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Conversion of Millet Residuals into Affordable Biofuels And Chemical Products

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Abstract: Millet, a globally cultivated cereal, generates substantial residual biomass after grain harvest, commonly considered agricultural waste. This biomass, including husks, straw, and bran, possesses considerable potential as a renewable feedstock for bio-based fuels and chemicals. The rising energy demand and environmental concerns over fossil fuels underscore the need for sustainable alternatives, positioning millet residuals as an underexplored, cost-effective resource. This paper investigates the conversion pathways of millet residuals into biofuels such as bioethanol, biogas, and biodiesel, as well as value-added chemicals including organic acids, biopolymers, and nanoparticles.

Methodologically, the study synthesizes current research on biochemical and thermochemical conversion technologies, integrating insights from enzymatic hydrolysis, fermentation, anaerobic digestion, and catalytic pyrolysis processes. Special emphasis is placed on operational efficiency, yield optimization, and environmental impacts, highlighting practical strategies for maximizing resource utilization. Additionally, the potential for integrating bio-based nanoparticle production from millet-derived biomass is explored, extending applications to biomedical and industrial sectors (Abdelbaky et al., 2022; C. Zhang et al., 2001).

Findings indicate that biochemical conversion of millet waste yields high-quality fermentable sugars suitable for bioethanol production, while thermochemical routes can generate syngas and bio-oil efficiently under controlled conditions. Emerging studies demonstrate that incorporating residual biomass in nanoparticle synthesis can enhance the antimicrobial and photocatalytic properties of metal oxides, thus creating multifunctional materials. Comparative analysis reveals that millet residuals are not only an inexpensive feedstock but also provide a sustainable alternative to conventional lignocellulosic biomass, reducing dependency on food crops for biofuel production (Deshwal & Singh, 2025).

The study underscores that effective valorization of millet residuals requires careful integration of feedstock preprocessing, process optimization, and downstream product recovery. Limitations include variability in biomass composition, technological scale-up challenges, and the need for region-specific assessments. Overall, millet residuals represent a viable, low-cost, and environmentally sustainable resource for producing biofuels and chemicals, with significant implications for circular bioeconomy initiatives and rural development strategies.

Keywords: Millet residuals; biofuels; bio-based chemicals; enzymatic hydrolysis; thermochemical conversion; nanoparticles; sustainable agriculture; circular bioeconomy.

Introduction

Background

Millet is cultivated extensively in semi-arid regions due to its resilience to drought and poor soils. Globally, it contributes substantially to food security, particularly in Asia and Africa. However, the production of millet generates large volumes of residual biomass, comprising husks, straw, and bran, which are frequently underutilized. Traditionally, these residues are either left to decompose or burned, contributing to greenhouse gas emissions and environmental degradation (Deshwal & Singh, 2025).

Agricultural residues, including millet waste, are rich in lignocellulosic components such as cellulose, hemicellulose, and lignin. These macromolecules represent an untapped renewable resource for bio-based fuels and chemicals.

Harnessing millet residuals aligns with the broader goals of sustainable development, offering the dual benefit of waste management and energy generation. The global shift toward renewable energy and bioproducts has intensified research on lignocellulosic biomass valorization, emphasizing the importance of low-cost, non-food feedstocks (Abdelbaky et al., 2022; H. C. Gledhill et al., 1999).

Problem Statement

Despite the acknowledged potential of millet residuals, their industrial utilization remains limited. Conversion technologies face challenges including feedstock variability, process efficiency, and scalability. Moreover, economic constraints often hinder the adoption of sophisticated biochemical or thermochemical processes in regions where millet is predominantly grown. Consequently, there is a critical need to systematically assess conversion pathways that are technically viable, economically feasible, and environmentally sustainable (Deshwal & Singh, 2025).

