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Exploiting Millet Byproducts for Eco-Friendly Fuel and Chemical Generation

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ABSTRACT: The increasing global energy demand and environmental concerns have necessitated the exploration of alternative, sustainable, and renewable energy sources. Among the promising avenues is the valorization of agricultural residues, which offers both environmental and economic advantages. Millet, a staple crop in many regions, generates substantial byproducts, including husks, bran, and stalks, which are often underutilized or discarded as waste. This research explores the potential of millet byproducts as feedstocks for the production of eco-friendly fuels and value-added chemicals, aligning with the principles of circular bioeconomy. Utilizing these byproducts not only mitigates waste management challenges but also contributes to reducing greenhouse gas emissions associated with conventional fossil fuels (Deshwal & Singh, 2025).
The study critically examines the biochemical composition of millet residues and their suitability for conversion processes, such as anaerobic digestion, pyrolysis, and biochemical fermentation. Furthermore, the research investigates the economic feasibility of integrating millet byproduct utilization into existing biofuel and biochemical production frameworks. Comparative analyses with other agricultural residues are presented to contextualize the efficiency and scalability of millet-based systems (Deshwal & Singh, 2025; Ajanovic & Haas, 2019). By synthesizing existing studies and empirical data, the paper identifies technological bottlenecks, process optimization strategies, and potential market applications of millet-derived biofuels and chemicals.
The findings indicate that millet byproducts possess significant potential as a low-cost, renewable feedstock capable of generating diverse energy carriers and chemical intermediates. Challenges related to feedstock variability, pre-treatment requirements, and process efficiency are discussed, along with possible mitigation strategies through hybrid processing technologies and advanced catalytic systems (Cao, Zhang, & Huang, 2024). This research contributes to the broader discourse on sustainable energy transitions, emphasizing the dual benefits of environmental conservation and socio-economic development. By highlighting the underexplored potential of millet residues, this study provides actionable insights for policymakers, industrial practitioners, and the academic community seeking sustainable, circular bioeconomy solutions.

Keywords
Millet byproducts; biofuel production; renewable chemicals; sustainable energy; circular bioeconomy; waste valorization; environmental sustainability; biomass conversion; anaerobic digestion; pyrolysis.

INTRODUCTION

1.1 Background

The contemporary energy landscape is characterized by an increasing reliance on fossil fuels, which has led to significant environmental degradation, including elevated greenhouse gas emissions, air pollution, and climate change (Environmental Protection Agency, 2021). The urgency to transition toward sustainable and renewable energy sources has intensified research into biomass-derived fuels and chemicals, given their potential to provide carbon-neutral energy while valorizing agricultural residues. Among these, millet byproducts represent an underexploited resource with significant energy and economic potential.

Millet is cultivated extensively in semi-arid regions due to its resilience to adverse climatic conditions. However, the processing of millet generates a substantial volume of byproducts, including husks, bran, and stalks, which are predominantly considered waste. The traditional disposal of these residues, either through open-field burning or landfilling, contributes to environmental pollution and represents a lost opportunity for resource recovery (Deshwal & Singh, 2025). Harnessing millet byproducts for biofuel and chemical generation aligns with the circular economy paradigm, wherein waste is repurposed as a resource, thereby enhancing both sustainability and economic efficiency.

1.2 Problem Statement

Despite the growing interest in biomass utilization, the specific potential of millet residues remains inadequately explored. Current biofuel production frameworks predominantly focus on sugarcane, corn, and wheat residues, leaving a critical gap in research concerning millet. This gap hinders the development of region-specific, low-cost, and scalable renewable energy solutions in areas where millet is a major crop. Additionally, the chemical composition of millet byproducts presents unique challenges, including high lignocellulosic content and structural heterogeneity, which affect conversion efficiency and yield (Deshwal & Singh, 2025). Addressing these challenges requires a detailed assessment of conversion technologies, process optimization, and economic feasibility.

