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Circular Bioeconomy Pathways for Converting Agricultural Residues into Value

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Abstract

Agricultural production generates large quantities of straw, husks, stalks, shells, leaves, bagasse, pruning residues, processing by-products, and other biomass that frequently remains underutilized despite retaining substantial carbon, nutrients, fibers, polymers, and biologically active compounds. Conventional practices such as uncontrolled burning, dumping, or low-efficiency disposal convert potentially valuable biological resources into environmental liabilities. Circular bioeconomy thinking offers an alternative in which agricultural residues are progressively recovered, transformed, reused, and returned to productive systems through material, biochemical, agronomic, and energy pathways. The present conceptual review examines how agricultural residues can be converted into value through an integrated hierarchy that includes direct agricultural reuse, compost and organic fertilizer production, anaerobic digestion, biochar, biofuels, biochemicals, biodegradable polymers, fiber-based materials, nanomaterials, and integrated biorefineries. The analysis emphasizes that residue valorization should not be reduced to a single waste-to-energy strategy. Instead, feedstock composition, moisture, spatial availability, nutrient content, cellulose and lignin fractions, processing requirements, transportation distance, market demand, environmental performance, and local infrastructure should determine the most appropriate pathway. Published research indicates that biochemical and thermochemical routes can produce biogas, bioethanol, bio-oil, syngas, biochar, fertilizers, chemical intermediates, packaging materials, and advanced functional products from agricultural biomass.

Integrated systems can further improve resource efficiency by converting secondary streams such as digestate and pyrolysis by-products into additional products. However, technological feasibility alone does not guarantee circularity. Economic viability, collection logistics, competing uses of residues, soil-carbon requirements, farmer incentives, product standards, life-cycle performance, and equitable distribution of benefits remain central concerns. The study proposes a value-cascade perspective in which higher-value material and biochemical uses are considered alongside nutrient recycling and energy recovery rather than treating all biomass as a uniform fuel resource. Such an approach can reduce open burning, create decentralized rural enterprises, substitute selected fossil-derived products, recycle nutrients, and strengthen more resource-efficient agricultural systems. Future development should prioritize locally appropriate integrated biorefineries, transparent sustainability assessment, decentralized processing, reliable residue markets, and policies that recognize both the economic value and ecological functions of agricultural biomass.

Keywords: Circular bioeconomy; agricultural residues; biomass valorization; biorefinery; biochar; biogas; bio-based materials; resource recovery; agricultural waste; sustainable agriculture

1. Introduction

Agricultural systems are designed principally to produce food, feed, fiber, industrial crops, and other marketable commodities, yet the harvest and processing of these products inevitably generate large volumes of residual biomass. Straw from cereal cultivation, rice husks, maize cobs, sugarcane bagasse, cotton stalks, fruit peels, nut shells, oilseed residues, pruning biomass, cassava stems, vegetable processing residues, and similar materials contain considerable biological and chemical value even after the primary agricultural product has been removed. Their designation as "waste" therefore reflects the absence of a productive use or viable market more than an absence of intrinsic value.

The scale of the resource is substantial. Recent literature estimates global agricultural residue generation at more than 5.5 billion tonnes annually, although estimates vary according to residue definitions and calculation methods. At the same time, the Food and Agriculture Organization reports that approximately 450 million tonnes of crop residues are burned globally each year. These quantities indicate that agricultural residues represent not merely a waste-management problem but a potentially significant renewable feedstock base.

The urgency of developing alternative uses becomes clearer when residue burning is examined. FAO notes that open burning contributes to seasonal air pollution and causes losses of nutrients and organic matter that might otherwise remain within agricultural systems. For rice straw specifically, burning one tonne can result in losses of nitrogen, phosphorus, potassium, and sulfur, in addition to adverse effects on soil and air quality. The environmental consequences therefore extend beyond visible smoke. They include the removal of biologically useful nutrients, the release of greenhouse gases and particulates, and the destruction of a potential raw material for other industries.

Circular bioeconomy approaches challenge the assumption that the economic life of biomass ends when the principal crop is harvested. Khanna and colleagues describe circular bioeconomy development as a transition away from linear "take-make-waste" patterns toward systems that reduce, recycle, recover, reuse, and regenerate biological resources while replacing selected fossil-based products with bio-based alternatives. They also emphasize that circularity requires an economic and social perspective rather than a purely technological one. This distinction is important because a technically successful conversion pathway may still be unsuitable if residue collection is too costly, if farmers lose essential soil cover, if the final product lacks a market, or if environmental benefits are smaller than the burdens introduced by processing.

