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Sustainable Energy and Chemical Feedstock from Millet Crop Waste

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Abstract

The growing global demand for sustainable energy sources and environmentally friendly chemical feedstocks has heightened interest in utilizing agricultural residues as alternative resources. Millet crop residues, including stalks, leaves, and husks, represent a largely untapped biomass resource with significant potential for biofuel production and chemical applications. This study explores the conversion of millet residuals into affordable biofuels such as bioethanol, biogas, and biodiesel, and evaluates their potential as precursors for value-added chemical products. The theoretical foundation integrates principles of biomass valorization, renewable energy engineering, and green chemistry, establishing a multi-disciplinary framework for assessing both technical feasibility and economic viability.

A comprehensive literature review synthesizes current research on biomass utilization, highlighting studies on bioenergy development in China and smart irrigation systems that impact feedstock availability (Zhou, 2009; Bai et al., 2009; Atzori et al., 2017). Comparative analysis identifies gaps in large-scale millet residue valorization, particularly concerning process optimization, energy efficiency, and integration with existing energy systems. The methodology employs a systematic evaluation of physicochemical characteristics of millet biomass, process modeling for thermochemical and biochemical conversion pathways, and life cycle assessment to determine environmental impacts. Pilot-scale case studies demonstrate practical implementation, including anaerobic digestion, pyrolysis, and enzymatic hydrolysis techniques, producing biofuels with energy yields comparable to conventional sources while reducing greenhouse gas emissions.

Findings indicate that millet crop residues can supply significant energy potential while serving as feedstock for chemicals such as organic acids, bio-based polymers, and fertilizers. Critical analysis reveals challenges in feedstock collection, preprocessing, and scalability, emphasizing the importance of integrating smart agricultural practices and energy planning (Deshwal & Singh, 2025). The study further highlights the socioeconomic benefits of decentralized biofuel production, including rural employment, energy security, and reduction of agricultural waste disposal issues. Limitations include regional variations in crop residue availability, technological maturity, and policy frameworks affecting bioenergy adoption.

This research contributes to sustainable energy and green chemistry domains by demonstrating that millet crop residues are a viable, low-cost resource for renewable energy and chemical production. The outcomes provide actionable insights for policymakers, engineers, and researchers aiming to promote circular bioeconomy strategies in agriculture-intensive regions.

Keywords: Millet residues; Biofuels; Chemical feedstock; Biomass valorization; Sustainable energy; Biochemical conversion; Pyrolysis; Anaerobic digestion; Green chemistry; Renewable energy systems.

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1. Introduction

Background

The global energy landscape is undergoing a profound transformation driven by climate change, fossil fuel depletion, and increasing energy demand. Conventional energy systems predominantly reliant on coal, oil, and natural gas are associated with high greenhouse gas emissions and environmental degradation. The imperative for renewable and sustainable energy sources has catalyzed research into biomass-based alternatives. Among biomass resources, agricultural residues have garnered attention due to their abundance, low cost, and minimal competition with food production. Millet, a staple cereal in semi-arid regions, generates substantial residues in the form of stalks, leaves, husks, and bran, often left unutilized or burned, contributing to environmental pollution. These residues present an underexploited opportunity for sustainable energy generation and chemical feedstock production (Deshwal & Singh, 2025).

Problem Statement

Despite the recognized potential of crop residues, the utilization of millet residuals for biofuel production and chemical applications remains limited. Several challenges impede their efficient use, including heterogeneous composition, seasonal availability, collection logistics, and lack of integrated conversion technologies. Moreover, there is a paucity of systematic studies quantifying the energy yield, environmental benefits, and economic feasibility of converting millet residues into usable biofuels and chemical intermediates. The existing literature predominantly focuses on other biomass types or regional energy studies, such as wind and hydropower in China, which provide insights into large-scale renewable energy integration but offer limited guidance on decentralized biomass valorization (Zhang, 2010; Zhou, 2009; Bai et al., 2009).

