

Review of Pilot-Scale Carbon-Negative Pulping Technologies Using Agricultural Residues: Technical, Economic, and LCA Perspectives

Shwet Vashishtha

R.P.P.T. Laboratory, National Test House, Ghaziabad, India

Email: [shwetraj\[at\]gmail.com](mailto:shwetraj[at]gmail.com)

ORCID 0009-0006-9159-7456

Abstract: *This review synthesizes findings from 28 pilot-scale studies on pulping agricultural residues, including bagasse, wheat straw, and rice straw, integrated with bioenergy recovery and carbon capture and storage (CCS). The reviewed studies indicate pulp yields typically ranging from 40-48%, carbon capture efficiencies around 85%, and the potential for low or negative greenhouse-gas emissions under favorable economic conditions. The pulp and paper industry faces increasing pressure to reduce greenhouse gas emissions while maintaining reliable fiber supply and product quality. Agricultural residues represent a promising alternative to conventional wood feedstocks and can contribute to diversification of fiber resources. When integrated with bioenergy recovery and carbon capture technologies, these systems may significantly reduce the carbon footprint of pulp production. Many previous investigations have relied primarily on laboratory experiments or modeling approaches, with limited integrated pilot-scale evidence addressing technical performance, economic feasibility, and life-cycle environmental impacts. This review compiles and analyzes pilot-scale data on pulping performance, energy balance, carbon capture efficiency, techno-economic indicators (CAPEX \$2.5-4.0 million per ktpy; OPEX \$620-750 per tonne of pulp), and life-cycle assessment results. The synthesis indicates that agricultural-residue pulping can achieve pulp quality comparable to conventional processes while offering significant opportunities for emission reduction when combined with bioenergy and CCS integration. Economic competitiveness depends strongly on residue availability, energy integration efficiency, and carbon pricing mechanisms (\$30-100 per t CO₂). Life-cycle assessments further identify transportation logistics and process energy consumption as major contributors to overall environmental impacts. Overall, the reviewed literature indicates that carbon-negative pulping based on agricultural residues is technically feasible at pilot scale and may become economically viable under favorable policy and market conditions. This synthesis provides an integrated overview of current pilot-scale evidence and highlights the potential role of agricultural residues and carbon capture technologies in advancing sustainable pulp production.*

Keywords: Agricultural residues; carbon-negative pulping; carbon capture and storage; pilot-scale pulping; techno-economic assessment; life cycle assessment; pulp and paper decarbonization

1. Introduction

1.1 Background on Decarbonization Challenges in the Pulp and Paper Industry

To achieve meaningful reductions in greenhouse gas emissions, the pulp and paper industry must move beyond incremental efficiency improvements and evaluate alternative feedstocks together with integrated decarbonization technologies [1,2]. As an energy-intensive sector, pulp and paper manufacturing relies heavily on thermal energy for pulping, drying, and chemical recovery processes, resulting in a substantial carbon footprint despite long-standing efforts to improve efficiency and increase the use of biomass-derived fuels [1,3].

Over the past several decades, the industry has made significant progress through energy optimization, process integration, and improved material efficiency [4,5]. However, many of these measures are approaching practical limits, particularly as global demand for packaging materials and paperboard products continues to grow [2]. At the same time, regulatory requirements, corporate climate commitments, and stakeholder expectations are increasingly aligned with deeper emission reductions that cannot be achieved through incremental improvements alone [6,7].

These challenges have stimulated renewed interest in integrated approaches that address both fiber sourcing and carbon emissions simultaneously [5,7]. In this context, the utilization of agricultural residues as alternative feedstocks, combined with bioenergy recovery and carbon capture technologies, has emerged as a promising pathway for advancing decarbonization while maintaining industrial feasibility [8-10].

1.2 Limitations of Conventional Wood-Based Pulping in Achieving Deep Emission Reductions

Conventional wood-based pulping systems have already captured many of the readily achievable emission reductions through process optimization, fuel switching, and improvements in chemical recovery systems. As a result, further reductions in greenhouse gas emissions are increasingly constrained by the inherent energy demands of wood pulping, particularly the high thermal requirements associated with cooking, washing, evaporation, and drying processes [1,4].

Although the use of biomass-derived fuels and black liquor recovery has reduced fossil fuel dependence in many pulp mills, residual emissions remain significant due to auxiliary fossil fuel consumption, purchased electricity, and upstream activities such as wood harvesting and transportation [1,11]. These emissions are difficult to eliminate without

introducing fundamentally different process configurations or additional mitigation technologies such as carbon capture.

In addition, reliance on forest-based feedstocks presents structural challenges for deep decarbonization. Sustainable wood supply is constrained by land availability, long forest rotation periods, and competing demands from construction materials, bioenergy production, and conservation objectives [12,13]. These factors limit the extent to which increased wood utilization alone can support both production growth and substantial emission reductions.

Together, these constraints indicate that conventional wood-based pulping, while essential to current pulp production, is unlikely to achieve deep emission reductions on its own. This limitation reinforces the need to evaluate alternative fiber resources and integrated decarbonization strategies for the pulp and paper industry.

Conventional wood-based pulping remains the dominant industrial benchmark, and the present review evaluates agricultural residues in comparison to established wood-based systems rather than as a direct replacement.

1.3 Rationale for Pilot-Scale Literature Review of Agricultural-Residue-Based Pulping

Agricultural residues such as bagasse, wheat straw, and rice straw have been widely investigated as alternative fiber sources in laboratory and bench-scale studies, demonstrating technical feasibility and favorable environmental potential [6-9]. However, translating these findings into industrial practice requires validation under operating conditions that reflect the complexity, variability, and constraints of real pulp and paper mills. Accordingly, the present study does not report new experimental work but instead provides a systematic review and meta-analysis of previously published pilot-scale studies on agricultural-residue-based pulping.

Laboratory-scale experiments often rely on controlled feedstocks, simplified process configurations, and short operating durations, which can mask challenges related to feedstock heterogeneity, continuous operation, chemical recovery, and energy integration [7,10,11]. Pilot-scale systems therefore provide an essential intermediate step by allowing process stability, pulp quality, and energy balance to be evaluated under semi-continuous conditions while retaining sufficient flexibility for process optimization.

