

Low-Cost Energy Management Strategies for a Commercial Biodiesel Plant in Malaysia: A Case Study Based on Industrial Operation and Aspen Plus Simulation

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Abstract

This study investigates low- and no-capital energy management strategies for a commercial 500-metric-ton-per-day biodiesel plant located within a Malaysian oleochemical complex in the Klang Valley. Drawing on several years of industrial operating experience and a validated Aspen Plus V10 steady-state process simulation, the work provides a comprehensive mass- and energy-balance assessment under typical operating conditions, with particular emphasis on the first five years of plant operation. The simulation model was validated against more than ten steady-state plant operating cases collected over a one-year period following commissioning, demonstrating good agreement with plant operating data. The baseline process was found to have a specific energy consumption of approximately 200 kWh per metric ton of oil input under an oil-to-methanol ratio of 1:5. Unlike most existing studies, which focus on capital-intensive measures such as waste-gas recovery, steam-network optimization, and heat-exchanger retrofits, this case study concentrates on operational and process-engineering levers—including methanol feed-ratio optimization, reflux stream management, and improved production planning and scheduling—to reduce fuel consumption without requiring plant modifications. The analysis showed that reducing the oil-to-methanol ratio from 1:5 to 1:4.5 reduced process energy consumption by 7.6% while maintaining a biodiesel conversion of 98.5% and meeting EN 14214 biodiesel quality requirements. By integrating real plant data with simulation-based energy-stream analysis, the study delivers actionable, low-cost energy management measures that can be readily adopted by Malaysian biodiesel producers to improve energy efficiency, reduce CO₂ emissions, and support business viability in an export-oriented, subsidy-influenced fuel market, while also identifying waste-heat recovery without capital expenditure as a key area for future research.

Keywords

Commercial Biodiesel Plant, Aspen Simulation, Low-Cost Energy Management Strategies

1. Introduction

The recent Iran-Israel-United States confrontation has put upward pressure on global fuel markets, prompting policy responses from oil-importing and subsidy-reliant countries. The Malaysian government has announced plans to increase domestic biodiesel blending from B10 to B15 from June 2026; nineteen licensed biodiesel plants will be responsible for the expanded blend mandate [1]. The change will require around 800,000 tonnes of additional crude palm oil relative to current B10 consumption and is expected to cut annual fuel-subsidy expenditure by approximately RM1.5 billion. The higher-blend strategy aims to reduce exposure to volatile international oil markets and to bolster the local palm oil industry, but its success hinges on overcoming bottlenecks in national blending capacity and distribution logistics. Beyond these infrastructure constraints, concerns remain about the energy efficiency of biodiesel production and whether producers will be willing to adopt B15 in the absence of sufficient profitability and energy-saving incentives.

This paper examines the energy efficiency of biodiesel production in Malaysian oleochemical-linked plants using process simulation with Aspen Plus combined with biodiesel operational experience. While several studies have examined biodiesel policy and engine-performance impacts in Malaysia, there remains a shortage of plant-level process-simulation work that quantifies and optimizes the energy efficiency of oleochemical-based biodiesel production under an evolving B10 - B15 mandate. This paper provides the first plant-scale Aspen Plus-based energy-efficiency analysis tailored to Malaysian oleochemical-linked biodiesel facilities under the B10 - B15 transition, generating specific heat-integration and operating-window insights that are directly implementable by industrial operators. The novelty of this work lies in (i) a flowsheet-level, Aspen Plus-based energy-efficiency analysis specifically calibrated to Malaysian oleochemical-linked biodiesel plants; (ii) qualitative assessment of operating-parameter base on non-capital energy management levers; and (iii) the translation of these findings into practical recommendations for plant operators seeking to meet higher-blend mandates while minimizing energy use and production costs.

The Malaysian economy is strongly dependent on palm oil and oleochemicals. In 2025, Malaysia produced 20.28 million MT of crude palm oil, making the country an important supplier of edible oil, palm-based commodities, and renewable products such as biodiesel to the global economy. According to MPOB [2], 57,149 (353,780) metric tonnes of biodiesel were exported in 2025, accounting for 0.28%

14.3% of total CPO production volume. Malaysia has 19 biodiesel producers with a combined capacity of 2,652,020 tonnes of biodiesel per annum (TPA) [3], yet the sector operated at only 46% utilization in 2025 [2]. This underutilization highlights the presence of latent production capacity that could be mobilized under the government's planned increase in domestic biodiesel blending from B10 to B15 from June 2026. The higher-blend mandate, which will require around 800,000 tonnes of additional crude palm oil relative to current B10 consumption, offers an opportunity to absorb more internally produced biodiesel while still maintaining an export surplus. However, realizing this potential depends not only on policy-driven demand but also on improving the energy efficiency and cost-competitiveness of existing oleochemical-linked biodiesel plants.

Previous studies have shown that biofuels, including biodiesel, can reduce greenhouse gas (GHG) emissions by approximately 25% to 100% compared with petroleum-based diesel [4]. Renewable energy sources such as biodiesel have gained increasing attention in recent years because of the depletion of global petroleum reserves, rising energy demand, growing concern over greenhouse gas emissions, and higher petroleum prices [5]. These conditions have strengthened the case for alternative fuels that can support both energy security and environmental sustainability.

The oleochemical industry is widely regarded as a green industry because it primarily uses vegetable oils as feedstock. However, it is also energy intensive, particularly because thermal separation processes often require distillation and fractionation units. As Malaysia's oleochemical industry is export-oriented, producers must comply with increasingly stringent waste gas emission regulations to remain competitive in international markets. Malaysia has reaffirmed its commitment to achieving carbon neutrality by 2050 through national climate policy statements and its third Nationally Determined Contribution (NDC) submitted in 2025 [6]. For international clients, compliance with the 2015 Paris Agreement, European Union (EU) 20/20/20 remain important [7]. As a result, Malaysian oleochemical producers are under increasing pressure to improve environmental performance and strengthen energy management systems.

In Malaysian industry, a common strategy for improving fuel cost management is to reduce fuel use and the associated carbon footprint. However, the literature shows limited research on non-capital-expenditure energy management strategies that are integrated with practical industrial operating experience in the oleochemical sector. Because energy management can directly lower fuel consumption, it provides a practical means to improve both energy efficiency and environmental performance. In the context of biodiesel production, in particular, energy management has the potential to deliver a twofold benefit by reducing fuel use and lowering carbon emissions.