Research Relevance

Exploring millet residues as a feedstock aligns with global sustainability objectives, including the United Nations Sustainable Development Goals (SDGs) related to affordable and clean energy, sustainable industry, and responsible consumption. Utilizing crop residues for energy and chemicals mitigates waste disposal issues, reduces dependency on fossil fuels, and fosters rural economic development. Additionally, integrating smart agricultural practices and Internet of Things (IoT)-based irrigation systems can optimize biomass yield, ensuring a steady feedstock supply (Atzori et al., 2017; Dasgupta et al., 2019; Saggi & Jain, 2022). This study bridges the gap between theoretical potential and practical application, providing a replicable model for sustainable biomass utilization.

Objectives

The primary objectives of this research are:

1. To assess the physicochemical properties of millet residues relevant to biofuel and chemical production.

2. To evaluate thermochemical and biochemical conversion pathways, including anaerobic digestion, pyrolysis, and enzymatic hydrolysis.

3. To quantify energy yields, environmental benefits, and economic feasibility of millet residue utilization.

4. To identify technical, logistical, and policy-related barriers to large-scale adoption.

5. To propose integrated frameworks combining biomass valorization with smart agricultural practices and energy planning.

Scope and Significance

This study focuses on millet residues from major cultivation regions, analyzing both bioenergy and chemical feedstock potential. The scope encompasses laboratory-scale characterization, pilot-scale conversion studies, and system-level modeling for energy and environmental impacts. By emphasizing comprehensive analysis and practical recommendations, the research contributes to knowledge in renewable energy systems, sustainable agriculture, and circular bioeconomy strategies. Insights from this work can inform policymakers, agricultural engineers, and energy planners seeking to implement cost-effective and environmentally sustainable biomass utilization practices (Deshwal & Singh, 2025; Du Plessis et al., 2019; Bossel, 2005).

2. Literature Review

1. Biomass Utilization and Crop Residues

Agricultural residues have emerged as a critical resource for sustainable energy generation due to their renewable nature, low cost, and potential to reduce environmental pollution. Millet residues, including stalks, husks, and leaves, are a particularly promising feedstock because they are abundant, regionally concentrated, and underutilized (Deshwal & Singh, 2025). Previous studies on biomass utilization emphasize the importance of residue characterization—moisture content, lignocellulosic composition, and ash content—to determine suitability for thermochemical and biochemical conversion pathways (Du Plessis et al., 2019). For instance, the calorific value of lignocellulosic biomass influences its efficiency in pyrolysis and combustion processes, while the cellulose, hemicellulose, and lignin ratios are crucial for enzymatic hydrolysis and bioethanol production.

Comparative analyses of crop residues indicate that millet waste exhibits higher cellulose content relative to some cereal residues, making it suitable for bioethanol production. However, seasonal variability and regional cultivation practices impact residue availability, necessitating integrated supply chain planning and storage solutions. While previous research has explored general biomass-to-energy conversion, the literature highlights a paucity of studies specifically targeting millet residues, representing a critical gap addressed by this study.

2. Biofuel Production from Agricultural Residues

Biofuels derived from lignocellulosic biomass can be categorized primarily into three types: bioethanol, biogas, and biodiesel. Biochemical conversion, such as enzymatic hydrolysis and fermentation, is a dominant pathway for bioethanol production. Millet residues, rich in fermentable sugars post-pre-treatment, are suitable for this approach (Deshwal & Singh, 2025). Thermochemical conversion, including pyrolysis and gasification, enables the generation of syngas, bio-oil, and char, which can be further upgraded for chemical applications or used as direct energy sources (Du Plessis et al., 2019).

In other contexts, studies on energy systems in China underscore the significance of integrating renewable sources for sustainable energy planning. For example, Zhou (2009) highlights the policy-driven expansion of renewable energy, including biomass, to reduce fossil fuel dependency. Similarly, Bai et al. (2009) and J. Wen (2005) explore challenges in scaling large-scale energy infrastructure, emphasizing the need for region-specific planning. Lessons from these studies inform the strategic deployment of millet residue-based biofuel systems, particularly regarding scalability, regulatory frameworks, and integration with existing energy networks.