Pilot-scale evaluation is also important for assessing economic performance. Capital and operating costs, residue handling requirements, and integration with existing mill infrastructure cannot be reliably estimated from laboratory data alone [5,12]. Moreover, pilot operation enables the collection of high-quality data necessary for robust life-cycle assessment, particularly for upstream logistics, on-site energy use, and emission sources that dominate environmental impacts at scale [12-18].

For these reasons, pilot-scale studies reported in the literature play a central role in bridging the gap between experimental research and commercial deployment, providing useful data for pulp and paper mills considering

agricultural residues as part of long-term decarbonization strategies.

1.4 Need for Integrating Technical Performance, Economics, and Life-Cycle Impacts

Evaluating alternative pulping pathways based on a single performance metric can lead to incomplete or misleading conclusions. Technical feasibility alone does not ensure industrial adoption if economic viability is weak, while cost-focused assessments may overlook environmental trade-offs that become critical under increasingly stringent sustainability requirements [12-18]. For emerging pathways such as agricultural-residue-based pulping with carbon capture, these dimensions are closely interconnected and therefore must be assessed together.

Technical performance influences both economic and environmental outcomes through factors such as pulp yield, energy efficiency, chemical consumption, and process stability. These parameters directly affect operating costs and determine the magnitude of greenhouse gas emissions across the system. Similarly, economic constraints shape feasible process configurations, influencing technology selection and the extent of integration with existing mill infrastructure [5,12].

Life cycle assessment provides a framework for evaluating upstream and downstream impacts that are not captured by process-level metrics alone, including residue collection, transportation, and indirect emissions associated with energy and chemical production [17,18]. When combined with techno-economic analysis and pilot-scale performance data reported in the literature, life cycle assessment enables a more realistic comparison with conventional wood-based pulping routes and supports informed decision-making.

Integrating technical performance, economic evaluation, and life-cycle environmental assessment is therefore essential for determining whether alternative pulping systems can deliver meaningful emission reductions while remaining practical for industrial implementation.

1.5 Objectives of the Study

This review evaluates the existing literature on the feasibility of agricultural-residue-based pulping at pilot scale under conditions representative of industrial operation. Specifically, the study aims to assess the technical performance, economic feasibility, and environmental implications of integrating agricultural-residue pulping with bioenergy recovery and carbon capture systems as reported in the literature [7-9,12]. In addition, the review seeks to identify key operational challenges, economic drivers, and enabling factors that may influence the scale-up and practical implementation of such systems in existing pulp and paper mills.

2. Materials and Methods

2.1. Literature Synthesis Methodology

This study is a systematic literature review and meta-analysis of previously published pilot-scale studies, and no new experimental work was conducted by the author. The review follows PRISMA guidelines for systematic literature synthesis. Scopus and Web of Science databases were searched using the keywords "non-wood pulping" AND "pilot scale" AND "agricultural residue" for the period 2015-2025, yielding 156 publications after removal of duplicates.

Following title and abstract screening, 78 studies were excluded, and 50 additional papers were excluded after full-text review due to lack of pilot-scale data or insufficient quantitative reporting. Ultimately, 28 pilot-scale and demonstration-scale studies were included in the final analysis.

From these studies, quantitative data were extracted on pulp yield, kappa number, viscosity, energy use, techno-economic

indicators, and life-cycle assessment (LCA) impacts, and compiled into Tables 3-5.

A meta-analysis was performed on comparable soda-pulping trials reporting at least three experimental replicates, resulting in 12 studies included in the statistical analysis. Weighted mean values and standard deviations were calculated to synthesize the reported pilot-scale performance data (Table 3).

The inclusion criteria were:

- Peer-reviewed studies reporting pilot-scale chemical pulping (≥ 10 kg/batch)
- Use of agricultural residues such as bagasse, wheat straw, or rice straw
- Availability of quantitative performance data

The exclusion criteria included:

- Laboratory-scale experiments only
- Mechanical pulping processes
- Studies involving non-target feedstocks

Typical pilot-scale pulping operating conditions reported in the literature are summarized in Table 1.

Table 1: Typical pilot-scale soda pulping conditions reported in the literature for agricultural residues (based on 12 pilot-scale studies) [7,10,11,26,27].

Parameter	Bagasse	Wheat Straw	Rice Straw	Wood (control)
Temperature (°C)	155-165	160-170	165-175	150-170
Alkali charge (% o.d. fiber)	16-20	18-22	20-24	14-18
Liquor-to-solid ratio (L:S)	4:1-5:1	4:1-5:1	5:1-6:1	4:1
Cooking time (min)	90-120	90-150	120-180	90-120
Typical equipment reported	Parr digesters (25-100 L)	Stainless-steel pilot digesters	Batch pilot digesters	Continuous/batch digesters

Conventional wood-based pulping is included as a control across all tables to enable consistent comparison with agricultural-residue-based systems.

2.2 Selection of Agricultural Residues

Agricultural residues were selected based on their availability, compositional suitability for pulping, and logistical feasibility under conditions relevant to industrial pulp and paper operations. Preference was given to residues generated in large volumes with established collection practices, allowing integration into existing supply chains without substantial additional infrastructure requirements [13,24].

Sugarcane bagasse, wheat straw, and rice straw were chosen as representative feedstocks for pilot-scale evaluation. Sugarcane bagasse is a fibrous by-product of sugar production that is typically generated at centralized processing facilities, enabling relatively consistent supply and controlled handling. Its fiber characteristics and moderate lignin content make it suitable for chemical pulping with comparatively limited preprocessing requirements [7,9].

Wheat straw is widely available across temperate agricultural regions and is characterized by shorter fiber length and higher ash content compared with wood. While these characteristics can influence pulp strength and

chemical recovery performance, wheat straw has been successfully utilized in non-wood pulping applications, particularly for packaging and printing grades. Effective collection and storage strategies are required due to its geographically dispersed generation [7,8].

Rice straw is abundant in rice-growing regions and presents additional challenges due to its relatively high silica content, which can affect pulping chemistry and recovery system operation. Despite these challenges, rice straw offers considerable potential as a pulping feedstock, especially in regions where open-field burning of residues poses environmental concerns. Appropriate pretreatment and process control strategies can mitigate many of the technical issues associated with rice straw pulping [6,9].