2. Objective and Motivation of the Study

Most biodiesel plants in Malaysia are supplied with technology from providers

such as Desmet, Lurgi, and Lipico [8]–[10]. This study is based on a 500-metric-tons-per-day (MTPD) biodiesel plant located in the Klang Valley, which operates within a Malaysian oleochemical factory. The main objective of this work is to provide a comprehensive assessment of this commercial biodiesel plant under typical operating conditions from an energy- and mass-balance perspective and, in doing so, to translate industrial operational experience into practical guidance for lower-cost biodiesel production.

Aspen Plus V10 is used to develop a steady-state process simulation and to perform Stream Energy-balance analysis, with a focus on identifying fuel-saving and waste-heat recovery opportunities. By systematically analyzing energy streams and heat-integration possibilities, the study aims to quantify how improved energy-management practices can reduce thermal energy consumption, lower the plant's carbon footprint, and support more cost-effective operation. This work therefore presents a case analysis of the simulated process and its associated energy streams, highlighting practical measures—grounded in real industrial experience—that can be implemented to enhance energy efficiency while supporting Malaysia's broader goals of reducing fuel-subsidy burdens and greenhouse gas emissions from the oleochemical-biodiesel sector.

3. Literature Review

3.1. Biodiesel: Production Routes, Economics, and Challenges

The world's energy demand is projected to increase by nearly 50% by 2050 [11] due to a rise in the global population and increased economic activities. According to the 2023 energy statistic, renewable energy will account for 65% of all primary energy supplies to the world by 2050, including the majority of renewable energy supply (biofuels and waste-derived bioenergy). Transportation will consume 24.7% of total energy consumption [12]. However, the development of renewable energy markets, such as biofuels, is largely driven by national support policies, including mandates for blending into petrol and diesel. To put it succinctly, vegetable oil can qualify as an advanced biofuel under the Renewable Fuel Standard (RFS) rules (OECD-FAO 2023), and biofuels like biodiesel possess comparable properties to fossil diesel.

Biodiesel can be produced through several pathways, including pyrolysis, microemulsion, supercritical processes, and transesterification [13]. In commercial practice, biodiesel production is commonly carried out in batch or continuous modes [8]. Among these routes, transesterification remains the most widely used because it is relatively simple, and capable of producing high yields. Both homogeneous and heterogeneous catalysts have been applied in transesterification, and the process may proceed through acid-catalyzed, base-catalyzed, or non-catalytic routes [14].

Although biodiesel offers environmental benefits and supports the palm oil downstream industry, its wider adoption in Malaysia is constrained by economics. A major barrier is the country's subsidized diesel policy [15], which keeps

conventional diesel prices low and reduces the commercial incentive for producers to expand biodiesel output. In addition, biodiesel production remains feedstock-intensive, and feedstock costs account for a substantial share of total production expenses *i.e.* raw material cost accounts for about 75% - 90% of the total biodiesel production cost [16]. As a result, the high cost of biodiesel production, combined with relatively cheap subsidized fossil diesel, weakens producer motivation to invest in biodiesel ventures. This challenge limits the advancement of palm-based biodiesel production despite Malaysia's strong palm oil industry and its potential contribution to value-added downstream development.

However, the unit cost of biodiesel production can be lowered by increasing process productivity, reducing feedstock cost, and minimizing utility demand. Recent literature indicates that improved production methods can enhance biodiesel yield and process efficiency, while an effective energy management scheme can significantly reduce utility expenses [17].

3.2. Transesterification Process

Figure 1 shows the process flow diagram of vegetable oil transesterification in one of the Malaysian commercial biodiesel plants. The feedstock of refined, bleached, and deodorized palm oil (RBDPO) is fed into a dryer for dewatering and degassing purposes. The RBDPO continuously feeds into a mixer, excess methanol with 99.9% purity, and catalyst dose is injected into the mixer for well-mixing purposes before it is fed into Reactor 1. as excess methanol drives the reaction forward in accordance with oil transesterification stoichiometric reaction shown in Equation (1).

Transesterification is a reaction to react 3 moles of methanol with 1 mole of oil or triglyceride to produce 3 moles of biodiesel and 1 mole of glycerol (glycerin). Removing the glycerol continuously from the reactors is needed for ensuring high biodiesel yield by shifting the reaction forward. Reactors 1, 2 and 3 are equipped with a circulation pump to enhance the reaction rate of oil transesterification by mixing methanol into the oil [13] [18]. The mixer and circulation pump allows keeping certain mixing degrees inside the reactors.

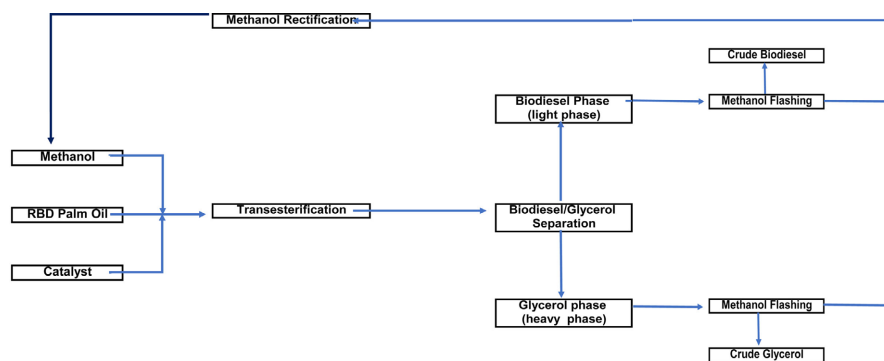
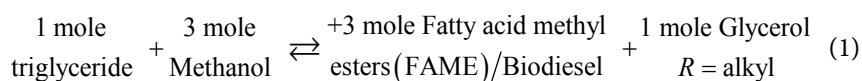
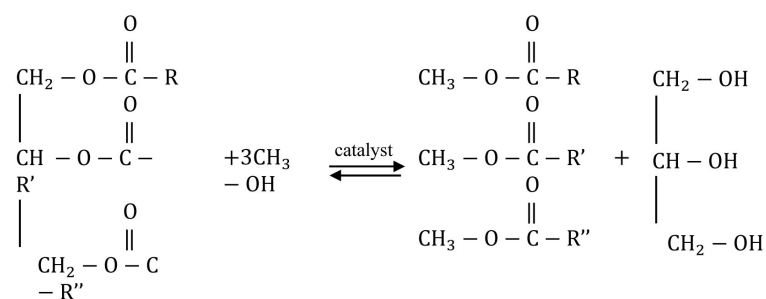


Figure 1. Typical commercial biodiesel plant process flow diagram of palm oil transesterification.



