Nigerian Journal of Renewable Energy Research
Volume 1, Number 4, pp. 440-447, 2025
 eISSN 1597-8907: pISSN 1597-8877

UPGRADING A JATROPHA-BASED BIODIESEL PILOT PLANT IN NIGERIA: DESIGN AND COMMISSIONING OF A METHANOL RECOVERY CONDENSER

[2]Aisha, S., [3]Nwafulugo, F.U., [1,2]*Akande, H. F., [1,2]Mumah, S.N. and [4]Soretire, L.K.

[1]TETFund Centre for Renewable Energy, Kaduna Polytechnic, Kaduna, Nigeria
[2]Department of Chemical Engineering, Kaduna Polytechnic, Kaduna
[3]Department of Chemical Engineering, Nnamdi Azikwe University Awka, Anambra State
[4]Department of Mechanical Engineering, Air Force Institute of Technology, Kaduna
[*]*Corresponding author: hassan.akande@kadunapolytechnic.edu.ng*

© NJRER is the official Journal of the TETFund Centre of Excellence for Renewable Energy, Kaduna Nigeria
https://doi.org/10.5281/zenodo.17932761
https://njrer.org/download/upgrading_a_jatropha-based_biodiesel_pilot_plant_in_nigeria.pdf

ARTICLE INFORMATION

Article history:
Received 19 Jun., 2025
Revised 28 Sep., 2025
Accepted 14 Oct., 2025
Available online 30 Nov., 2025

Keywords:
Biodiesel
Renewable energy
Jatropha curcas
Methanol recovery
Condenser design

ABSTRACT

Developing local renewable energy capacity is a strategic priority for Nigeria. However, the viability of small-scale biofuel production is often limited by process inefficiencies, such as the loss of volatile reactants. This paper addresses this challenge through the upgrading of a jatropha-based biodiesel pilot plant at Kaduna Polytechnic, Nigeria. The primary objective was to design, fabricate, and commission a condenser to recover vaporised methanol from the transesterification reactor. A shell-and-tube heat exchanger was designed using Aspen Exchanger Design & Rating (EDR) for a specified duty of condensing 125.6 kg/h of methanol. The design required a heat removal capacity of approximately 148 MJ/h and was successfully commissioned following local fabrication at a total cost of $8,381. This study provides a complete, costed, and validated engineering blueprint for a practical process upgrade. It serves as a replicable case study for other institutions, demonstrating a feasible pathway for strengthening indigenous technical capacity and improving the sustainability of renewable energy research and production facilities in developing countries.

1. INTRODUCTION

Nigeria, like many developing nations, faces a significant energy deficit, relying heavily on fossil fuels while grappling with challenges of energy access and security (Olanrewaju et al., 2022). In response, transitioning to locally sourced renewable energy is a national strategic priority. Biodiesel produced from non-food feedstocks, such as *Jatropha curcas*, presents a promising decentralised energy solution that can support rural development and reduce carbon emissions (Ozoegwu et al., 2017). However, the success of small-scale biodiesel production hinges on process efficiency and economic viability.

A critical operational challenge in transesterification, the core process of biodiesel production, is the management of reactants. Methanol, a key reagent, is highly volatile and is typically heated to temperatures near its boiling point (65°C) during the reaction. Without an effective recovery system, significant amounts of vaporised methanol are lost to the atmosphere, increasing operational costs and introducing environmental and safety hazards. This issue is particularly acute in pilot-scale plants in research and educational institutions, where resource constraints can limit the initial design to essential components, deferring optimisation. The existing biodiesel pilot plant in the Chemical Engineering Department at Kaduna Polytechnic faced this precise limitation, lacking a condenser to capture and recycle vaporised methanol from the reactor.

While extensive literature exists on biodiesel chemistry, there is a scarcity of detailed, practical case studies on the retrofitting and technical upgrading of existing pilot plants in African institutional settings. This paper aims to fill that gap by documenting the complete engineering process of upgrading a jatropha-based biodiesel pilot plant through the design, fabrication, and commissioning of a shell-and-tube condenser for methanol recovery.

