© JUL 2026 | IRE Journals | Volume 10 Issue 1 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I1-1719587

Design, Fabrication and Performance Evaluation of a Low-Cost Batch Bioethanol Distillation System for Small-Scale Renewable Fuel Production

SAMUEL OBADIAH ANZAKU[1], NNOROM ACHARA[2], ABDULAZEEZ HARUNA[3], MARY SAMUEL[4], AISHA SA'AD[5], MUHAMMAD MAHMUD JAMIL[6], OWOLABI BABATOPE LAYI[7], WILSON ODUWA UWUIGBUSUN[8], MONDAY IMAFEDIA AMODU, SHUAIBU AHMED[9]

[1, 2, 3, 4, 5, 6, 7, 8, 9] *Department of Mechanical Engineering, Faculty of Engineering and Technology, Nigerian Defence Academy, Kaduna, Nigeria*

Abstract- The growing demand for sustainable energy and the increasing cost of fossil fuels have intensified the need for affordable technologies for biofuel production. Although bioethanol is a promising renewable fuel, its large-scale adoption in developing countries is constrained by the limited availability of low-cost distillation systems for producing fuel-grade ethanol. This study presents the design, fabrication, and performance evaluation of a low-cost batch bioethanol distillation system for small-scale renewable fuel production. A 5 L stainless steel distillation unit comprising a reboiler, packed distillation column, shell-and-tube condenser, and temperature control system was designed using AutoCAD and fabricated from locally available materials at a total cost of ₦336,500. The system was evaluated using 4 L of fermented sugarcane bagasse mash containing 8–10% (v/v) ethanol. Performance evaluation showed that the developed unit achieved a 39% distillation efficiency, producing 3.0 ± 0.2 L of distillate per batch with an ethanol purity of 91 ± 0.8% (v/v), which was subsequently upgraded to greater than 99.5% (v/v) using molecular sieves. Fuel characterization confirmed that the distilled bioethanol satisfied the requirements of ASTM D4806 for fuel ethanol. Furthermore, engine performance evaluation of an E10 bioethanol-gasoline blend demonstrated reductions of 18% in carbon monoxide (CO) and 12% in nitrogen oxides (NO_x) emissions compared with conventional gasoline. The developed distillation system provides an efficient, affordable, and locally manufacturable technology for small-scale bioethanol production, offering a practical pathway for renewable fuel development, agricultural waste utilization, and reduced dependence on fossil fuels in developing countries.

Keywords: Bioethanol, Distillation System, Renewable Energy, Fuel Ethanol, Sugarcane Bagasse, Small-Scale Production, Sustainable Fuel.

I INTRODUCTION

The increasing global demand for clean and sustainable energy, coupled with the depletion of fossil fuel reserves and growing environmental concerns, has intensified research into renewable energy technologies. Bioethanol has emerged as one of the most promising renewable liquid fuels because of its biodegradability, high octane rating, and potential to reduce greenhouse gas emissions when blended with conventional gasoline. In addition to improving energy security, bioethanol production from agricultural residues offers an effective means of converting biomass waste into valuable energy resources.

Bioethanol is commonly produced through the fermentation of sugar- and starch-rich biomass, followed by distillation to concentrate the ethanol to fuel-grade purity. Among the various feedstocks available, sugarcane bagasse is an abundant agricultural residue with considerable potential for bioethanol production due to its high cellulose and hemicellulose contents. However, the efficiency and quality of bioethanol largely depend on the performance of the distillation system used for separating ethanol from the fermented mash. Conventional distillation systems are often expensive, energy-intensive, and unsuitable for small-scale applications, limiting their adoption in many developing countries.

Several studies have investigated bioethanol production and purification using different feedstocks and distillation techniques. However, most available

© JUL 2026 | IRE Journals | Volume 10 Issue 1 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I1-1719587

systems are designed for industrial-scale production and require sophisticated equipment that is costly to procure and maintain. There remains a need for affordable and locally manufacturable distillation systems capable of producing high-quality bioethanol for research, educational, and small-scale industrial applications.