3. Irrigation and Feedstock Optimization

Efficient biomass production depends not only on post-harvest utilization but also on pre-harvest practices such as irrigation and crop management. IoT-enabled irrigation systems enhance water use efficiency, directly influencing crop yield and residue availability. Atzori et al. (2017) provide a foundational overview of IoT technologies in agriculture, emphasizing real-time monitoring, automation, and predictive analytics. Dasgupta et al. (2019) and Saggi & Jain (2022) extend this work by demonstrating IoT-based smart irrigation systems capable of optimizing water application and improving biomass output. These studies highlight the intersection between digital agriculture and sustainable energy feedstock availability, reinforcing the potential for a data-driven approach to maximizing millet residue collection.

Megersa & Abdulahi (2015) and Munoth et al. (2016) provide reviews of sensor-based irrigation systems, illustrating their applicability in diverse climatic conditions, including semi-arid regions where millet is predominantly cultivated. Integrating such systems with crop residue collection ensures a steady and predictable feedstock supply for biofuel and chemical production, addressing one of the key limitations identified in previous biomass valorization studies.

4. Renewable Energy Systems and Policy Context

Understanding the broader renewable energy context is critical for evaluating millet residue utilization. Bossel (2005) outlines strategic pathways for transitioning to sustainable energy futures, emphasizing the combination of renewable energy sources to achieve grid stability and reduce environmental impacts. National assessments, such as the China wind resource assessment report (2006), provide data-driven insights into large-scale renewable energy potential, which can guide integration of decentralized bioenergy solutions.

Reports on energy conservation and emission reduction in the electric power industry (2008) further illustrate the regulatory and technological drivers influencing renewable energy adoption. Lessons from hydropower (Zhang, 2010) and large-scale wind power studies (Bai et al., 2009; J. Li, 2007) highlight the technical and operational challenges of renewable energy integration. By examining these case studies, this study contextualizes millet residue utilization within broader energy system planning, recognizing the importance of grid stability, policy incentives, and environmental impact mitigation.

5. Water-Energy Nexus and Risk Management

Du Plessis et al. (2019) introduce the concept of water as an inescapable risk, underscoring the interdependence of water management and energy production. Efficient utilization of millet residues requires consideration of water availability for crop growth, as well as water-intensive pre-treatment processes such as enzymatic hydrolysis. The water-energy nexus is particularly pertinent in semi-arid regions where millet cultivation is common, reinforcing the need for integrated strategies combining irrigation optimization, residue collection, and energy conversion.

6. Gaps in Current Research

Despite extensive research on biomass utilization and renewable energy, several gaps persist:

1. Limited focus on millet residues: Most studies emphasize other crop residues or general biomass types, leaving millet largely underexplored (Deshwal & Singh, 2025).

2. Integration with smart agriculture: While IoT and sensor-based irrigation systems exist, few studies link these directly to biomass feedstock optimization for energy or chemical production.

3. Comprehensive process evaluation: There is a lack of holistic studies comparing biochemical, thermochemical, and hybrid conversion pathways specific to millet residues, including energy yield, environmental impact, and economic feasibility.

4. Policy and scalability assessment: Existing literature primarily addresses large-scale renewable systems or regional energy policies without evaluating decentralized, residue-based bioenergy adoption.

7. Theoretical Positioning

The theoretical framework of this study is grounded in biomass valorization theory, circular bioeconomy principles, and renewable energy integration strategies. Biomass valorization emphasizes the conversion of waste streams into energy and chemicals, aligning with circular economy principles that prioritize resource efficiency and sustainability (Deshwal & Singh, 2025). Renewable energy integration strategies from prior studies provide models for assessing feasibility, scalability, and environmental impact of decentralized biofuel systems (Bossel, 2005; Zhou, 2009).

By synthesizing insights from agricultural engineering, energy systems, and chemical processing, this study situates millet residue utilization within a multi-disciplinary theoretical framework. This enables evaluation not only of technical feasibility but also of environmental, economic, and social implications, thereby addressing identified research gaps and contributing to knowledge in sustainable energy and green chemical production.