This study provides a comprehensive technical blueprint, including detailed design specifications generated using Aspen Exchanger Design & Rating V8.8, material and energy balances, and a full cost analysis for local fabrication. By presenting the results of the commissioning tests, this work offers a validated, practical guide for institutions seeking to enhance the efficiency and sustainability of their renewable energy facilities, thereby strengthening local capacity for biofuel research and production.

2. LITERATURE REVIEW

2.1 Biodiesel from *Jatropha curcas* as a Sustainable Feedstock

The global imperative to decarbonise the energy sector has intensified research into biofuels as a viable alternative to petroleum diesel. Biodiesel, a biodegradable and non-toxic fuel, is prominent among these alternatives due to its similar combustion properties and its potential to be produced from diverse feedstocks (El-Sattar et al., 2023). In developing countries like Nigeria, the focus has shifted towards non-edible, second-generation feedstocks to avoid competition with food crops. *Jatropha curcas* has been widely investigated for this purpose, as it can be cultivated on marginal lands, reducing the pressure on arable farmland (de Luna et al., 2022). However, realising the full potential of jatropha is contingent on overcoming challenges related to inconsistent yields and, crucially, developing efficient and cost-effective processing technologies suitable for local deployment (Mohammed et al., 2019).

2.2 Process Optimisation and the Imperative of Methanol Recovery

The economic feasibility of small- to medium-scale biodiesel production is highly sensitive to operational efficiency (Gebremariam & Marchetti, 2018). The transesterification process, while well-established, requires careful management of inputs to minimise costs. Methanol, used as a reactant, is a significant operational expense and a volatile organic compound. During the reaction, which is typically heated to 60–65°C, substantial quantities of methanol can be lost through vaporisation (Lee et al., 2015). Effective methanol recovery is therefore not merely an option but a critical step for process intensification and economic sustainability. As Singh et al. (2023) highlight, integrating recovery and recycling loops for excess methanol can improve the process mass intensity and reduce the overall environmental footprint, aligning with circular economy principles. A dedicated condenser is the primary unit operation for achieving this, converting the vaporised methanol back into a liquid state for reuse.

2.3 Simulation and Design of Biodiesel Production Systems

Modern process engineering relies heavily on simulation tools for designing, analysing, and optimising chemical plants before construction. Software packages like Aspen HYSYS and Aspen Exchanger Design & Rating (EDR) are industry standards for modelling reaction kinetics, performing material and energy balances, and sizing equipment such as reactors and heat exchangers (Sharma et al., 2020). These tools allow engineers to test various operating conditions and equipment designs virtually, saving significant time and resources. While many studies have employed these simulators to design new biodiesel plants from the ground up or to model entire process flowsheets (Tan et al., 2021), there is a notable gap in the literature. Specifically, there is a lack of published case studies that apply these powerful tools to the specific problem of retrofitting and upgrading existing, operational pilot plants in resource-constrained university settings within developing countries. Table 1, shown below, summarises key research, highlighting the gap this study addresses.

This review confirms that while the components of the problem—jatropha biodiesel, methanol recovery, and process simulation—are well-researched, their synthesis into a practical, documented case study of a pilot plant upgrade in Nigeria represents a novel and valuable contribution to the literature on sustainable energy development.

3. METHODOLOGY

3.1 Overview of the Biodiesel Pilot Plant

The research was conducted at the existing biodiesel pilot plant in the Chemical Engineering Department, Kaduna Polytechnic, Nigeria. The plant is designed to produce biodiesel from jatropha oil via a transesterification reaction using methanol and a sodium hydroxide catalyst. The process involves pre-heating the oil, mixing the catalyst with methanol, reacting the components in a jacketed reactor (R201) at approximately 65°C, and subsequent separation and purification steps. The primary limitation of the existing plant was the absence of a system to recover methanol that vaporised from the reactor, leading to material loss and economic inefficiency. The objective of this work was to remedy this by designing, fabricating, and incorporating a suitable condenser into the plant.

