

Research Article

Alternative Low-Cost Biomass from Millet Residues for Renewable Energy and Chemical Production

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Abstract

The increasing global demand for sustainable energy and chemical feedstocks necessitates the exploration of alternative low-cost biomass resources. Millet residues, generated as agricultural by-products, offer a promising, underutilized source for renewable energy and chemical production due to their abundant availability, low economic cost, and high cellulose and hemicellulose content. This study investigates the potential of millet waste as a feedstock for biofuels and value-added chemicals, emphasizing its applicability in pyrolysis, anaerobic digestion, and combustion processes. The research synthesizes evidence from prior studies on lignocellulosic biomass utilization, bioenergy conversion efficiencies, and economic feasibility of residue valorization, providing a holistic understanding of millet residues' potential.

The methodology integrates both qualitative and quantitative frameworks to assess biomass conversion pathways, including thermochemical and biochemical processes. Comparative analyses highlight millet residues' advantages over conventional biomass sources, such as reduced land-use competition and lower cost of collection and processing. Furthermore, the study examines the challenges related to feedstock variability, moisture content, and logistics, contextualizing these factors within existing biomass energy models.

Findings suggest that millet residues can achieve energy conversion efficiencies comparable to other agro-wastes while offering additional economic incentives through chemical by-product recovery. However, practical implementation requires careful consideration of process optimization, supply chain management, and environmental sustainability metrics. This research underscores the strategic role of millet residues in transitioning toward circular bioeconomies, enhancing rural energy security, and promoting sustainable agricultural waste management.

Overall, the study contributes to the growing discourse on sustainable biomass utilization by presenting a comprehensive evaluation of millet residues as a low-cost feedstock. The insights provide a foundation for future experimental studies and industrial-scale applications, facilitating informed decision-making for policy, research, and commercial stakeholders (Deshwal & Singh, 2025).

Keywords

Millet residues; Renewable energy; Biofuels; Biomass valorization; Lignocellulosic biomass; Pyrolysis; Anaerobic digestion; Circular bioeconomy; Agro-waste management; Low-cost feedstock.

INTRODUCTION

Background

The global energy landscape is undergoing a transformative shift driven by the need to mitigate climate change, reduce reliance on fossil fuels, and achieve sustainable development goals. Biomass has emerged as a pivotal renewable energy source, providing both fuel and chemical feedstocks while contributing to carbon neutrality when properly managed (Gutiérrez et al., 2020). Agricultural residues, particularly those generated from cereal crops, represent a significant portion of available biomass worldwide. Among these, millet residues remain largely underutilized despite their widespread cultivation in arid and semi-arid regions (Deshwal & Singh, 2025).

Millet, a group of small-seeded cereals, is primarily grown for food security in regions with marginal soils and low water availability. Post-harvest, substantial quantities of residues—including stalks, husks, and leaves—are generated. Conventionally, these residues are either left in fields, burned, or underutilized as low-value fodder. However, their biochemical composition, comprising cellulose, hemicellulose, and lignin, positions them as suitable candidates for bioenergy and chemical production via thermochemical or biochemical conversion processes (Demirbas, 2010).

Problem Statement

Despite the recognized potential of millet residues, there exists a significant gap in their systematic assessment for energy and chemical production. Current research has predominantly focused on maize, wheat, and rice residues, resulting in limited practical knowledge on millet biomass valorization. Moreover, socio-economic constraints, including low-cost collection, seasonal availability, and logistics, pose

challenges for large-scale implementation (Jbaili et al., 2022). Consequently, there is a pressing need to explore the technical feasibility, energy yield, and chemical potential of millet residues within an integrated bioeconomy framework.

Research Relevance

Valorizing millet residues aligns with global efforts to develop low-cost, sustainable bioenergy solutions that minimize environmental impact while enhancing rural livelihoods. Utilizing these residues for biofuel and chemical production offers multiple benefits: reduction in open-field burning, generation of renewable energy, creation of value-added products, and support for circular bioeconomy strategies (Deshwal & Singh, 2025). Additionally, millet-based biomass can provide a reliable feedstock for decentralized energy systems in resource-constrained regions, thereby improving energy access and supporting climate mitigation strategies (Bucchignani et al., 2018).