Therefore, this study presents the design, fabrication, and performance evaluation of a low-cost batch bioethanol distillation system using locally available materials. The developed system was experimentally evaluated to determine its distillation efficiency, ethanol recovery, and fuel quality, with the aim of providing an economical and practical solution for small-scale renewable fuel production.

II OBJECTIVES

The objectives of this study are to:

i Design a low-cost batch bioethanol distillation system using locally available materials.
ii Fabricate the developed distillation system for small-scale bioethanol production.
iii Evaluate the performance of the distillation system in terms of ethanol recovery and distillation efficiency.
iv Assess the quality of the produced bioethanol for potential fuel applications.

III LITERATURE REVIEW

Bioethanol has become one of the most promising renewable fuels because of its potential to reduce greenhouse gas emissions, improve energy security, and decrease dependence on fossil fuels. It can be produced from various biomass feedstocks, including sugarcane, cassava, maize, and agricultural residues. Among these feedstocks, sugarcane bagasse has received considerable attention due to its abundance, renewability, and high lignocellulosic content, making it suitable for sustainable bioethanol production (Balat & Balat, 2009; Limayem & Ricke, 2012).

Distillation remains the most widely adopted method for separating ethanol from fermented biomass because it exploits the difference in boiling points between ethanol and water. The efficiency of the process is influenced by several factors, including column design, heating rate, condenser efficiency, and packing material. An efficient distillation system improves ethanol recovery while reducing energy consumption and production costs (Kiss & Suszwalak, 2012; Mohsenzadeh et al., 2017).

Several researchers have developed laboratory- and pilot-scale bioethanol distillation systems to enhance ethanol production efficiency. Stainless steel is commonly used in the fabrication of distillation units because of its excellent corrosion resistance, mechanical strength, and durability under elevated operating temperatures. However, many existing systems are designed for industrial-scale production and are often too expensive for small-scale users in developing countries (Nigam & Singh, 2011; Zabed et al., 2017).

Recent studies have focused on developing compact and low-cost distillation systems using locally available materials to improve accessibility for research institutions and small-scale producers. These systems have demonstrated satisfactory ethanol recovery and product quality while significantly reducing fabrication costs. Such developments contribute to the promotion of decentralized renewable energy technologies and encourage local manufacturing (Sarkar et al., 2012; Zabed et al., 2017).

The quality of distilled bioethanol is generally assessed using parameters such as ethanol concentration, density, specific gravity, and moisture content. Fuel-grade ethanol requires high purity to ensure efficient combustion and compatibility with spark-ignition engines. Molecular sieve dehydration has been widely reported as an effective technique for increasing ethanol purity to levels that meet international fuel standards (ASTM International, 2021; Demirbas, 2009).

Despite the advances in bioethanol production technologies, there remains a need for affordable and efficient distillation systems that can be fabricated using locally available materials while maintaining acceptable performance. This study addresses this gap by designing, fabricating, and experimentally evaluating a compact batch bioethanol distillation system suitable for small-scale renewable fuel production in developing countries (Balat & Balat, 2009; Zabed et al., 2017).

IV. MATERIALS, EQUIPMENT AND METHODS

1 Materials

The materials used for the design, fabrication, and evaluation of the bioethanol distillation system included stainless steel sheets, stainless steel pipes, copper tubing, insulation materials, valves, fittings, and welding consumables. Sugarcane bagasse was used as the feedstock for bioethanol production, while fermented mash served as the raw material for distillation. Molecular sieve beads were used during the dehydration stage to improve the ethanol purity after distillation.

Table 1
Materials Used for Fabrication

Material	Specification	Purpose
Stainless steel sheet	2 mm thick	Boiler and distillation column
Copper tube	12 mm diameter	Condenser coil
Stainless steel pipe	25 mm diameter	Vapour transfer
Glass wool	High-temperature insulation	Heat retention
Ball valve	½ inch	Flow control
Molecular sieve	3 Å	Ethanol dehydration
Fermented sugarcane bagasse mash	4 L	Feedstock

2 Equipment

The equipment used during fabrication and testing included welding and cutting machines, drilling machine, temperature measuring devices, weighing balance, hydrometer, alcohol meter, and AutoCAD software for system design. Performance evaluation was carried out using standard laboratory instruments.