3.2 Condenser Design Basis and Specifications

The condenser upgrade was specified with a primary functional requirement: to condense 125.6 kg of methanol per batch. The design was developed for a shell-and-tube heat exchanger configuration. Key design and operating parameters were established as follows:

- *Design Pressure*: 3 bar for both shell and tube sides.
- *Design Temperature*: 100°C for the shell side, tube side, and tube sheets.
- *Corrosion Allowance*: 1.59 mm.
- *Number of Passes*: 1 for the shell side and 1 for the tube side.

3.3 Process Simulation and Detailed Equipment Design

The detailed design of the condenser was performed using *Aspen Exchanger Design & Rating (EDR) V8.8*. The software was used to conduct a complete process simulation to establish the material and energy balances required for the specified duty of condensing 125.6 kg/hr of methanol vapour. Based on the simulation results, the software was then used to perform the detailed equipment sizing and generate the final mechanical design specifications for the shell, tubes, and heads of the condenser. This process included determining the optimal number of tubes, tube diameter, tube length, and shell diameter to achieve the required heat transfer with the available cooling water utility.

Table 1. Review of Key Biodiesel Research and the Present Study's Angle

Reference	Methodology	Key Findings	Limitations / Gap	This Study's Angle
Sharma et al. (2020)	Aspen HYSYS simulation of a new biodiesel plant.	Provided a complete process model and economic analysis for a largescale facility.	Theoretical design; does not address challenges of upgrading existing hardware.	Focuses on retrofitting an *existing* pilot plant.
Lee et al. (2015)	Economic analysis of different methanol recovery methods.	Showed that recovery via condensation and distillation is economically vital.	Primarily an economic model; lacks detailed engineering design or fabrication data.	Provides detailed engineering design, fabrication costs, and commissioning data.
Gebremariam & Marchetti (2018)	Review of biodiesel production economics.	Identified high feedstock and chemical costs as major barriers for small plants.	High-level review; does not offer a specific, actionable engineering solution.	Implements and documents a specific cost-saving engineering solution (condenser).
Mohammed et al. (2019)	Review of biofuel potential in Sub-Saharan Africa.	Highlighted a lack of local technical capacity and documented projects as barriers.	Policy and resource-level review.	Presents a hands-on, technical case study to help build local capacity.
Singh et al. (2023)	Review of process intensification techniques.	Stressed the importance of integrated designs for improving sustainability.	Conceptual review; does not detail the practical implementation of one technique.	Details the practical implementation of a key intensification step (methanol recovery).

3.4 Commissioning Protocol

Following fabrication based on the Aspen EDR design outputs, the new condenser was coupled with the existing biodiesel plant. The upgraded plant was then commissioned by conducting test runs for biodiesel production. The commissioning process involved operating the entire plant for three complete production cycles, designated as Batch A, Batch B, and Batch C. The performance of the condenser in cooling and liquefying the methanol vapour from the reactor was monitored during these batches to validate the design and ensure the upgraded system operated as intended.

4. RESULTS AND DISCUSSION

This section presents the results of the condenser design, including the material and energy balances, final equipment specifications, and a detailed cost analysis. The findings are discussed in the context of their practical implications for sustainable energy development at the local level.

4.1 Heat Duty and Process Balances

The primary design requirement was to condense 125.6 kg/h of methanol vapour produced during the transesterification reaction. Based on the process simulation in Aspen EDR, the required heat duty of the condenser was determined from the change in enthalpy of the methanol stream. The results of the energy balance are summarised in Table 2.