The circular treatment of agricultural residues should therefore begin by recognizing biomass as a heterogeneous resource. Agricultural residues differ substantially in moisture content, ash, lignin, cellulose, hemicellulose, starch, protein, oils, minerals, extractives, and degradability. Cardona Alzate and colleagues demonstrated this principle through regional biomass characterization in Colombia, showing that different feedstocks were better suited to thermochemical conversion, anaerobic digestion, or higher-value biorefinery applications depending on their properties. A uniform waste-management technology applied to every residue would consequently ignore important biochemical and economic differences.

This study examines the major pathways through which agricultural residues can be converted into value while remaining consistent with circular bioeconomy principles. The central argument is that residue valorization should follow a cascading logic. Biomass fractions capable of generating relatively high-value compounds, fibers, polymers, or functional materials should not automatically be directed toward low-value combustion. Nutrients and organic carbon that provide significant agronomic benefit should not necessarily be removed from soil systems merely because an energy market exists. Conversely, highly dispersed, contaminated, degraded, or low-value fractions may be more appropriately converted into energy or stabilized through biological and thermochemical processes.

The resulting question is not whether agricultural residues can be valorized, because numerous technologies already demonstrate that they can. The more important question is how a portfolio of conversion routes can be selected and integrated so that economic value, resource efficiency, soil health, renewable energy, environmental protection, and rural development are considered simultaneously.

2. Literature Review and Research Basis

The conceptual foundations of agricultural-residue valorization have expanded considerably with the development of biorefinery science. Awasthi and colleagues presented agricultural-waste biorefineries as an important route toward circular bioeconomy development because biological residues can support multiple products rather than a single final output. Their analysis identified both technological potential and the challenges associated with establishing economically viable biorefineries capable of using agricultural wastes as renewable resources.

This multi-product concept differs from conventional waste treatment. Traditional waste management usually attempts to reduce the quantity or environmental hazard of a residue. Biorefinery thinking instead asks which components of the biomass can be separated and converted into products of different economic value. Cellulose can provide fermentable sugars, fibers, nanocellulose, and polymer precursors. Hemicellulose can generate sugars and chemical intermediates. Lignin can contribute to fuels, carbon materials, adhesives, and aromatic compounds. Starch-rich and sugar-rich residues can support fermentation, while nutrient-rich wet residues may be suited to anaerobic digestion or fertilizer production.

Polipalli and colleagues reviewed chemical and biochemical pathways for agricultural-residue value addition and showed that pyrolysis, gasification, combustion, transesterification, digestion, fermentation, composting, and enzymatic processing can convert residues into biochar, syngas, bio-oil, biodiesel, biogas, biofuels, and soil amendments. Their analysis emphasizes that integrating these pathways through biorefineries can increase resource utilization rather than treating individual conversion technologies as isolated solutions.

Anaerobic digestion provides one of the most established biological pathways. Alengebawy and colleagues describe anaerobic digestion as a process capable of simultaneously managing organic agricultural waste and producing renewable biogas. Digestate remaining after digestion retains nutrients and organic constituents and may potentially be used as a soil amendment when its quality and application are properly managed. This dual-product relationship illustrates an important characteristic of circular systems: the residue from one process can become a useful input to another.

Thermochemical conversion has particular importance for lignocellulosic residues that have relatively low moisture and appropriate fuel characteristics. Pyrolysis converts biomass under restricted oxygen conditions into solid, liquid, and gaseous fractions. The relative proportions depend on temperature, heating rate, reactor configuration, residence time, and biomass characteristics. Biochar is among the most widely discussed outputs because it can function as a carbon-rich material with potential applications in soil management, pollutant adsorption, carbon storage, and advanced materials.

The value of thermochemical processing, however, depends strongly on feedstock characteristics. Cardona Alzate and colleagues found that rice husks, corn cobs, and cassava stems in their regional case study showed differing suitability for thermochemical upgrading because moisture content, fuel ratio, ash, and chemical composition altered process performance. This evidence reinforces the need for feedstock-specific pathway selection.

