International Journal of Computational Research in Science and Technology
E-ISSN: 3108-0871, Volume 2 Issue 3
May-Jun 2026, PP 01-08

Comparative Process Design and Modeled Performance of a Small-Scale Bioethanol Production System Using Agricultural Residues

Samriddha Sharma[1], Om Prakash Sondhiya[2]
[1] Student, Department of Mechanical Engineering, IET-DAVV, Indore (MP), India
[2]Assistant Professor, Department of Mechanical Engineering, IET-DAVV, Indore (MP), India

Abstract. The increasing environmental and economic concerns associated with fossil-fuel dependency have intensified global interest in renewable transportation fuels. Among alternative biofuels, bioethanol has emerged as one of the most commercially viable and widely adopted options because it can be produced from renewable biomass resources and integrated into existing fuel infrastructures. This study presents a comparative process-design assessment of a compact bioethanol production system utilizing three abundant lignocellulosic agricultural residues: rice straw, sugarcane bagasse, and corn stover. A literature-informed process model was developed for a small-scale educational bioethanol unit comprising feedstock preparation, dilute-acid pretreatment, enzymatic hydrolysis, yeast fermentation, and reflux-assisted distillation. The investigation evaluates the influence of biomass composition on fermentable sugar recovery, ethanol yield, process efficiency, and energy demand. The modeled analysis indicates that sugarcane bagasse demonstrates the most favorable conversion performance under the selected operating assumptions, yielding approximately 74 g/L fermentable sugars and 34.5 g/L ethanol prior to separation. Corn stover exhibited intermediate performance, whereas rice straw produced comparatively lower ethanol concentrations because of its elevated ash and silica content, which reduce carbohydrate accessibility during pretreatment. The results further reveal that pretreatment and distillation account for the majority of the process energy requirement, highlighting the importance of heat integration, solids management, and process optimization in improving system efficiency. The study concludes that a modular small-scale bioethanol system can serve as an effective educational and research platform for demonstrating biomass-to-fuel conversion technologies. Furthermore, transparent presentation of modeled assumptions and calculation procedures strengthens the academic reliability of design-stage biofuel studies intended for instructional and comparative analysis.

Keywords: Bioethanol, Agricultural Residues, Lignocellulosic Biomass, Fermentation, Renewable Energy, Process Design, Biomass Conversion.

I. Introduction

The growing depletion of fossil-fuel reserves, increasing greenhouse-gas emissions, and concerns regarding environmental sustainability have accelerated research into renewable energy technologies. Transportation fuels derived from biomass are considered promising alternatives because they offer the potential to reduce dependence on petroleum while lowering net carbon emissions. Among the available biofuels, ethanol has achieved widespread commercial acceptance due to its compatibility with conventional internal combustion engines and its suitability for blending with gasoline to enhance octane rating and combustion efficiency.

Conventional first-generation ethanol production technologies rely primarily on sugar- and starch-based feedstocks such as sugarcane juice, corn grain, and wheat. Although technologically mature, these pathways have been criticized for competing with food supplies, agricultural land, and freshwater resources. Consequently, increasing research attention has shifted toward second-generation bioethanol production using lignocellulosic residues, including rice straw, sugarcane bagasse, and corn stover. These materials are abundant, inexpensive, and often treated as agricultural waste streams, making them attractive candidates for sustainable fuel production.

Despite their advantages, lignocellulosic feedstocks present substantial technical challenges. Their complex structure—composed of cellulose, hemicellulose, and lignin—limits direct microbial conversion and necessitates pretreatment processes to enhance enzymatic accessibility. Furthermore, process efficiency is influenced by feedstock variability, inhibitor formation, hydrolysis performance, and energy-intensive downstream separation.