Objectives

The primary objectives of this study are:

1. To evaluate the chemical and physical properties of millet residues that influence their suitability for bioenergy and chemical production.
2. To analyze different biomass conversion pathways, including pyrolysis, anaerobic digestion, and combustion, in the context of millet residues.
3. To compare the energy and chemical yield of millet residues against conventional biomass sources.
4. To assess the economic feasibility and sustainability implications of utilizing millet residues at both local and industrial scales.
5. To identify critical research gaps and provide recommendations for future

experimental and commercial studies.

Scope and Significance

This research focuses exclusively on millet residues as an alternative biomass feedstock, incorporating empirical data and insights from prior studies on lignocellulosic biomass conversion, biofuel production, and agro-waste management (Paper & Hawboldt, 2015; Gey et al., 1998). By restricting the scope to millet, the study provides a targeted and detailed assessment, avoiding overgeneralization from other crop residues.

The significance of this research lies in its potential to inform both scientific inquiry and policy development. By demonstrating the technical viability and economic potential of millet residues, the study supports evidence-based decisions for bioenergy initiatives, waste management programs, and rural development strategies. Moreover, the research contributes to the theoretical understanding of biomass valorization by integrating chemical, energy, and economic dimensions within a single analytical framework (Deshwal & Singh, 2025).

In conclusion, the introduction establishes the urgent need to explore millet residues as a sustainable, low-cost biomass resource. The following sections provide a detailed literature review, methodological framework, results, discussion, and conclusions, synthesizing evidence and offering critical insights for future research and practical application.

LITERATURE REVIEW

Overview of Biomass Utilization

Biomass has long been recognized as a versatile resource for renewable energy and chemical production. Lignocellulosic biomass, in particular, provides structural polymers—cellulose, hemicellulose, and lignin—that can be converted into biofuels, chemicals, and materials through thermochemical and biochemical processes (Demirbas, 2010). Among agro-residues, millet residues remain relatively underexplored despite their abundance and favorable biochemical properties (Deshwal & Singh, 2025).

The utilization of agricultural residues addresses both energy and environmental challenges by reducing dependence on fossil fuels and minimizing open-field burning of crop residues. According to Gutiérrez et al. (2020), direct combustion and anaerobic digestion of crop residues yield substantial energy potential while maintaining nutrient recycling in soils. These approaches provide a foundational framework for assessing millet residues, which share compositional similarities with other cereal by-products.

Thermochemical Conversion

Thermochemical conversion processes, including pyrolysis, gasification, and direct combustion, transform solid biomass into energy-dense fuels or intermediate chemicals. Paper and Hawboldt (2015) provide a comprehensive review of woody biomass pyrolysis, emphasizing the importance of process conditions, feedstock particle size, and reaction kinetics. While their study focuses on wood, the principles are transferable to millet residues, which exhibit comparable cellulose-lignin structures.

Combustion of millet residues represents the simplest utilization pathway, offering direct heat and potential for electricity generation. Gutiérrez et al. (2020) highlight that energy yield from direct combustion depends on moisture content, bulk density, and lignocellulosic composition—parameters critical for optimizing millet residue utilization. Pyrolysis offers additional advantages by producing bio-oil, syngas, and biochar, which can be applied in chemical synthesis or soil amendment. Kinetic modeling of biomass pyrolysis, as discussed by Paper and Hawboldt (2015), is essential for predicting energy outputs and designing reactors suitable for millet residues.

Biochemical Conversion

Biochemical pathways, notably anaerobic digestion, convert biomass into biogas through microbial decomposition. This approach not only produces renewable energy but also generates nutrient-rich digestate suitable for soil amendment. Gutiérrez et al. (2020) demonstrate that agro-industrial residues, including livestock

and slaughterhouse waste, can achieve high methane yields under controlled digestion conditions. Analogous treatment of millet residues can provide sustainable energy solutions in rural and peri-urban contexts (Deshwal & Singh, 2025).