Material valorization offers another major development. Sanoja-López and colleagues reviewed the conversion of agricultural residues into high-value nanomaterials, including carbonaceous materials, polymers, silica-based materials, and other advanced structures for applications extending from agriculture to water treatment and medicine. The economic logic of these pathways differs considerably from producing heat or electricity because smaller quantities of highly processed biomass may generate substantially greater value per unit mass.

Similar developments are occurring in packaging. Plant-derived agricultural wastes contain cellulose, starch, pectin, lignin, and related biopolymers that can contribute to biodegradable films, composites, coatings, and functional food-packaging systems. Recent literature describes the use of agricultural and agro-industrial residues as sources for biodegradable materials intended to reduce reliance on conventional fossil-derived packaging.

These emerging applications support a broader concept of resource cascading. Under cascading use, biomass is retained at its highest feasible functional value for as long as practical before lower-value recovery occurs. A clean cellulose-rich fraction might first be converted into fibers or advanced materials. Residues that remain after extraction could then undergo fermentation or digestion. Secondary solids might subsequently be pyrolyzed. Nutrients and stable carbon could eventually return to agricultural soils. Such sequential use can potentially extract more economic and functional value from one unit of biomass than immediate combustion.

Table 1: Major Agricultural-Residue Valorization Pathways

Residue Characteristic	Appropriate Conversion Route	Principal Products	Circular Value Potential
Wet, readily biodegradable biomass	Anaerobic digestion	Biogas, biomethane, digestate	Energy recovery with nutrient recycling
Dry lignocellulosic residues	Pyrolysis	Biochar, bio-oil, combustible gases	Carbon products, soil amendment and energy
Sugar- or starch-rich	Fermentation	Bioethanol, organic acids	Substitution of selected

Residue Characteristic	Appropriate Conversion Route	Principal Products	Circular Value Potential
residues		and biochemical intermediates	fossil-derived chemicals and fuels
Cellulose-rich residues	Fiber extraction and fractionation	Pulp, cellulose, nanocellulose and composites	High-value material recovery
Nutrient-rich plant residues	Composting or controlled biological conversion	Compost, organic fertilizer and soil conditioners	Nutrient and organic-matter return
Suitable fibrous biomass	Composite and packaging processing	Boards, molded products and biodegradable packaging	Material substitution and prolonged biomass use
Selected mineral-rich residues	Advanced extraction or thermal treatment	Silica and functional mineral products	High-value specialty applications
Mixed secondary processing residues	Integrated biorefinery	Multiple material, chemical, energy and soil products	Maximum cascading resource recovery

The literature nevertheless warns against assuming that all residue removal is environmentally desirable. Some crop residues protect soil from erosion, return carbon and nutrients, conserve moisture, and support soil biological processes. FAO's work on rice-straw valorization in Punjab therefore modeled commercial mobilization using only a proportion of available residues rather than assuming that all straw should be removed from fields. This demonstrates the need to determine sustainable removable quantities rather than simply maximizing industrial collection.

Economic considerations are equally important. Khanna and colleagues argue that a sustainable circular bioeconomy must consider costs, benefits, environmental externalities, distributional consequences, technology, regulation, and equity. Small farmers cannot be expected to bear disproportionate collection, certification, or technology costs in order to provide inexpensive feedstock to downstream industries. Circular value creation therefore depends on how benefits are distributed through the supply chain.

3. Research Gap, Objectives and Method

Existing research provides extensive information on individual technologies, but three gaps remain particularly important. First, many studies evaluate one conversion process without adequately considering whether another pathway could preserve greater economic or functional value. Second, agricultural-residue management is often assessed primarily from the perspective of disposal or energy recovery even though biomass can also generate chemicals, materials, fertilizers, carbon products, and specialized functional compounds. Third, technically efficient systems may perform poorly when collection costs, seasonal availability, soil-residue requirements, fragmented farm holdings, weak markets, or inadequate policy incentives are considered.

The present study therefore develops a conceptual pathway framework rather than claiming new experimental performance data. The objective is to identify how different residue characteristics can be matched with conversion routes while maintaining a circular hierarchy of value retention. A second objective is to examine how biochemical, thermochemical, agronomic, and material pathways can be integrated. A third objective is to identify the conditions under which residue conversion can create genuine environmental and rural-economic value rather than merely shifting environmental burdens from one stage of the system to another.