Excess methanol which more than stoichiometric need to supply into the transesterification reaction, aims to shift the reaction forward. After the biodiesel process is almost complete in the reactor, the excess methanol and crude biodiesel and glycerol is discharged. After separation, methanol is available for recovery and reuse by using the methanol rectification column. The liquefied methanol is then fed directly into the methanol rectification column.

The rectification process yields methanol with a purity of 99.9%, which is collected via the overhead condenser. Part of this methanol is returned to the column as reflux, while the remainder is discharged into a storage tank for feeding into the reactor. The column operates under slight atmospheric pressure, maintaining a temperature of 65°C at the top of the column and 100°C at the bottom stream.

Recycling methanol is energy intensive providing an opportunity for energy efficiency opportunities evaluation during biodiesel operation [19]-[21]. According to the 2009 USA National Biodiesel Board, the energy consumption for industrial biodiesel production is an average of 4.4 MJ/gal of biodiesel [20], with plant capacity unknown. Energy consumption for algae oil and waste cooking oil was 1.94 MJ/gal biodiesel and 1.94 MJ/gal biodiesel, respectively. Energy for methanol recovery in biodiesel processes accounts for up to 50% of the plant operating cost [19].

3.3. Process Simulation

Software solutions for process simulation, integration, and optimization have been widely employed, assisting process sector businesses in meeting their operational objectives. There are numerous effective tools accessible, each with its own set of advantages. **Table 1** displays the market's current commercial software program bundle.

Table 1. Process simulator software. Adopted from chemical engineering process simulation [22].

Corporation	Software
AspenTech	Aspen One Engineering
Honeywell	Unisim Design

Continued

Schneider Electric	SimSci PRO/II
Chemstation	ChemCAD
WinSim	DESIGN II FOR Windows
Intelligen	SuperPro Designer SchdulePro
Bryan Research & Engineering	Promax
Process Systems Enterprise	gPROMS

Process simulation which first appeared in the 1960s, uses computer-based mass and energy balance computations for steady-state processes [22]-[24] described process simulation as a mathematical model that represents the processes of a chemical plant and facilitates data sourcing through computer aid.

Process modelling is under the purview of process synthesis. it is a reliable method for improving current processes at a cheap cost [25].

Balance reconciliation and flowsheeting simulation are extensively used for sustainability design and savings analysis, establishing themselves as important assets in a process engineer's toolset [26]. Flowsheets are optimal processing system and unit design arrangements [27]. Flowsheet synthesis employs a three-level hierarchical approach: synthesis optimization, design optimization, and operational optimization [28]. Flowsheet evolves through iterations of major equipment blocks and allows for the specification of specifics for both new and existing plants, such as flow rates, temperatures, and pressures. Additionally, it is subdivided further (process analysis) to evaluate the effectiveness of each component [22].

AspenTech [29] provides integrated process simulation software for industries such as oil and gas, chemicals, and oleochemicals. Aspen Plus is widely used for process modelling, conceptual design, optimization, and performance monitoring. It includes extensive databanks for pure-component properties and phase-equilibrium data for conventional chemicals, electrolytes, solids, and polymers. The software also supports rigorous sizing and rating of key equipment, including heat exchangers and distillation columns, within the simulation environment. Hill and Justice [30] reported that commonly used thermodynamic property methods in Aspen Process Simulator are summarized in **Table 2**.

Table 2. Thermodynamic property set model category and its commonly used models, adopted from [30].

Model Category	Most commonly Used Models	System type	Examples
Equation of State (EOS)	SRK Peng-Robinson	Real Gas + Ideal Liquid	Petroleum pseudo-components Similar hydrocarbon Light Gases
Binary Interaction Parameter (BIP) Activity Coefficient	NTRL Wilson	Ideal Gas + Polar Liquid	Water + organics Dissimilar hydrocarbon Mineral acids + water Dissimilar organics

The following researchers have advised using caution while selecting thermodynamic property models. For example, [31] [32] used non-random two liquids (NRTL) models or Universal Quasi Chemical (UNIQUAC) models as thermodynamic models because methanol and glycerol are polar components, and NRTL-SRK and UNIQUAC-SRK models were used for equipment where the vapour-liquid equilibria were calculated. However, researchers such as [29] [33] [34] have reported using Dortmund modified UNIFAC for biodiesel process simulation. Their findings show that the models are capable of predicting the physical attributes of the components under consideration. The summary depicted in **Table 3**.

Table 3. Summary of thermodynamic models used in aspen simulation.

No	Author	Area of research	Thermodynamic model used
1	Zhang <i>et al.</i> (2003) [31]	Canola virgin vegetable oil/waste cooking oil, alkaline/acidic catalyst (Transesterification method)	i) HYSYS ii) NTRL, UNIQUAC
2	West <i>et al.</i> (2008) [35]	Waste cooking oil used Zhang <i>et al.</i> , (2003) processes (Supercritical fluid method)	i) Aspen HYSYS V7.0 software ii) NTRL
3	Kiss A. (2009) [34]	Reactive distillation using heterogenous catalyst	i) Aspen ii) Dortmund modified UNIFAC
5	Garcia <i>et al.</i> (2010) [32]	Sunflower oil to make biodiesel (Transesterification method)	i) Aspen HYSYS V7.0 software ii) NTRL and UNIQUAC
6	Nicola <i>et al.</i> (2010) [36]	Refined vegetable oil (no mention of which type of refined oil used in the study) (Transesterification)	i) ASPEN Plus ii) Dortmund modified UNIFAC
7	Sharma and Rangaiah (2013) [37]	Waste cooking oil (Transesterification)	i) Aspen HYSYS ii) UNIQUAC
8	Patle <i>et al.</i> (2014) [33]	RBD palm oil and waste cooking oil (Esterification and transesterification)	i) Aspen Plus V 8 ii) Dortmund modified UNIFAC
9	Aboelazayem <i>et al.</i> (2018) [38]	Rapeseed oil (Supercritical fluid method)	i) Aspen HYSIS V 8.8 ii) NTRL
10	Granjo <i>et al.</i> (2020) [39]	Soy bean oil (Transesterification)	i) Aspen Plus ii) UNIQUAC and NTRL
11	Medeirosa, Hugo A.D. <i>et al.</i> (2020) [40]	Methanol recovery	i) Aspen HYSIS ii) NTRL
12	Petrescu, L. <i>et al.</i> , (2020) [41]	Biodiesel production	i) Aspen Plus and ChemCAD ii) UNIFAC
13	Rios, B. <i>et al.</i> (2023) [42]	Glycerol, Alcohol, Safflower biodiesel system	UNIQUAC
14	Azad, A.K. <i>et al.</i> (2024) [43]	Design and simulation of the biodiesel process plant	NRTL

3.4. Energy Management for Oleochemical

Even if the literature on oleochemical energy management is limited on unit operation application [44] [45]. However, Zarlie [46] has supplied an overview write-up for oleochemical distillation and fractionation procedures. He stated that because fatty acids are heat instable, designing a distillation machine for thermolabile fatty acids required caution. To prevent cracking or polymerization, high vacuum and low temperature conditions are used. It is critical to have a short residence time at the column bottom. Deaerators, thermal oil, or high-pressure steam are used as heat sources in distillation processes, along with condensing and vacuum. Overall, it is an energy-intensive procedure. Indeed, as shown in **Table 4** there are emerging literatures in the Malaysian oleochemical industry [45] [47] [48].