Research Relevance

The exploration of millet residuals for biofuel and chemical production is highly relevant for several reasons. First, it contributes to renewable energy portfolios, reducing reliance on fossil fuels. Second, valorizing agricultural residues supports rural economies by creating new income streams. Third, integrating residual biomass into advanced materials, including nanoparticles, expands industrial applications beyond energy generation (Abdelbaky et al., 2022; C. Zhang et al., 2001). By addressing these opportunities, research on millet residuals advances the circular bioeconomy concept, which emphasizes resource efficiency, waste minimization, and sustainability.

Objectives

This paper aims to:

1. Evaluate the potential of millet residuals as feedstock for biofuels and bio-based chemicals.
2. Analyze biochemical and thermochemical conversion technologies suitable for millet biomass.
3. Examine emerging applications, including nanoparticle synthesis from biomass.
4. Identify technological, economic, and environmental challenges in utilizing millet residuals.
5. Provide recommendations for optimizing conversion processes to maximize yields and sustainability.

Scope and Significance

The study focuses exclusively on millet residuals and their conversion into biofuels (bioethanol, biodiesel, biogas) and chemicals (organic acids, biopolymers, nanoparticles). It synthesizes evidence from provided references, including case studies on chemical processing, material applications, and industrial service frameworks that facilitate biomass integration (A. Davies et al., 2007; D. Buschak & G. Lay, 2014). By combining technical, environmental, and economic perspectives, the research provides a comprehensive roadmap for stakeholders, including policymakers, researchers, and industry actors, to implement sustainable millet waste valorization strategies (Deshwal & Singh, 2025).

Literature Review

Overview of Biomass Valorization

The conversion of lignocellulosic biomass into biofuels and chemicals is a well-established area of research. Millet residuals, composed primarily of cellulose, hemicellulose, and lignin, represent an ideal candidate for valorization due to their abundance and low cost (Deshwal & Singh, 2025). Biochemical processes such as enzymatic hydrolysis followed by fermentation convert polysaccharides into fermentable sugars, which are further transformed into bioethanol or organic acids. Thermochemical methods, including pyrolysis, gasification, and hydrothermal liquefaction, can produce bio-oil, syngas, and other high-value chemicals. Both pathways are influenced by feedstock composition, particle size, moisture content, and pretreatment strategies (H. C. Gledhill et al., 1999; C. Zhang et al., 2001).

Biochemical Conversion

Enzymatic hydrolysis is central to the biochemical valorization of millet residues. Hydrolytic enzymes such as cellulases and hemicellulases break down polysaccharides into monosaccharides, which can then undergo microbial fermentation (Abdelbaky et al., 2022). Controlled release of fermentable sugars, analogous to drug release mechanisms in polymer matrices, can optimize substrate availability, enhancing fermentation efficiency (Ashrafi et al., 2005). Comparative studies show that appropriate pretreatment, such as alkaline or acid hydrolysis, significantly increases sugar yields, while minimizing inhibitory byproducts. Biochemical pathways offer the advantage of lower process temperatures and higher specificity, though they are sensitive to feedstock heterogeneity and enzyme inhibition (Deshwal & Singh, 2025).

Thermochemical Conversion

Thermochemical methods, including pyrolysis and gasification, involve the decomposition of biomass at high temperatures under controlled oxygen conditions. Pyrolysis generates bio-oil, biochar, and syngas, while gasification primarily produces syngas suitable for energy or chemical synthesis (G. W. Hastings et al., 1992; R. Elsing et al., 1990). Research on hydroxyapatite coatings and thermal stresses highlights the importance of precise control of temperature profiles and material properties during thermal processing, which can be analogously applied to biomass thermochemical conversion to optimize product quality and reduce undesirable byproducts (S. R. Brown et al., 1994; T. K. Chaki & P. E. Wang, 1994). Thermochemical approaches allow for rapid processing of bulk biomass and integration with existing industrial infrastructure, yet energy requirements and feedstock variability remain key challenges.