The research uses a structured conceptual review. It is not presented as a PRISMA systematic review or meta-analysis. Peer-reviewed literature and institutional evidence relevant to circular bioeconomy, agricultural-residue valorization, biorefinery development, anaerobic digestion, pyrolysis, biochar, materials recovery, and economic circularity were examined, with greater emphasis on recent work published between 2022 and 2026 while retaining important conceptual studies where required. Targeted scholarly searches used combinations of terms including “agricultural residues,” “circular bioeconomy,” “agricultural waste valorization,” “biorefinery,” “biochar,” “anaerobic digestion,” “pyrolysis,” “bio-based materials,” and “value-added products.” Studies were considered especially relevant when they described a defined residue stream, conversion technology, final product, sustainability implication, or economic pathway.

The analytical synthesis categorized pathways according to feedstock condition, conversion mechanism, product class, expected value retention, nutrient recovery, and applicability within an integrated circular system. No numerical process-performance dataset was manufactured for this paper. Where quantitative values are reported, they originate from the referenced sources.

Table 2: Proposed Five-Item Stakeholder Questionnaire for Future Validation

No.	Proposed Question
1	Which agricultural residue generated in your area currently has the lowest economic value or highest disposal difficulty?
2	What is the main constraint preventing farmers from selling or processing agricultural residues instead of burning or discarding them?
3	Which residue-derived product would have the strongest local market demand: fertilizer, fuel, animal-use product, construction material, packaging material, or industrial raw material?
4	How important are transportation distance and storage cost when deciding whether agricultural residues can be commercially recovered?
5	Would farmers supply residues consistently if a transparent purchasing system provided additional income while preserving sufficient biomass for soil health?

4. Circular Bioeconomy Pathways for Residue Conversion

The simplest circular pathway is direct agricultural reuse. Not every residue requires industrial processing. Crop residues can provide mulch, soil cover, organic amendments, bedding materials, animal feed components, or composting feedstock when agronomically and hygienically appropriate. Direct use may preserve more value than industrial conversion when processing would require substantial transport, drying, chemical inputs, or energy.

Composting is especially relevant for heterogeneous residues that can be biologically stabilized and returned to soils. Through controlled decomposition, readily degradable organic matter becomes a more stable material capable of supplying organic carbon and nutrients. The circular benefit arises from returning biological resources to the production system rather than permanently removing nutrients from agriculture. Composting does not normally generate the highest financial value per unit mass, but its relatively modest technological requirements can make it suitable for decentralized or community-scale applications.

Anaerobic digestion is more appropriate when residues have significant biodegradable organic fractions and sufficient moisture. The process produces a methane-containing gas that can be used for heat, electricity, upgraded biomethane, or other energy applications. The remaining digestate retains nutrients and may be recycled into agriculture when quality standards and nutrient-management requirements are satisfied. Alengebawy and colleagues emphasize that digestate can contain nitrogen, phosphorus, potassium, micronutrients, organic material, and microbial biomass, although its composition varies substantially with feedstock and process conditions.

A circular digestion system therefore seeks value from both energy and nutrient streams. Treating digestate as an unwanted by-product would weaken the circularity of the process. Conversely, poorly controlled land application could create nutrient losses or environmental contamination. The value of digestate depends on characterization, storage, transportation, agronomic demand, contamination control, and application rates.

Pyrolysis provides a contrasting pathway for relatively dry biomass. The process thermally decomposes biomass under limited oxygen and generates biochar, condensable liquids, and combustible gases. Biochar is especially interesting because its properties can be adjusted through feedstock selection and process conditions. Depending on quality and intended use, it can contribute to soil management, adsorption, filtration, carbon materials, or other applications.