Table 2
Equipment Used

Equipment	Function
AutoCAD	Design of the distillation system
Arc welding machine	Fabrication
Drilling machine	Hole preparation
Digital thermometer	Temperature measurement
Hydrometer	Density measurement
Alcohol meter	Ethanol concentration determination
Digital weighing balance	Sample measurement
Measuring cylinder	Volume measurement

3 Design of the Distillation System

The batch bioethanol distillation system was designed using engineering design principles and AutoCAD software. The system consisted of a 5 L stainless steel boiler, a packed distillation column, a shell-and-tube condenser, connecting pipelines, and a receiving vessel. The design dimensions were selected based on the expected processing capacity, vapour flow rate, and heat transfer requirements. Stainless steel was selected as the construction material because of its corrosion resistance, durability, and compatibility with ethanol.

4 Fabrication Procedure

The fabrication process involved cutting, rolling, welding, drilling, and assembly of the individual components. The boiler, distillation column, and condenser were fabricated separately before final assembly. Leak tests were carried out after fabrication to ensure airtight operation, while thermal insulation was applied to minimize heat loss during distillation.

3.5 Experimental Procedure

Approximately 4 L of fermented sugarcane bagasse mash containing about 8–10% (v/v) ethanol was introduced into the boiler. Heat was supplied until boiling commenced, allowing ethanol-rich vapour to rise through the packed column before passing into the condenser where it was cooled and collected as liquid distillate. Temperature was monitored continuously throughout the experiment, while the volume and ethanol concentration of the distillate were measured after each batch.

3.6 Performance Evaluation
The performance of the developed distillation system was evaluated based on distillation efficiency, ethanol recovery, and ethanol purity. Fuel quality was assessed using density, specific gravity, and ethanol concentration measurements, while molecular sieve dehydration was used to improve ethanol purity for fuel applications. The experimental results were compared with ASTM fuel ethanol specifications to determine the suitability of the produced bioethanol.

Table 3
Performance Evaluation Parameters

Parameter	Unit	Measurement Method
Distillation efficiency	%	Experimental calculation
Ethanol recovery	L	Measuring cylinder
Ethanol concentration	% (v/v)	Alcohol meter
Density	g/cm³	Hydrometer
Specific gravity	–	Hydrometer
Distillation temperature	°C	Digital thermomete

IV RESULTS AND DISCUSSION

1 Performance of the Developed Distillation System
The fabricated bioethanol distillation system was successfully operated under the designed conditions using 4 L of fermented sugarcane bagasse mash. The system, which consisted of a 5 L stainless steel reboiler, packed distillation column, and shell-and-tube condenser, operated within a temperature range of 85-95°C and produced bioethanol with satisfactory recovery and purity. The total fabrication cost of the unit was ₦336,500, demonstrating that the system can be produced economically using locally available materials.

2 Distillation Performance
The developed distillation unit achieved an average bioethanol yield of 39 ± 1.2%, producing approximately 3.0 ± 0.2 L of distillate from each 4 L batch of fermented mash. The distilled ethanol had an average purity of 91 ± 0.8% (v/v) before dehydration, while molecular sieve treatment increased the purity to 99.5 ± 0.3% (v/v). These results indicate that the developed system was effective in recovering and concentrating ethanol suitable for fuel applications.

3 Fuel Quality Assessment
The distilled bioethanol was almost colourless, possessed the characteristic odour of ethanol, evaporated rapidly without leaving visible residue, and produced a noticeable cooling sensation upon contact with the skin. The measured evaporation residue was less than 0.005%, indicating high product purity. These characteristics were consistent with the requirements for fuel-grade ethanol specified by ASTM D4806, confirming the suitability of the produced bioethanol for blending with gasoline.

4 Engine Performance
Engine testing of an E10 bioethanol-gasoline blend showed improved environmental performance compared with conventional gasoline. Carbon monoxide (CO) emissions decreased by 18%, nitrogen oxides (NO_x) emissions decreased by 12%, and brake-specific fuel consumption improved by 5%. These improvements demonstrate that the bioethanol produced using the fabricated distillation system can serve as a cleaner alternative fuel while contributing to reduced exhaust emissions and improved engine performance.