The present study develops a comparative academic assessment of a small-scale bioethanol production system utilizing representative agricultural residues. Unlike experimental pilot-plant investigations, the study adopts a modeled engineering framework informed by published literature and standard biochemical conversion principles. The objective is to evaluate comparative feedstock behavior, process configuration, expected conversion efficiency, and operational considerations within an educational-scale bioethanol production system.

II. Design Basis and Process Scope

A nominal production capacity of 25 L/day of fuel-grade ethanol equivalent was selected as the design basis for the proposed system. This scale was intentionally chosen to balance practical operability with educational relevance. The configuration is sufficiently large to demonstrate key thermochemical and biochemical conversion principles while remaining feasible for laboratory-scale implementation within an academic institution.

The defined process boundary begins with biomass drying and size reduction and concludes with ethanol recovery through reflux-assisted distillation at an estimated purity of 91–93 vol%. The simplified model excludes advanced wastewater treatment, co-product valorization, and molecular dehydration to anhydrous ethanol. Similarly, fermentation kinetics were simplified through the assumption of batch operation using Saccharomyces cerevisiae as the representative microorganism.

Three agricultural residues were selected because of their contrasting physicochemical characteristics and widespread availability:

- Rice straw — characterized by relatively high ash and silica content.

- Sugarcane bagasse — notable for its high cellulose fraction and established industrial supply chain.
- Corn stover — representing a balanced lignocellulosic composition commonly studied in second-generation biofuel research.

The variation in biomass composition provides a useful basis for evaluating the relationship between feedstock properties and process performance.

III. Methodology

Representative biomass compositions and operating assumptions were synthesized from authoritative renewable-energy literature and biofuel process-design studies. The modeled system consisted of five principal stages:

1. Feedstock preparation
2. Dilute-acid pretreatment
3. Enzymatic hydrolysis
4. Batch fermentation
5. Reflux-assisted distillation

Pretreatment was modeled using dilute sulfuric-acid conditioning combined with steam-assisted heating to improve cellulose accessibility while minimizing sugar degradation and inhibitor formation. Enzymatic hydrolysis was assumed to occur at 48–50°C for 48 h using commercial cellulase formulations sized according to accessible cellulose content.

Fermentation was simulated in batch mode at 30–32°C for 36 h using yeast inoculum concentrations sufficient for rapid fermentation initiation. Ethanol production was estimated using the theoretical glucose-to-ethanol stoichiometric conversion factor of 0.511 g ethanol/g glucose and adjusted according to modeled fermentation efficiency. The study emphasizes comparative engineering interpretation rather than experimental validation. Accordingly, all numerical values are explicitly presented as literature-informed modeled estimates rather than measured laboratory data.

Representative Biomass Composition

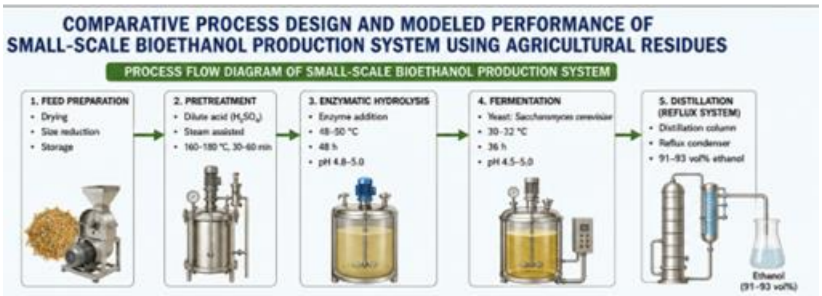
Feedstock	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Moisture (%)	Ash (%)
Rice straw	34	24	18	10	14

Feedstock	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Moisture (%)	Ash (%)
Sugarcane bagasse	42	27	21	8	2
Corn stover	38	29	17	9	7

Key Equipment Assumptions
The proposed educational-scale bioethanol unit includes:

- Feed preparation hopper
- Jacketed pretreatment reactor
- Hydrolysis tank with low-speed agitation
- Fermentation vessel with pH and temperature monitoring
- Packed or plate distillation column
- Shell-and-coil condenser
- Product collection vessels

Stainless steel was assumed for all wet-contact process components because of its corrosion resistance and hygienic properties. The design prioritizes operational visibility, instrumentation accessibility, and laboratory safety rather than industrial compactness. A batch-processing approach was selected to support teaching-laboratory schedules and permit direct observation of process transitions between hydrolysis, fermentation, and distillation stages.