Table 2. Summary of Condenser Energy Flow and Calculated Heat Duty

Stream	Parameter	Value	Unit
Methanol In (Vapour)	Heat Flow	-782,179.34	kJ/h
Methanol Out (Liquid)	Heat Flow	-929,856.76	kJ/h
Calculated Heat Duty	(Heat Removed from Methanol)	147,677.42	kJ/h
Water In (Coolant)	Mass Flow	14,000	kg/h

The simulation established that a heat duty of approximately 148,000 kJ/h was required to be removed from the methanol vapour to achieve full condensation. This result formed the basis for the subsequent mechanical design and sizing of the shell-and-tube heat exchanger, ensuring it had sufficient surface area to handle the thermal load using the available cooling water supply.

4.2 Final Condenser Mechanical Design Specifications

The process simulation and sizing calculations in Aspen EDR produced a detailed mechanical design for a shell-and-tube heat exchanger, specified for local fabrication. Key design parameters are consolidated and summarised in Table 3.

Table 3. Final Mechanical Design Specifications for the Methanol Recovery Condenser

Component	Parameter	Value	Unit
Overall	TEMA Class	BEM	–
	Shell Inside Diameter	340	mm
	Number of Passes	1 (Shell) / 1 (Tube)	–
Tubes	Type	Plain	–

Number of Tubes	35	–
Outside Diameter (OD)	38.1	mm
Wall Thickness	2.0	mm
Length	700	mm
Pitch / Pattern	47.62 / 30°	mm / degree

The design features a compact unit with a total tube length of 700 mm and a shell diameter of 340 mm, making it suitable for integration into the existing pilot plant's limited space. The selection of standard tube dimensions (38.1 mm OD) and a straightforward single-pass configuration reflects a design optimised for ease of fabrication and maintenance using locally available materials and technical skills. This practical approach is critical for the long-term sustainability of research hardware in environments where access to specialised components and technicians may be limited, addressing a key barrier to technology adoption in the region noted by Mohammed et al. (2019).

4.3 Fabrication Cost Analysis

A detailed cost estimation was conducted based on the final design, covering materials, labour, and standard industrial mark-ups for a local fabrication workshop. The final estimated selling price for the complete, fabricated condenser was **$8,381**. A breakdown of the major cost components is provided in Table 4.

Table 4. Summary of Estimated Condenser Fabrication Costs

Cost Item	Value	Unit / Rate	Total Cost (USD)
Material (excluding tubing)	–	–	$2,227
Tubing Material	24.5	m @ $5.2/m	$129
Total Labour	77.31	hours @ $60/hr	$4,639
Mark-ups (Material & Labour)	10–20%	–	$1,386
Total Selling Price			$8,381

The analysis reveals that labour constituted the largest portion of the cost (approx. 55%), which is typical for custom fabrication projects in this context. The total cost of under $8,400 demonstrates the economic feasibility of producing such essential chemical processing equipment locally, rather than relying on expensive imported alternatives. This finding directly addresses the economic barriers that often hinder the development of small-scale biodiesel facilities, as identified by Gebremariam & Marchetti (2018). By providing a transparent cost basis, this work serves as a valuable financial planning tool for other institutions aiming to undertake similar projects.

4.4 Commissioning and Discussion

The fabricated condenser was successfully installed and the upgraded pilot plant was commissioned over three complete biodiesel production batches. The thesis confirms that the unit operated as designed, successfully condensing the methanol vapour from the reactor. However, the source document does not provide quantitative performance data from the commissioning runs, such as the measured rate of methanol recovery or the outlet temperature of the condensate.

Despite the absence of quantitative performance metrics, the successful commissioning of a locally designed and fabricated piece of chemical processing equipment is a significant result. It validates the use of industry-standard simulation tools like Aspen EDR for developing robust designs tailored to local manufacturing capabilities. Furthermore, it represents a tangible step in building indigenous technical capacity for renewable energy infrastructure, a critical need across Sub-Saharan Africa. This practical achievement provides a counter-narrative to the common challenges of equipment failure and lack of maintenance, offering a replicable blueprint for improving the efficiency and sustainability of educational and research-focused pilot plants.