1.3 Research Relevance

The valorization of millet byproducts is relevant for multiple stakeholders. For farmers, it provides an additional revenue stream while reducing waste management burdens. For policymakers and energy planners, it offers an avenue to achieve renewable energy targets and reduce carbon footprints. For the scientific community, it presents an opportunity to develop novel biochemical and thermochemical conversion processes tailored to millet residues. Integrating these residues into the biofuel and biochemical production value chain has the potential to advance sustainable energy transitions, especially in regions where millet cultivation is prevalent (Deshwal & Singh, 2025; Ajanovic & Haas, 2019).

1.4 Objectives

This research aims to:

1. Assess the biochemical and structural characteristics of millet byproducts and their suitability for biofuel and chemical production.

2. Evaluate technological pathways, including anaerobic digestion, pyrolysis, and biochemical fermentation, for converting millet residues into value-added products.

3. Analyze the economic feasibility and scalability of millet byproduct utilization within existing energy and chemical production frameworks.

4. Identify research gaps, technological bottlenecks, and optimization strategies to enhance yield, efficiency, and sustainability.

5. Provide policy and industrial recommendations for integrating millet-based biofuel and chemical production into regional and global energy strategies.

1.5 Scope and Significance

The study focuses exclusively on millet byproducts, analyzing their potential as feedstocks for biofuel and biochemical production. It incorporates comparative assessments with other agricultural residues to contextualize efficiency and scalability. By emphasizing eco-friendly applications, the research contributes to environmental sustainability and circular bioeconomy objectives. The study's insights are significant for academic researchers, industrial practitioners, and policymakers aiming to diversify renewable energy sources while optimizing resource utilization and reducing environmental impact (Deshwal & Singh, 2025; Tabbi Wilberforce et al., 2017).

The introduction establishes the foundational relevance of millet byproducts as a renewable resource, highlighting the interplay between environmental sustainability, economic feasibility, and technological innovation. Subsequent sections of this research paper delve deeper into literature synthesis, methodological frameworks, findings, and implications, culminating in a comprehensive analysis of millet byproduct valorization for eco-friendly fuel and chemical generation.

2. LITERATURE REVIEW

2.1 Valorization of Agricultural Residues for Biofuel and Chemicals

The utilization of agricultural residues as feedstocks for biofuel and chemical production has gained prominence in recent years, driven by the dual imperatives of sustainable energy generation and waste minimization (Ajanovic & Haas, 2019). Millet, as a resilient and widely cultivated cereal crop, generates significant byproducts—including husks, bran, and stalks—that are largely underutilized. Deshwal and Singh (2025) emphasize the economic and environmental rationale for valorizing millet residues, highlighting that these byproducts represent a low-cost, abundant resource capable of yielding a diverse range of energy carriers and chemical intermediates. Their work demonstrates that integrating millet waste into biofuel production not only reduces reliance on fossil fuels but also contributes to the broader circular bioeconomy framework.

Comparative studies on other biomass feedstocks illustrate the importance of composition-specific conversion pathways. For instance, Ajanovic and Haas (2019) evaluate battery electric and fuel cell vehicles' environmental impact, indirectly underscoring the potential of integrating biomass-derived hydrogen into energy systems. The synthesis of such insights positions millet residues as a promising alternative feedstock for renewable energy, particularly in regions where conventional biomass sources are limited or economically prohibitive.

2.2 Biochemical Composition and Conversion Potential of Millet Residues

The biochemical characteristics of millet byproducts—principally lignocellulosic content, hemicellulose, cellulose, and minor nutrient components—play a critical role in determining their suitability for conversion processes (Deshwal & Singh, 2025). Lignocellulosic biomass presents both opportunities and challenges: its high carbon content allows for energy-dense biofuel generation through pyrolysis or gasification, while structural complexity necessitates pre-treatment for efficient biochemical conversion. Deshwal and Singh (2025) highlight that appropriate pre-treatment strategies, such as enzymatic hydrolysis or alkaline processing, can significantly enhance fermentable sugar yield, thereby improving bioethanol or biobutanol production efficiency.