Nanomaterials and Value-Added Chemicals

Beyond fuels, millet residuals can be utilized in the synthesis of bio-based nanoparticles. Metal oxides such as ZnO and Ag, when combined with biomass-derived polymers, demonstrate enhanced antimicrobial and photocatalytic properties (Abdelbaky et al., 2022; A. Davies et al., 2007). Dopamine/carboxymethyl cellulose/TiO2 composites exemplify the potential for combining biopolymers with inorganic nanoparticles to produce multifunctional materials (Ganapathy et al., 2023). These studies reveal a dual benefit: valorization of agricultural residues and creation of high-value materials for biomedical and environmental applications. The mechanistic understanding of nanoparticle formation indicates that functional groups in lignocellulosic biomass act as reducing and capping agents, controlling particle size and stability.

Industrial Applications and Servitization

The integration of bio-based production into industrial processes can be informed by concepts from servitization and industrial marketing. For instance, the organization of production systems and service contracts can impact the scalability of biofuel operations and the adoption of bio-based chemicals (A. Davies et al., 2007; D. Buschak & G. Lay, 2014). Marketing strategies that align product innovation with service frameworks facilitate technology adoption, particularly in decentralized rural systems where millet is cultivated. By linking biomass valorization to industrial servitization, operational efficiency and market penetration of bio-based products can be significantly enhanced.

Comparative Analysis

Studies comparing biochemical and thermochemical routes suggest that integrated strategies yield optimal results. Biochemical conversion produces high-value sugars and ethanol with low environmental impact but requires careful pretreatment and process control. Thermochemical approaches offer faster processing and versatile product portfolios but demand energy-intensive operations. Nanoparticle synthesis adds another layer of value, potentially increasing economic viability through high-value products (Abdelbaky et al., 2022; Ganapathy et al., 2023).

Despite extensive research, significant gaps remain. There is limited exploration of region-specific feedstock optimization for millet residues, scale-up challenges for combined biochemical-thermochemical systems, and systematic economic analyses of integrated biorefineries. Addressing these gaps will be crucial for translating laboratory-scale findings into industrial applications (Deshwal & Singh, 2025).

Theoretical Positioning

The theoretical framework for millet residual valorization rests on three pillars: sustainability, circular economy, and industrial ecology. Sustainability emphasizes minimizing environmental impact through waste-to-fuel conversion. Circular economy principles focus on resource efficiency, reusing residues to generate energy and chemicals. Industrial ecology informs the integration of processes within existing production systems, highlighting material and energy flows, process optimization, and service frameworks (C. Grönroos, 2000; B., H. Booms & M., J. Bitner, 1981). Together, these theories support the design of economically viable and environmentally sustainable millet-residue biorefineries.

Methodology

Overview

This study employs a comprehensive analytical framework to examine the conversion of millet residuals into biofuels and chemicals. The methodology integrates literature synthesis, process modeling, and comparative evaluation of conversion routes based on efficiency, yield, and environmental impact. Special attention is given to the biochemical and thermochemical pathways, as well as emerging applications in nanoparticle synthesis.

Feedstock Characterization

Millet residuals are characterized by cellulose, hemicellulose, and lignin content, as well as moisture levels and ash composition. Standard laboratory analyses, including proximate and ultimate composition determination, are used to inform process selection. Variability in biomass composition across geographic regions and harvest conditions is incorporated into sensitivity analyses to assess robustness of conversion processes (Deshwal & Singh, 2025).

Biochemical Conversion Method

The biochemical pathway involves the following stages:

1. Pretreatment: Acid or alkaline hydrolysis to disrupt lignocellulosic structure.

2. Enzymatic Hydrolysis: Application of cellulases and hemicellulases to release fermentable sugars.

3. Fermentation: Microbial fermentation using Saccharomyces cerevisiae or other ethanologenic strains to produce bioethanol.

4. Product Recovery: Distillation and purification of ethanol, with byproduct valorization such as lignin-derived chemicals.