Energy management implementation guided by its framework and standards. It provide a structure for conducting energy reviews and audits. These processes allow for the analysis of energy consumption, assessment of heat recovery potential, and identification of opportunities for energy savings [49]. EN 16001 [50] is the energy management system of the European standard published in 2009. It complies with ISO 14001 and is based on the plan-do-check-act cycle. EN 16001 aids organizations setting up a comprehensive energy management system and regularly improve their energy utilization performance, leading to lower energy costs and fewer greenhouse gas emissions [50].

ISO 50001 consists of five phases which emphasize continual improvement; policy, planning, implementation, checking and corrective action and management review. Adoption of the ISO 50001 framework in an organization is one of the options for energy management to consider [51]. It is a plan-do-check-act cycle management system which is designed to follow the Deming quality management system.

Although literature on oleochemical energy management remains limited, recent studies have begun to address energy use and waste heat recovery in the Malaysian oleochemical industry. Zarlie [46] provided an overview of oleochemical distillation and fractionation, noting that fatty acids are thermally sensitive and therefore require careful column design under high-vacuum and low-temperature conditions to minimize cracking and polymerization. Because distillation in this sector is energy intensive, utilities such as thermal oil, high-pressure steam, condensers, and vacuum systems are commonly used. Khong [52] has provided literature gap in oleochemical section for energy management typically in waste heat recovery, however, the current literature still provides limited guidance on decision frameworks for energy management, particularly for evaluating waste heat recovery opportunities in biodiesel. This gap warrants further investigation within the Malaysian oleochemical industry. **Table 4** illustrates the research on energy management and waste heat recovery in the Malaysian oleochemical industry.

Energy management systems provide a framework for energy reviews and audits, helping organizations identify energy-saving opportunities and waste heat recovery potential. EN 16001 [50], published in 2009, was an early European standard based on the plan-do-check-act cycle. It has since been superseded by ISO 50001, the current international standard, which supports continual improvement in energy performance through policy setting, planning, implementation, checking, and management review [51].

Although literature on energy management in oleochemical unit operations remains limited, recent studies have begun to address energy use and waste heat recovery in the Malaysian oleochemical industry [44] [45]. Zarlie [46] provided an overview of oleochemical distillation and fractionation, noting that fatty acids are thermally sensitive and therefore require careful column design under high-vacuum and low-temperature conditions to minimize cracking and polymerization. Because distillation in this sector is energy intensive, utilities such as thermal oil, high-pressure steam, condensers, and vacuum systems are commonly required.

Energy management systems provide a structured framework for energy reviews and audits, enabling organizations to assess energy consumption, identify heat-recovery potential, and determine opportunities for energy savings. Early standards such as EN 16001 were based on the plan-do-check-act cycle and later informed the development of ISO 50001, which remains the international benchmark for continual improvement in energy performance through policy development, planning, implementation, checking, and management review [51].

Table 4 Emerging energy management research works undertaken for Malaysian oleochemical firms.

Year	Author	Research work undertaken	Impact of study
2019	Koh, K.S. <i>et al.</i> , [47]	Utilization of waste gas recovery case studies, focusing on reduction of fuel consumption and greenhouse gas emission in Malaysian oleochemical firm	A saving of 17.29% of fuel consumption and approximated 149.49 tonnes per annum of carbon dioxide gas (CO ₂)
2021	Trisha, V. <i>et al.</i> , [45]	Applied Aspen Energy Analyser V 10 to retrofit heat exchanger network of an oleochemical plant	Save over 80% in annual costs and reducing energy consumption by 1,882,711 gigajoules per year (GJ/year)
2022	Lee, R.A. <i>et al.</i> , [48]	Steam Network Optimization and CO ₂ reduction in an oleochemical production complex	29.56% - 50.82% cost saving and reduction of CO ₂ emissions of 95,222 tonne carbon per year

However, current literature still provides limited guidance on how such frameworks can be applied to Malaysian oleochemical plants, particularly for evaluating waste heat recovery opportunities in biodiesel-related processes. Khong [52] also highlighted the limited research on energy management in the oleochemical sector, especially in relation to waste heat recovery. This gap warrants further inves-

tigation into energy management strategies for the Malaysian oleochemical industry. **Table 4** depicted the Emerging energy management research works undertaken for Malaysian oleochemical firms.

3.5. Energy Efficiency in Industrial Energy System

Energy efficiency is commonly defined as the effectiveness with which energy resources are converted into useful work [53]. In industrial settings, improving energy efficiency requires structured reviews of energy consumption through audits and assessments, which can reveal opportunities for heat recovery and other energy-saving measures. However, technical solutions alone are not sufficient. Successful implementation of energy-efficiency programs also depends on organizational commitment, staff engagement, and system knowledge. Recent studies on ISO 50001 implementation indicate that these managerial and behavioral factors remain essential for effective energy management and continual improvement in energy performance [54].

Energy-efficiency improvement is often a complex and time-consuming process that typically begins with energy audits, consumption mapping, and identification of improvement measures. The commitment of management, employee awareness of energy wastage, knowledge of the system under study, and support from internal or external experts are key factors for successful implementation [49] [54] [55]. In addition, efficient energy use is a cost-effective strategy that can reduce CO₂ emissions, improve productivity, and lower dependence on imported energy sources [56].

Although research on energy efficiency has grown in recent years, gaps remain in the methods used to assess and improve industrial energy performance [57]. Previous studies have examined energy-intensive motor systems, the integration of energy management with pinch analysis in petrochemical plants, and the use of intelligent energy-saving systems in industrial buildings [49] [58] [59]. However, fewer studies have applied process simulation tools such as Aspen Plus to evaluate energy efficiency at the unit-operation and plant level, particularly in oleochemical and biodiesel production systems. Aspen simulation is important because it enables detailed modeling of mass and energy flows, identification of high-consumption equipment, and assessment of heat-recovery opportunities under realistic operating conditions. In this way, Aspen Plus provides a rigorous framework for translating energy-efficiency concepts into practical, process-specific improvement strategies.

