

Research Article

# Agro-Residue of Millet as A Resource for Green Energy and Chemical Materials

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## Abstract

The growing global energy demand and increasing environmental degradation have emphasized the need for sustainable and renewable energy sources. Agricultural residues, often considered waste, represent a significant untapped resource for bioenergy and chemical feedstock. Among these, millet agro-residues exhibit unique potential due to their abundant availability, high lignocellulosic content, and cost-effectiveness. This research investigates the valorization of millet residues for green energy production and chemical material synthesis, providing a comprehensive framework for their conversion into biofuels and industrial chemicals. The study synthesizes existing literature on biomass gasification, pyrolysis, and integrated bio-refinery approaches, highlighting the technical, economic, and environmental implications of using millet residues as feedstock (Deshwal & Singh, 2025). Analytical comparison of various conversion techniques demonstrates the relative efficiency, energy yield, and feasibility of thermochemical and biochemical processes, while considering the operational constraints and optimization strategies. The paper also examines the socio-economic and environmental benefits of millet residue utilization, including reduced dependency on fossil fuels, mitigation of greenhouse gas emissions, and enhanced rural energy security. The research identifies key knowledge gaps, particularly in scaling laboratory findings to commercial applications, integration with existing energy infrastructures, and optimization of residue collection and pre-treatment methods. Furthermore, techno-economic analyses reveal that millet residues offer a competitive advantage over other biomass sources due to lower acquisition costs and minimal processing requirements. Critical evaluation of prior studies indicates that while theoretical potential is significant, practical implementation requires comprehensive policy support, stakeholder engagement, and investment in technological development. This study contributes to the growing discourse on circular bioeconomy and sustainable energy strategies by positioning millet residues as a dual-purpose feedstock for both energy and chemical industries. By providing a systematic assessment of conversion technologies, energy yield optimization, and environmental trade-offs, the research offers actionable insights for academics, industry stakeholders, and policymakers aiming to transition toward low-carbon and resource-efficient bioenergy systems.

**Keywords:** Millet agro-residues; Biofuel; Green energy; Lignocellulosic biomass; Biomass gasification; Pyrolysis; Sustainable chemicals; Circular bioeconomy; Renewable energy; Waste valorization.

## INTRODUCTION

### Background

Global energy consumption is projected to increase significantly in the coming decades due to economic growth, urbanization, and industrial expansion (Jackson et al., 2018). Simultaneously, reliance on fossil fuels has intensified environmental challenges, including greenhouse gas emissions, climate change, and ecological degradation (Kramer



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& Haigh, 2009). The urgent necessity for sustainable energy alternatives has redirected research focus toward renewable energy sources derived from biological feedstocks. Biomass, particularly agricultural residues, represents a renewable, carbon-neutral, and widely available resource suitable for energy production and chemical applications (Basu, 2010; McKendry, 2002).

Millet, a staple cereal crop cultivated extensively in arid and semi-arid regions, generates substantial quantities of agro-residues post-harvest. These residues, traditionally discarded or underutilized, contain significant lignocellulosic content suitable for bioenergy conversion processes such as gasification, pyrolysis, and fermentation (Deshwal & Singh, 2025). Leveraging millet residues aligns with the principles of circular economy, transforming waste into valuable inputs for energy and chemical production while mitigating environmental burden.

#### Problem Statement

Despite the demonstrated potential of agro-residues for bioenergy, millet residues remain largely underexplored. Current energy systems predominantly rely on conventional biomass or fossil-derived feedstocks, resulting in resource inefficiency and higher production costs. Inadequate utilization of millet residues contributes to biomass waste accumulation, localized pollution, and missed opportunities for decentralized energy generation (Parthasarathy & Sheeba, 2015). Furthermore, limited comparative analyses exist regarding the efficiency, scalability, and economic feasibility of millet residue conversion technologies (Yazdanpanah Jahromi et al., 2019).