Isothermal and non-isothermal kinetic studies further elucidate the decomposition behavior of biomass under controlled conditions, providing insights into optimal reaction parameters (Gey et al., 1998). These kinetic analyses are critical for scaling biochemical conversion processes for millet residues, ensuring efficient biogas production while minimizing inhibitory by-products.

Comparative Analysis of Millet Residues

Existing literature indicates that millet residues possess several advantages over more commonly studied agro-wastes. Deshwal and Singh (2025) identify high cellulose and hemicellulose content in millet stalks, which correlates with enhanced biofuel and chemical yields. Additionally, millet cultivation occurs in marginal soils with low fertilizer inputs, resulting in residues with relatively low ash content compared to other cereals (Deshwal & Singh, 2025).

Comparative assessments suggest that millet residues can achieve energy conversion efficiencies similar to wheat straw or rice husks while offering additional economic and environmental benefits. For example, the collection and transportation of millet residues are less cost-intensive due to localized farming practices, reducing logistical barriers often associated with biomass valorization (Jbaihi et al., 2022). Furthermore, the potential integration of millet residues into hybrid renewable energy systems, such as CSP+PV, enhances energy security in resource-constrained regions (Jbaihi et al., 2022).

Chemical Production Potential

Beyond energy generation, millet residues serve as a feedstock for chemical production. Thermochemical conversion produces bio-oil, which can be upgraded into liquid fuels or platform chemicals, while biochemical processes

yield intermediates for biochemical synthesis (Demirbas, 2010). Studies on other lignocellulosic residues indicate that compounds such as levoglucosan, furfural, and phenolic derivatives are recoverable during pyrolysis, representing significant economic value (Paper & Hawboldt, 2015).

Millet residues also offer potential for algae-based chemical production, as demonstrated in Demirbas and Demirbas (2010), where biomass provides carbon-rich substrates for lipid accumulation in microalgae. Such integration of lignocellulosic residues with biotechnological applications exemplifies the multi-faceted utility of millet biomass, reinforcing its role in circular bioeconomies.

Environmental and Socioeconomic Considerations

Effective utilization of millet residues aligns with sustainability principles by mitigating greenhouse gas emissions associated with residue burning. Bucchignani et al. (2018) emphasize the broader implications of climate change on biomass availability, particularly in semi-arid regions where millet is cultivated. Implementing residue valorization strategies contributes to rural resilience by generating income streams, enhancing energy access, and fostering local industry development.

Economic feasibility is a crucial determinant of large-scale adoption. Studies on biofuels from grasses and other low-cost feedstocks indicate that feedstock availability, collection cost, and processing efficiency are decisive factors (Gupta & Demirbas, 2010). Millet residues, characterized by their local abundance and low economic value, present a practical solution to these challenges (Deshwal & Singh, 2025).

Research Gaps and Theoretical Positioning

Despite their promise, several research gaps hinder the comprehensive utilization of millet residues. Existing studies predominantly focus on energy yield estimation without detailed techno-economic or life-cycle analyses. Moreover, integration of biochemical and thermochemical pathways for simultaneous energy and chemical

production remains underexplored. Limited kinetic data specific to millet residues restrict accurate process modeling and scale-up potential (Gey et al., 1998; Paper & Hawboldt, 2015).

The theoretical positioning of this research lies at the intersection of biomass valorization theory, circular bioeconomy principles, and sustainable energy systems. By systematically analyzing millet residues within these frameworks, the study addresses gaps in knowledge regarding feedstock-specific energy potential, chemical yield, and process feasibility. This positioning provides a robust foundation for methodological design, enabling the development of scalable, economically viable, and environmentally sustainable bioenergy solutions (Deshwal & Singh, 2025).

METHODOLOGY

Research Framework

This study adopts a multi-layered methodological framework integrating qualitative and quantitative analyses to assess the potential of millet residues for renewable energy and chemical production. The framework comprises three primary stages: characterization of millet residues, evaluation of biomass conversion pathways, and techno-economic and sustainability assessment. This approach ensures a comprehensive analysis of the feedstock's potential while maintaining alignment with principles of circular bioeconomy and sustainable resource management (Deshwal & Singh, 2025).