4. Methodology

4.1. Framework

The overall methodological framework for this study is presented in **Figure 2**. However, this case study focuses only on Phase 1, which involves the process simulation and validation of the biodiesel plant.

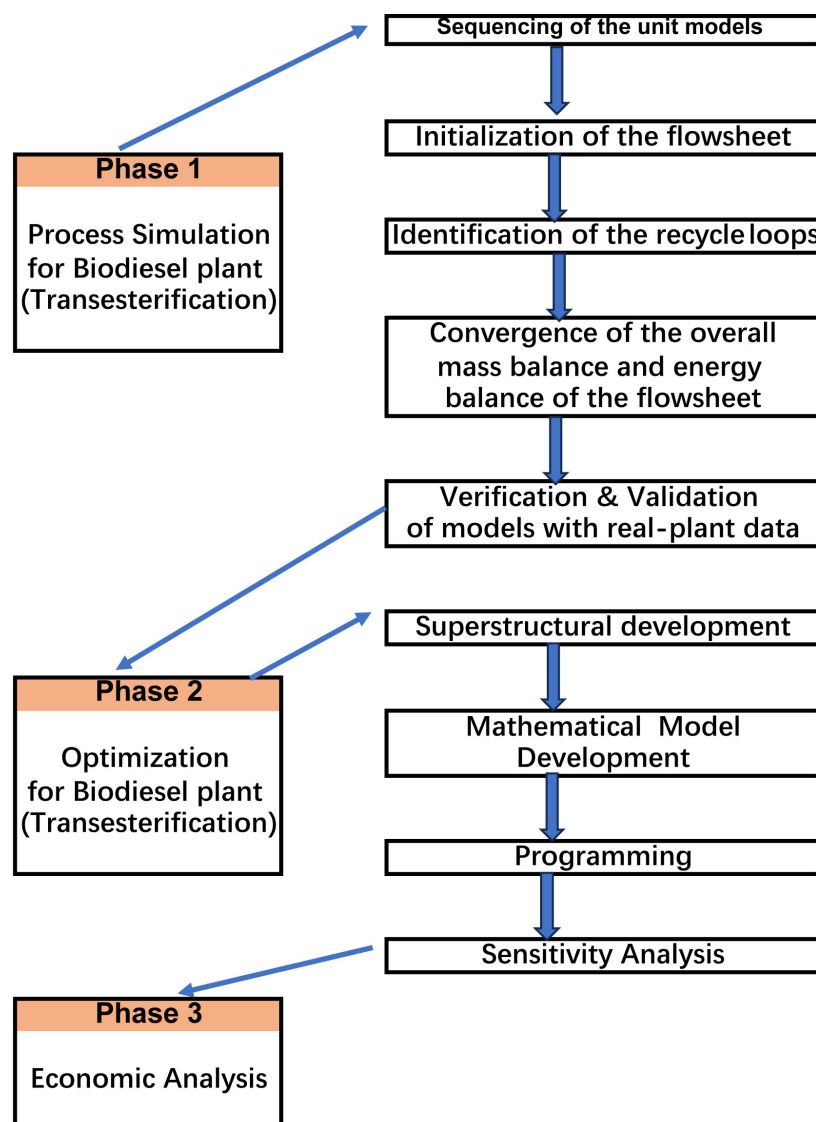


Figure 2. Overall methodology framework.

4.2. Aspen Simulation for a Commercial Biodiesel Plant

Aspen simulation for the commercial biodiesel plant starting with registration of new components (triglyceride, methanol, glycerol and biodiesel) in the properties section then followed selection of thermodynamic model to enable physical properties estimation of simulation. Dortmund modified UNIFAC (UNIF-DMD) and None Two Random Liquid (NTRL) have been selected as the thermodynamic model used in this study. Literature review showed that these two thermodynamic models has been widely used by the researcher like Zhang [31] and Granjo [39] and Azad [43].

Following is the unit models built according to Sequencing of unit models method for easier managing the complex flowsheet [22]. These models are built according to the mass balance illustrated in **Figure 3**, the simulation model iteratively until converged.

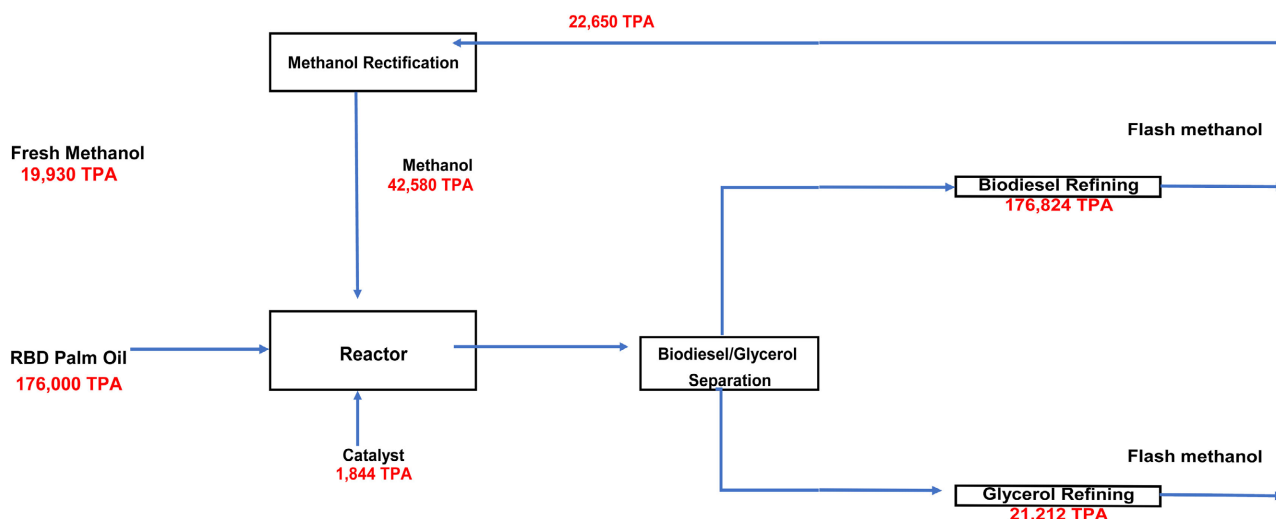


Figure 3. The overall mass balance of the commercial biodiesel plant with 176,000 TPA as oil input.