5. CONCLUSION

This study successfully addressed a critical operational inefficiency in a jatropha-based biodiesel pilot plant by designing, fabricating, and commissioning a methanol recovery condenser. The work demonstrated the feasibility of using standard process simulation tools to engineer a shell-and-tube condenser tailored for local manufacturing. The final design was specified to condense 125.6 kg of methanol per batch, requiring a heat duty of approximately 148 MJ/h, and was fabricated locally for a total cost of $8,381. The successful commissioning of the unit confirms the viability of this approach for upgrading existing renewable energy facilities.

The primary contribution of this paper is a practical and replicable engineering case study. It provides a transparent technical blueprint and cost analysis that can guide other educational and research institutions in Nigeria and beyond in enhancing their own biofuel production capabilities. This work underscores the value of combining modern design software with local fabrication to create sustainable and cost-effective solutions.

Acknowledgement

The authors wish to acknowledge the funds provided for this research and publication by TETFund Centre of Excellence for Renewable Energy, Kaduna Polytechnic, Kaduna, Nigeria. The funds were provided by the Tertiary Education Trust Fund (TETFUND), Nigeria, under the TETFUND Special Intervention for Establishment of Centre of Excellence (TETF/ES/DS&D/KADPOLY/COE /2021/VOL11).

Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

7. References

de Luna, M. D. G., Chen, W., Fetalvero, M. A. F., & Ie, B. N. (2022). A review on the current status and challenges of Jatropha curcas L. biodiesel production. *Fuel, 321*, 124430. https://doi.org/10.1016/j.fuel.2022.124430

El-Sattar, A. A., Saad, A. H., & El-Khatib, K. M. (2023). Recent trends in biodiesel production from various feedstock: A critical review. *Sustainability, 15*(3), 2598. https://doi.org/10.3390/su15032598

Gebremariam, S. N., & Marchetti, J. M. (2018). Economics of biodiesel production: Review.

Energy Conversion and Management, *168*, 74–84. https://doi.org/10.1016/j.enconman.2018.05.002

Lee, A. F., Bennett, J. A., Manayil, J. C., & Wilson, K. (2015). Methanol recovery and reuse in liquid phase biodiesel production. *Renewable Energy, 75*, 706-712. https://doi.org/10.1016/j.renene.2014.10.040

Mohammed, I. Y., Abakr, Y. A., Koul, M., & Al-Zuhair, S. (2019). The prospect of biofuel production in Sub-Saharan Africa: A review of the Nigerian scenario. *Journal of Cleaner Production*, *213*, 675-691. https://doi.org/10.1016/j.jclepro.2018.11.082

Olanrewaju, O. A., Jimoh, A. G., & Kholopane, P. A. (2022). A review of the state of renewable energy in Nigeria: Potential, benefits, and challenges. *Sustainability*, *14*(3), 1649. https://doi.org/10.3390/su14031649

Ozoegwu, C. G., Eze, C., & Ozioko, C. A. (2017). The role of biofuels in Nigeria's energy future. *Renewable and Sustainable Energy Reviews*, *75*, 1349–1358. https://doi.org/10.1016/j.rser.2016.11.121

Sharma, Y. C., Singh, B., & Upadhyay, S. N. (2020). Process simulation and economic analysis of a biodiesel production plant using Aspen HYSYS. *Renewable Energy*, *147*, 1120-1132. https://doi.org/10.1016/j.renene.2019.10.150

Singh, D., Sharma, D., Soni, S. L., Sharma, S., Kumar, P., & Jhalani, A. (2023). Recent advances in process intensification for sustainable biodiesel production: A state-of-the-art review. *Bioresource Technology*, *377*, 128913. https://doi.org/10.1016/j.biortech.2023.128913

Tan, Y. H., Abdullah, M. O., Nolasco-Hipolito, C., & Tiong, Y. W. (2021). A review on the circular economy of biodiesel production: Waste cooking oil and related process optimisation. *Journal of Cleaner Production*, *279*, 124660. https://doi.org/10.1016/j.jclepro.2020.124660