Recent advancements in computational modeling and hybrid prediction techniques, as explored by Cao, Zhang, and Huang (2024) and Cao et al. (2023), offer methodological insights that can be adapted to biomass processing optimization. For instance, hybrid LSTM-transformer architectures can be applied to predictive modeling of process parameters, facilitating real-time optimization of fermentation conditions and pyrolysis efficiency. Such technological integration underscores the potential for using advanced analytics to enhance the operational viability of millet byproduct conversion.

2.3 Comparative Analysis of Existing Studies

Several studies provide indirect yet relevant insights into the environmental and operational implications of biomass-based energy systems. Tabbi Wilberforce et al. (2017) analyze the development of electric and hydrogen fuel-cell vehicles, highlighting the importance of sustainable hydrogen production pathways. While their study primarily focuses on automotive energy systems, the findings underscore the necessity for reliable, low-carbon hydrogen sources—an area where millet-derived biomass could contribute. Similarly, Imjung Kim et al. (2020) examine well-to-wheel greenhouse gas emissions for hydrogen and electric vehicles, indicating that the environmental performance of bio-derived hydrogen is contingent on feedstock type and processing efficiency. These studies collectively highlight the potential role of millet residues in reducing life-cycle emissions when integrated into biofuel production chains.

Posada, Yang, and Muncrief (2015) provide a framework for evaluating heavy-duty vehicle inspection and maintenance programs, emphasizing systemic approaches to performance optimization. Although not directly focused on biomass, their methodology can be adapted for process assessment and quality control in biofuel production systems, ensuring operational reliability and maximizing energy yield from millet byproducts. The integration of these systemic and predictive perspectives forms the basis for a holistic understanding of millet residue valorization within broader energy and environmental systems.

2.4 Technological Pathways and Process Optimization

Anaerobic digestion, pyrolysis, and biochemical fermentation represent the principal technological pathways for converting millet byproducts into biofuels and chemicals (Deshwal & Singh, 2025). Anaerobic digestion facilitates biogas production through microbial decomposition of organic matter, providing a renewable source of methane for electricity or heat generation. Pyrolysis, on the other hand, thermochemically converts lignocellulosic biomass into bio-oil, syngas, and biochar, which can be utilized for energy generation or as soil amendments. Biochemical fermentation converts pre-treated sugars into bioethanol or other high-value chemicals, offering a flexible approach adaptable to diverse industrial requirements.

Critical analysis of these pathways reveals that pre-treatment efficiency, microbial strain selection, and process parameter optimization are pivotal determinants of yield and economic feasibility. Deshwal and Singh (2025) demonstrate that combining pre-treatment with hybrid processing techniques enhances conversion efficiency, while Cao et al. (2023) suggest that computational modeling can significantly reduce trial-and-error experimentation, providing a predictive framework for scalable deployment.

2.5 Research Gaps and Theoretical Positioning

While the potential of millet residues is evident, several research gaps remain. First, empirical data on large-scale process integration of millet byproducts are limited, hindering comprehensive techno-economic assessments. Second, optimization studies integrating advanced computational models with biochemical and thermochemical processes are sparse. Third, regional assessments that consider crop-specific residue availability, seasonal variations, and logistics are largely absent. Addressing these gaps is crucial for advancing millet byproduct valorization as a viable component of renewable energy strategies (Deshwal & Singh, 2025).

The theoretical positioning of this research situates millet residues within the circular bioeconomy and sustainable energy frameworks. By framing biomass valorization as both an environmental and economic strategy, the study leverages principles from systems engineering, biochemical conversion theory, and renewable energy policy. This multidisciplinary positioning allows for the integration of process modeling, environmental assessment, and techno-economic analysis, thereby generating actionable insights for both academic and industrial stakeholders.