4.3. Phase 1—Process Simulation and Validation

The process simulation model was divided into subsections, as shown in **Figure 4**, and each subsection was developed and run until convergence. Subsequently, the overall biodiesel model was established after combined all the sub-model, lastly the recycle methanol stream was developed till convergence. The simulation model was then brought to the DCS for model validation iteratively with small adjustment until process parameter and quality complied as depicted in **Figure 4**.

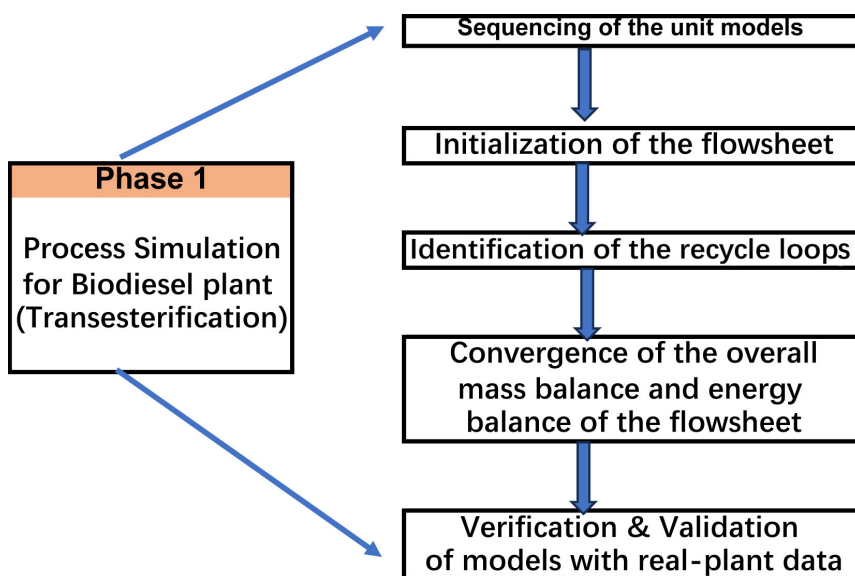


Figure 4. Phase 1—process simulation methodology framework.

The plant data used for model validation were collected over a one-year operating period following the successful commissioning of the biodiesel plant by the in-house Process Commissioning Team. More than ten steady-state operating

cases were selected and evaluated during the validation process.

Stable plant operating conditions were defined as periods with no interruptions to feed supply, electrical power, distributed control system (DCS) operation, or normal plant operations. During these periods, all major process variables, including pressure, temperature, mass flow rate, and liquid level, remained within their normal operating ranges without significant fluctuations.

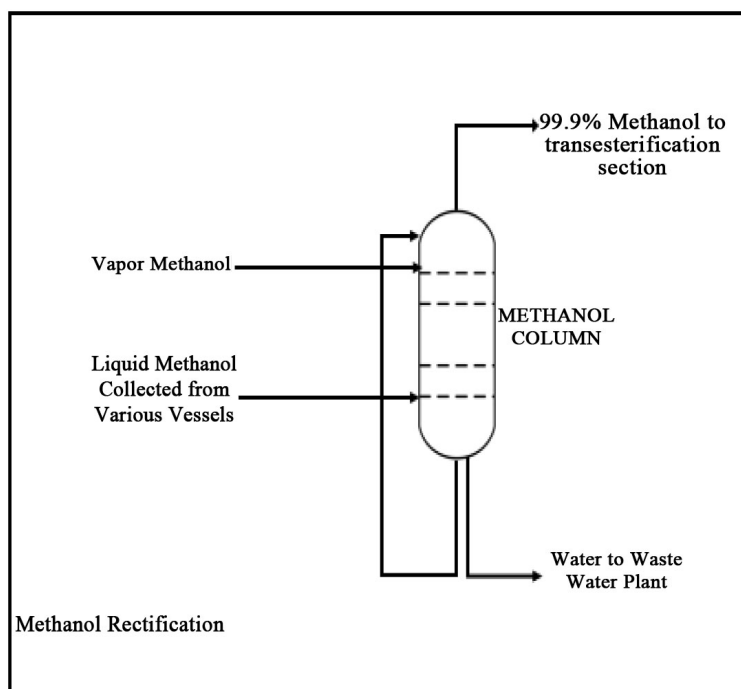
For each steady-state case, the simulation model was iteratively adjusted and validated against measured plant data using key process parameters (pressure, temperature, mass flow rate, and liquid level) and critical product quality indicators, such as methanol content in biodiesel and glycerol streams. The validation procedure was repeated until satisfactory agreement between the simulation results and plant data was achieved.

4.4. Model for Sub-Sections

Only the models for the major fuel-consumption units are presented here. The complete model, together with its validation, is available upon request for academic purposes. This limitation is intended to protect the intellectual property of the technology provider. The unit models listed are:

- a) Methanol rectification column (**Figure 5(a)**);
- b) First methanol stripper for crude biodiesel (**Figure 5(b)**);
- c) Second methanol stripper for refined biodiesel before the storage tank (**Figure 5(c)**);
- d) Methanol flasher for crude glycerol before the storage tank (**Figure 5(d)**).

These unit models are constructed as shown in **Figures 5(a)-(d)**.



(a)

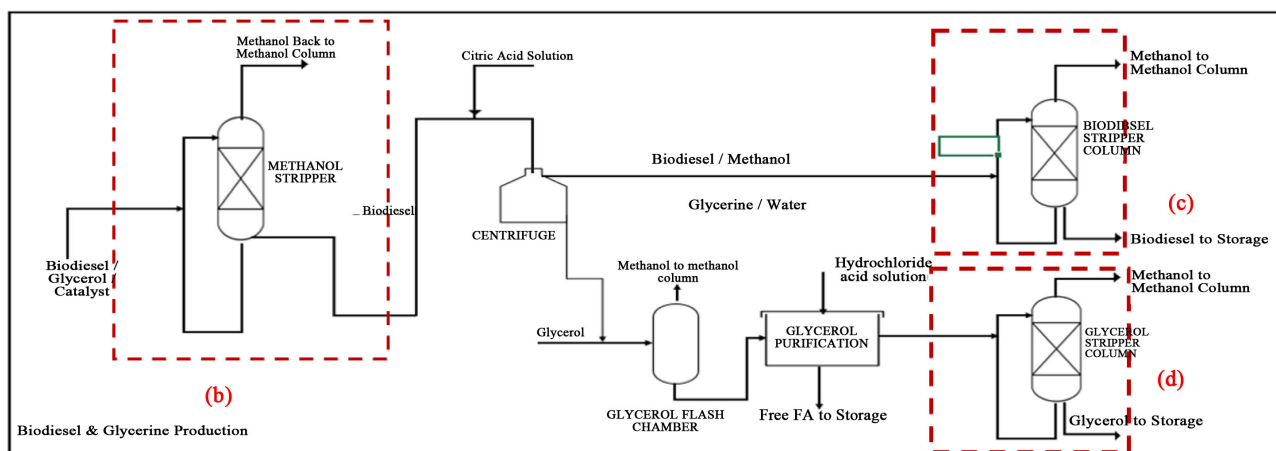


Figure 5. (a) Typical methanol rectification column. (b)-(d) Typical methanol removal unit for biodiesel and glycerol.