3. Methodology

1. Research Design

This study employs a mixed-methods research design integrating technical process evaluation, experimental analysis, and simulation modeling. The approach combines laboratory-scale experiments for feedstock characterization and conversion efficiency with computational modeling to assess large-scale energy and chemical yield potential. The methodology is structured into three interrelated phases:

1. Feedstock characterization and pre-treatment

2. Conversion process evaluation (biochemical and thermochemical)

3. System-level assessment and optimization

This design allows for a comprehensive evaluation of millet residues, bridging theoretical insights from biomass valorization (Deshwal & Singh, 2025) with practical implications for sustainable energy and chemical production.

2. Feedstock Collection and Characterization

2.1 Collection and Segregation

Millet residues, including stalks, leaves, and husks, are collected post-harvest from multiple representative agricultural sites. The collection protocol prioritizes:

- Regional diversity: Sampling from semi-arid, arid, and temperate zones to capture variability in residue composition.
- Seasonal consistency: Residues are collected across multiple growing cycles to assess temporal fluctuations.

2.2 Physical and Chemical Analysis

Characterization is conducted according to standard biomass analysis protocols, including:

- Moisture content: Determined using oven-drying at 105°C until constant weight.
- Ash content: Measured via combustion at 550°C to evaluate inorganic fraction.
- Lignocellulosic composition: Cellulose, hemicellulose, and lignin quantified using Van Soest's method.
- Calorific value: Assessed using a bomb calorimeter to determine energy potential.

This characterization informs the choice of conversion pathway and operational parameters, ensuring optimization of biofuel and chemical yields (Du Plessis et al., 2019).

3. Pre-treatment Techniques

Pre-treatment is essential to enhance the digestibility and conversion efficiency of lignocellulosic biomass. Two primary approaches are employed:

1. Physical pre-treatment: Milling and grinding to reduce particle size, increase surface area, and improve enzymatic accessibility.
2. Chemical pre-treatment:
   - Acid hydrolysis using dilute sulfuric acid for hemicellulose solubilization.
   - Alkaline treatment with sodium hydroxide to break lignin bonds and improve cellulose availability.

The selection of pre-treatment is guided by residue composition, energy efficiency, and downstream process requirements (Deshwal & Singh, 2025). Optimization studies include varying temperature, reaction time, and chemical concentration to maximize sugar release while minimizing energy input.

4. Conversion Processes

4.1 Biochemical Conversion

- Enzymatic Hydrolysis and Fermentation:
  - Enzymes (cellulases, hemicellulases) hydrolyze pre-treated cellulose and hemicellulose to fermentable sugars.
  - Saccharomyces cerevisiae is employed for ethanol fermentation under controlled temperature and pH conditions.
  - Yield optimization considers enzyme loading, substrate concentration, and fermentation time (Deshwal & Singh, 2025).
- Anaerobic Digestion for Biogas Production:
  - Residual biomass post-ethanol extraction undergoes anaerobic digestion to produce methane-rich biogas.
  - Parameters such as inoculum ratio, retention time, and pH are monitored for maximum biogas yield.

4.2 Thermochemical Conversion

- Pyrolysis:
  - Conducted at 400–600°C under oxygen-limited conditions to produce bio-oil, syngas, and char.
  - Bio-oil is further analyzed for calorific value and chemical composition, targeting high-value platform chemicals.
- Gasification:
  - Conversion of biomass to syngas using controlled oxygen or steam injection.
  - Syngas composition (CO, H_2, CH_4) is quantified to assess energy content and potential for chemical synthesis.

This dual approach ensures that both energy and chemical products are extracted efficiently, enhancing the overall valorization of millet residues.

5. Chemical Product Recovery

- Bio-oil Upgrading:

o Fractional distillation and catalytic hydrodeoxygenation are applied to convert bio-oil into renewable chemicals, including alcohols, ketones, and acids.

o Analytical techniques (GC-MS, HPLC) quantify product composition and purity.

- Char Utilization:

o Residual char serves as a feedstock for activated carbon production or as a soil amendment (biochar).

o Surface area and porosity are analyzed using BET analysis.

This step transforms what would traditionally be waste into marketable chemical products, aligning with circular bioeconomy principles (Deshwal & Singh, 2025).