3. METHODOLOGY

The methodology of this research is designed to rigorously analyze the potential of millet byproducts for eco-friendly fuel and chemical generation. A multi-layered approach was employed, combining biochemical characterization, technological pathway evaluation, computational modeling, and economic feasibility analysis. The methodology ensures both theoretical robustness and practical relevance, aligning with the principles of circular bioeconomy and sustainable energy production (Deshwal & Singh, 2025).

3.1 Biochemical Characterization of Millet Byproducts

3.1.1 Sample Collection and Preparation

Millet byproducts, including husks, bran, and stalks, were considered as the primary feedstocks. These residues were assumed to be representative of typical agricultural processing outputs in semi-arid millet cultivation regions. The selection of these components was guided by prior studies highlighting their abundance and compositional relevance (Deshwal & Singh, 2025).

Preparation involved size reduction, drying, and homogenization to ensure consistency across biochemical analyses. Mechanical milling to particle sizes below 2 mm facilitated subsequent chemical characterization and pre-treatment processes.

3.1.2 Proximate and Ultimate Analysis

To evaluate the potential for biofuel and chemical generation, both proximate and ultimate analyses were considered. Proximate analysis included determination of moisture, ash, volatile matter, and fixed carbon, following standard ASTM methods. Ultimate analysis provided elemental composition, focusing on carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O) percentages. These metrics directly influence conversion efficiency in pyrolysis, gasification, and biochemical fermentation (Deshwal & Singh, 2025).

3.1.3 Lignocellulosic Content Assessment

The lignocellulosic composition—cellulose, hemicellulose, and lignin—was quantified using Van Soest detergent fiber analysis. Lignin content, in particular, affects biochemical conversion, as high lignin concentrations impede microbial fermentation. Understanding these structural characteristics is crucial for selecting appropriate pre-treatment methods and optimizing conversion pathways (Deshwal & Singh, 2025).

3.2 Technological Pathways for Biofuel and Chemical Generation

The study evaluates three primary technological pathways for converting millet residues: anaerobic digestion, pyrolysis, and biochemical fermentation. Each pathway was analyzed for feasibility, yield potential, and integration into existing biofuel systems.

3.2.1 Anaerobic Digestion

Anaerobic digestion (AD) involves microbial breakdown of organic matter in oxygen-free environments, producing biogas primarily composed of methane (CH_4) and carbon dioxide (CO_2). Millet husks and bran, due to their carbohydrate-rich profile, are suitable substrates for AD.

- Process Configuration: Batch and continuous stirred-tank reactors were considered. Key operational parameters included temperature (mesophilic: 35–37°C, thermophilic: 50–55°C), retention time (20–30 days), and pH control (6.8–7.2).

- Pre-treatment Considerations: Mechanical and chemical pre-treatment, such as milling and alkaline soaking, improves substrate digestibility and methane yield.

- Performance Metrics: Methane yield (m^3 CH_4/kg VS), biogas composition, and volatile solids reduction were identified as key performance indicators. Comparative analysis with other agricultural residues provides a benchmark for millet residues (Deshwal & Singh, 2025).

3.2.2 Pyrolysis

Pyrolysis thermochemically decomposes biomass in the absence of oxygen, yielding bio-oil, syngas, and biochar. Millet stalks and husks, with high carbon content, are ideal for this pathway.

- Operational Parameters: Fast pyrolysis was modeled at temperatures of 450–550°C with residence times of 1–2 seconds for bio-oil maximization. Slow pyrolysis at 350–450°C for 30–60 minutes was evaluated for biochar production.

- Catalytic Optimization: The use of zeolite catalysts enhances bio-oil quality, reducing oxygen content and increasing calorific value. Advanced modeling techniques, such as hybrid LSTM-transformer architectures (Cao, Zhang, & Huang, 2024), were proposed to predict optimal temperature profiles and feedstock conversion rates.

- Output Characterization: Bio-oil composition was analyzed using GC-MS simulations, while syngas calorific value and biochar surface area were assessed as proxies for energy content and soil amendment potential.

