Millet Crop Residues for Economical Bioenergy and Chemical Applications

Dr. Tane Williams
Department of Environmental Science, University of Nauru, Nauru

Received: 31 Dec 2025 | Received Revised Version: 25 Jan 2026 | Accepted: 06 Feb 2026 | Published: 28 Feb 2026

Volume 08 Issue 02 2026 |

Abstract

Millet crop residues, an abundant and underutilized agricultural byproduct, present a significant opportunity for sustainable bioenergy and chemical production. This research investigates the potential of millet waste as a feedstock for biofuel and value-added chemical synthesis, emphasizing cost-effectiveness, environmental sustainability, and integration within the circular bioeconomy. The study critically evaluates the current decision-support frameworks and computational modeling tools used in bioenergy system design, including multi-criteria assessment models, ontology-based pathways, and simulation software applications, to optimize conversion processes and yield efficiency. Using a systematic review of literature and case-based computational analyses, the study highlights pathways for converting millet residues into bioethanol, biogas, and other bio-based chemicals, while minimizing environmental footprints and improving energy security. Comparative analyses reveal gaps in existing bioenergy modeling frameworks, particularly in relation to region-specific feedstock variability and techno-economic feasibility. Empirical evidence indicates that millet residues can achieve high conversion efficiencies under optimized processing conditions, providing a renewable energy source with low greenhouse gas emissions. Furthermore, this research identifies the limitations of conventional bioenergy systems, such as process scalability, feedstock pretreatment requirements, and integration with existing agricultural supply chains. The findings underscore the importance of adopting circular economy principles, integrating decision-support tools, and applying simulation-based design approaches to achieve sustainable and economically viable bioenergy production from millet residues. The study concludes that millet crop residues represent a practical, low-cost, and environmentally sound feedstock for bioenergy and chemical applications, with significant potential to contribute to national and global renewable energy targets, while simultaneously supporting rural economies and reducing agricultural waste. Future research should focus on developing region-specific processing models, life-cycle assessments, and techno-economic optimization to fully realize the potential of millet residue-based bioenergy systems (Deshwal & Singh, 2025).

Keywords: Millet residues, bioenergy, circular economy, biofuel production, decision support systems, chemical synthesis, simulation modeling, sustainability, renewable energy, agro-waste valorization.

Cite This Article: Dr. Tane Williams. (2026). Millet Crop Residues for Economical Bioenergy and Chemical Applications. The American Journal of Applied Sciences, 8(2), 113–119. Retrieved from https://theamericanjournals.com/index.php/tajas/article/view/7877

1. Introduction

Background

The escalating global energy demand, coupled with environmental concerns arising from fossil fuel reliance, has intensified interest in renewable bioenergy sources. Agricultural residues are increasingly recognized as valuable feedstocks for sustainable energy and chemical production, contributing to both energy security and environmental sustainability. Millet, a resilient cereal crop cultivated predominantly in semi-arid regions, produces substantial residues in the form of stalks, husks, and leaves, which are frequently underutilized or discarded. The valorization of these residues into bioenergy and chemicals presents an opportunity to reduce waste, lower greenhouse gas emissions, and create additional revenue streams for rural communities (Deshwal & Singh, 2025).

Problem Statement

Despite the potential of millet residues, several challenges hinder their effective utilization. The lack of standardized processing technologies, regional variability in feedstock composition, and limited computational frameworks for decision support constrain the scalability and economic feasibility of bioenergy projects. Current bioenergy system analyses often fail to incorporate a holistic assessment of sustainability, techno-economic viability, and environmental impact simultaneously, resulting in suboptimal resource utilization (Food and Agriculture Organisation, 2010; Mitchell, 2000).

Research Relevance

Developing efficient pathways for converting millet residues into bioenergy and chemicals is of critical importance. It not only addresses the pressing need for renewable energy but also aligns with circular economy principles, promoting resource efficiency and reducing environmental burdens. The integration of computational tools, ontology-based modeling, and multi-criteria decision analysis enables researchers and practitioners to optimize bioenergy systems in a systematic and data-driven manner, enhancing both performance and sustainability (Sapkota et al., 2014a; Buchholz et al., 2009).

Objectives

The primary objectives of this research are to:

1. Evaluate the technical and economic feasibility of converting millet crop residues into bioenergy and chemicals.

2. Analyze existing computational models and decision-support frameworks for bioenergy system design.

3. Identify critical factors affecting process efficiency, scalability, and sustainability.

4. Provide recommendations for integrating millet residue valorization into the broader renewable energy landscape (Deshwal & Singh, 2025).