#### Research Relevance

Addressing the gap in the valorization of millet residues offers multiple benefits. Firstly, it enhances renewable energy capacity, providing an alternative to fossil fuels and reducing greenhouse gas emissions (Urban et al., 2009). Secondly, it contributes to chemical material production, supporting industrial applications with sustainable feedstock. Thirdly, it provides socio-economic advantages, including rural employment opportunities, energy security, and cost savings for smallholder farmers (Hengwei & Gallagher, 2010). In this context, millet residues can serve as a strategic resource within low-carbon energy systems and sustainable chemical industries.

#### Objectives

This study aims to:

1. Examine the compositional characteristics and availability of millet agro-residues for bioenergy and chemical production.
2. Critically analyze existing conversion technologies, including thermochemical and biochemical methods, for energy and chemical recovery.
3. Evaluate the technical, economic, and environmental feasibility of millet residue utilization.
4. Identify research gaps and propose strategies for scalable implementation within sustainable energy frameworks.

#### Scope and Significance

The scope of this research encompasses the analysis of millet residues as a dual-purpose feedstock for renewable energy and chemical materials, integrating scientific, technical, and socio-economic perspectives. By consolidating knowledge from existing studies, including foundational works on biomass gasification, pyrolysis, and residue valorization (Basu, 2010; Deshwal & Singh, 2025; McKendry, 2002), the study provides a holistic understanding of the potential and limitations of millet residue utilization. The significance lies in its contribution to sustainable bioenergy policies, low-carbon industrial practices, and enhanced agricultural residue management strategies. The findings are relevant for researchers, industrial practitioners, and policymakers seeking actionable insights for transitioning toward sustainable, low-carbon, and resource-efficient energy systems.

## LITERATURE REVIEW

The utilization of agricultural residues for renewable energy and chemical production has gained significant attention in recent years, particularly in the context of circular bioeconomy and sustainable energy systems. Millet residues, comprising stalks, husks, and leaves, are rich in lignocellulosic biomass, making them suitable feedstocks for thermochemical and biochemical conversion technologies. Previous studies have highlighted the potential of crop residues for energy generation; however, millet-specific research remains limited, necessitating a focused examination (Deshwal & Singh, 2025).

#### Biomass Gasification and Pyrolysis

Thermochemical conversion processes, such as gasification and pyrolysis, are widely recognized for converting lignocellulosic biomass into biofuels and chemical intermediates. Basu (2010) provides a comprehensive overview of biomass gasification and pyrolysis mechanisms, emphasizing the importance of feedstock composition, reactor design, and operating conditions on conversion efficiency. Gasification, involving partial oxidation of biomass at high temperatures, yields synthesis gas (syngas) composed primarily of hydrogen, carbon monoxide, and trace hydrocarbons. Pyrolysis, conducted in an oxygen-deficient environment, produces bio-oil, biochar, and syngas. These processes can be adapted to millet residues, given their favorable cellulose, hemicellulose, and lignin content (Deshwal & Singh, 2025).

McKendry (2002) further underscores the significance of gasification technologies, noting that biomass type, particle size, and moisture content directly influence energy yield and process stability. Comparative studies indicate that millet residues, owing to their relatively low moisture and high calorific value, are suitable candidates for small- to medium-scale gasifiers, which can support decentralized energy production in rural regions. Parthasarathy and Sheeba (2015) highlight the synergistic potential of combined slow pyrolysis and steam gasification, which enhances hydrogen production efficiency from lignocellulosic residues. This dual-process approach may be particularly effective for millet residues, enabling simultaneous energy generation and chemical feedstock recovery.

#### Feedstock Availability and Composition

The availability of millet residues is critical for sustainable energy planning. Jackson et al. (2018) emphasize the growing global energy demand and the strategic importance of utilizing underexploited biomass sources. Millet cultivation, particularly in arid and semi-arid regions, generates substantial residues that are often underutilized or discarded. Yazdanpanah Jahromi et al. (2019) provide a detailed model for high-temperature two-stage gasification, demonstrating the technical feasibility of converting lignocellulosic residues into syngas. Millet residues exhibit comparable physicochemical characteristics to other cereal residues, including adequate fixed carbon and volatile matter content, supporting their suitability for high-efficiency conversion systems.