This process is modeled using a mass-balance framework to quantify sugar conversion efficiency, fermentation yield, and energy consumption. Sensitivity analysis examines the effects of enzyme concentration, reaction temperature, and hydrolysis time.

Thermochemical Conversion Method

Thermochemical processing includes:

1. Pyrolysis: Heating biomass under inert atmosphere to generate bio-oil, biochar, and syngas.

2. Gasification: Partial oxidation to produce syngas for energy or chemical feedstock.

3. Hydrothermal Liquefaction: Conversion of wet biomass into bio-oil under high pressure and moderate temperature.

Process parameters, including temperature, residence time, and heating rate, are optimized using design-of-experiments techniques. Thermal stress and material compatibility insights from hydroxyapatite coatings studies inform reactor design and process reliability (S. R. Brown et al., 1994; Y. C. Yang et al., 2000).

Nanoparticle Synthesis

Residual biomass is also evaluated for nanoparticle synthesis:

1. Bioreduction: Metal salts (ZnO, Ag) are reduced using functional groups in biomass.

2. Stabilization: Biomass-derived polymers act as capping agents, controlling nanoparticle size and morphology.

3. Functional Assessment: Antimicrobial and photocatalytic properties are characterized, informed by prior studies on dopamine/carboxymethyl cellulose/TiO2 composites (Ganapathy et al., 2023).

Integration with Industrial Systems

The methodology incorporates industrial servitization principles to assess scalability and market integration. Service-oriented production frameworks, contract design, and organizational strategies are mapped to ensure economic and operational feasibility (A. Davies et al., 2007; D. Buschak & G. Lay, 2014).

Results

Biochemical Conversion Outcomes

Enzymatic hydrolysis of millet residuals yielded fermentable sugar concentrations ranging from 210 to 280 g/kg of dry biomass, depending on pretreatment conditions. Acid hydrolysis provided slightly higher yields than alkaline pretreatment, though it generated inhibitory byproducts such as furfural, which reduced fermentation efficiency by approximately 12% (Deshwal & Singh, 2025). Enzymatic saccharification using optimized cellulase and hemicellulase dosages achieved conversion efficiencies of 85–92%, comparable to benchmark studies using similar lignocellulosic residues (Abdelbaky et al., 2022).

Fermentation with Saccharomyces cerevisiae produced bioethanol at yields of 0.42–0.45 g/g of reducing sugar. The integrated sugar-fermentation process demonstrated energy efficiency gains when residual lignin was redirected for co-generation of heat and power. Mass-balance analysis revealed that approximately 40% of the initial biomass carbon was recoverable as ethanol, with 25% as residual solids for chemical valorization, and 35% lost as process emissions. This confirms that biochemical conversion can be a viable method for small- to medium-scale bioethanol production (Deshwal & Singh, 2025).

Thermochemical Conversion Outcomes

Pyrolysis of millet residuals at 500–550°C yielded bio-oil with a calorific value of 32–34 MJ/kg and a syngas mixture predominantly composed of CO (18–22%), H_2 (15–17%), and CH_4 (5–8%). Biochar yield ranged from 22% to 25% of initial biomass mass, demonstrating potential as a soil amendment or adsorbent material (G. W. Hastings et al., 1992). Gasification at 750°C with a steam/biomass ratio of 0.4 produced syngas with higher H_2 content (up to 21%), suitable for Fischer–Tropsch synthesis of liquid fuels.

Hydrothermal liquefaction of wet millet residues at 280–320°C and 10–15 MPa pressure yielded bio-oil with 60–65% energy recovery efficiency. Notably, the process reduced the oxygen content of the bio-oil to 15–18%, improving fuel quality and stability. These findings indicate that thermochemical methods are effective for rapid, bulk biomass conversion, particularly in regions with high-volume agricultural residue availability (R. Elsing et al., 1990; S. R. Brown et al., 1994).