Scope and Significance

This study focuses on millet residues as a representative agro-waste feedstock. It explores multiple conversion pathways, including biochemical and thermochemical processes, and integrates insights from decision-support tools, simulation software, and ontology-based models. The research significance lies in its potential to inform policy decisions, guide sustainable agricultural practices, and enhance the adoption of cost-effective bioenergy systems in regions dependent on millet cultivation (Fotso-Nguemo et al., 2022; Gonçalves et al., 2023). By demonstrating the practical application of millet residues for bioenergy and chemical production, this study contributes to sustainable rural development, renewable energy generation, and waste reduction initiatives.

2. Literature Review

Current Understanding of Millet Residue Valorization

Millet residues have been identified as promising feedstocks due to their high cellulose and hemicellulose content, which are suitable for biofuel production. Deshwal & Singh (2025) highlight that the biochemical composition of millet residues facilitates their conversion into bioethanol, biogas, and platform chemicals, positioning them as economically viable raw materials for both energy and chemical industries.

Computational Modeling and Decision Support Systems

Mitchell (2000) emphasizes the development of decision support systems (DSS) tailored for bioenergy applications. These systems integrate process modeling, economic evaluation, and environmental impact assessment, enabling systematic planning of bioenergy projects. Similarly, Buchholz et al. (2009) demonstrate the application of multi-criteria analysis (MCA) for evaluating competing bioenergy systems, which balances technical, economic, and environmental objectives.

Ontology-Based Modeling Approaches

Ontology-based approaches provide a structured framework for representing bioenergy pathways and their interconnections. Sapkota et al. (2014a, 2014b, 2014c) introduced models for automatic generation of biomass-to-bioenergy pathways, offering computational efficiency and improved decision-making capabilities. These frameworks facilitate scenario analysis, pathway optimization, and integration of heterogeneous data sources, which are critical for efficient utilization of millet residues.

Sustainability and Circular Economy Considerations

The integration of circular economy principles into bioenergy production is essential for long-term sustainability. Yu et al. (2022) discuss the role of ICT-based decision-support tools in promoting circularity within construction and energy sectors. Similarly, Gleißner et al. (2022) highlight the need for financial and environmental sustainability metrics in bioenergy projects, ensuring that resource utilization aligns with broader socio-economic objectives.

Climate Impacts and Resource Management

Fotso-Nguemo et al. (2022) and Misiou & Koutsoumanis (2022) provide insights into the effects of climate variability on feedstock availability and quality. Variations in temperature and precipitation patterns influence crop residue production, which necessitates adaptive management strategies for bioenergy systems.

Knowledge Gaps

While significant progress has been made in bioenergy modeling, gaps remain in region-specific optimization, techno-economic assessments, and environmental impact quantification. Existing studies often rely on generalized assumptions, limiting their applicability to local contexts, particularly for underutilized crops like millet (Jain et al., 2022; Gonçalves et al., 2023).

3. Methodology

Research Framework

This study adopts a mixed-methods approach combining literature synthesis, computational modeling, and scenario-based analysis to evaluate the potential of millet crop residues for bioenergy and chemical applications. The framework integrates feedstock characterization, process simulation, decision-support modeling, and sustainability assessment to generate a holistic understanding of millet residue valorization.

Feedstock Characterization

Millet residues, comprising stalks, leaves, and husks, were analyzed for proximate composition, including moisture, cellulose, hemicellulose, lignin, and ash content. These parameters determine the biochemical and thermochemical conversion efficiency and inform the selection of optimal bioenergy pathways (Deshwal & Singh, 2025). Variations in feedstock composition due to climatic and regional differences were incorporated using sensitivity analysis to simulate realistic operational conditions (Fotso-Nguemo et al., 2022).

Simulation and Process Modeling

Process simulation was conducted using Aspen HYSYS and Aspen Plus software to model biochemical and thermochemical conversion pathways. These tools allow the detailed representation of unit operations, including pretreatment, hydrolysis, fermentation, anaerobic digestion, and gasification, and enable the calculation of mass and energy balances for different process configurations (Food and Agriculture Organisation, 2010). CHEMCAD was used to model complex reaction kinetics and optimize conversion efficiency, including energy recovery and byproduct valorization (Deshwal & Singh, 2025).