5. Case Study

This study uses data from a commercial 500 TPD biodiesel plant located in the Klang Valley, Malaysia. The primary data were obtained from instrument readings recorded in the Distributed Control System (DCS) under stable plant operating conditions. In addition, the technology provider supplied a set of operating conditions together with their associated heat loads to the plant owner as part of the reference documentation for verifying utility consumption, as agreed in the plant purchase and sale contract, named technology provider given dataset (TPGS).

Objectives of the case study are addressed as follows:

- 1) To develop and validate an Aspen Plus V10 simulation model for stream mass and energy balance analysis, thereby minimizing model error and enabling comprehensive evaluation of the biodiesel plant.
- 2) To estimate the total energy consumption required to produce one metric ton of biodiesel based on the preset methanol-to-feedstock ratio and refined, bleached, and deodorized (RBD) oil feed conditions.
- 3) To provide the process engineering team with a validated model that can be used to evaluate alternative fuel-reduction and waste heat recovery strategies and to support recommendations to the process and production management team without testing them on the real plant, thereby minimizing resource wastage and avoiding the generation of off-specification products.
- 4) To explore energy management opportunities based on the validated Aspen Plus simulation model, combined with practical plant operational expertise, to achieve lower fuel consumption and sustained biodiesel production for the Malaysia oleochemical industry without incurring plant modification expenditures within the first five years of plant operation.

5.1. Simulation and Validation

The Aspen Plus V10 simulation was developed by first registering the key

process components, including triglycerides, methanol, glycerol, and biodiesel (FAME), in the Properties environment. Thermodynamic properties were estimated using the Dortmund Modified UNIFAC (UNIF-DMD) and Non-Random Two-Liquid (NRTL) property methods. UNIF-DMD was applied to the transesterification section involving triglycerides, biodiesel, methanol, and glycerol, while NRTL was used for the methanol recovery and purification sections.

The transesterification reactor was represented as a reactor vessel without explicitly modeling the reaction kinetics or stoichiometric conversion equations for simplicity as the reaction is not the primary analysis in this case study. Key distillation-column specifications, including operating pressure, reflux ratio, and product purity targets, were based on actual plant operating conditions. The simulation model was subsequently validated using industrial plant data and used for the energy-analysis study.

The Aspen Plus V10 model was validated using plant operating data collected during stable operating conditions. Validation was performed by comparing simulated and measured values for key process variables, including major equipment heat duties, biodiesel and glycerol flowrates, methanol recovery purity, biodiesel methanol content, and glycerol quality. The percentage error for each variable was calculated relative to the corresponding plant measurement.

For example, the accuracy of the model for the first methanol stripper was evaluated using the Mean Absolute Percentage Error (MAPE), as defined in Equation (2). **Table 5** presents the plant and simulation data, together with the corresponding percentage errors, for the first methanol stripper. The results showed satisfactory agreement between the simulation model and the industrial plant data, confirming the suitability of the model for energy-calculation studies. The calculated MAPE was 1.48%. All the validation is performed in these manners.

Mean Absolute Percentage Error (MAPE)

$$\text{MAPE} = \frac{1}{n} \sum_{i=1}^n \left| \frac{\text{Simulation}_i - \text{Plant}_i}{\text{Plant}_i} \right| \times 100 \quad (2)$$

Table 5. Comparison of plant data and simulation data.

Parameter	Plant Data	Simulation Data	Error (%)
Biodiesel flowrate - feed stream (kg/h)	20,800	20,800	0
Methanol + water Flowrate - flashed stream (kg/h)	412 + 138 = 550	403 + 140 = 543	1.27
Biodiesel Flowrate - discharge stream (kg/hr)	20,250	20,257	0.03

Continued

Methanol content in feed stream (%)	2.1	2.1	0
Methanol +water content in flashed stream (%)	75	74.2	1.00
Methanol in discharge stream (%)	0.15	0.16	6.67

5.2. Heat Loads of the Four Major Energy Consumers at Various Excess Methanol Feed Ratios in the Transesterification Reactor, Depicted in Table 6

The specific energy consumption for the baseline case was determined to be 200 kWh per metric ton (MT) of oil input based on the process simulation results at 500 MPD plant capacity. This value was obtained under steady-state operating conditions using the validated simulation model of the biodiesel production plant at an oil-to-methanol ratio of 1:5. Martin and Grossmann [20], citing data from the 2009 National Biodiesel Board, reported an average industrial energy consumption of approximately 4.4 MJ/gal biodiesel for unknown plant capacity, equivalent to about 367 kWh/MT biodiesel. The baseline case developed in this study showed a specific process energy consumption of 200 kWh/MT oil input at 500 MPD. Direct comparison should be interpreted with caution because of differences in the calculation basis and process boundary definitions.

The operating basis corresponds to the baseline process configuration with the original energy optimization setup provided by the technology provider. The reported energy consumption was calculated from the simulated process energy requirements, including the heating and cooling duties of the process units. Electrical power consumption associated with equipment such as pumps, motors, and auxiliary utilities was not considered in this calculation. Therefore, the reported value represents the process energy demand predicted by the simulation model for biodiesel production from the specified oil feedstock.

Table 6. Comparative heat loads at an Oil: Methanol Molar Ratio of 1:5 used in the transesterification reactor. (Given dataset and simulated dataset)

Equipment	First Methanol stripper for the crude biodiesel from transesterification plant	Second methanol stripper for refined biodiesel before to storage tank	Methanol stripper for crude glycerine before to storage tank	Methanol Purification column
Heat load from TGDS	Heating load (QH) = 958 KW	Heating load (QH) = 1121 KW	Heating load (QH) = 1062 KW	Heating load (QH) = 4298 KW
Heating load (QH) KW from the validated simulation model	Heating load (QH) = 888 KW	Heating load (QH) = 1089 KW at reflux flowrate 633 kg/hr	Heating load (QH) = 1032 KW	Heating load (QH) = 4257 KW

Continued

Difference Heat Load TPD - Simulation heat load	Heating load (QH) = 70 KW	Heating load (QH) = 32 KW	Heating load (QH) = 30 KW	Heating load (QH) = 41 KW
Difference (%) relative to Simulation heat load	7.8%	2.9%	3%	1%

After operating the biodiesel plant for three years, several valuable insights have been identified for dissemination to oleochemical industry stakeholders to support lower energy consumption through energy management, without incurring additional expenditure as listed below.