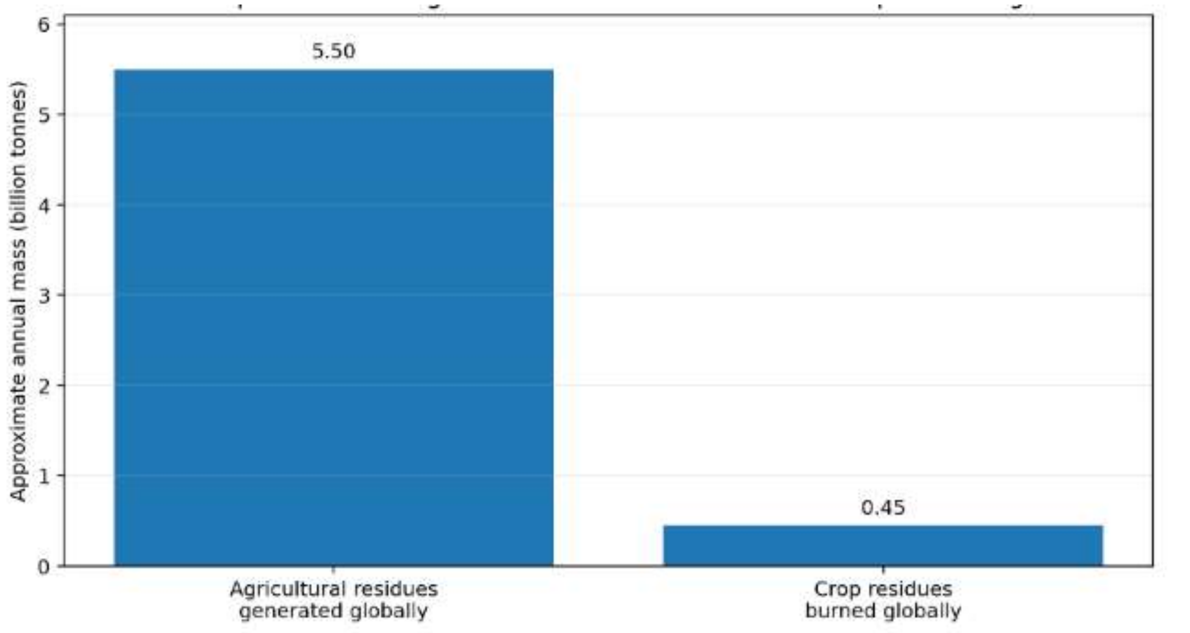
Integrated anaerobic digestion and pyrolysis demonstrates the potential for cascading. Singh and colleagues discuss systems in which digestate undergoes pyrolysis and generated biochar is reused for process stabilization, gas purification, or soil application. Such configurations aim to increase carbon and nutrient utilization while obtaining energy from multiple fractions.

Fermentation creates another pathway for carbohydrates contained in agricultural residues. Lignocellulosic biomass is structurally resistant because cellulose and hemicellulose are protected by lignin and complex plant architecture. Pretreatment and enzymatic hydrolysis can release fermentable sugars, which may then support the production of ethanol, organic acids, solvents, enzymes, or other biochemical products. The economic feasibility depends heavily on pretreatment cost, inhibitor formation, enzyme efficiency, sugar yield, product recovery, and the market value of co-products.

A major strength of biorefineries is their ability to avoid dependence on one product. A facility producing only low-value fuel may face greater vulnerability to energy prices than one capable of recovering high-value chemicals before converting remaining fractions to energy. Awasthi and colleagues therefore emphasize integrated agricultural-waste biorefineries as a mechanism for improving resource efficiency and economic sustainability.

Material pathways can further increase value retention. Fibrous residues can be converted into particleboards, molded products, composite reinforcement, cellulose-based films, packaging, pulp, or functional fibers. Agro-residue-derived materials can potentially substitute a fraction of virgin wood, petroleum-based polymers, or mineral-intensive products, although environmental advantages must be confirmed through life-cycle assessment rather than assumed.

Graph 1: Scale of Agricultural Residue Generation and Open Burning



Source: Author-prepared graph using an estimate of more than 5.5 billion tonnes of annual agricultural residues reported in the recent review literature and approximately 450 million tonnes of annually burned crop residues reported by FAO. The open-burning quantity is a subset of total residues, and the two estimates originate from different sources and methodological bases.

The graph demonstrates the scale of the potential resource base rather than suggesting that all generated biomass is available for industrial extraction. A substantial portion has existing functions, including animal feeding, soil cover, household fuel, bedding, informal markets, and nutrient cycling. Sustainable residue availability is therefore lower than gross residue generation.

This distinction is central to circular bioeconomy design. Excessive removal of crop residues from fields may reduce organic-carbon return and increase erosion or moisture loss in some production systems. FAO's Punjab rice-straw assessment explicitly recognized this trade-off by modeling industrial mobilization of only a portion of available residues. Circularity should consequently maximize useful value from sustainably available residues rather than maximize biomass extraction itself.

5. Results and Discussion

The conceptual synthesis indicates that no universal "best technology" exists for agricultural-residue valorization. The strongest pathway depends on the interaction among biomass characteristics, location, existing uses, product markets, infrastructure, environmental objectives, and scale.