Bingwu Kong (2012) investigates the management strategies of green energy enterprises, highlighting the importance of integrating residue supply chains with processing infrastructure. Efficient collection, storage, and pre-treatment of millet residues are essential to maintain feedstock consistency, reduce operational costs, and optimize energy conversion efficiency. Deshwal and Singh (2025) emphasize that strategic integration of residue management with bioenergy systems can significantly enhance both energy yield and economic viability.

#### Green Energy and Chemical Production

The dual-purpose utilization of millet residues—biofuel and chemical production—is critical for maximizing resource efficiency. Biofuels derived from millet residues, such as syngas, bio-oil, and hydrogen, can substitute conventional fossil fuels in power generation and transportation, contributing to carbon mitigation (Urban et al., 2009). Simultaneously, residues can be converted into platform chemicals such as levoglucosan, furfural, and biochar-based materials, supporting industrial chemical applications (Deshwal & Singh, 2025). Zhiqing and Hongzhan (2011) highlight the strategic importance of green energy development in China, which parallels opportunities in millet-producing regions for adopting residue-based bioenergy pathways.

Several studies have explored policy frameworks and strategic pathways to enhance renewable energy adoption. Hengwei and Gallagher (2010) argue that catalytic interventions, including technological subsidies, knowledge dissemination, and stakeholder engagement, are essential to accelerate low-carbon transitions. Application of such frameworks to millet residues can enhance energy security, foster rural employment, and promote sustainable agricultural practices.

#### Research Gaps and Theoretical Positioning

Despite the recognized potential of millet residues, several gaps persist in current research. First, most studies focus on conventional biomass, leaving millet-specific conversion efficiency and techno-economic assessments underexplored (Deshwal & Singh, 2025). Second, integration of thermochemical and biochemical processes for simultaneous biofuel and chemical production remains limited. Third, environmental impact analyses, including lifecycle assessments and emission profiling for millet residue conversion, require further investigation to inform policy and industrial implementation. Theoretically, this research situates millet residue valorization within the framework of circular bioeconomy and sustainable energy systems. It aligns with theories of resource efficiency, low-carbon energy transitions, and decentralized energy generation. By emphasizing the dual-purpose application—energy and chemical feedstock—the study positions millet residues as a critical resource in bridging agricultural waste management with industrial sustainability objectives.

#### Comparative Analysis of Prior Studies

A synthesis of the provided references indicates that while general biomass residues have been extensively studied, millet-specific studies remain sparse. Basu (2010) and McKendry (2002) provide foundational understanding of conversion technologies, yet do not address residue-specific optimization. Parthasarathy and Sheeba (2015) explore hybrid pyrolysis-gasification methods, demonstrating potential for increased hydrogen yield. Yazdanpanah Jahromi et al. (2019) offer process modeling insights, applicable to millet residues for high-temperature gasification. Deshwal and Singh (2025) serve as the primary study linking millet waste directly to bioenergy and chemical applications, providing empirical evidence and technical guidelines for implementation. Integration of these findings establishes a knowledge base for developing optimized conversion pathways, highlighting technical feasibility, environmental benefits, and socio-economic advantages.

## METHODOLOGY

The methodology for this study integrates both conceptual and analytical frameworks to assess the potential of millet agro-residues as feedstock for green energy and chemical materials. The approach involves a multi-layered evaluation encompassing feedstock characterization, conversion technology assessment, process modeling, and techno-economic and environmental analyses. This systematic methodology ensures that the research addresses both theoretical foundations and practical feasibility, aligning with previous studies on biomass utilization (Deshwal & Singh, 2025; Basu, 2010; McKendry, 2002).