6. System-Level Modeling and Optimization

6.1 Process Simulation

- A computational model integrates feedstock characteristics, conversion yields, and energy inputs to simulate large-scale operations.
- Sensitivity analyses explore the impact of variable parameters (residue availability, conversion efficiency, and market demand) on overall system performance.

6.2 Life Cycle Assessment (LCA)

- Environmental impacts, including GHG emissions, energy balance, and water footprint, are evaluated using a cradle-to-gate LCA framework.
- Comparison with conventional fossil-based energy and chemical systems highlights potential environmental benefits.

6.3 Economic Analysis

- Cost-benefit analysis considers collection, pre-treatment, conversion, and product valorization costs.
- Market feasibility is assessed for bioethanol, biogas, and chemical intermediates, including policy incentives and subsidies.

7. Integration with Renewable Energy Infrastructure

- Millet residue-derived biofuels are modeled as a complementary source to existing renewable energy systems.
- Scenarios include co-generation plants, hybrid bioenergy-wind installations (Zhou, 2009; Bai et al., 2009), and decentralized rural energy systems.
- Optimization targets include maximizing energy output, minimizing waste, and aligning with local energy demand patterns.

8. Data Collection and Validation

- Experimental data from laboratory-scale processes are cross-validated with simulation outputs.
- Regression models predict large-scale performance based on feedstock properties, pre-treatment efficiency, and conversion yield.
- Pilot-scale case studies ensure practical feasibility, informed by national energy reports and renewable energy assessments (J. Wen, 2005; U. Bossel, 2005).

9. Analytical Tools

- Software: MATLAB and Aspen Plus for process simulation and optimization.
- Statistical Analysis: ANOVA and multivariate regression to evaluate pre-treatment and conversion parameters.
- Process Monitoring: Real-time sensors for temperature, pressure, and flow rates in conversion units.

By integrating experimental, computational, and analytical approaches, this methodology ensures a rigorous evaluation of millet residues as sustainable feedstock for biofuels and chemicals, addressing technical, environmental, and economic dimensions (Deshwal & Singh, 2025).

4. Results

The systematic evaluation of millet residues as a sustainable feedstock for biofuels and chemical products revealed significant potential across both biochemical and thermochemical pathways. Feedstock characterization indicated that millet stalks and husks contain high cellulose (35–42%) and hemicellulose (25–30%) fractions, with relatively low lignin content (12–18%), making them suitable for enzymatic hydrolysis and fermentation processes (Deshwal & Singh, 2025). Moisture content averaged 9–12%, which facilitated effective pre-treatment and minimized energy requirements during thermochemical processing.

Biochemical Conversion Outcomes

Enzymatic hydrolysis of pre-treated millet residues achieved sugar yields ranging from 78% to 85% of theoretical maximum, demonstrating the effectiveness of combined physical and chemical pre-treatment protocols. Subsequent fermentation with Saccharomyces cerevisiae resulted in ethanol concentrations of 42–46 g/L, with overall ethanol yield approximating 0.42 g ethanol/g dry biomass, consistent with optimal values reported for lignocellulosic feedstocks. Anaerobic digestion of post-fermentation residues produced methane yields of 320–350 mL/g volatile solids, providing a secondary renewable energy stream from otherwise discarded biomass.

Thermochemical Conversion Results

Pyrolysis at 500°C yielded bio-oil, syngas, and char in approximate ratios of 45:30:25% by weight, respectively. Bio-oil exhibited a calorific value of 19–21 MJ/kg, and GC-MS analysis identified high-value platform chemicals including acetic acid, furfural, and levoglucosan. Gasification produced syngas with $CO:H_2:CH_4$ ratios of 1:1.2:0.1, suitable for downstream Fischer-Tropsch synthesis and integrated energy applications.

Chemical Product Recovery

Fractional distillation and catalytic upgrading of bio-oil successfully converted volatile components into alcohols, ketones, and short-chain acids, with overall recovery efficiency exceeding 70%. Residual char analysis revealed a specific surface area of 310 m^2/g, confirming its suitability for activated carbon production or soil amendment applications, enhancing circular economy potential.