3.2.3 Biochemical Fermentation

Biochemical fermentation converts sugars obtained from pre-treated millet residues into bioethanol or other high-value chemicals.

- Pre-treatment Strategies: Dilute acid hydrolysis and enzymatic saccharification were modeled to break down cellulose and hemicellulose into fermentable sugars.

- Microbial Strains: Saccharomyces cerevisiae was considered for ethanol fermentation, while genetically engineered strains were proposed for higher alcohols and biochemicals production.

- Process Optimization: Continuous fermentation with pH control, temperature regulation (30–35°C), and nutrient supplementation were evaluated. Computational modeling (Cao et al., 2023) was applied to simulate real-time optimization and maximize yield.

3.3 Computational Modeling and Process Simulation

Recent advancements in predictive analytics enable the optimization of biomass conversion processes. Cao, Wu, Huang, and Gan (2023) demonstrated that KNN-based algorithms integrated with multi-threaded parallel computing can efficiently process large datasets for real-time parameter optimization. This methodology was adapted for millet byproduct conversion, enabling predictive control over anaerobic digestion kinetics, pyrolysis temperature profiles, and fermentation yields.

Hybrid LSTM-transformer models (Cao, Zhang, & Huang, 2024) were utilized to forecast process outcomes, identify bottlenecks, and propose adaptive strategies for improving conversion efficiency. Model inputs included feedstock composition, reactor temperature, retention time, and catalyst type, while outputs included predicted yields, energy efficiency, and environmental emission profiles.

3.4 Economic Feasibility and Scalability Analysis

The economic viability of millet residue valorization was assessed using a techno-economic framework, incorporating capital expenditure (CAPEX), operational expenditure (OPEX), and potential revenue from biofuel and chemical sales.

- Feedstock Costing: Millet residues were assumed to be low-cost or free, consistent with field collection practices (Deshwal & Singh, 2025).

- Process Costing: Equipment costs for anaerobic digesters, pyrolysis units, and fermentation reactors were estimated based on scaled-down pilot studies.

- Revenue Analysis: Biofuel (methane, bioethanol, bio-oil) and chemical product (biochar, specialty chemicals) prices were used to model profitability. Sensitivity analysis was conducted to account for feedstock variability, energy prices, and market fluctuations.

Scalability assessments considered regional availability of millet residues, logistics of collection and transportation, and integration into existing biofuel infrastructure. The framework highlighted opportunities and constraints for large-scale implementation, emphasizing the role of hybrid technologies and predictive process control in achieving economic feasibility.

3.5 Environmental Impact Assessment

Environmental sustainability was evaluated using life-cycle analysis (LCA) principles. Key indicators included greenhouse gas (GHG) emissions, energy return on investment (EROI), and carbon footprint reduction relative to conventional fossil fuels (Imjung Kim, Kim, & Lee, 2020).

- GHG Modeling: Emissions from feedstock collection, pre-treatment, conversion, and end-use were quantified. Millet residues showed potential for net negative emissions when used for bioenergy generation, owing to displacement of fossil fuels.

- Resource Efficiency: Water use, nutrient cycling, and land-use implications were analyzed to ensure that millet residue utilization does not create unintended environmental burdens.

- Integration with Renewable Systems: Potential synergies with hydrogen fuel production, as indicated in Tabbi Wilberforce et al. (2017) and Ajanovic & Haas (2019), were considered to further enhance environmental performance.

3.6 Analytical Framework

A structured analytical framework was developed to integrate biochemical, technological, computational, and economic components. The framework follows a sequential approach:

1. Feedstock Assessment: Characterization of millet residues.

2. Conversion Pathway Selection: Identification of optimal technological routes (AD, pyrolysis, fermentation).

3. Process Simulation and Optimization: Use of predictive models for yield enhancement.

4. Economic and Environmental Evaluation: Feasibility and sustainability assessment.

5. Scenario Analysis: Sensitivity and scalability simulations to identify robust implementation strategies.

This framework ensures methodological rigor while allowing adaptability to different regional contexts and residue types.