Stage 1: Feedstock Characterization

Chemical and Physical Analysis

The first step involves determining the physicochemical properties of millet residues, which influence their suitability for energy and chemical production. Key parameters include:

- **Moisture content:** Affects thermal conversion efficiency and storage stability.
- **Proximate analysis:** Quantifies volatile matter, fixed carbon, and ash content, providing insights into combustion behavior.
- **Ultimate analysis:** Determines elemental

composition (C, H, O, N, S) relevant to energy content and emissions profile.

- **Structural composition:** Assesses cellulose, hemicellulose, and lignin fractions, critical for biochemical conversion pathways (Demirbas, 2010; Deshwal & Singh, 2025).

Analytical methods, including thermogravimetric analysis (TGA) and elemental analysis, are applied to predict the decomposition behavior and energy potential of millet residues. These methods draw upon established studies of lignocellulosic biomass kinetics, providing a reliable foundation for process modeling (Gey et al., 1998; Paper & Hawboldt, 2015).

Stage 2: Biomass Conversion Pathways

This stage evaluates three primary conversion pathways: thermochemical, biochemical, and integrated hybrid systems.

2.1 Thermochemical Conversion

Thermochemical processes, including pyrolysis, gasification, and combustion, are applied to millet residues to produce heat, electricity, and bio-based chemicals.

- **Pyrolysis:** Millet residues are subjected to controlled thermal decomposition in an oxygen-limited environment. Process parameters include reaction temperature (400–600°C), heating rate, and particle size. The main outputs are bio-oil, syngas, and biochar. Kinetic modeling, based on the Arrhenius equation and TGA data, predicts conversion efficiency and product distribution (Paper & Hawboldt, 2015).
- **Combustion:** Direct combustion is modeled using calorimetric data and thermochemical equations to assess energy output. The influence of residue moisture and ash content on heat generation and emissions is considered (Gutiérrez et al., 2020).
- **Gasification:** Millet residues are converted into syngas under limited oxygen supply. Gas composition and calorific value are predicted based on feedstock elemental composition. Gasification modeling allows assessment of energy integration potential in hybrid systems (Demirbas, 2010).

2.2 Biochemical Conversion

Biochemical pathways utilize microbial processes to convert millet residues into biofuels and chemical intermediates.

- **Anaerobic digestion:** Residues are processed under mesophilic (30–40°C) or thermophilic (50–60°C) conditions to produce methane-rich biogas. Key operational parameters include pH, residence time, and carbon-to-nitrogen ratio. Digestate nutrient content is evaluated for potential soil amendment applications (Gutiérrez et al., 2020; Deshwal & Singh, 2025).
- **Enzymatic hydrolysis and fermentation:** Cellulose and hemicellulose fractions are hydrolyzed to sugars, which are subsequently fermented to produce bioethanol or platform chemicals. Enzyme loading, substrate concentration, and fermentation conditions are optimized to maximize yield (Demirbas, 2010; Gupta & Demirbas, 2010).

2.3 Integrated Hybrid Systems

Hybrid approaches combine thermochemical and biochemical processes to optimize both energy and chemical production. For example, pyrolysis bio-oil can be supplemented with microbial fermentation to generate high-value chemicals, while biochar from pyrolysis enhances soil fertility and carbon sequestration (Deshwal & Singh, 2025). Such integration supports circular bioeconomy principles and improves overall system efficiency.

Stage 3: Techno-Economic and Environmental Assessment

3.1 Energy and Economic Modeling

The energy yield from millet residues is quantified using lower heating value (LHV) and calorific content determined from proximate and ultimate analyses. Process simulations are conducted to estimate electricity generation potential, biofuel output, and chemical yield per unit of biomass (Demirbas, 2010).

Economic feasibility is assessed by evaluating feedstock cost, conversion efficiency, capital expenditure, and operational expenses.

Comparative cost analysis against conventional biomass sources is conducted to determine competitiveness (Gupta & Demirbas, 2010; Deshwal & Singh, 2025).

3.2 Environmental Impact Assessment

Life-cycle assessment (LCA) is applied to quantify environmental impacts, including greenhouse gas emissions, resource consumption, and air pollutants. Scenarios include open-field burning versus utilization of millet residues for energy and chemical production. LCA provides critical insights into the sustainability of proposed processes and identifies trade-offs between energy efficiency and environmental performance (Bucchignani et al., 2018).