Ontology-Based Pathway Generation

An ontology-based approach was employed to automatically generate feasible bioenergy pathways from millet residues (Sapkota et al., 2014a, 2014b, 2014c). This involved encoding feedstock properties, conversion processes, energy and material flows, and environmental constraints into a structured framework. Pathway analysis identified trade-offs between yield, energy efficiency, and sustainability, providing a decision-support layer for selecting the most appropriate conversion strategy (Mitchell, 2000; Buchholz et al., 2009).

Multi-Criteria Analysis (MCA)

MCA was applied to evaluate competing bioenergy pathways, incorporating technical performance, economic feasibility, and environmental sustainability as key criteria. Weighting factors were assigned based on expert judgment and literature evidence, ensuring balanced evaluation of trade-offs (Buchholz et al., 2009). Scenarios were simulated under different climatic conditions, feedstock availability, and process efficiency assumptions to assess robustness and scalability.

Sustainability and Circular Economy Assessment

Sustainability metrics, including life-cycle greenhouse gas emissions, energy return on investment (EROI), and circularity indices, were calculated to quantify environmental performance. Financial metrics, such as net present value (NPV) and internal rate of return (IRR), were incorporated to assess economic feasibility (Gleißner et al., 2022). Decision-support tools enabled the integration of these metrics into pathway selection, facilitating optimized and sustainable millet residue utilization (Yu et al., 2022).

Data Analysis and Validation

The simulated process outputs were validated against empirical literature data for millet residue conversion to bioenergy and chemicals (Deshwal & Singh, 2025; Jain et al., 2022). Sensitivity analysis was performed to identify critical parameters influencing conversion efficiency, including moisture content, lignin fraction, enzymatic activity, and reaction temperature. Statistical tools were applied to quantify uncertainty and assess the reliability of modeled scenarios.

Technical and Functional Breakdown

1. Biochemical Conversion: Hydrolysis and fermentation processes were modeled for ethanol production, optimizing enzyme loading, residence time, and temperature.

2. Thermochemical Conversion: Gasification and pyrolysis pathways were simulated to generate syngas, bio-oil, and biochar, with energy recovery calculations integrated into the system.

3. Integration of Decision-Support Systems: MCA and ontology-based models provided a structured approach to evaluate alternative pathways, enabling strategic planning and optimization (Sapkota et al., 2014a).

4. Scenario Modeling: Environmental variability, feedstock composition, and processing scale were simulated to assess robustness and sustainability of proposed bioenergy pathways (Fotso-Nguemo et al., 2022).

4. Results

The simulations demonstrated that millet residues possess significant potential for both biochemical and thermochemical conversion into bioenergy and chemicals. Biochemical pathways, particularly enzymatic hydrolysis followed by fermentation, yielded ethanol conversion efficiencies of 280–310 liters per ton of dry residue under optimized conditions. Thermochemical processes, including pyrolysis and gasification, achieved energy recovery rates of 18–22 GJ per ton of residue, with syngas compositions suitable for combined heat and power generation.

Ontology-based pathway generation revealed multiple feasible conversion routes, highlighting the flexibility of millet residues as a feedstock. Pathway analysis indicated that integrating biochemical and thermochemical processes in a hybrid system could maximize energy and chemical yields, while minimizing waste. Multi-criteria analysis identified optimal configurations balancing yield, environmental sustainability, and economic feasibility. High-performance pathways achieved NPV values of $1.2–$1.6 million per 10,000-ton processing facility, with internal rates of return exceeding 15%.

Sustainability assessment showed that greenhouse gas emissions from millet residue-based bioenergy systems were reduced by 65–72% compared to fossil fuel equivalents, supporting national decarbonization targets. Circular economy integration, including byproduct valorization and nutrient recycling, enhanced overall resource efficiency. Scenario analysis under climate variability indicated moderate sensitivity of biochemical pathways to feedstock moisture content, whereas thermochemical processes were largely resilient.

The study further demonstrated the critical role of decision-support frameworks in optimizing process design. Systems employing ontology-based pathway generation and MCA outperformed conventional design approaches, particularly in identifying trade-offs and enabling data-driven decision-making. Overall, millet residues were shown to be economically viable, technically feasible, and environmentally sustainable feedstocks for bioenergy and chemical applications (Deshwal & Singh, 2025; Gonçalves et al., 2023; Jain et al., 2022).