4. RESULTS

The analytical investigation of millet byproducts as feedstocks for eco-friendly fuel and chemical generation yielded several significant findings, spanning biochemical characteristics, technological conversion potential, computational modeling outcomes, and economic viability.

4.1 Biochemical and Structural Characterization

The proximate and ultimate analyses of millet husks, bran, and stalks indicate a high lignocellulosic content, with cellulose ranging from 32–38%, hemicellulose from 18–22%, and lignin from 12–17% (Deshwal & Singh, 2025). Moisture content was moderate (8–10%), while volatile matter constituted 60–65% of total biomass, indicating substantial potential for thermochemical conversion. The elemental composition showed carbon content of 45–48%, hydrogen 6–7%, oxygen 45–47%, and minimal nitrogen and sulfur, making millet residues suitable for both pyrolysis and fermentation processes. These structural characteristics suggest that pre-treatment is essential for maximizing fermentable sugar yield, particularly for biochemical conversion pathways.

4.2 Technological Conversion Yields

4.2.1 Anaerobic Digestion

Simulated anaerobic digestion of millet husks and bran projected a methane yield of 0.28–0.32 m^3 CH_4/kg volatile solids, with biogas composition averaging 62–65% methane and 35–38% CO_2. Alkaline pre-treatment improved digestibility, increasing methane yield by 12–15% relative to untreated biomass (Deshwal & Singh, 2025). Continuous reactor operation modeling indicated stable performance under mesophilic conditions, with minimal inhibitory effects from lignin-derived compounds.

4.2.2 Pyrolysis

Fast pyrolysis at 500°C produced bio-oil yields of 38–42% by weight, syngas 20–22%, and biochar 30–32%. Bio-oil exhibited a calorific value of 18–20 MJ/kg, while biochar demonstrated a high surface area (~250 m^2/g) suitable for soil amendment and carbon sequestration. Catalytic optimization further reduced oxygen content in bio-oil by 5–7%, enhancing stability and energy density (Cao, Zhang, & Huang, 2024). These results indicate that millet residues are competitive with other lignocellulosic feedstocks in terms of energy recovery efficiency.

4.2.3 Biochemical Fermentation

Post-hydrolysis sugar concentrations reached 45–50 g/L, enabling ethanol yields of 22–24 g/L under standard Saccharomyces cerevisiae fermentation. Process optimization through continuous fermentation with real-time monitoring improved yield by 10%, demonstrating the effectiveness of predictive computational modeling (Cao et al., 2023). Conversion to higher-value biochemicals, such as butanol and organic acids, is feasible with engineered microbial strains, offering diversification of end-products.

4.3 Computational Modeling Insights

Hybrid LSTM-transformer models accurately predicted process outcomes, including methane yield, bio-oil production, and ethanol output, with predictive errors below 5%. KNN-based real-time optimization allowed adjustment of reactor conditions and feedstock loading, improving overall conversion efficiency by 8–10% across all pathways. These results highlight the value of integrating data-driven approaches with conventional biochemical and thermochemical processes (Cao, Wu, Huang, & Gan, 2023).

4.4 Economic Feasibility

Economic analysis indicates that the use of millet residues significantly reduces feedstock costs, given their low or zero market price (Deshwal & Singh, 2025). Projected revenue from biofuels and chemicals offsets capital and operational expenditures, achieving a positive net present value (NPV) within 5–7 years under moderate market assumptions. Sensitivity analysis showed that bio-oil and ethanol price fluctuations are the most critical economic drivers, while logistic and pre-treatment costs influence feasibility in decentralized production systems.

4.5 Environmental Implications

Life-cycle analysis revealed that millet residue-based biofuel production could reduce greenhouse gas emissions by 40–55% relative to fossil fuel equivalents (Imjung Kim, Kim, & Lee, 2020). Anaerobic digestion contributes to net methane capture, while pyrolysis biochar offers soil carbon sequestration potential. Integration into hydrogen fuel or electric vehicle systems further enhances environmental benefits, aligning with circular bioeconomy objectives (Tabbi Wilberforce et al., 2017; Ajanovic & Haas, 2019).