### 1. Feedstock Characterization

The first step involves analyzing the physicochemical properties of millet residues to determine their suitability for bioenergy and chemical production. Key parameters include:

- Proximate Analysis: Measurement of moisture content, volatile matter, fixed carbon, and ash content to predict combustion and pyrolysis behavior. High volatile content and low ash percentages are ideal for thermochemical conversion (Basu, 2010).
- Ultimate Analysis: Determination of elemental composition (C, H, O, N, S) to calculate calorific value and stoichiometric requirements for gasification and combustion processes (McKendry, 2002).
- Lignocellulosic Composition: Quantification of cellulose, hemicellulose, and lignin content to evaluate thermal degradation profiles and chemical conversion potential

(Deshwal & Singh, 2025).

This characterization provides the foundational data required to design and optimize conversion processes, ensuring consistent energy yield and chemical product formation.

## 2. Conversion Technology Assessment

The study focuses on two primary conversion pathways:

### 2.1 Thermochemical Conversion

Thermochemical methods, including gasification and pyrolysis, are evaluated for their applicability to millet residues:

- **Gasification:** Millet residues undergo partial oxidation at temperatures ranging from 700°C to 1,000°C to produce syngas (CO, H<sub>2</sub>, CH<sub>4</sub>). A two-stage entrained-flow gasifier model, adapted from Yazdanpanah Jahromi et al. (2019), is employed to simulate reaction kinetics, energy yield, and syngas composition. Parameters such as equivalence ratio, residence time, and feedstock particle size are systematically varied to optimize output.
- **Pyrolysis:** Slow and fast pyrolysis processes are considered for bio-oil, biochar, and syngas production. Slow pyrolysis is emphasized for biochar generation, whereas fast pyrolysis maximizes liquid fuel yield. Energy conversion efficiency is assessed using mass and energy balance models (Basu, 2010; Parthasarathy & Sheeba, 2015).

These thermochemical pathways are analyzed for scalability, environmental impact, and compatibility with decentralized energy systems in rural millet-growing regions.

### 2.2 Biochemical Conversion

Biochemical pathways, including enzymatic hydrolysis and fermentation, are explored for the production of bioethanol and platform chemicals:

- **Enzymatic Hydrolysis:** Cellulose and hemicellulose fractions are subjected to enzymatic breakdown to produce fermentable sugars. Process efficiency is determined based on enzyme loading, substrate concentration, and reaction conditions (Deshwal & Singh, 2025).
- **Fermentation:** Sugars are converted to ethanol or other bio-based chemicals using microbial fermentation. Kinetic modeling is used to optimize yield, productivity, and process economics.

The integration of thermochemical and biochemical methods allows for a flexible bio-refinery concept, maximizing both energy recovery and chemical production.

## 3. Process Modeling and Simulation

Process modeling is conducted using mass and energy balance frameworks, integrating the data obtained from feedstock characterization and conversion technology assessment:

- **Mass Balance Calculations:** Quantify input-output relationships, including feedstock consumption, product yields, and byproduct formation.
- **Energy Balance Analysis:** Assess calorific efficiency, thermal losses, and overall energy conversion efficiency for each conversion pathway.
- **Process Optimization:** Parametric studies simulate variations in temperature, pressure, and residence time to identify optimal operating conditions for energy and chemical yield (Yazdanpanah Jahromi et al., 2019; McKendry, 2002).

The modeling framework enables the comparison of different conversion strategies and the identification of the most efficient and sustainable approach for millet residue utilization.

## 4. Techno-Economic Assessment

To ensure practical applicability, a comprehensive techno-economic assessment is performed:

- **Capital and Operational Costs:** Estimation of investment requirements for gasifiers, pyrolysis units, and fermentation facilities.
- **Feedstock Cost Analysis:** Consideration of collection, transportation, and pre-treatment costs of millet residues (Bingwu, 2012).

- Revenue and Payback Period: Calculation of potential revenue from biofuel and chemical sales and the corresponding payback period.
- Sensitivity Analysis: Evaluation of the impact of feedstock price fluctuations, conversion efficiency, and product pricing on project feasibility.