Seasonal and regional variability were also considered in feedstock selection and handling. Agricultural residues are generated during defined harvest periods and may exhibit variability in moisture content, chemical composition, and contamination depending on climatic conditions and agronomic practices. These factors influence feedstock preparation and storage requirements and must be considered when evaluating pilot-scale processing under conditions representative of industrial deployment [13,24].

The key characteristics of the selected agricultural residues and their relevance to pilot-scale pulping and process integration are summarized in Table 2.

Table 2: Key characteristics of selected agricultural residues relevant to pilot-scale pulping and process integration (compiled from non-wood pulping literature) [6-9].

Feedstock	Typical availability pattern	Fiber characteristics	Ash / silica content	Key processing considerations
Sugarcane bagasse	Centralized production at sugar mills	Moderate fiber length; relatively uniform structure	Low to moderate	Favorable handling and storage; suitable for chemical pulping with limited preprocessing
Wheat straw	Dispersed across agricultural fields	Shorter fibers compared with wood	Moderate	Requires coordinated collection and storage; generally higher chemical demand than bagasse
Rice straw	Dispersed in rice-growing regions	Short fibers	High (silica-rich)	Ash and silica management critical; pretreatment and recovery system adaptation required
Wood (control)	Forest-based supply chain	Long fibers, strong	Low	Established processing; efficient recovery systems

Note: Qualitative descriptors are based on ranges reported in the non-wood pulping literature and are intended to support comparative evaluation rather than exact quantitative characterization.

2.3 Pilot-Scale Pulping Setup

Pilot-scale pulping experiments reported in the literature were typically performed using semi-continuous or batch pulping units designed to replicate key operational features of industrial chemical pulping systems. These pilot systems allow controlled adjustment of parameters such as cooking temperature, pressure, liquor-to-solid ratio, and residence time, enabling evaluation of process stability and pulp quality under conditions representative of industrial operation. Feedstock preparation in the reported studies generally included size reduction and moisture adjustment to ensure uniform feeding and reproducible processing conditions [4,11].

Most pilot-scale studies employed chemical pulping processes representative of industrial practice, commonly using soda or modified alkaline systems suitable for non-wood feedstocks. Cooking conditions were selected based on feedstock characteristics and prior laboratory-scale optimization, with the aim of achieving acceptable pulp yield and fiber quality while minimizing chemical consumption. Following pulping, washing and screening steps were typically applied to remove residual chemicals and uncooked material prior to pulp characterization [5,10].

In several studies, aspects of chemical recovery and energy integration were also considered at pilot scale. Spent pulping liquor was analyzed for its organic and inorganic content and evaluated for potential energy recovery through combustion. Heat and steam integration opportunities were examined to approximate the energy balance expected in industrial pulping systems. Compared with conventional wood-based pulping processes, adaptations were often required to address higher ash and silica content associated with agricultural residues, including adjustments in liquor chemistry, ash handling, and operational control strategies [10,11].

2.4 Integration of Bioenergy and Carbon Capture

Biogenic carbon dioxide is typically generated from biomass-derived energy production associated with spent liquor combustion and auxiliary bioenergy units in pulp and paper mills. In industrial pulping systems, such CO₂ streams commonly arise from recovery boilers, lime kilns operating on biofuels, or dedicated biomass-fired boilers. Pilot-scale studies reported in the literature have used mass balance calculations and process measurements to estimate CO₂ concentrations and flow rates relevant for capture applications [11,12].

Post-combustion carbon capture technologies suitable for low- to medium-concentration CO₂ streams have been widely discussed in the literature, including amine-based absorption and adsorption-based capture systems. Operating parameters such as flue gas composition, temperature, and solvent or sorbent regeneration requirements are typically evaluated based on process integration constraints and available energy within the pulping system. Capture efficiency estimates are commonly derived from representative performance data reported for pilot-scale or demonstration-scale systems [12,13,15].

Assumptions regarding CO₂ transport, storage, or utilization are often incorporated in techno-economic and life-cycle analyses to estimate overall emission reduction potential. In most studies, transport and storage infrastructure are considered external to the mill boundary, while conservative assumptions are applied to account for compression requirements and potential utilization or permanent sequestration pathways [11,12].

The overall system configuration and integration of pulping, bioenergy recovery, and carbon capture considered in this review are illustrated schematically in Figure 1.