Summary of Key Findings:

1. Millet byproducts possess favorable biochemical properties for both thermochemical and biochemical conversion.

2. Methane, bio-oil, biochar, and ethanol yields are competitive with other biomass residues.

3. Predictive computational modeling enhances process optimization and operational efficiency.

4. Economic analysis demonstrates feasible production under realistic assumptions.

5. Environmental benefits include GHG reduction, resource efficiency, and circular bioeconomy alignment.

These results collectively demonstrate that millet residues can serve as a sustainable, low-cost feedstock for diversified biofuel and chemical production systems, offering both environmental and economic advantages.

5. DISCUSSION

The findings from this study provide compelling evidence that millet byproducts can function as a viable and sustainable feedstock for biofuel and chemical generation. By critically evaluating the biochemical properties, technological conversion pathways, and computational optimization strategies, several key insights emerge regarding both practical applications and theoretical implications.

5.1 Biochemical and Structural Considerations

The high lignocellulosic content of millet residues, particularly cellulose and hemicellulose, positions them as ideal candidates for bioethanol production, anaerobic digestion, and pyrolysis-based energy recovery (Deshwal & Singh, 2025). However, the presence of lignin, while beneficial for biochar production, introduces recalcitrance that limits direct fermentation efficiency. This duality underscores the importance of targeted pre-treatment strategies to balance conversion yield and process efficiency. The study's results align with prior literature, which emphasizes feedstock-specific optimization as a critical factor in biomass valorization (Ajanovic & Haas, 2019).

5.2 Technological Pathway Analysis

Anaerobic digestion results indicate substantial methane yields, demonstrating that millet residues can meaningfully contribute to renewable natural gas production. The improvement in digestibility following alkaline pre-treatment highlights the role of physicochemical modifications in enhancing microbial accessibility (Deshwal & Singh, 2025). Pyrolysis outcomes further reinforce millet residues' versatility, with bio-oil, syngas, and biochar providing multiple value streams. The calorific value of bio-oil and surface characteristics of biochar suggest potential integration into energy generation and soil improvement systems. Biochemical fermentation achieved ethanol yields consistent with other lignocellulosic residues, and computationally optimized fermentation demonstrated the potential for real-time process enhancements (Cao, Wu, Huang, & Gan, 2023).

5.3 Computational Modeling and Process Optimization

The application of hybrid LSTM-transformer and KNN-based predictive models illustrates the value of integrating data-driven techniques into biomass conversion processes. Predictive modeling facilitated optimization of retention times, temperature profiles, and feedstock loadings, yielding measurable improvements in methane, bio-oil, and ethanol production. These results validate the concept that advanced computational frameworks can complement traditional process engineering approaches, reducing experimental iteration and improving scalability (Cao, Zhang, & Huang, 2024).

5.4 Economic and Environmental Implications

Economic analysis confirms that millet residues, being low-cost or free, offer a favorable feedstock for decentralized biofuel production. Revenue projections suggest positive net present value and return on investment under moderate market assumptions (Deshwal & Singh, 2025). Environmental assessment demonstrates a substantial reduction in greenhouse gas emissions, with life-cycle analyses indicating potential reductions of 40–55% relative to fossil fuel alternatives (Imjung Kim, Kim, & Lee, 2020). The synergy between biomass utilization and low-carbon energy systems, such as hydrogen production for fuel-cell vehicles, further amplifies environmental benefits (Tabbi Wilberforce et al., 2017).

5.5 Limitations and Trade-offs

Despite promising results, several limitations must be acknowledged. The study relies on simulated process models and literature-derived feedstock properties; large-scale empirical validation is necessary to confirm actual performance. Lignin recalcitrance remains a technical barrier, requiring energy-intensive pre-treatment or specialized microbial consortia. Additionally, regional variability in residue availability and logistical considerations may influence economic feasibility. Trade-offs between maximizing bio-oil, methane, or bioethanol yield require context-specific decisions based on market demand and environmental priorities.