5.2.1. Oil to Methanol Ratio

After the plant reached stable operation, the process engineering team focused on the methanol purification column, which is the largest energy consumer in the biodiesel production process. As shown in **Table 7**, energy savings were evaluated by reducing the methanol feed ratio to the transesterification reactor while maintaining transesterification performance and product quality.

The simulation results indicate that reducing the oil-to-methanol ratio from 1:5 to 1:4.5 achieved an energy saving of 7.6% compared with the baseline case. At the same time, the biodiesel yield remained at 98.5% conversion, with no significant deterioration in product quality. The biodiesel product continued to satisfy the export-grade requirements specified in EN 14214. These results demonstrate that the lower methanol ratio can be implemented without compromising transesterification performance while providing a measurable reduction in process energy consumption.

Table 7. Heat Loads at an Oil: Methanol Molar Ratio of 4.5 and 6:1 in the transesterification reactor.

Equipment	Methanol Purification column	Case	Reboiler Duty (KW)	Percentage of Increase
Oil to methanol ratio 1:4.5	3931 KW	4.5 mole	1450	-7.6%
Ol to methanol ratio 1:5	4257 KW	Base 5 mole (methanol)	1570	0%
Oil to methanol ratio 1:6	4895 KW	6 moles	1810	15.3%

5.2.2. Production Planning and Scheduling

Production planning and scheduling is the second key action that directly affects energy management for the process engineering team. Starting up production or

changing over feedstock, which interrupts production stability and may produce off-specification product, will erode the business viability of the biodiesel plant. Detailed production planning is pivotal to the biodiesel plant.

5.2.3. Optimization of Refine Biodiesel Using Validated Simulation Model

By diverting a portion of the mass flowrate to the reflux stream (**Table 8**), the total heat load can be calculated with methanol content and operating pressure held constant. The results show that the heat load ranges from 1080 to 1097 kW, which indicates that heat load is not the primary optimization point in biodiesel plant. Exploring other factors is therefore vital.

Table 8. Biodiesel - methanol stripper.

Feed to second biodiesel stripper	Diverted reflux flowrate to stripper prior to the preheater	feed to preheater prior to stripper	Methanol content in biodiesel stream (Target 0.2% MAX)	Reboiler heat duty @ pressure 0.4 barg	Stripper reboiler duty	Total heat load
kg/hr	kg/hr	kg/hr	W/W%	KW	KW	KW
21,100	633	20,467	0.166%	451	638	1089
21,100	1055	20,045	0.167%	463	625	1088
21,100	2110	18,990	0.167%	488	592	1080
21,100	3165	17,935	0.167%	534	559	1093
21,100	4220	16,880	0.167%	569	526	1095
21,100	5275	15,825	0.167%	604	493	1097

5.2.4. Optimization of Refine Glycerine Using Validated Simulation Model

By diverting a portion of the mass flowrate to the reflux stream (**Table 9**), the total heat load can be calculated with methanol content and operating pressure held constant. The results show that the heat load ranges from 883 to 884 kW, which indicates that heat load is not the primary optimization point in the biodiesel plant. Exploring other factors is therefore vital.

Table 9. Glycerol - Methanol stripper.

Feed to Glycerine Methanol stripper	Diverted reflux flowrate to stripper prior to the preheater	feed to preheater prior to stripper	Methanol content in refine glycerol stream	Reboiler heat duty @ pressure 1.12 barg	Preheater	Total heat load
kg/hr	kg/hr	kg/hr	W/W %	KW	KW	KW
4172	417	3755	0	800	83	883
4172	834	3338	0	810	74	884
4172	1250	2922	0	820	65	885
4172	1670	2502	0	830	55	885
4172	2086	2086	0	838	46	884

6. Outlook and Novelty

This study addresses a critical gap in the Malaysian oleochemical literature by focusing specifically on energy management in biodiesel production during the first five years of plant operation without incurring plant modification expenditures. While existing research has predominantly explored waste gas recovery, steam network optimization, and heat exchanger retrofitting these approaches typically require capital investment and plant modifications [45] [48]. In contrast, this work emphasizes operational and process engineering strategies—such as optimizing methanol feed ratios, refining production planning and scheduling, and leveraging validated Aspen Plus simulation models—to reduce energy consumption without additional expenditure.

Furthermore, this study contributes novel insights by:

1) Integrating industrial practice with simulation: Combining three years of actual plant operational data from a commercial 500 TPD biodiesel plant in the Klang Valley with validated Aspen Plus V10 modeling to provide both theoretical and practical perspectives on energy management.

2) Focusing on the early operational phase: Specifically addressing energy management opportunities within the first five years of plant operation, a period that has been largely overlooked in academic literature but is critical for establishing sustainable operational practices.

3) Identifying non-capital energy management levers: Highlighting that heat load optimization is not the primary concern; instead, process parameters such as methanol feed ratio, reflux stream management, and production scheduling are more critical for achieving energy savings without capital expenditure.

4) Bridging the decision-making gap: Exploring the underlying forces that drive decision-making for waste heat recovery and energy management implementation in oleochemical factories, an area identified as under-researched in existing literature.

By addressing these gaps, this study provides actionable, low-cost energy management strategies that are immediately applicable to Malaysian biodiesel producers seeking to comply with stricter global CO₂ emission standards while maintaining business viability in an export-oriented market.

7. Conclusion

Building on these identified gaps, this study offers a novel contribution by focusing on low- or no-capital energy management strategies for Malaysian biodiesel production within the oleochemical industry. Rather than emphasizing conventional modification-based approaches such as major equipment retrofits, this work integrates five years of industrial operating experience with a validated Aspen Plus V10 simulation model to identify practical, operational levers for reducing energy consumption, particularly during the first five years of plant operation. The case study presented here does not yet explore waste heat recovery options that may be viable without capital expenditure, which highlights an ad-

ditional opportunity for future work. By demonstrating how optimized process conditions, improved planning and scheduling, and better use of existing heat integration can lower utility usage without additional expenditure, the study provides a pragmatic pathway for industry stakeholders to enhance energy efficiency, support CO₂ emission reduction efforts, and strengthen the long-term competitiveness of Malaysia's oleochemical biodiesel sector.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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