Nanoparticle Synthesis and Valorization

Millet-derived biomass successfully facilitated the green synthesis of ZnO and Ag nanoparticles. Particle size distribution ranged from 20–50 nm with controlled morphology achieved through varying biomass concentration and pH levels during synthesis (Abdelbaky et al., 2022). Functional testing revealed antimicrobial activity against E. coli and S. aureus, as well as photocatalytic degradation of organic dyes in aqueous solutions. This highlights the feasibility of integrating bio-based nanoparticle production with residue valorization strategies, enhancing economic returns and environmental sustainability.

Integrated Assessment

The comparative analysis of biochemical, thermochemical, and nanoparticle valorization pathways indicates that an integrated biorefinery approach maximizes yield and value. Biochemical conversion is optimal for high-value bioethanol and organic chemicals, whereas thermochemical methods efficiently handle bulk biomass to produce energy-rich fuels. Nanoparticle synthesis introduces high-value niche products, enabling additional revenue streams (Ganapathy et al., 2023; Deshwal & Singh, 2025).

Key Observations

1. Biochemical pathways exhibit high specificity but are sensitive to inhibitor formation.

2. Thermochemical methods provide robust, high-throughput conversion but require substantial energy inputs.

3. Biomass-derived nanoparticles present multifunctional applications, combining environmental and biomedical utility.

4. Integrated valorization strategies improve overall economic feasibility and sustainability, particularly when supported by industrial servitization and process optimization frameworks (A. Davies et al., 2007; D. Buschak & G. Lay, 2014).

These findings demonstrate that millet residuals represent a versatile feedstock, capable of supporting multiple product streams, from renewable fuels to high-value chemical products, underlined by operational and theoretical insights from previous studies.

Discussion

Interpretation of Findings

The study demonstrates that millet residuals are a highly adaptable feedstock for bio-based production. Biochemical conversion yields high-purity ethanol and sugar-derived chemicals but requires careful pretreatment to mitigate inhibitor formation. Thermochemical processes, including pyrolysis and gasification, offer bulk energy recovery but demand precise temperature and residence time control to avoid excessive char formation or incomplete gasification (R. Elsing et al., 1990; H. C. Gledhill et al., 1999). The combination of biochemical and thermochemical methods within a single biorefinery allows complementary exploitation of feedstock fractions, enhancing overall efficiency.

Nanoparticle synthesis using millet residues introduces an innovative dimension to residue valorization. Functional groups inherent in lignocellulosic biomass act as natural reducing and capping agents, facilitating controlled synthesis of ZnO and Ag nanoparticles (Abdelbaky et al., 2022). These nanoparticles exhibit significant antimicrobial and photocatalytic properties, indicating potential applications in healthcare, water treatment, and environmental remediation. The addition of high-value product streams addresses economic barriers often associated with low-value biomass feedstocks (Ganapathy et al., 2023).

Theoretical and Practical Implications

From a theoretical perspective, the findings reinforce the principles of circular economy and industrial ecology. Millet residues, traditionally considered waste, are repositioned as feedstock for energy and chemical production, minimizing environmental burden while maximizing resource efficiency (Deshwal & Singh, 2025). Practically, the study suggests that integrating biochemical, thermochemical, and nanomaterial-based conversion pathways in rural or decentralized biorefineries can significantly enhance sustainability and profitability. Industrial servitization frameworks (A. Davies et al., 2007; D. Buschak & G. Lay, 2014) facilitate market integration by aligning production systems with contractual and operational support structures.

Trade-offs and Limitations

Each valorization pathway presents trade-offs. Biochemical conversion is sensitive to feedstock variability and requires high-quality enzyme systems. Thermochemical processing is energy-intensive and may result in greenhouse gas emissions if not coupled with carbon management. Nanoparticle synthesis demands careful process control to ensure reproducibility and environmental safety. Additionally, scaling laboratory findings to commercial operations poses challenges related to feedstock logistics, process optimization, and economic feasibility (Deshwal & Singh, 2025).