IV. Modeled Comparative Results

The modeled results demonstrate significant dependence of ethanol production performance on feedstock composition and pretreatment effectiveness.

Table 2. Comparative Modeled Performance Metrics

Feedstock	Pretreatment Recovery (%)	Fermentable Sugar (g/L)	Fermentation Efficiency (%)	Ethanol Before Separation (g/L)	Distillate Purity (vol%)
Rice straw	82	68	83	28.9	91
Sugarcane bagasse	85	74	87	34.5	93
Corn stover	84	71	85	31.8	92

Sugarcane bagasse exhibited the highest modeled fermentable sugar concentration and ethanol productivity. Its comparatively high cellulose content and lower ash fraction contributed to improved pretreatment efficiency and enhanced enzymatic accessibility. Conversely, rice straw produced the lowest ethanol concentration because of its elevated ash and silica content, which negatively affect pretreatment effectiveness and hydrolysis performance.

Corn stover demonstrated intermediate conversion behavior, suggesting that it represents a balanced compromise between feedstock availability and conversion efficiency.

Interpretation of Feedstock Behavior

The observed performance trends are consistent with established lignocellulosic bioethanol literature, which identifies cellulose accessibility and inhibitor generation as dominant factors influencing ethanol yield. Pretreatment severity plays a critical role in determining the balance between sugar release and degradation products.

From an educational perspective, the comparative analysis illustrates how feedstock properties influence downstream engineering parameters, including:

- Slurry rheology
- Agitation requirements
- Enzyme dosage
- Fermentation kinetics
- Distillation energy demand

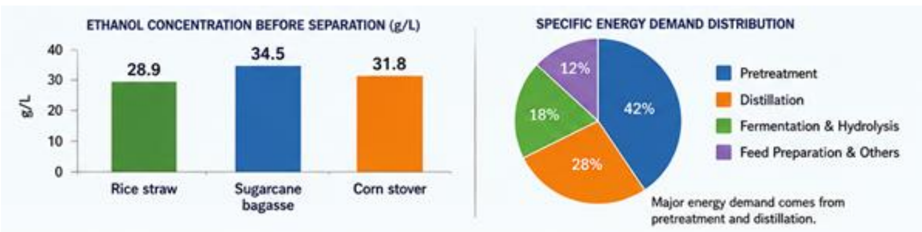
Consequently, the proposed system offers significant instructional value by demonstrating the integrated nature of biomass conversion engineering.

Mass-Balance Assessment

Using a basis of 100 kg dry biomass feedstock, the modeled system yielded the following ethanol-equivalent outputs:

Feedstock	Recovered Sugar (kg)	Ethanol Equivalent (kg)	Solid Residue (kg)
Rice straw	41.5	21.0	33.0
Sugarcane bagasse	49.8	25.1	31.7
Corn stover	46.0	23.2	32.4

Residual lignin-rich solids may be utilized as low-grade process fuel or as feedstock for future biorefinery applications. Recognition of co-product utilization pathways is important because economic viability in lignocellulosic ethanol production often depends on integrated resource utilization rather than ethanol revenue alone.



V. Energy and Operability Assessment

Although ethanol yield is a critical performance metric, process operability and energy efficiency are equally important in evaluating small-scale biofuel systems. The modeled assessment indicates that pretreatment and distillation dominate overall energy consumption because of thermal heating requirements and vapor–liquid separation duty.

This trend aligns with broader industrial findings in second-generation bioethanol research, where biomass conditioning and product purification are consistently identified as major contributors to operational cost and energy demand.