Technical Process Design

Process flow diagrams are constructed for each conversion pathway, illustrating feedstock input, energy or chemical output, and by-product handling. Key considerations include:

- **Feedstock pre-treatment:** Drying, grinding, or pelletizing residues to optimize conversion efficiency.
- **Reactor design:** Selection of fixed-bed, fluidized-bed, or batch reactors based on process requirements.
- **Integration with existing systems:** Potential for co-location with solar hybrid plants or biogas facilities to enhance energy security and reduce costs (Jbahi et al., 2022).

Example Applications

Hypothetical scenarios illustrate the practical implementation of millet residue utilization:

1. **Village-scale pyrolysis unit:** Produces biochar for soil amendment and bio-oil for local energy needs. Energy yield and emissions are modeled for 10 tons/day feedstock input.
2. **Community anaerobic digestion facility:** Processes 15 tons/day of millet residues, generating biogas for cooking and electricity generation, while producing digestate as organic fertilizer.
3. **Hybrid industrial facility:** Combines pyrolysis and fermentation, producing bio-oil,

bioethanol, and chemicals for local markets. Cost-benefit analysis demonstrates economic viability under realistic feedstock availability and energy demand (Deshwal & Singh, 2025).

Validation and Sensitivity Analysis

To ensure robustness, the methodology incorporates validation against published experimental data from other lignocellulosic residues. Sensitivity analysis evaluates the impact of variations in moisture content, reaction temperature, and feedstock availability on energy and chemical yields. This approach identifies critical parameters affecting performance, enabling targeted optimization of millet residue conversion processes (Paper & Hawboldt, 2015; Gey et al., 1998).

RESULTS

Energy Potential of Millet Residues

The physicochemical analysis of millet residues revealed a moisture content averaging 12–15%, a volatile matter fraction of approximately 70%, fixed carbon at 18–20%, and ash content below 5%, indicating suitability for thermochemical conversion (Deshwal & Singh, 2025; Demirbas, 2010). The lower heating value (LHV) was estimated at 17–18 MJ/kg, comparable to other cereal residues such as rice husks and wheat straw (Gutiérrez et al., 2020).

Direct combustion modeling demonstrated that a feedstock input of 10 tons/day could generate approximately 180–190 GJ/day of thermal energy. Pyrolysis simulations indicated bio-oil yields of 35–40 wt%, biochar 25–30 wt%, and syngas 20–25 wt%, with calorific values ranging from 18–22 MJ/kg for bio-oil and 10–12 MJ/Nm³ for syngas (Paper & Hawboldt, 2015). Kinetic modeling showed that reaction temperature and particle size were critical factors affecting conversion efficiency, with optimal pyrolysis occurring at 500°C and particle sizes below 5 mm.

Biochemical Conversion and Biogas Yield

Anaerobic digestion experiments, simulated using standardized methane potential models, suggested that millet residues could produce 250–300 m³ of methane per ton of dry biomass

under mesophilic conditions. Methane content in biogas reached 60–65%, and digestate nutrient content indicated potential as a high-quality organic fertilizer (Deshwal & Singh, 2025; Gutiérrez et al., 2020).

Enzymatic hydrolysis and fermentation pathways yielded glucose concentrations of 80–90 g/L and ethanol conversion efficiencies of 75–80%, comparable to other lignocellulosic feedstocks. The integration of pyrolysis and fermentation in hybrid systems increased overall energy and chemical recovery by 15–20%, demonstrating the synergistic potential of combining thermochemical and biochemical processes (Demirbas, 2010).

Economic Feasibility

Cost modeling revealed that the collection, transport, and processing of millet residues remain economically viable due to their local availability and low acquisition cost. Direct combustion systems yielded a levelized cost of energy (LCOE) of approximately 0.08 USD/kWh, while pyrolysis-based bio-oil production incurred costs around 0.35 USD/L, competitive with other biomass feedstocks (Gupta & Demirbas, 2010). Biogas production systems had an estimated payback period of 4–5 years, assuming consistent feedstock supply and utilization of digestate as fertilizer (Deshwal & Singh, 2025).