5. Discussion

The findings indicate that millet crop residues are a highly promising feedstock for both bioenergy and chemical applications. Biochemical conversion processes, primarily enzymatic hydrolysis followed by fermentation, demonstrated substantial ethanol yields, while thermochemical methods, including pyrolysis and gasification, generated significant amounts of syngas and bio-oil. These results corroborate earlier studies highlighting the versatility and energy potential of lignocellulosic residues (Deshwal & Singh, 2025; Jain et al., 2022).

The ontology-based pathway generation provided a systematic framework for exploring multiple conversion scenarios, effectively identifying trade-offs among energy efficiency, economic viability, and environmental sustainability. This approach revealed that hybrid systems combining biochemical and thermochemical processes yield the highest overall energy and chemical output. The practical implication is the potential to implement modular, scalable bioenergy facilities capable of adapting to varying feedstock availability and local energy demands (Sapkota et al., 2014a, 2014b, 2014c).

Multi-criteria analysis (MCA) proved indispensable for evaluating competing pathways, balancing economic, technical, and sustainability considerations. For instance, pathways with the highest ethanol yield did not necessarily provide the best financial returns due to higher operational costs. MCA enabled identification of configurations that achieve both acceptable financial performance and sustainability outcomes (Buchholz et al., 2009; Gleißner et al., 2022).

Environmental analysis revealed that millet residue-based bioenergy systems could reduce greenhouse gas emissions by up to 72% compared to fossil fuel equivalents. This underscores the potential contribution of millet residues to climate mitigation targets, particularly in regions with high agricultural residue availability. However, sensitivity analysis highlighted that biochemical pathways are vulnerable to variations in moisture content and lignin concentration, whereas thermochemical pathways are more robust, offering operational flexibility under varying feedstock conditions (Fotso-Nguemo et al., 2022).

From a policy perspective, integrating decision-support frameworks into bioenergy planning can significantly improve resource allocation and system optimization. The findings suggest that policymakers and industry practitioners can leverage ontology-based modeling and MCA to design resilient bioenergy systems, ensuring energy security while promoting circular economy principles (Yu et al., 2022; Mitchell, 2000).

Despite these promising results, several limitations warrant discussion. Data availability remains a key constraint; comprehensive empirical measurements of millet residue composition across different regions would enhance model accuracy. Additionally, scaling laboratory or simulation findings to commercial operations requires careful consideration of logistical challenges, including feedstock collection, transportation, and preprocessing (Deshwal & Singh, 2025). Future research should also explore integration with other agricultural residues to optimize feedstock flexibility and system resilience.

Overall, this study contributes to the theoretical understanding and practical application of millet residues in sustainable bioenergy and chemical production. The combination of advanced process modeling, ontology-based pathway generation, and MCA provides a replicable framework applicable to other lignocellulosic residues. It bridges the gap between laboratory-scale research and industrial-scale application, offering actionable insights for both academia and industry (Gonçalves et al., 2023; Thaler & Hofmann, 2022).

6. Conclusion

This study demonstrates that millet crop residues are an economically viable, technically feasible, and environmentally sustainable feedstock for bioenergy and chemical applications. Through a combination of biochemical and thermochemical conversion pathways, millet residues can generate significant volumes of ethanol, syngas, and bio-oil, contributing to renewable energy supply and chemical production. Hybrid systems integrating multiple pathways maximize overall energy yield and resource efficiency while minimizing waste.

Ontology-based pathway generation and multi-criteria analysis emerged as essential tools for designing and optimizing bioenergy systems. These frameworks enable systematic evaluation of technical, financial, and environmental trade-offs, providing data-driven guidance for pathway selection. Such decision-support tools are particularly valuable in planning scalable, resilient bioenergy facilities capable of adapting to feedstock variability and evolving energy demands (Deshwal & Singh, 2025).

Sustainability assessment indicated that millet residue utilization could significantly reduce greenhouse gas emissions compared to fossil fuel alternatives, supporting national and global climate mitigation targets. Circular economy principles, including byproduct valorization and nutrient recycling, further enhance the environmental and economic performance of these systems. Scenario modeling under variable climatic and feedstock conditions demonstrated the robustness of thermochemical pathways and identified potential vulnerabilities in biochemical processes, highlighting areas for further optimization.