High-moisture residues generally favor biological conversion because drying may consume substantial energy. Dry lignocellulosic residues can be attractive for pyrolysis or material processing. Relatively pure cellulose-rich streams may justify fractionation into higher-value products, while contaminated or highly heterogeneous residues may be better suited to energy or stabilization processes. Cardona Alzate and colleagues reached a similar conclusion in their regional case analysis, where different biomass types were assigned to thermochemical, digestion, or biorefinery pathways according to their composition and processing characteristics.

A second result is that circular value increases when multiple products are considered together. Single-output conversion leaves economic value vulnerable to one market and may discard useful secondary fractions. Integrated biorefineries can distribute value across materials, chemicals, energy, carbon products, and nutrients. This is consistent with the agricultural-waste biorefinery framework presented by Awasthi and colleagues and with integrated digestion-pyrolysis strategies discussed by Singh and colleagues.

A third result concerns the distinction between economic value and circular value. The product with the highest market price is not automatically the most sustainable pathway. Processing a residue into a specialized chemical could require large quantities of solvents, energy, water, and purification infrastructure. Similarly, transporting low-density straw hundreds of kilometers may reduce environmental and economic benefits. Life-cycle and techno-economic evaluation should therefore accompany product selection.

Khanna and colleagues' economic analysis is especially relevant here because they caution against treating maximum circularity as an end in itself. Circular systems require comparison of social costs, environmental benefits, market incentives, equity effects, and technological costs. In practice, some residue may appropriately remain in fields, some may enter local feed or compost markets, some may supply decentralized bioenergy systems, and selected high-quality fractions may enter industrial biorefineries.

Decentralization is likely to be important for bulky agricultural biomass. Residues are frequently seasonal, spatially dispersed, low in bulk density, and expensive to transport relative to their initial value. Local preprocessing through baling, pelletization, drying, ensiling, briquetting, size reduction, extraction, or community-scale digestion can reduce logistical constraints before downstream processing.

The FAO rice-straw case in Punjab illustrates how logistics can determine the viability of otherwise technically useful residues. Farmers face narrow periods between rice harvest and subsequent wheat planting, while collection and storage infrastructure strongly influence whether straw can reach commercial markets. This means that residue burning cannot be addressed simply by identifying an alternative product. The entire collection and value chain must function within agricultural time constraints.

Farmer participation should therefore be treated as part of biorefinery design. Residue supply depends on whether farmers receive sufficient economic value, whether collection interferes with planting, whether soil requirements are respected, and whether payment mechanisms are reliable. A circular bioeconomy that creates profitable downstream companies while transferring collection costs to farmers would struggle to maintain a stable feedstock supply.

Local ownership models may improve these incentives. Cooperatives, farmer producer organizations, rural enterprises, municipalities, and small processing companies could potentially aggregate biomass and retain a larger portion of value within agricultural regions. Instead of exporting untreated straw as a low-value feedstock, regions could perform initial processing and sell densified fuel, compost, biochar, fibers, extracts, or other intermediate products.

Policy instruments also influence pathway choice. Subsidies focused entirely on one end product can distort residue markets. If energy subsidies make combustion artificially more profitable than material recovery or soil recycling, biomass that could support higher-value circular uses may be diverted prematurely to power generation. Policy should therefore remain sufficiently technology-neutral to encourage solutions based on verified environmental and economic performance.

Standards are equally important. Biochar, digestate, compost, packaging materials, fuels, and biochemicals all require reliable specifications if they are to obtain market confidence. Farmers will hesitate to purchase residue-derived fertilizers when nutrient content and contamination are uncertain. Food companies cannot adopt residue-derived packaging without safety and performance evidence. Industrial customers require predictable composition and quality.

Digital systems may further strengthen circular biomass markets by linking residue suppliers, collectors, processors, and buyers. Geographic information, harvest forecasting, biomass-quality data, traceability, storage availability, and transport optimization can reduce uncertainty. Khanna and colleagues identify emerging digital technologies as potentially important for benchmarking and demonstrating sustainability performance within circular systems.

Environmental assessment must remain central. Avoided burning can provide major benefits, but residue conversion can also generate emissions through transport, electricity consumption, thermal processing, chemicals, wastewater, and drying. Carbon accounting should consider counterfactual use: what would have happened to the residue without the project? If straw would otherwise have remained as soil cover, its removal has different implications than if it would otherwise have been burned.