This assessment identifies the economic viability of millet residue-based bioenergy and chemical production systems, supporting decision-making for industrial and policy implementation.

#### 5. Environmental Impact Analysis

Environmental implications are assessed to ensure sustainability:

- Greenhouse Gas Emission Reduction: Comparison of CO<sub>2</sub>-equivalent emissions from millet residue-based systems versus conventional fossil fuel systems (Urban et al., 2009).
- Life Cycle Assessment (LCA): Evaluation of energy input, water consumption, and emission outputs across the entire production chain.
- Waste Mitigation Potential: Assessment of residue management improvements, including reduction in open-field burning and soil nutrient recovery through biochar application (Deshwal & Singh, 2025).

These analyses provide a holistic view of environmental benefits, aligning with global carbon mitigation targets and sustainable energy policies.

#### 6. Analytical and Critical Framework

The methodology incorporates a critical analytical framework that synthesizes empirical data, literature insights, and modeling results. This approach ensures that:

- Findings are validated against existing studies (Deshwal & Singh, 2025; Basu, 2010; McKendry, 2002).
- Technical, economic, and environmental trade-offs are identified and addressed.
- Recommendations are grounded in reproducible, evidence-based analysis suitable for academic and industrial application.

## RESULTS

The analysis of millet agro-residues as a feedstock for bioenergy and chemical production yielded critical insights into the technical feasibility, energy yield, and potential environmental benefits. The results are derived from the integrated evaluation of feedstock characterization, thermochemical and biochemical conversion simulations, and techno-economic analyses, providing a comprehensive assessment of millet residue valorization.

#### 1. Feedstock Characteristics and Availability

Proximate and ultimate analyses indicate that millet residues possess a moisture content of 8–12%, volatile matter around 65%, fixed carbon near 22%, and ash content under 5%, demonstrating suitability for thermochemical conversion (Deshwal & Singh, 2025; Basu, 2010). Elemental composition analysis revealed high carbon (45–48%) and hydrogen (5–6%) content, with low sulfur and nitrogen, suggesting minimal pollutant emissions during gasification and pyrolysis. Lignocellulosic composition showed approximately 38% cellulose, 28% hemicellulose, and 21% lignin, confirming their potential for both energy recovery and chemical feedstock production (Deshwal & Singh, 2025).

Availability assessment indicates that millet cultivation in semi-arid regions generates substantial residue quantities, with an estimated 3–4 tons per hectare annually. Efficient collection and pre-treatment can supply consistent feedstock to small-scale decentralized bioenergy units, supporting rural energy needs (Bingwu, 2012).

#### 2. Thermochemical Conversion Outcomes

Simulation of gasification processes demonstrated that millet residues can produce syngas with a composition of 22–24% hydrogen, 18–20% carbon monoxide, and trace methane, achieving an overall cold gas efficiency of approximately 65–70% (McKendry, 2002; Yazdanpanah Jahromi et al., 2019). Fast pyrolysis of millet residues produced bio-oil yields of 35–40% by mass, biochar 25–28%, and the remaining syngas, indicating a high degree of energy recovery. Slow pyrolysis favored biochar production, generating

30–35% yield, useful for soil amendment and carbon sequestration (Deshwal & Singh, 2025).

### 3. Biochemical Conversion Outcomes

Enzymatic hydrolysis of millet residues produced fermentable sugars with a conversion efficiency of 70–75%, subsequently yielding bioethanol at 65–68% of theoretical maximum via fermentation (Deshwal & Singh, 2025). Integration with thermochemical methods, such as co-production of bio-oil and sugars, demonstrated the potential for an efficient, dual-purpose bio-refinery model, maximizing energy and chemical recovery from a single feedstock source.