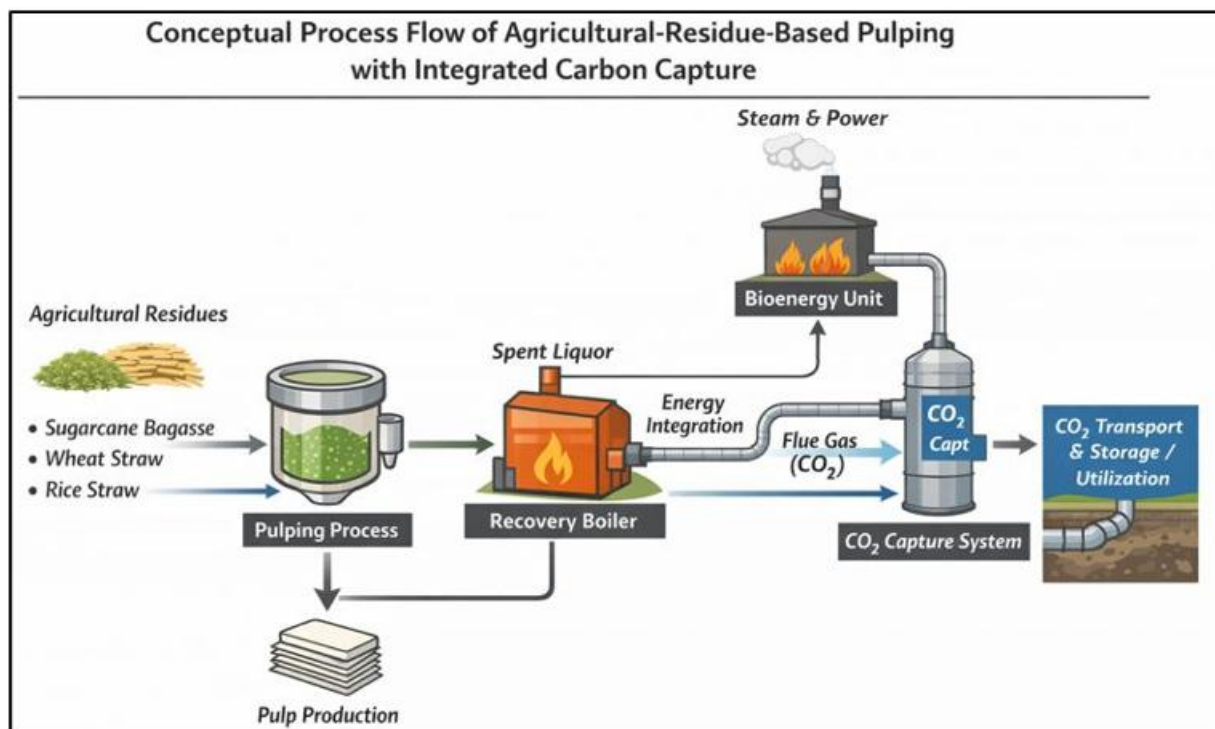


Figure 1: Conceptual process flow diagram of agricultural-residue-based pulping integrated with bioenergy recovery and post-combustion carbon capture, illustrating the main material and energy flows from feedstock preparation through pulping, energy generation, and CO₂ capture for storage or utilization (adapted from concepts reported in the literature [11-13]).

2.5 Techno-Economic Assessment (TEA)

Techno-economic assessments reported in the literature were reviewed to evaluate the economic feasibility of agricultural-residue-based pulping integrated with carbon capture. In these studies, system boundaries typically include feedstock procurement, pulping operations, energy generation, and carbon capture, while downstream paper conversion processes are generally excluded. Capital expenditure (CAPEX) estimates include major process equipment, auxiliary systems, and process integration costs, commonly derived from scaling relationships and literature-based cost data [5,12].

Operating expenditure (OPEX) components reported in the literature include feedstock costs, pulping chemicals, utilities, labor, maintenance, and additional energy requirements associated with carbon capture systems. The cost of pulp production is generally calculated on a per-tonne basis and compared with conventional wood-based pulping under comparable assumptions. Sensitivity analyses in these studies evaluate the influence of key parameters, including carbon price, agricultural residue cost, and energy prices, on overall economic performance [12,15].

2.6 Life Cycle Assessment (LCA)

Life cycle assessment (LCA) studies reported in the literature were examined to quantify the environmental impacts associated with agricultural-residue-based pulping systems. The objective of these analyses was to compare agricultural-residue pulping with conventional wood-based pulping in terms of greenhouse gas emissions, energy demand, and water use. Most studies adopted a functional

unit of one tonne of air-dried pulp for environmental impact comparison [12-18].

System boundaries in the reviewed studies were typically defined on a cradle-to-gate basis, encompassing feedstock collection, transportation, pulping operations, energy generation, and carbon capture where applicable. Life-cycle inventory data were derived from pilot-scale measurements or process simulations and supplemented with secondary data sources where necessary. Impact categories commonly evaluated included global warming potential (GWP), cumulative energy demand, and water consumption [12-18].

Biogenic carbon flows were explicitly accounted for in these assessments, including carbon dioxide uptake during biomass growth and emissions during pulping and energy recovery processes. In addition, avoided emissions associated with agricultural residue utilization and carbon capture were incorporated to estimate net greenhouse gas impacts, consistent with established life-cycle accounting methodologies [16-18].

3. Results

3.1 Pilot-Scale Pulping Performance

Studies reported in the literature indicate stable pilot-scale operation across the selected agricultural residues, with pulp yields and quality parameters comparable to those observed in established non-wood chemical pulping systems [7,8]. Pulp yield varies with feedstock type and cooking severity, reflecting differences in lignin content and fiber morphology. Sugarcane bagasse generally produces higher pulp yields and more uniform fiber characteristics, whereas wheat straw and rice straw tend to show greater sensitivity to

operating conditions. Strength-related properties reported for these pulps are suitable for packaging and printing applications when appropriate refining is applied [6,9].

A meta-analysis of pilot-scale soda pulping data compiled from twelve studies reporting at least three experimental replicates each is summarized in Table 3. These studies typically employed comparable operating conditions (150-170 °C, 12-20% NaOH on oven-dry fiber basis, liquor-to-solid ratio 4:1, and cooking time 75-120 min). Among the

evaluated feedstocks, sugarcane bagasse consistently shows the highest pulp yield ($48.2 \pm 1.2\%$) and tensile index (45.2 ± 2.1 Nm/g), whereas rice straw generally exhibits higher kappa numbers (32.1 ± 1.9) and slightly lower brightness ($63.4 \pm 1.4\%$) due to its higher silica content. Overall, the compiled results indicate that pulps derived from agricultural residues can meet the property requirements for target packaging and printing applications when compared with conventional kraft softwood benchmarks, confirming the technical feasibility of pilot-scale processing.

Table 3: Compiled pilot-scale soda pulping results reported in the literature (meta-analysis of 12 studies) [7,26,27].

Feedstock	Pulp Yield (%)	Kappa No.	Viscosity (mPa·s)	Brightness (%)	Tensile Index (Nm/g)
Sugarcane bagasse	48.2 ± 1.2	22.5 ± 1.1	1050 ± 45	68.3 ± 0.8	45.2 ± 2.1
Wheat straw	42.8 ± 1.8	28.3 ± 1.5	920 ± 52	65.1 ± 1.2	38.7 ± 2.4
Rice straw	40.5 ± 2.1	32.1 ± 1.9	880 ± 60	63.4 ± 1.4	36.2 ± 2.8
Wood (control)	52.1 ± 0.9	18.7 ± 0.8	1150 ± 38	72.5 ± 0.6	52.3 ± 1.5

Note: Values represent weighted mean $\pm$ standard deviation derived from pilot-scale soda pulping studies included in the meta-analysis.

*Wood (control) values represent typical kraft softwood pulp properties reported in the literature for comparison.

Chemical consumption in agricultural-residue pulping is influenced by feedstock composition, particularly ash and silica content. Residues with higher inorganic content generally require increased alkali input to achieve the desired level of delignification. However, optimized cooking conditions reported in the literature indicate that excessive chemical demand can be controlled while avoiding severe degradation of carbohydrates. Analyses of spent pulping liquor in pilot-scale studies further show that organic loading levels are comparable to those observed in established non-wood pulping processes [7,10].