Nutrient accounting is similarly necessary. Agricultural residues contain nitrogen, phosphorus, potassium, sulfur, and micronutrients. Exporting biomass from farms without returning nutrients can create additional fertilizer demand. Circular systems should seek routes through which digestate, compost, ash, or other safe nutrient-containing fractions return to agricultural production where agronomically justified.

This approach transforms the biorefinery from a factory that consumes agricultural waste into a component of a regional biological resource system. Inputs and outputs circulate between farms, processing plants, energy users, manufacturers, and soils. The more effectively useful carbon, nutrients, materials, and energy are retained within productive cycles, the stronger the circularity of the system.

The analysis therefore suggests four broad value levels. Direct agronomic reuse preserves ecological function with minimal processing. Biological and thermochemical pathways convert bulk residues into energy, fertilizer, and carbon products. Material and biochemical processing increase product specificity and potential economic value. Integrated biorefineries combine these levels so that remaining fractions from one process become inputs to subsequent processes.

6. Practical Implications, Challenges and Future Direction

The practical implication is that agricultural-residue policy should begin with regional biomass mapping rather than technology procurement. Policymakers and investors need reliable information on what residues exist, when they are generated, existing uses, sustainable removable quantities, moisture, composition, geographic concentration, and realistic collection costs.

A rice-growing district should not automatically receive the same conversion infrastructure as a sugarcane, horticultural, oilseed, maize, or fruit-processing region. Bagasse concentrated at a sugar mill creates a very different logistical opportunity from dispersed cereal straw collected from thousands of individual fields. Fruit-processing residues may contain higher-value biochemical fractions, while rice husks may offer opportunities related to silica and carbon materials.

Technology selection should therefore follow biomass characterization. Cardona Alzate and colleagues' approach demonstrates the value of examining chemical composition, proximate properties, moisture, and energy characteristics before selecting conversion pathways. Applying this logic more broadly can reduce the risk of constructing facilities that later struggle with unsuitable feedstock.

Future circular bioeconomy development will also require stronger links between agriculture and manufacturing. Agricultural ministries frequently view crop residues as a farm-management issue, while energy departments consider them fuels and materials industries consider them feedstocks. Circularity requires cross-sector planning because the same tonne of biomass cannot simultaneously satisfy every potential use.

Competition between uses is likely to intensify as bio-based industries grow. Residues currently available at low prices may become economically scarce once multiple plants compete for them. Future feasibility studies should therefore avoid assuming that historical residue prices remain constant under expanded demand.

Economic assessments should also incorporate seasonality. A plant operating throughout the year may require substantial storage even when biomass is harvested within a few weeks. Storage introduces land requirements, fire risk, dry-matter losses, moisture changes, handling costs, and working-capital requirements.

Smaller decentralized conversion systems can reduce transport distance but may have higher unit processing costs than centralized facilities. Larger plants benefit from economies of scale but require larger biomass catchment areas. The optimal design depends on the balance between processing economies and feedstock logistics.

Research should increasingly examine hybrid systems that combine local preprocessing with regional advanced conversion. Farmers or cooperatives could perform baling, shredding, drying, fermentation stabilization, or densification, while specialized facilities carry out biochemical extraction, polymer processing, advanced pyrolysis, or chemical refining.

High-value applications deserve further attention because they can improve the economics of biomass utilization. Nanomaterials, biopolymers, specialty chemicals, functional extracts, and advanced composites may generate more revenue from smaller feedstock volumes than bulk combustion. Sanoja-López and colleagues' review illustrates the expanding technical possibilities for converting agricultural residues into advanced nanomaterials.

Nevertheless, high-value products frequently have smaller markets. A region producing millions of tonnes of residue cannot assume that all biomass can be sold as nanocellulose or specialty chemicals. Circular bioeconomy planning therefore requires a portfolio in which limited quantities enter premium markets while larger volumes enter fertilizers, materials, fuels, soil products, or energy pathways.

Life-cycle assessment and techno-economic analysis should be conducted together. An environmentally attractive process that depends permanently on uneconomic subsidies may be difficult to sustain, while a profitable process with high emissions may fail sustainability objectives. The circular bioeconomy requires simultaneous evaluation of environmental and financial performance.