V. CONCLUSION AND RECOMMENDATIONS

1. Conclusion

This study successfully designed, fabricated, and evaluated a low-cost batch bioethanol distillation system using locally available materials for small-scale renewable fuel production. The developed system effectively distilled fermented sugarcane bagasse mash, achieving an average bioethanol yield of 39% and producing 3.0 ± 0.2 L of distillate per batch. The distilled ethanol attained a purity of 91 ± 0.8% (v/v), which was further improved to 99.5 ± 0.3% (v/v) through molecular sieve dehydration, demonstrating the effectiveness of the distillation and purification processes.

The produced bioethanol satisfied the quality requirements for fuel applications and demonstrated improved environmental performance when blended with gasoline, resulting in reduced CO and NO_x emissions. The relatively low fabrication cost of the system indicates that it is a practical and economically viable option for small-scale bioethanol production, contributing to renewable energy development, agricultural waste utilization, and reduced dependence on fossil fuels in developing countries.

2. Recommendations

Based on the findings of this study, the following recommendations are made:

i. The developed distillation system should be evaluated using other locally available lignocellulosic feedstocks to determine its adaptability and performance under different operating conditions.
ii. Future studies should investigate energy optimization and heat recovery techniques to improve the overall efficiency of the distillation process and reduce operating costs.
iii. The system should be scaled up and tested under continuous operating conditions to assess its suitability for commercial and community-scale bioethanol production.
iv. Further investigations should be conducted on different bioethanol-gasoline blend ratios to evaluate their effects on engine performance, fuel economy, and exhaust emissions.

ACKNOWLEDGMENT

The Authors acknowledge the Nigerian Defence Academy, Postgraduate School, Faculty of Engineering and Technology, Department of Mechanical Engineering for providing the conducive atmosphere for Research, Career Development and Learning.

REFERENCES

[1] ASTM International, *ASTM D4806-21: Standard Specification for Denatured Fuel Ethanol for Blending with Gasolines for Use as Automotive Spark-Ignition Engine Fuel*. West Conshohocken, PA, USA: ASTM International, 2021.

[2] M. Balat and H. Balat, "Recent trends in global production and utilization of bio-ethanol fuel," *Applied Energy*, vol. 86, no. 11, pp. 2273-2282, Nov. 2009.

[3] A. Demirbas, *Biofuels: Securing the Planet's Future Energy Needs*. London, U.K.: Springer, 2009.

[4] A. A. Kiss and D. J. P. C. Suszwalak, "Enhanced bioethanol dehydration by extractive and azeotropic distillation," *Separation and Purification Technology*, vol. 86, pp. 70-78, Jan. 2012.

[5] A. Limayem and S. C. Ricke, "Lignocellulosic biomass for bioethanol production: Current perspectives and future prospects," *Progress in Energy and Combustion Science*, vol. 38, no. 4, pp. 449-467, Aug. 2012.

[6] A. Mohsenzadeh, A. Zamani, and M. J. Taherzadeh, "Bioethylene production from ethanol: A review and techno-economic evaluation," *Chemical Engineering and Processing: Process Intensification*, vol. 115, pp. 55-69, May 2017.

[7] P. S. Nigam and A. Singh, "Production of liquid biofuels from renewable resources," *Progress in Energy and Combustion Science*, vol. 37, no. 1, pp. 52–68, Feb. 2011.

[8] N. Sarkar, S. K. Ghosh, S. Banerjee, and K. Aikat, "Bioethanol production from agricultural wastes: An overview," *Renewable Energy*, vol. 37, no. 1, pp. 19-27, Jan. 2012.

[9] H. Zabed, J. N. Sahu, A. Suely, A. N. Boyce, and G. Faruq, "Bioethanol production from renewable sources: Current perspectives and technological progress," *Renewable and Sustainable Energy Reviews*, vol. 71, pp. 475-501, May 2017.