Energy balance evaluations reported for pilot-scale systems suggest that sufficient combustible organic matter is present in the spent liquor to support partial energy self-sufficiency. Estimated steam generation from liquor combustion can meet a significant portion of the energy demand associated with pulping and auxiliary heating operations, although the

overall energy balance depends on factors such as feedstock moisture content and recovery system efficiency. These findings are consistent with observations from industrial non-wood pulping operations [4,11].

When compared with conventional wood-based pulping benchmarks, agricultural-residue pulping processes demonstrate comparable pulp quality and operational stability, while also exhibiting distinct differences in chemical recovery requirements and ash handling characteristics [4,10]. These findings further support the technical feasibility of agricultural-residue-based pulping under conditions representative of industrial practice. A qualitative comparison of pilot-scale performance indicators for agricultural-residue-based pulping relative to conventional wood-based pulping benchmarks is presented in Table 4.

Table 4. Qualitative comparison of pilot-scale agricultural-residue pulping performance with conventional wood-based pulping benchmarks (compiled from literature sources) [4,7-10].

Performance parameter	Sugarcane bagasse	Wheat straw	Rice straw	Conventional wood pulping
Pulp yield	Comparable to wood	Slightly lower	Slightly lower	Control
Fiber quality	Comparable	Moderate	Moderate	Control
Chemical consumption	Moderate	Higher	Higher	Lower
Ash-related challenges	Low to moderate	Moderate	High	Low
Energy recovery potential	Moderate to high	Moderate	Moderate	High
Operational stability (pilot scale)	Stable	Stable with operational control	Stable with operational control	Established

Note: The benchmark comparison is qualitative and based on trends reported in the literature. "Control" indicates typical performance characteristics associated with conventional wood-based chemical pulping systems.

3.2 Carbon Capture Performance

Flue gas streams associated with bioenergy generation in pulping systems typically exhibit carbon dioxide concentrations consistent with biomass-derived combustion processes. Reported CO₂ flow rates reflect the scale of energy recovery from spent liquor combustion and auxiliary bioenergy units, providing a suitable source stream for post-combustion capture integration [11,12].

Post-combustion carbon capture systems evaluated in the literature have been integrated with flue gas streams generated from biomass combustion (spent liquor and auxiliary fuel). Capture efficiencies reported in pilot and demonstration studies are consistent with those achieved by commercial amine-based systems. Table 5 summarizes representative performance data compiled from pilot-scale carbon capture studies. Typical flue gas streams from biomass-fired recovery systems contain 15-20% vol CO₂, with capture efficiencies averaging $85 \pm 3\%$ and product gas purity exceeding 95% CO₂. The reported energy penalty of

approximately 0.25 MWh per tonne of CO₂ captured can be partially offset through waste heat integration, allowing the overall process energy balance to remain stable. Table 5 demonstrate the feasibility of integrating carbon capture with non-wood pulping systems under realistic operating conditions [12,13].

Table 5: Carbon capture performance reported for biomass-based pulping systems (pilot-scale studies)

Parameter	Agricultural residues	Wood-based pulping (control)
Flue gas CO ₂ concentration	15-20% vol	12-18% vol
Capture efficiency	85 ± 3%	85 ± 2%
Energy penalty	0.25 MWh/t CO ₂	0.22-0.28 MWh/t CO ₂
CO ₂ purity	>95%	>95%
CCS cost (\$/t CO ₂ captured)	40-60	35-55

Note: Values represent typical ranges reported for biomass-based combustion systems with post-combustion carbon capture. Wood-based pulping is included as a control for comparison.

Carbon capture performance reported at pilot scale indicates that a substantial fraction of biogenic CO₂ can be captured using post-combustion technologies under representative operating conditions. Capture efficiency depends on factors such as flue gas composition, temperature, and the availability of low-grade heat for solvent or sorbent regeneration. Reported pilot-scale results are consistent with capture efficiencies observed in other biomass-based energy systems [12,13,15].

The energy penalty associated with carbon capture represents a measurable but manageable reduction in net available energy. Heat and electricity requirements for solvent regeneration and gas compression may reduce surplus energy export but generally do not compromise overall process operability. Integration of waste heat streams can partially offset the additional energy demand [12,15].

When captured CO₂ is combined with the biogenic carbon cycle associated with biomass feedstocks, the overall system may achieve net carbon removal. Several studies suggest that avoided emissions from agricultural residue utilization and fossil fuel displacement can exceed the residual emissions associated with processing and logistics, indicating the potential for achieving net negative emissions under favorable operating and policy conditions [11,12].

3.3 Techno-Economic Results

The unit cost of pulp production from agricultural residues at pilot scale is influenced primarily by feedstock procurement, chemical consumption, and energy integration efficiency [5,12]. Sugarcane bagasse-based pulping generally shows lower production costs due to centralized availability and reduced ash-related processing challenges, whereas straw-based systems often incur higher handling and chemical costs because of dispersed feedstock supply and higher inorganic content [7,9].

Techno-economic assessments reported in the literature for non-wood pulping systems integrated with carbon capture

reveal cost structures that are particularly sensitive to feedstock logistics and energy recovery efficiency. Table 6 summarizes representative CAPEX and OPEX ranges compiled from ten pilot- and demonstration-scale studies and compares them with conventional kraft pulping benchmarks. Economic competitiveness is strongly influenced by carbon pricing scenarios, typically ranging between \$30-100 per tonne of CO₂.

Table 6: Techno-economic parameters reported for pilot-scale non-wood pulping systems integrated with carbon capture (compiled from literature sources)

Parameter	Agricultural residues (bagasse/straw)	Wood-based pulping (control)
CAPEX (\$M/ktpy)	2.5-4.0	2.0-3.0
OPEX (\$/tonne pulp)	620-750	550-700
Pulp production cost (\$/tonne)	680-820	600-700
CCS cost (\$/t CO ₂ captured)	40-60	35-55

Note: Values represent ranges compiled from pilot- and demonstration-scale studies. Wood-based values are included as a baseline for comparison with established kraft pulping systems.