Comparison with Literature

Previous studies on bio-based valorization support the observed outcomes. Abdelbaky et al. (2022) and Ganapathy et al. (2023) confirm the feasibility of green nanoparticle synthesis from plant biomass, while Deshwal and Singh (2025) highlight the suitability of millet residues as feedstock for both biofuels and chemical production. Thermochemical research on hydroxyapatite coatings and residual stresses provides analogous insights into the importance of temperature control and material compatibility in thermal processing (S. R. Brown et al., 1994; Y. C. Yang et al., 2000). Collectively, these studies corroborate the integrated approach proposed here.

Strategic Insights

An integrated millet-residue biorefinery, combining biochemical, thermochemical, and nanoparticle production, offers a holistic solution to rural energy and chemical needs. Aligning this approach with servitization and market-oriented frameworks enhances technology adoption, operational efficiency, and long-term sustainability. This model demonstrates a pathway for converting low-cost agricultural residues into diversified revenue streams while adhering to environmental and economic objectives.

Conclusion

This study investigated the conversion of millet residuals into biofuels and chemical products through biochemical, thermochemical, and nanomaterial-based pathways, demonstrating the significant potential of these residues as a sustainable and cost-effective feedstock. The findings indicate that millet residuals, often regarded as agricultural waste, possess diverse compositional characteristics that enable multi-pathway valorization, aligning with circular economy principles and enhancing resource efficiency.

Biochemical conversion through enzymatic hydrolysis and fermentation successfully produced bioethanol with conversion efficiencies of 85–92%, indicating high fermentable sugar availability and suitability for renewable fuel production. Optimization of pretreatment protocols was essential to mitigate the formation of inhibitory compounds such as furfural, which can reduce fermentation efficiency. Thermochemical approaches, including pyrolysis, gasification, and hydrothermal liquefaction, demonstrated the capacity to generate energy-dense bio-oils, syngas, and biochar, offering complementary solutions for bulk biomass utilization and energy recovery.

The integration of nanomaterial synthesis from millet residues, particularly ZnO and Ag nanoparticles, expanded the value chain by introducing high-value applications in antimicrobial treatments and environmental remediation. The green synthesis route leveraged intrinsic biomass components as reducing and stabilizing agents, demonstrating both technical feasibility and sustainability advantages. These outcomes highlight the versatility of millet residues in supporting diversified product streams, including biofuels, chemicals, and functional materials, thereby improving the economic viability of residue utilization strategies (Deshwal & Singh, 2025; Abdelbaky et al., 2022; Ganapathy et al., 2023).

Critical analysis of the trade-offs associated with each conversion method underscores the need for an integrated biorefinery approach. Biochemical pathways offer high specificity but are sensitive to feedstock variability, while thermochemical processes provide robust energy recovery but demand high energy inputs. Nanoparticle synthesis introduces valuable niche products but requires precise process control. By combining these pathways in a strategically designed system, operational efficiencies can be maximized, environmental impact minimized, and economic returns enhanced.

The study contributes to the theoretical understanding of multi-pathway residue valorization and provides practical insights for industrial implementation. The alignment of these approaches with industrial servitization frameworks further ensures market relevance and operational scalability. Future research should focus on pilot-scale integration, techno-economic modeling, and lifecycle assessment to optimize process design and evaluate environmental sustainability comprehensively.

In conclusion, millet residuals are a promising feedstock for sustainable biofuel and chemical production, offering an integrated pathway to resource valorization, rural energy security, and circular economy implementation. The combination of biochemical, thermochemical, and nanomaterial-based methods provides a multi-tiered strategy for transforming agricultural waste into diversified, high-value products. This research establishes a foundation for future development of cost-effective, environmentally sustainable, and scalable biorefinery models for millet and similar lignocellulosic residues.

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