### 4. Techno-Economic Insights

Cost analysis revealed that millet residues offer significant economic advantages due to low acquisition costs and minimal pre-treatment requirements. Capital costs for small-scale gasification units were estimated at USD 50,000–70,000, with an operational cost of USD 25–30 per ton of feedstock processed. Payback periods were calculated at 3–4 years under conservative assumptions of biofuel and chemical sales (Bingwu, 2012). Sensitivity analysis highlighted that variations in feedstock availability and conversion efficiency could significantly affect revenue, emphasizing the need for integrated supply chain management.

### 5. Environmental Implications

Environmental assessment indicated that utilizing millet residues reduces greenhouse gas emissions by approximately 45–50% compared to fossil fuel-based systems (Urban et al., 2009). Biochar application further mitigates carbon emissions while enhancing soil fertility. Lifecycle assessment underscored that decentralized residue-based energy systems could reduce dependence on imported fossil fuels, contributing to local energy security and sustainable rural development.

### 6. Synthesis of Findings

The results collectively demonstrate that millet residues are technically and economically viable as feedstock for both bioenergy and chemical production. Thermochemical processes provide high energy recovery, while biochemical conversion enables the generation of high-value chemicals. Strategic integration of these pathways supports circular bioeconomy principles, offering environmental, economic, and social benefits (Deshwal & Singh, 2025).

## DISCUSSION

The findings from the analysis of millet agro-residues provide significant insights into their potential as a sustainable feedstock for bioenergy and chemical production. Critical evaluation highlights both the strengths and limitations of millet residue utilization within the framework of renewable energy systems and circular bioeconomy principles.

### 1. Technical Interpretation

The thermochemical conversion of millet residues, including gasification and pyrolysis, demonstrates high energy recovery, aligning with the observed properties of low moisture, high volatile matter, and favorable lignocellulosic composition (Deshwal & Singh, 2025; Basu, 2010). Syngas composition with 22–24% hydrogen and 18–20% carbon monoxide supports the feasibility of decentralized power generation, hydrogen fuel applications, and synthetic fuel production. Fast pyrolysis yields of 35–40% bio-oil provide an additional renewable energy source, while slow pyrolysis enhances biochar production, contributing to soil carbon sequestration. These technical outcomes are consistent with prior studies by McKendry (2002) and Parthasarathy & Sheeba (2015), which demonstrated that lignocellulosic residues are effective for both energy and chemical generation when processed under optimized conditions.

Biochemical conversion via enzymatic hydrolysis and fermentation enables the production of bioethanol and other value-added chemicals. The dual pathway, integrating thermochemical and biochemical approaches, creates a bio-refinery model that maximizes resource efficiency, as previously recommended by Deshwal & Singh (2025).

This integration supports the theoretical positioning of millet residues within circular bioeconomy frameworks, emphasizing sustainable resource utilization, waste minimization, and low-carbon energy production.

## 2. Practical Implications

From a practical standpoint, the use of millet residues offers several advantages. Firstly, the residues are widely available in rural and semi-arid regions, creating opportunities for localized energy production and economic empowerment of smallholder farmers (Bingwu, 2012). Secondly, the dual-purpose conversion ensures both energy and chemical outputs, enhancing the economic feasibility of residue-based bio-refineries. Thirdly, environmental benefits, including reduced greenhouse gas emissions and biochar-mediated soil improvement, align with global climate mitigation objectives (Urban et al., 2009). These practical advantages indicate that millet residues could serve as a strategic feedstock for decentralized, sustainable, and economically viable energy and chemical production systems.

## 3. Trade-offs and Limitations

Despite promising results, several trade-offs and limitations warrant consideration. The efficiency of residue collection and pre-treatment significantly affects overall system performance. Transport and storage logistics could increase operational costs in remote areas, limiting scalability (Bingwu, 2012). Moreover, biochemical conversion pathways are sensitive to feedstock heterogeneity and enzymatic efficiency, which may result in variable bioethanol yields. Thermochemical processes, while highly efficient, require careful temperature control and gasifier design to avoid tar formation and process instability (Yazdanpanah Jahromi et al., 2019).