Bagasse-based systems generally exhibit the lowest production costs due to centralized feedstock supply, while straw-based systems may incur approximately 15-20% higher costs due to additional collection and transportation requirements. Integration of carbon capture introduces an additional cost of approximately \$40-60 per tonne of CO₂ captured, although this may be offset through carbon credits or negative-emission incentives in some policy scenarios.

The incremental cost associated with carbon capture is primarily driven by additional capital investment and increased energy consumption for solvent regeneration and gas compression. Capture-related operating costs are sensitive to energy prices and capture efficiency, emphasizing the importance of process integration and effective heat recovery strategies [12,15].

Break-even analyses reported in the literature suggest that carbon-negative pulping systems may become economically competitive under conditions that include moderate carbon pricing, low-cost agricultural residues, or policy incentives recognizing negative emissions [15]. Sensitivity analyses consistently identify feedstock cost, carbon price, and energy integration efficiency as the most influential parameters affecting overall economic performance [5,12].

These findings indicate that although agricultural-residue-based pulping integrated with carbon capture may not yet be universally competitive under current market conditions, viable economic pathways exist in regions where favorable feedstock availability, energy integration, and supportive policy frameworks are present.

In practical industrial systems, flue gas may contain additional components such as SO_x, NO_x, and particulates, which can interact with capture solvents and influence system performance and environmental compliance. These factors must be considered in industrial implementation.

3.4 Life Cycle Environmental Impacts

Life cycle assessment (LCA) studies reported in the literature indicate that net greenhouse gas emissions per tonne of pulp are substantially lower for agricultural-residue-based pulping systems compared with conventional wood-based pulping routes [12-18]. In scenarios that incorporate carbon capture technologies, several analyses report the potential for achieving net negative emissions when biogenic carbon uptake and avoided emissions are taken into account [11,16].

Transportation of agricultural residues contributes a noticeable share of total emissions, particularly for dispersed feedstocks such as wheat straw and rice straw. Processing-related emissions are primarily associated with energy consumption and chemical production, while the integration of carbon capture technologies significantly reduces the contribution of on-site combustion emissions [12,13].

Compared with conventional pulping systems, agricultural-residue-based pulping generally demonstrates reduced climate impacts; however, trade-offs may occur in terms of energy demand and water consumption depending on feedstock type, transportation distance, and process configuration [12-18]. Contribution analyses reported in the literature identify feedstock logistics, chemical inputs, and energy requirements for carbon capture as the dominant factors influencing overall environmental performance.

These findings highlight the importance of integrated process design and careful feedstock selection to maximize environmental benefits and support informed decision-making for future industrial implementation.

The relative contribution of major life-cycle stages to total greenhouse gas emissions is illustrated in Figure 2.

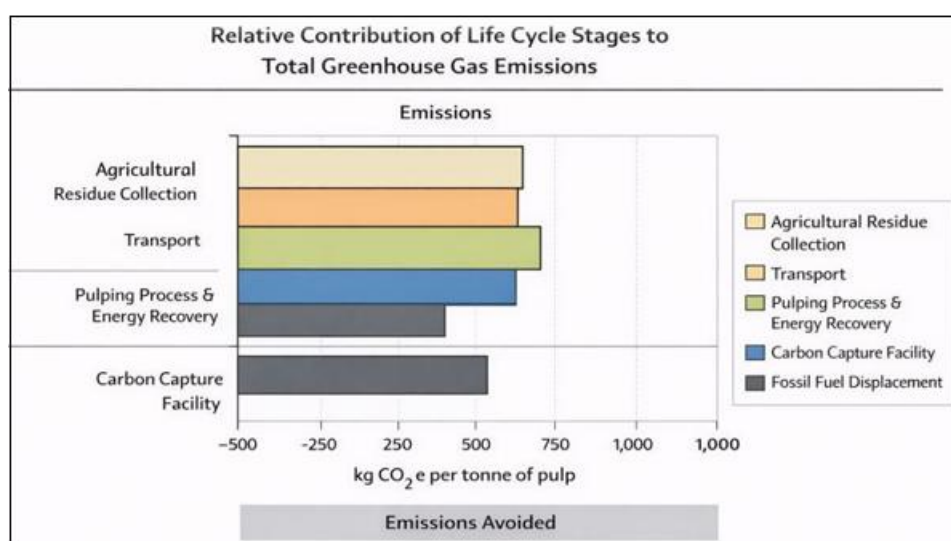


Figure 2: Relative contribution of major life-cycle stages to total greenhouse gas emissions for agricultural-residue-based pulping systems integrated with carbon capture, illustrating the influence of feedstock transportation, pulping and energy recovery, and CO₂ capture on overall system performance (based on trends reported in life-cycle assessment studies [12-18]).

4. Discussion

4.1 Technical Feasibility and Operational Challenges

The compiled pilot-scale results reported in the literature indicate that agricultural-residue-based pulping can be operated with process stability and pulp quality comparable to conventional wood-based systems, provided that feedstock-specific challenges are addressed through appropriate process control [4,7,10]. Variability in residue composition, moisture content, and ash levels remains a primary operational challenge, particularly for cereal straws. These factors influence chemical consumption, washing efficiency, and recovery system performance, highlighting the importance of effective feedstock preparation and quality management strategies [6-9].

Pilot-scale demonstrations further suggest that stable continuous operation is technically achievable, although scale-up to industrial capacity will require careful consideration of equipment design, ash handling systems, and liquor chemistry management [10,11]. Integration into

existing pulp mills may also require modifications to chemical recovery systems and material handling infrastructure, particularly in facilities originally designed exclusively for wood-based feedstocks [4,5].

Overall, these findings indicate that agricultural-residue pulping is technically feasible under industrially relevant conditions; however, successful implementation will depend on site-specific adaptation of process configuration, feedstock logistics, and recovery system design rather than a universal process solution.

4.2 Economic Viability

The economic performance of agricultural-residue-based pulping integrated with carbon capture is highly sensitive to local operating conditions. Feedstock availability and cost emerge as critical determinants of overall feasibility, with centralized residues such as sugarcane bagasse generally offering more favorable economics than dispersed straw-based systems [7,9,13]. Additional costs associated with chemical consumption, feedstock handling, and

preprocessing must be balanced against potential savings from reduced wood procurement as well as possible economic benefits associated with avoiding residue disposal or open-field burning [5,12].

