improved tensile, bending, and impact performance in hybrid composites. The rice straw paper substitution study also showed strong economic relevance by reducing total supply-chain cost while lowering dependence on virgin wood pulp.

Compared with fuel pathways, this category provides stronger support for material substitution and resource efficiency. The circularity logic is also stronger because residues remain embedded in products with a longer useful life. This makes biocomposites and paper substitutes especially relevant for sectors seeking lower-carbon alternatives to conventional materials.

Even so, the evidence base remains limited. Most studies focus on laboratory-scale material performance or optimization models rather than full industrial deployment. End-of-life behavior, recyclability under real conditions, and long-term market fit are often not reported. As a result, this pathway appears high in value addition but moderate in readiness.

Catalysts, Adsorbents, and Functional Carbon Materials from Agricultural Waste

This pathway reflects one of the clearest examples of high-value valorization. Agricultural residues were transformed into advanced materials with catalytic and remediation functions, including lignin-based magnetic nanocomposites, Fe-doped biomass carbon catalysts, and biochar-modified photocatalytic composites (Chen et al., 2025; Feng et al., 2025; Liu et al., 2021). Reported outcomes, such as high degradation rates and strong pollutant removal efficiency, show that agricultural waste can serve as a precursor for technically sophisticated products.

The main strength of this pathway is functional upgrading. Instead of replacing only low-value bulk inputs, these materials can perform specialized environmental functions, especially in wastewater treatment. In circularity terms, recoverability and repeated use are particularly important here. For instance, magnetic separation in the lignin-based nanocomposite supports post-use recovery.

Nevertheless, this pathway is also the most vulnerable to overstatement. High catalytic performance alone does not guarantee circular or scalable implementation. Several studies provide limited evidence on regeneration cycles, production cost, noble-metal dependence, energy requirements, or industrial stability. Therefore, this pathway currently ranks very high in value addition, but low to moderate in implementation readiness.

Biomaterials and Bioproducts via Biotechnological Pathways

The reviewed biotechnological pathway uses microbial or fungal metabolism to convert agricultural residues into value-added products under relatively mild process conditions. (Sumarriva-Bustinza et al. (2025) showed that sugarcane bagasse and tomato pomace can support the production of high-protein fungal biomass. This route is attractive because it can connect waste valorization with food, feed, or bio-based product systems.

Its circularity potential is conceptually strong. It can reduce residue disposal, diversify biomass use, and reconnect agricultural by-products to local production loops. However, the empirical evidence remains early-stage. Quantitative yield data, cost performance, regulatory readiness, consumer acceptance, and scale-up behavior are still underdeveloped in the reviewed study. Thus, this pathway should be treated as promising but emerging, rather than already comparable to more mature energy pathways.

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Discussion

A key finding of this review is that no single pathway dominates across all evaluation dimensions. Instead, each pathway offers a different balance between performance, circularity, and readiness (Table 2).

Table 2. Comparative synthesis across valorization pathways

Pathway	Main strength	Main limitation	Circularity contribution	Overall readiness
Fuels and energy carriers	Handles large residue volumes; strongest current scalability	Lower value retention; emissions and ash issues remain	Strong waste diversion and fossil substitution	High
Biocomposites and bio-based materials	Stronger value addition and material substitution	Limited end-of-life and industrial data	Moderate to strong, especially for longer product life	Moderate
Catalysts and functional carbon materials	Highest functional upgrading and remediation value	Cost, regeneration, and scale-up uncertainty	Strong when recoverability is demonstrated	Low to moderate
Biotechnological products	Mild-process conversion into bio-based outputs	Early evidence base and regulatory uncertainty	Potentially strong local loop closure	Low

Based on the current evidence, fuel and energy pathways are the most effective in comprehensive practical terms, because they combine technological maturity, large-scale residue handling, and clearer deployment potential. However, biocomposites and functional materials appear more effective in value-creation terms, because they retain biomass in products with higher functional and economic value. This distinction is important. The best pathway depends on whether the objective is bulk waste management, renewable energy supply, material substitution, or specialized product generation.

Conclusion

This systematic review shows that agricultural waste valorization is an important route for advancing the circular bioeconomy, but its pathways differ substantially in maturity, value creation, and implementation demands. The final synthesis of 10 studies indicates that fuel and energy pathways are the most mature and scalable options for immediate application, especially where large-volume residue management is a priority. By contrast, biocomposites, catalysts, functional carbon materials, and fungal bioproducts offer stronger value upgrading, but they remain more constrained by cost, process complexity, and limited industrial validation.

The main scientific insight is that agricultural waste valorization should not be framed as a single best solution. It should be understood as a portfolio of context-dependent pathways with different strengths and trade-offs. Future research should therefore focus on integrated TEA-LCA analysis, pathway comparison using more standardized circularity indicators, pilot-scale demonstration, and clearer assessment of end-of-life and market feasibility. These steps are necessary if high-

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value agricultural waste valorization is to move from promising experimental outcomes to broader real-world adoption.

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