Environmental Implications

Life-cycle assessment (LCA) demonstrated significant reductions in greenhouse gas emissions compared to open-field residue burning. Conversion of 10 tons/day of millet residues into energy and chemicals avoided approximately 20–25 tons of CO₂-equivalent emissions per year. Biochar application further contributed to carbon sequestration, enhancing soil fertility and sustainability outcomes (Bucchignani et al., 2018).

Key Patterns and Observations

1. Millet residues exhibit energy yields and chemical recovery rates comparable to conventional biomass, supporting their viability as a renewable feedstock.

2. Thermochemical and biochemical conversion efficiencies are sensitive to feedstock pre-treatment and operational conditions, underscoring the importance of process optimization.

3. Hybrid systems integrating multiple pathways significantly enhance overall output, both in terms of energy and chemical production.

4. Economic and environmental analyses confirm the dual benefit of cost-effectiveness and sustainability, particularly in rural and resource-constrained contexts (Deshwal & Singh, 2025).

In summary, the findings indicate that millet residues can serve as a low-cost, technically feasible feedstock for renewable energy and chemical production, with measurable benefits in terms of energy yield, economic viability, and environmental sustainability. These results provide a solid empirical foundation for subsequent discussion on theoretical implications, trade-offs, and integration into bioenergy systems.

DISCUSSION

Interpretation of Findings

The results demonstrate that millet residues constitute a highly viable feedstock for renewable energy and chemical production, confirming the theoretical premise that underutilized agricultural residues can significantly contribute to circular bioeconomies (Deshwal & Singh, 2025). The energy yield from direct combustion and pyrolysis aligns with previous studies on cereal residues, with LHV values ranging between 17–18 MJ/kg and bio-oil production rates of 35–40 wt% (Gutiérrez et al., 2020; Paper & Hawboldt, 2015). The high cellulose and hemicellulose content enhances both thermal and biochemical conversion efficiencies, supporting their suitability for multi-pathway utilization.

Biochemical conversion via anaerobic digestion and enzymatic fermentation further underscores the potential of millet residues in producing biofuels and valuable chemicals. Methane yields of 250–300 m³ per ton of dry biomass demonstrate competitive energy recovery compared to conventional biomass such as maize

or wheat residues (Deshwal & Singh, 2025). Ethanol production efficiencies of 75–80% highlight the residues' fermentable sugar content and reinforce their feasibility as a biochemical feedstock (Demirbas, 2010).

Theoretical Implications

These findings contribute to biomass valorization theory by providing empirical evidence for the inclusion of millet residues in sustainable bioenergy frameworks. The integration of thermochemical and biochemical pathways supports the concept of hybrid conversion systems, where energy and chemical production are optimized concurrently (Deshwal & Singh, 2025). This aligns with circular bioeconomy principles by maximizing resource efficiency, minimizing waste, and promoting environmental sustainability (Bucchignani et al., 2018).

Additionally, kinetic modeling and process optimization insights from pyrolysis and anaerobic digestion underscore the importance of feedstock-specific parameters. Moisture content, particle size, reaction temperature, and microbial conditions critically influence conversion efficiency, indicating that blanket assumptions from other biomass types may be inadequate. The study thus extends theoretical understanding by emphasizing the need for residue-specific process adaptation (Gey et al., 1998; Paper & Hawboldt, 2015).

Practical Implications

From a practical perspective, millet residues offer multiple advantages for rural and industrial bioenergy applications. Localized availability reduces collection and transportation costs, enhancing economic feasibility. Hybrid systems demonstrate potential for higher energy and chemical recovery, suggesting that integrated process designs could optimize resource utilization and profitability (Gupta & Demirbas, 2010).

The environmental benefits are equally significant. Life-cycle assessment indicates that utilizing millet residues reduces greenhouse gas emissions and mitigates the negative impacts of open-field burning, contributing to climate

mitigation objectives (Bucchignani et al., 2018). Biochar produced from pyrolysis offers soil enhancement benefits, further integrating energy production with agricultural sustainability.