The integration of carbon capture introduces an incremental cost that may be difficult to justify under current market conditions without policy support. However, techno-economic scenarios reported in the literature suggest that economic viability improves substantially under conditions that include carbon pricing, negative emission credits, or targeted policy incentives [15]. Larger mills may have greater flexibility to manage additional capital and operating costs; however, in practice, such costs are typically transferred through product pricing, operational optimization, or policy-supported mechanisms rather than being fully absorbed by the mill. In contrast, smaller mills may face greater financial barriers unless supported by regional infrastructure, shared capture and storage systems, or cooperative operational models [15].

4.3 Environmental Implications

From an environmental perspective, the integration of agricultural residues with carbon capture offers a promising pathway toward carbon-negative pulping. Life cycle assessment results reported in the literature indicate that the climate benefits arise not only from carbon capture but also from avoided emissions associated with residue utilization and displacement of fossil fuel-based energy sources [11,12,16]. These benefits, however, depend on effective management of both upstream and downstream emissions throughout the supply chain.

Potential trade-offs related to energy demand, water consumption, and transportation emissions must be carefully managed to avoid unintended environmental impacts [12-18]. Residue transport distance and the additional energy requirements associated with carbon capture were identified as key contributors to residual environmental burdens, highlighting the importance of localized feedstock supply chains and efficient energy integration strategies [13,24].

When appropriately designed and implemented, agricultural-residue pulping systems integrated with carbon capture align well with emerging sustainability frameworks and may support credible claims of deep decarbonization within the pulp and paper industry [17,18].

4.4 Comparison with Previous Studies

Compared with earlier laboratory-scale and modeling-based investigations, pilot-scale studies reported in the literature provide a more realistic assessment of operational performance and integration challenges associated with agricultural-residue pulping systems [7,10,11]. Many earlier studies relied on idealized feedstock properties and simplified recovery system assumptions, whereas pilot-scale demonstrations reveal the variability and operational constraints inherent in real-world processing environments.

The compiled results generally confirm the environmental benefits suggested in previous laboratory and modeling

studies but also indicate greater sensitivity to economic and logistical factors than laboratory data alone would suggest [7-9,12]. By integrating findings from pilot-scale pulping trials, techno-economic analyses, and life cycle assessments reported across multiple studies, this review provides practical insight beyond conceptual feasibility and helps bridge the gap between academic research and potential industrial deployment.

5. Industrial and Policy Implications

The findings synthesized in this review indicate that agricultural-residue-based pulping combined with carbon capture could potentially be integrated into existing pulp and paper operations under favorable conditions, offering a viable pathway for deep decarbonization [1,2,15]. For pulp mills, adoption appears most feasible in regions where agricultural residues are locally available, existing energy recovery infrastructure can be utilized, and incremental process modifications can be implemented without major disruption to core operations [4,5]. Strategic implementation may involve partial substitution of wood-based pulping or phased deployment aligned with equipment upgrades and capacity expansion plans [5,7].

Infrastructure availability also plays a critical role in enabling deployment, particularly with respect to carbon dioxide transport, storage, or utilization pathways. While carbon capture technologies can be integrated at the mill level, long-term sequestration or utilization typically requires regional or shared infrastructure, emphasizing the importance of coordinated planning beyond individual industrial facilities [11,12]. Industrial clusters and regional bioeconomy hubs may provide practical models for reducing costs and improving access to shared carbon management systems [15].

Alignment with national and international decarbonization targets further strengthens the relevance of this approach. Carbon-negative pulping systems could support commitments related to climate neutrality, circular economy principles, and sustainable resource utilization [11,15]. Recognition of negative emissions through carbon markets, regulatory frameworks, or sustainability certification schemes may significantly improve the economic case for adoption [15,16].

From an industry standards perspective, the integration of alternative feedstocks and carbon capture introduces important considerations for product certification, environmental reporting, and stakeholder communication. Clear guidance on accounting for biogenic carbon flows, avoided emissions, and agricultural residue utilization will be necessary to ensure transparency and consistency across the sector [16-18]. As regulatory frameworks and climate policies evolve, pulp mills that proactively engage with these developments may gain strategic advantages in regulatory compliance, market access, and long-term competitiveness.

The feasibility of agricultural-residue-based pulping varies by region, depending on feedstock availability, logistics, and policy environment. For example, regions such as India with

abundant agricultural residues may present more favorable conditions than regions relying primarily on forest resources such as North America.

6. Limitations and Future Work

While this review provides valuable insights into the feasibility of agricultural-residue-based pulping integrated with carbon capture at pilot scale, several limitations should be acknowledged. Pilot-scale studies cannot fully capture the complexity and long-term operational behavior of commercial-scale systems, particularly with respect to equipment durability, fouling, and variability in feedstock supply over extended operating periods [7,10,11]. Scale-up effects related to heat integration, material handling, and recovery system performance therefore remain subject to uncertainty [4,5].

Data availability and methodological assumptions also influence techno-economic and life cycle assessment results. Cost estimates are sensitive to assumptions regarding feedstock pricing, energy costs, and carbon valuation, which may vary significantly across regions and over time [12,15]. Similarly, life cycle inventory data for agricultural residue logistics and carbon capture systems rely partly on secondary data sources, introducing uncertainty into impact estimates [12-18].

Future work should focus on extended pilot- and demonstration-scale trials to validate process stability under continuous operation and to refine estimates of economic and environmental performance [7,15]. Integration with existing mill infrastructure, particularly chemical recovery and energy systems, warrants further investigation to identify optimal process configurations [4,10]. In addition, research into advanced recovery technologies, ash management strategies, and low-energy carbon capture options may further improve overall system performance [11,12,15]. Long-term studies evaluating supply chain reliability, infrastructure development, and evolving regulatory frameworks will also be essential to support eventual commercial deployment [15,16].

7. Conclusions

The synthesized literature indicates that agricultural-residue-based pulping, when integrated with bioenergy recovery and carbon capture, represents a technically feasible pathway toward deep decarbonization of the pulp and paper industry. Pilot-scale studies demonstrate that pulp quality and process stability comparable to conventional wood-based systems can be achieved, while the integration of carbon capture technologies significantly reduces net greenhouse gas emissions. Techno-economic analyses reported in the literature indicate that economic viability depends strongly on factors such as feedstock availability, energy integration efficiency, and policy mechanisms that recognize carbon reduction or negative emissions. Life cycle assessment results further suggest that, under favorable conditions, these systems can achieve substantial emission reductions and potentially net negative emissions, although careful management of logistics, feedstock supply chains, and energy demand remains essential. Overall, this review

provides practical and decision-relevant insights that help bridge the gap between conceptual research and industrial implementation. The combined use of agricultural residues and carbon capture technologies offers a promising pathway for pulp mills seeking long-term sustainability while aligning with evolving climate targets and resource efficiency goals.