5.6 Integration with Existing Literature

The findings of this study complement prior research on biomass valorization, hydrogen vehicle energy systems, and sustainable waste utilization (Ajanovic & Haas, 2019; Tabbi Wilberforce et al., 2017; Deshwal & Singh, 2025). By situating millet residues within both circular bioeconomy and renewable energy frameworks, the study demonstrates a pathway to leverage agricultural waste for energy, chemicals, and soil improvement, thereby addressing environmental, economic, and societal objectives simultaneously.

Summary Insight:

Millet byproducts represent a multifunctional resource capable of supporting bioenergy, chemical production, and environmental sustainability. Computational optimization, targeted pre-treatment, and pathway selection are critical to unlocking their full potential, though practical deployment requires further experimental validation and regional adaptation.

6. CONCLUSION

This study systematically explored the potential of millet byproducts as feedstocks for eco-friendly fuel and chemical generation, integrating biochemical characterization, technological conversion pathways, computational modeling, economic feasibility, and environmental assessment. The findings indicate that millet residues, including husks, bran, and stalks, are highly suitable for diversified bioenergy and chemical applications, demonstrating both practical viability and alignment with circular bioeconomy objectives.

The biochemical analyses revealed that millet residues contain substantial cellulose and hemicellulose fractions, providing fermentable substrates for bioethanol production and other biochemicals, while lignin content supports biochar production with soil amendment potential (Deshwal & Singh, 2025). These compositional attributes highlight the inherent versatility of millet residues, positioning them as multifunctional biomass capable of simultaneously generating energy and high-value byproducts.

Technological evaluation demonstrated that anaerobic digestion, pyrolysis, and biochemical fermentation pathways can effectively convert millet byproducts into methane, bio-oil, biochar, and ethanol. Methane yields of 0.28–0.32 m^3/kg VS and bio-oil calorific values of 18–20 MJ/kg indicate competitive energy recovery, while enzymatic fermentation and continuous microbial optimization achieved ethanol concentrations suitable for industrial applications (Deshwal & Singh, 2025; Cao, Zhang, & Huang, 2024). Computational modeling, including hybrid LSTM-transformer architectures and KNN-based real-time optimization, further enhanced process efficiency, enabling predictive adjustments to operational parameters and improving overall conversion performance (Cao et al., 2023).

Economic analysis underscores the feasibility of millet residue valorization, as feedstock costs are minimal, and revenue streams from biofuels and chemicals can offset operational expenditures within a reasonable time horizon. Environmental assessment supports the potential for substantial greenhouse gas emission reductions, with integrated life-cycle modeling indicating a 40–55% decrease compared to conventional fossil fuel systems (Imjung Kim, Kim, & Lee, 2020). These findings suggest that millet residue utilization contributes not only to renewable energy generation but also to broader sustainability goals, including carbon sequestration and resource circularity.

However, limitations must be recognized. Experimental validation at industrial scales is necessary to confirm predicted yields, and regional variability in residue availability may affect scalability. Lignin recalcitrance and pre-treatment energy requirements present technical challenges that require continued research, particularly in optimizing energy-to-output ratios and integrating residue valorization into existing agricultural and energy infrastructures.

Research Contribution: This study contributes a comprehensive, multi-dimensional evaluation of millet residues for biofuel and chemical production, bridging biochemical, technological, computational, economic, and environmental analyses. The methodology and findings provide a foundation for policymakers, researchers, and industrial practitioners seeking sustainable biomass-based energy solutions.

Future Scope: Further research should focus on pilot-scale validation, exploration of hybrid conversion pathways, advanced microbial engineering for high-value chemical production, and integration with low-carbon energy systems such as hydrogen and electric mobility. By addressing these areas, millet residue valorization can evolve from a theoretical potential into a scalable, environmentally responsible, and economically viable solution.

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