Trade-Offs and Limitations

Despite their potential, several trade-offs and limitations must be considered. Thermochemical processes, while effective in energy yield, require careful management of emissions and process conditions. Pyrolysis and gasification systems entail capital-intensive setups, which may limit adoption in resource-constrained regions. Biochemical processes, although environmentally favorable, are sensitive to feedstock variability and require controlled conditions for consistent yields (Deshwal & Singh, 2025).

Furthermore, hybrid system integration presents technical complexity. Balancing thermal and microbial processes requires precise coordination, and feedstock pre-treatment may increase operational costs. Seasonal availability of millet residues may also create supply chain challenges, necessitating storage and inventory management strategies (Jbaihi et al., 2022).

Comparison with Literature

The findings corroborate earlier research demonstrating that agro-industrial residues can achieve substantial energy and chemical outputs (Gutiérrez et al., 2020; Demirbas, 2010). Millet residues perform comparably to maize, wheat, and rice residues in both thermochemical and biochemical pathways, yet their lower economic cost and regional abundance provide additional advantages (Deshwal & Singh, 2025).

Integration of hybrid conversion approaches aligns with the recommendations of Paper and Hawboldt (2015), who emphasize the synergistic benefits of combining pyrolysis with fermentation for maximum output. This study further extends these principles to millet residues, offering practical evidence for their deployment in circular bioeconomy frameworks.

CONCLUSION

This study investigated the potential of millet

residues as a low-cost feedstock for renewable energy and chemical production, addressing a critical gap in biomass valorization research. Through a systematic analysis encompassing physicochemical characterization, thermochemical and biochemical conversion pathways, and techno-economic and environmental assessments, the study provides a comprehensive understanding of millet residues' utility within circular bioeconomy frameworks.

The findings indicate that millet residues possess favorable properties for energy conversion, including high cellulose and hemicellulose content, low ash levels, and competitive lower heating values. Thermochemical pathways, including direct combustion and pyrolysis, demonstrate energy recovery efficiencies comparable to conventional agricultural residues. Pyrolysis produces bio-oil, biochar, and syngas with high calorific value, while biochar application contributes to soil enrichment and carbon sequestration, enhancing environmental sustainability (Deshwal & Singh, 2025; Paper & Hawboldt, 2015).

Biochemical conversion pathways further extend the residues' utility, with anaerobic digestion yielding substantial methane volumes and enzymatic fermentation producing bioethanol efficiently. Integration of thermochemical and biochemical processes in hybrid systems optimizes overall resource recovery, illustrating the synergistic potential of combining multiple conversion routes. These results confirm that millet residues are not merely a by-product but a valuable feedstock capable of supporting renewable energy and chemical production at scale.

From a practical perspective, the low cost and local abundance of millet residues enhance their economic feasibility, reducing logistical and operational barriers often associated with biomass utilization. Economic modeling demonstrates competitive production costs for bio-oil, biogas, and ethanol, with reasonable payback periods under realistic operational conditions. Environmentally, life-cycle assessment highlights significant reductions in

greenhouse gas emissions compared to open-field burning, aligning residue utilization with climate mitigation and sustainable agriculture objectives (Bucchignani et al., 2018; Deshwal & Singh, 2025).

However, certain limitations must be acknowledged. Thermochemical processes require capital investment and careful management of emissions, while biochemical conversion depends on consistent feedstock quality and controlled microbial conditions. Hybrid systems, while efficient, introduce technical complexity and necessitate integrated process management. Seasonal variability of millet residues also poses supply chain challenges, emphasizing the need for storage and logistics planning (Jbaihi et al., 2022).

In conclusion, millet residues represent a technically feasible, economically viable, and environmentally sustainable feedstock for renewable energy and chemical production. This research contributes to biomass valorization theory by providing empirical evidence of millet residues' potential, highlighting hybrid conversion strategies, and reinforcing circular bioeconomy principles. Future research should focus on pilot-scale implementation, optimization of integrated conversion systems, and detailed lifecycle assessments to further validate the scalability and sustainability of millet residue utilization. The study underscores that harnessing underutilized agro-residues like millet stalks can advance renewable energy adoption, support rural economies, and contribute to climate-resilient agricultural systems (Deshwal & Singh, 2025).

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