Opportunities for Process Improvement

Several engineering improvements could enhance overall system efficiency:

1. Heat integration between hot stillage and incoming slurry streams
2. Improved solids dewatering prior to distillation
3. Optimized pretreatment severity to minimize inhibitor formation
4. Enhanced process instrumentation for monitoring pH, temperature, and conductivity
5. Improved enzyme utilization strategies

Because small-scale systems cannot achieve the same degree of thermal integration as industrial facilities, their value lies primarily in demonstration, experimentation, and process education rather than commercial-scale efficiency.

VI. Environmental and Educational Relevance

The use of agricultural residues instead of food-grade biomass significantly improves the sustainability profile of bioethanol production. Residue-based ethanol pathways contribute to waste valorization, reduce open-field biomass burning, and support circular bioeconomy principles.

Within academic environments, a compact bioethanol production system can support multidisciplinary education in:

- Thermodynamics
- Renewable energy engineering
- Reaction engineering
- Unit operations
- Instrumentation and process control
- Sustainability analysis

The system also provides students with opportunities to perform practical measurements related to hydrolysis efficiency, fermentation behavior, and distillation performance.

Study Limitations

Several limitations should be acknowledged. The present study does not include:

- Experimental validation
- Detailed kinetic modeling
- Life-cycle assessment

- Economic optimization
- Inhibitor quantification
- Continuous-process operation

Actual industrial performance would vary according to feedstock variability, pretreatment conditions, enzyme formulation, contamination control, and process integration strategy.

Nevertheless, the transparency of assumptions and methodological clarity strengthen the educational and academic value of the study.

VII. Conclusion

This study presented a comparative process-design assessment of a small-scale bioethanol production system utilizing rice straw, sugarcane bagasse, and corn stover as representative lignocellulosic feedstocks. A modular conversion sequence involving pretreatment, hydrolysis, fermentation, and reflux-assisted distillation was evaluated under literature-informed operating assumptions.

Among the investigated residues, sugarcane bagasse demonstrated the most favorable modeled performance because of its higher cellulose accessibility and improved fermentable sugar recovery. Corn stover exhibited intermediate performance, while rice straw showed comparatively lower conversion efficiency because of its high ash and silica content.

The analysis further demonstrated that pretreatment and distillation are the most energy-intensive sections of the process and therefore represent key targets for optimization and heat-integration strategies.

Overall, the study highlights the educational and research value of compact bioethanol systems for demonstrating renewable-fuel conversion technologies. Future work should focus on experimental validation, inhibitor analysis, heat-recovery optimization, and techno-economic assessment to strengthen the applicability of the proposed design framework.

Acknowledgements. I would like to express my gratitude to everyone who has contributed, especially my family, friends and my mentor Om Prakash Sondhiya. I would especially like to give thanks Institute of Engineering and Technology, DAVV, Indore, MP, India, for offering a research facility

References

1. U.S. Department of Energy. Alternative Fuels Data Center: Ethanol Fuel Basics.
2. U.S. Department of Energy. Biofuels: Energy for Transportation.
3. Nabanita Sarkar, Ghosh, S. K., Banerjee, S., & Aikat, K. (2012). Bioethanol production from agricultural wastes: An overview. Renewable Energy, 37(1), 19–27.
4. Marek Broda, Yelle, D. J., & Serwańska, K. (2022). Bioethanol production from lignocellulosic biomass: Challenges and solutions. Molecules, 27(24), 8717.
5. Tse, T. J., Wiens, D. J., & Reaney, M. J. T. (2021). Production of bioethanol: A review of factors affecting ethanol yield. Fermentation, 7(4), 268.

6. Humbird, D., et al. (2011). Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol. National Renewable Energy Laboratory (NREL).
7. International Energy Agency. Advanced Biofuels and Renewable Transport Fuel Pathways.