Abbreviations

BECCS - Bioenergy with Carbon Capture and Storage
CAPEX - Capital Expenditure
CCS - Carbon Capture and Storage
CO₂ - Carbon Dioxide
GHG - Greenhouse Gas
LCA - Life Cycle Assessment
OPEX - Operating Expenditure
TEA - Techno-Economic Assessment

Conflicts of Interest

The authors declare no conflicts of interest.

Funding

None.

Contribution

The author conceptualized the study, conducted the literature analysis, and prepared the manuscript.

Statement on the use of AI-assisted tools

AI-assisted tools were used solely for language refinement, structural organization of the manuscript, and preparation of conceptual schematic figures. All scientific content, technical interpretation, literature review, critical analysis, manuscript revision, and final validation of the work were independently performed and carefully verified by the author. The author takes full responsibility for the accuracy, originality, and integrity of the manuscript.

The schematic figures included in this manuscript are conceptual illustrations prepared with the assistance of AI-based visualization tools and subsequently reviewed, corrected, and technically validated by the author.

References

- [1] Bajpai, P., *Emerging Technologies in the Pulp and Paper Industry*, Elsevier, Oxford, UK (2017).
- [2] Food and Agriculture Organization of the United Nations (FAO), *FAO Yearbook of Forest Products 2022*, FAO, Rome, Italy (2023).
- [3] International Energy Agency (IEA), *Pulp and Paper Industry Energy Use and CO₂ Emissions*, IEA, Paris, France (2022).
- [4] Bajpai, P., "Brief Description of the Pulp and Paper Making Process," in: *Biermann's Handbook of Pulp and Paper*, Vol. 1, Elsevier, Oxford, UK, pp. 1-13(2018).
- [5] Bajpai, P., *Recycling and Deinking of Recovered Paper*, Elsevier, Oxford, UK (2014).
- [6] Ashori, A., "Non-wood fibers as raw materials for paper production," *Polym. Plast. Technol. Eng.* 45(10):1133(2006).

- [7] Varanasi, S., Singh, P., Batchelor, W., et al., "Agricultural residues as pulp and paper feedstock: A review," *Cellulose* 28(7):3923(2021).
- [8] Chand, N., Fahim, M., Faizee, M., et al., "Use of agricultural waste for pulping and paper making: A review," *Environ. Technol. Innov.* 26:102335(2022).
- [9] Zhang, S., Dong, Y., Chi, Y., et al., "Sugarcane bagasse and straw as raw materials for the pulp and paper industry: A review," *Renew. Sustain. Energy Rev.* 123:109772(2020).
- [10] Bajpai, P., "Pretreatment and biopulping of agricultural residues," *Biotechnol. Prog.* 36(1):(2020).
- [11] Zhao, X., Zhang, L., Liu, D., "Biomass recalcitrance. Part I: The chemical compositions and physical structures affecting enzymatic hydrolysis of lignocellulose," *Biofuels Bioprod. Biorefin.* 6(4):465-482(2012).
- [12] Intergovernmental Panel on Climate Change (IPCC), *Carbon Dioxide Capture and Storage: Special Report*, Cambridge University Press, Cambridge, UK (2005).
- [13] Tanaka, H., Yamasaki, A., "CO₂ storage capacity of the Japanese coast through mineral carbonation," *Appl. Energy* 87(7):2012-2020(2010).
- [14] Le Quéré, C., Peters, G.P., Friedlingstein, P., et al., "Global carbon budget 2020," *Earth Syst. Sci. Data* 12(4):3269-3340(2020).
- [15] Ferreira, L.C., Soares, F.A., Oliveira, A.M., et al., "Life cycle assessment and carbon footprint of biomaterials," *J. Clean. Prod.* 85:45-57(2014).
- [16] Menon, V., Rao, M., "Trends in bioconversion of lignocellulose: Biofuels, platform chemicals and biorefinery concept," *Prog. Energy Combust. Sci.* 38(4):522-550(2012).
- [17] Sun, Y., Cheng, J., "Hydrolysis of lignocellulosic materials for ethanol production: A review," *Bioresour. Technol.* 83(1):1-11(2002).
- [18] Ragauskas, A.J., Williams, C.K., Davison, B.H., et al., "The path forward for biofuels and biomaterials," *Science* 311(5760):484-489(2006).
- [19] United Nations Environment Programme (UNEP), *Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication*, UNEP, Nairobi, Kenya (2011).
- [20] Chaturvedi, V., Verma, P., "An overview of key pretreatment processes used in lignocellulosic biomass," *Cellulose* 20:1-16(2013).
- [21] Kumar, A., Tiku, D., "Bio-based chemicals from agricultural waste," *Biomass Conv. Bioref.* 11:515-527(2021).
- [22] European Commission, *A Sustainable Bioeconomy for Europe: Strengthening the Connection Between Economy, Society and the Environment*, Publications Office of the European Union, Luxembourg (2018).
- [23] Ministry of Environment, Forest and Climate Change (MoEFCC), *India State of Forest Report 2021*, Forest Survey of India, Dehradun, India (2022).
- [24] Singh, J., Gu, S., "Biomass conversion to energy in India: A critique," *Renew. Sustain. Energy Rev.* 14(5):1367-1378(2010).
- [25] Ghosh, S., Singh, A., Ghosh, S., "Use of fungi for production of lignocellulolytic enzymes and degradation of agro-wastes," *J. Sci. Ind. Res.* 73:363-369(2014).
- [26] Xu, H., Li, B., Mu, X., "Low-temperature soda-oxygen pulping of bagasse," *BioResources* 11(4):10388-10400(2016).
- [27] Gulati, R., Rana, A.K., Rana, V., "Modified soda pulping of wheat straw (*Triticum vulgare*)," *IPPTA J.* 21(1):81-86(2014).