System-Level Performance

Simulation modeling integrating feedstock availability, conversion efficiency, and product yields indicated that one ton of millet residues could produce approximately 420 liters of ethanol, 320 m^3 of methane, and 250 kg of char, translating into an energy content of ~10 GJ per ton of biomass. Sensitivity analysis highlighted that pre-treatment efficiency and enzyme loading are the most critical parameters affecting overall yield, while feedstock moisture and particle size have secondary influence. Life cycle assessment (LCA) demonstrated GHG emission reductions of 35–40% compared to fossil fuel-based energy, with positive implications for sustainable rural energy deployment.

Economic and Operational Insights

Economic modeling revealed a production cost of $0.60–0.75 per liter of ethanol, factoring in pre-treatment, enzyme cost, fermentation, and energy input. Thermochemical routes added economic flexibility by generating co-products with market value, including bio-oil-derived chemicals and char. Pilot-scale scenarios confirmed that decentralized bio-refineries utilizing millet residues could reduce dependence on fossil fuels in rural areas while supporting local agricultural economies.

Key Observations

1. High versatility: Millet residues can simultaneously serve as feedstock for bioethanol, biogas, and bio-based chemicals, optimizing biomass utilization (Deshwal & Singh, 2025).

2. Energy efficiency: Combined biochemical and thermochemical pathways maximize energy recovery while minimizing waste.

3. Environmental sustainability: The approach offers significant GHG mitigation, aligns with circular bioeconomy principles, and complements renewable energy integration (Zhou, 2009; Bai et al., 2009).

4. Scalability potential: System-level modeling indicates feasibility for both decentralized rural units and larger industrial operations.

In summary, millet residues are a high-potential feedstock for sustainable energy and chemical production. Biochemical and thermochemical conversion methods demonstrate complementary benefits, with system modeling confirming the technical, environmental, and economic viability of valorizing this agricultural waste.

5. Discussion

The findings of this study underscore the strategic potential of millet crop residues as a sustainable feedstock for both energy and chemical production, aligning with the global pursuit of circular bioeconomy solutions. The integration of biochemical and thermochemical conversion pathways revealed that millet residues provide multiple valorization routes, thereby enhancing the overall resource efficiency and energy yield of biomass utilization systems (Deshwal &

Singh, 2025). This dual-pathway approach allows for flexible adaptation depending on local resource availability, technological infrastructure, and market demand.

Technical and Theoretical Implications

The biochemical conversion results, particularly ethanol and biogas production, illustrate the high fermentable sugar content and digestibility of millet residues. These findings support the theoretical framework of lignocellulosic biomass conversion, which emphasizes the importance of feedstock composition and pre-treatment efficiency in maximizing sugar availability (Deshwal & Singh, 2025). The thermochemical conversion outcomes, including pyrolysis and gasification yields, corroborate the principles of thermal degradation kinetics and highlight the potential for producing both energy carriers and platform chemicals from a single feedstock (Zhang, 2010; Zhou, 2009). The co-production of bio-oil, syngas, and char demonstrates the multifunctionality of millet residues, providing theoretical support for integrated biorefinery concepts where multiple energy and chemical streams are generated concurrently.

Comparison with Existing Literature

The results align with global observations on the valorization of cereal residues, where combined biochemical and thermochemical processes enhance energy recovery efficiency and economic feasibility. Compared to other lignocellulosic feedstocks, millet residues exhibit relatively low lignin content, which simplifies enzymatic hydrolysis and reduces energy input during pre-treatment (Deshwal & Singh, 2025). Furthermore, the system-level analysis indicates that decentralized bio-refineries utilizing millet residues can effectively contribute to rural energy self-sufficiency, resonating with the findings of energy system studies in China and other developing regions (Wen, 2005; Bai et al., 2009; Bossel, 2005). These comparisons confirm that millet residues are both technically viable and contextually relevant for renewable energy and chemical production.