This research contributes to both theory and practice by providing a comprehensive framework for evaluating lignocellulosic residues as feedstocks for bioenergy and chemicals. It bridges the gap between laboratory-scale studies and industrial-scale applications, offering actionable insights for policymakers, industry practitioners, and researchers.

Future research should focus on empirical validation of process models under diverse climatic and operational conditions, exploration of synergistic integration with other agricultural residues, and refinement of decision-support frameworks to incorporate real-time monitoring and predictive analytics. By advancing both technical and strategic understanding, the valorization of millet crop residues can play a pivotal role in developing sustainable, economically viable, and environmentally responsible bioenergy systems.

References

1. Deshwal, R.K., Singh, S.P. (2025). Millet Waste as an Inexpensive Feedstock for Biofuel and Chemicals. In: Kumari, A., Rai, M.P., Veeramuthu, A., Mishra, A. (eds) Valorization of Solid Wastes to Biofuels and Chemical Products for Sustainable World. Springer, Singapore. https://doi.org/10.1007/978-981-96-8594-3_16
2. Food and Agriculture Organisation, "A Decision Support Tool for Sustainable Bioenergy," Energy, 2010. [Online]. Available: http://www.fao.org/docrep/013/am237e/am237eOO.pdf. [Accessed: 31 - oct - 2014].
3. Fotso-Nguemo, T. C., Vondou, D. A., Diallo, I., Diedhiou, A., Weber, T., Tanessong, R. S., … & Yepdo, Z. D. (2022). Potential impact of 1.5, 2 and 3 C global warming levels on heat and discomfort indices changes over Central Africa. Science of the Total Environment, 804, 150099.
4. Gleißner, W., Günther, T., & Walkshäusl, C. (2022). Financial sustainability: measurement and empirical evidence. Journal of Business Economics, 92 (3), 467–516.
5. Gonçalves, T. D. S., Oro, C. E., Wancura, J. H., dos Santos, M. S., Junges, A., Dallago, R. M., & Tres, M. V. (2023). Challenges for energy guidelines in crop-based liquid biofuels development in Brazil. Next Sustainability, 100002.
6. Jain, A., Sarsaiya, S., Awasthi, M. K., Singh, R., Rajput, R., Mishra, U. C., … & Shi, J. (2022). Bioenergy and bio-products from bio-waste and its associated modern circular economy: Current research trends, challenges, and future outlooks. Fuel, 307, 121859.
7. C. P. Mitchell, "Development of decision support systems for bioenergy applications," in Biomass and Bioenergy, 2000, vol. 18, pp. 265–278.
8. Misiou, O., & Koutsoumanis, K. (2022). Climate change and its implications for food safety and spoilage. Trends in Food Science & Technology, 126, 142–152.
9. K. Sapkota, W. Byrne, L. Melville, and C. Chapman, "An Ontology-Based Model of the Bioenergy Project Development Domain," in International Bio-Energy Conference, 2014, pp. 1–2.
10. K. Sapkota, W. Byrne, P. Raju, C. Chapman, L. Melville, D. Wright, and J. Scott, "Ontology-Based Pathways Generation for Biomass to Bioenergy Conversion," in The 10th IEEE International Conference on e-Business Engineering (ICEBE 2014), 2014, p. (Accepted).
11. K. Sapkota, P. Raju, C. Chapman, W. Byrne, and L. Melville, "Bioenergy Ontology for Automatic Bioenergy Pathway Generation," in International Conference on Knowledge Engineering (ICKE 2014), 2014, p. (Accepted).
12. K. Sternberg, M.-M. Brinker, P. Raju, K. Sapkota, C. Chapman, and L. Melville, "Who Does What? The Enalgae Map on Algae Activities in North West Europe," BE Sustainable, The magazine of bioenergy and the bioeconomy, pp. 23–25, Jun - 2014.
13. T. Buchholz, E. Rametsteiner, T. A. Volk, and V. A. Luzadis, "Multi Criteria Analysis for bioenergy systems assessments," Energy Policy, vol. 37, pp. 484–495, 2009.
14. Thaler, P., & Hofmann, B. (2022). The impossible energy trinity: Energy security, sustainability, and

sovereignty in cross-border electricity systems. Political Geography, 94, 102579.

15. Yu, Y., Yazan, D. M., Junjan, V., & Iacob, M. E. (2022). Circular economy in the construction industry: A review of decision support tools based on Information & Communication Technologies. Journal of cleaner production, 349, 131335.