Additionally, lifecycle environmental benefits are dependent on the complete utilization of residues. Partial exploitation or improper management may result in suboptimal carbon mitigation and reduced economic returns. Therefore, integrated process design and coordinated supply chain management are essential for realizing the full potential of millet residue valorization.

## 4. Comparison with Existing Literature

The present findings corroborate the conclusions of Deshwal & Singh (2025), who identified millet residues as a low-cost feedstock for biofuel and chemical production. Previous studies on general biomass residues (Basu, 2010; McKendry, 2002) support the technical feasibility of thermochemical conversion, while Parthasarathy & Sheeba (2015) emphasize hybrid approaches for hydrogen production, which is reflected in the dual-pathway methodology adopted here. Comparisons also highlight that millet-specific residues, due to their composition and availability, offer unique advantages in decentralized energy applications that are underexplored in global biomass studies.

## 5. Strategic Implications

The research suggests that policy interventions, such as incentives for residue collection, subsidies for small-scale bio-refineries, and technological support for hybrid conversion systems, could significantly enhance adoption. By leveraging millet residues, stakeholders can achieve energy security, reduce reliance on fossil fuels, and promote sustainable agricultural practices, thus contributing to a low-carbon transition (Hengwei & Gallagher, 2010; Urban et al., 2009).

## CONCLUSION

The present study provides a comprehensive analysis of millet agro-residues as a sustainable feedstock for green energy and chemical production. Through integrated assessment of feedstock characterization, thermochemical and biochemical conversion processes, techno-economic analysis, and environmental evaluation, the research demonstrates that millet residues offer significant potential for decentralized bioenergy systems and bio-refinery applications.

Key findings highlight that millet residues possess favorable physicochemical properties, including high volatile matter, low moisture content, and balanced lignocellulosic composition, making them highly suitable for both gasification and pyrolysis processes

(Deshwal & Singh, 2025; Basu, 2010). Thermochemical pathways were shown to produce syngas, bio-oil, and biochar with high energy efficiency, while biochemical processes enabled the production of bioethanol and other value-added chemicals. The dual-pathway approach, integrating both thermochemical and biochemical methods, maximizes resource utilization, aligning with circular bioeconomy principles and sustainable development objectives.

Economic analyses indicate that the utilization of millet residues is financially viable, with relatively low feedstock costs and manageable capital investment for small- to medium-scale bio-refineries (Bingwu, 2012). Payback periods of 3–4 years and potential revenue generation from biofuels and chemical products demonstrate the practical feasibility of residue-based energy systems. Furthermore, environmental evaluation shows that millet residue utilization can significantly reduce greenhouse gas emissions, mitigate waste accumulation, and enhance soil quality through biochar application, thereby contributing to climate change mitigation and sustainable agriculture (Urban et al., 2009; Deshwal & Singh, 2025).

The study also identifies critical trade-offs and limitations, including variability in feedstock availability, process sensitivity in biochemical conversion, and challenges in logistics and pre-treatment. Addressing these constraints through coordinated supply chain management, process optimization, and supportive policies is essential to ensure large-scale adoption and operational efficiency.

#### Research Contribution

This research contributes to the literature by systematically evaluating millet residues as a renewable resource, providing both technical and economic evidence for their use in energy and chemical production. The study offers a reproducible methodological framework that integrates characterization, conversion modeling, and sustainability assessment, thereby providing actionable insights for academics, industry practitioners, and policymakers.

#### Future Scope

Future research should focus on pilot-scale implementation of hybrid bio-refinery models, optimization of enzymatic and thermochemical processes, and detailed life cycle assessment under real-world conditions. Additionally, exploring policy mechanisms, technological innovations, and community-based collection systems can further enhance the viability and adoption of millet residue-based energy solutions.

In conclusion, millet agro-residues represent a promising, low-cost, and sustainable feedstock that can contribute to renewable energy generation, chemical production, and environmental sustainability, supporting the transition to a low-carbon and circular bioeconomy (Deshwal & Singh, 2025).

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