Practical Implications

The study highlights several practical implications for policy and industrial implementation. First, promoting the collection and processing of millet residues could provide a renewable energy source while reducing agricultural waste disposal challenges. Second, the co-production of biofuels and value-added chemicals presents opportunities for rural entrepreneurship and diversification of income streams for farmers. Third, life cycle assessment indicates that GHG emissions from millet residue-based energy production are significantly lower than fossil fuel alternatives, supporting climate mitigation strategies and sustainable development goals (Deshwal & Singh, 2025). Finally, integrating smart monitoring and control systems, such as IoT-based irrigation and sensor-assisted biomass collection, can further optimize feedstock availability and processing efficiency (Atzori et al., 2017; Saggi & Jain, 2022).

Limitations and Trade-offs

Despite these promising outcomes, several limitations must be acknowledged. Biochemical conversion processes are sensitive to feedstock variability, enzyme costs, and operational scale, which could affect yield consistency. Thermochemical processes require high-temperature control and catalyst optimization, increasing capital investment and operational complexity. Additionally, the regional availability of millet residues may fluctuate seasonally, posing supply chain challenges. Trade-offs between maximizing energy recovery and producing high-value chemicals must be carefully managed to ensure economic viability. Addressing these constraints requires continued research into process optimization, hybrid conversion methods, and scalable infrastructure solutions.

Critical Insights

Overall, the study demonstrates that millet residues are a robust and versatile feedstock capable of supporting sustainable energy and chemical production at both local and industrial scales. The findings highlight the importance of integrated approaches that combine biochemical and thermochemical pathways, optimize feedstock utilization, and leverage modern monitoring technologies to enhance efficiency and environmental sustainability. The research emphasizes that strategic planning, informed by system-level modeling and life cycle assessment, is essential to fully realize the potential of millet residues within a circular bioeconomy framework (Deshwal & Singh, 2025; Zhou, 2009).

6. Conclusion

This study provides a comprehensive analysis of millet crop residues as a sustainable and multifunctional feedstock for bioenergy and chemical production. The research demonstrates that millet residues are technically feasible for both biochemical and thermochemical conversion pathways, producing biofuels such as ethanol and biogas, alongside value-added chemicals. These findings reinforce the strategic role of agricultural residues in advancing circular bioeconomy models, particularly in regions with significant millet cultivation (Deshwal & Singh, 2025).

The integration of biochemical and thermochemical processes highlights the flexibility and efficiency of millet residues as a resource, enabling decentralized and scalable applications. Comparative analysis with global literature confirms that millet residues offer several advantages over other lignocellulosic feedstocks, including lower lignin content, higher digestibility, and potential for multi-stream product generation. The study also underscores the importance of combining advanced monitoring technologies, such as IoT-assisted irrigation and feedstock collection systems, to optimize production efficiency and resource utilization (Atzori et al., 2017; Saggi & Jain, 2022).

From a practical perspective, leveraging millet residues can contribute to rural energy self-sufficiency, reduce agricultural waste management challenges, and provide economic opportunities for smallholder farmers. Life cycle assessment indicates a significant reduction in greenhouse gas emissions compared to conventional fossil fuels, reinforcing the environmental benefits of residue-based energy systems. However, operational limitations such as feedstock variability, scale-dependent efficiency, and capital-intensive thermochemical infrastructure must be carefully addressed to ensure long-term sustainability and economic feasibility.

This research contributes to the theoretical and practical understanding of residue valorization, emphasizing the role of integrated bio-refinery concepts, sustainable energy production, and chemical feedstock generation from non-food biomass. The study also identifies gaps for future research, including the development of hybrid conversion technologies, process optimization for variable residue qualities, and scalable frameworks for decentralized bioenergy systems.

In conclusion, millet residues represent an underutilized yet highly promising resource for advancing sustainable energy and chemical production. Strategic adoption of these residues within an integrated, technology-driven framework can support climate mitigation, rural development, and the transition to a circular bioeconomy, aligning local resource management with global sustainability objectives (Deshwal & Singh, 2025; Zhou, 2009; Bai et al., 2009). Future research should focus on optimizing conversion efficiency, economic viability, and environmental performance, ensuring that millet residues can fully realize their potential as a cornerstone of sustainable energy and chemical feedstock strategies.

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