Social inclusion is another important requirement. Khanna and colleagues note that circular-economy transitions can impose disproportionate costs on smaller and lower-income producers unless access to finance, technical assistance, and equitable incentive systems is provided. Farmers should therefore be recognized not merely as residue suppliers but as participants in value creation.

The long-term opportunity is the creation of regional biological-resource ecosystems in which waste is progressively replaced by secondary raw materials. A cereal residue may supply fiber and biochemical fractions, remaining solids may enter digestion or pyrolysis, generated energy may support processing, stable carbon may return to soil, and recovered nutrients may substitute part of external fertilizer demand. The objective is not perfect circularity but progressively improved resource productivity.

7. Conclusion

Agricultural residues should no longer be viewed primarily as inconvenient material requiring rapid disposal. They constitute heterogeneous renewable resources containing carbon, nutrients, cellulose, hemicellulose, lignin, sugars, fibers, minerals, and biologically active compounds capable of supporting a wide range of circular products.

Current evidence demonstrates technically viable pathways for transforming these resources into compost, fertilizers, biogas, biomethane, biochar, bio-oil, syngas, liquid biofuels, fibers, polymers, packaging materials, chemicals, nanomaterials, and other value-added products. The most promising strategy is not universal conversion through a single technology but selective matching between residue properties and product pathways.

Integrated biorefineries provide a particularly strong conceptual model because they allow several components of the biomass to be recovered sequentially. High-value materials and biochemical compounds can potentially be extracted before lower-value fractions proceed to energy recovery, while nutrient-rich and carbon-rich outputs can return to agricultural systems.

The study also demonstrates that technological feasibility alone is insufficient. Sustainable residue removal, transportation distance, seasonality, storage, market size, soil-carbon requirements, farmer incentives, product standards, life-cycle emissions, and equitable benefit distribution determine whether residue valorization becomes genuinely circular.

The environmental case remains compelling. FAO estimates that hundreds of millions of tonnes of crop residues continue to be burned each year, even though these materials may have alternative uses. Creating economically viable residue markets can therefore simultaneously address pollution, agricultural resource efficiency, rural enterprise development, and renewable-material production.

The future of agricultural residue management should consequently shift from "waste disposal" toward "biological resource allocation." The critical question is not simply how to eliminate residues but how to retain their carbon, nutrients, materials, and economic value for as long as technically, environmentally, and economically justified. Circular bioeconomy pathways provide the framework through which this transition can occur.

8. Limitations and Future Research

The present paper is a conceptual review and does not report a laboratory experiment, field trial, commercial plant dataset, or farmer survey. The proposed questionnaire has not been administered. Quantitative performance claims for individual conversion technologies should therefore be established through independent experimental, pilot-scale, or industrial evidence.

Future research should compare competing residue pathways using consistent functional units and system boundaries. Direct soil incorporation, composting, anaerobic digestion, pyrolysis, bioethanol, biomaterials, and integrated biorefineries should be evaluated through combined life-cycle assessment, techno-economic analysis, and social-impact assessment.Greater research is also required on sustainable residue-removal rates. The quantity technically collectable from a field is not necessarily the quantity that should be removed after erosion protection, soil-carbon maintenance, nutrient cycling, moisture conservation, livestock use, and existing local markets are considered.

Regional studies should evaluate decentralized and centralized processing configurations, biomass aggregation, long-term supply contracts, farmer revenue, storage systems, and transport optimization. High-value material applications should be investigated alongside realistic estimates of market size so that potential demand is not overstated.Further research should examine integrated sequential processing. Residues could first undergo extraction of valuable compounds, followed by enzymatic processing, fermentation, digestion, pyrolysis, and safe nutrient recycling. The objective should be to determine whether cascading conversion materially improves environmental and economic performance compared with single-product technologies.

9. Declarations

Conflict of Interest: The sample author declares no conflict of interest in relation to the conceptual preparation of this manuscript.

Funding: No external funding is reported for the preparation of this conceptual review.

Ethics Statement: The manuscript does not report research involving human participants or animals. The five questionnaire items included in the methodology are proposed for future research and were not administered. Appropriate ethics approval and informed consent should be obtained before any future human-participant implementation where required.

Data Availability: No original experimental dataset was generated. The graph uses published secondary estimates identified in the cited literature and institutional source.

Author Contribution: Sample authorship information must be replaced with verified contributor information before journal submission.

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