OPTIMIZATION OF BIOJET FUEL PRODUCTION FROM PALM KERNEL FATTY ACID DISTILLATE USING MICROWAVE-ASSISTED ESTERIFICATION AND DISTILLATION

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Abstract

The global reliance on fossil fuels has contributed significantly to environmental challenges, including greenhouse gas emissions and resource depletion, necessitating the search for renewable energy solutions. Biojet fuel has emerged as a viable alternative, with the potential to reduce carbon footprints and ensure sustainable energy for the aviation industry. This study explores the production of biojet fuel from palm kernel fatty acid distillate (KFAD), a cost-effective by-product of palm oil refining, using microwave-assisted esterification and fractional distillation. KFAD's high free fatty acid content makes it an ideal feedstock for renewable fuel production. The research adopts the Box–Behnken experimental design to optimize key reaction parameters, including the ratio of KFAD to methanol, temperature, and reaction time. The optimal conditions based on the model-predicted maximum yield for esterification, namely 80°C reaction temperature, a 1:9 KFAD-to-methanol molar ratio, and 30 min reaction time, achieved a high fatty acid methyl ester (FAME) rate of 97.23%. The distillation process focused on refining FAME into hydrocarbons within the C8-C16 range, crucial for aviation fuel applications. Using microwave-assisted fractional distillation at 300°C, the final product had 79.38% of its hydrocarbons in the desired range. The study underscores the advantages of microwave-assisted processes, including enhanced energy efficiency, precision, and reduced thermal gradients. These findings demonstrate the feasibility of integrating microwave technologies into biojet fuel production, contributing to the global transition toward renewable energy sources for aviation.

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Introduction

Emissions from the combustion of fossil fuels are significant contributors to global warming and environmental pollution (Negm *et al.*, 2018). Increasing environmental awareness, dwindling fossil fuel reserves, and the surge in energy demand and costs are driving the global pursuit of sustainable alternative energy sources. (Akram *et al*., 2022; Lim *et al*., 2023). Transportation fuel plays a critical role in supporting human activities worldwide. Over the past two decades, the consumption patterns of petroleum products have undergone significant changes. However, the majority of transportation fuels are derived from petroleum, a process that involves drilling, refining, and combustion, all of which contribute to the release of greenhouse gases, thereby exacerbating global warming (Dujjanutat and Kaewkannetra, 2020). Over the coming years, the world is expected to experience a significant increase in the production of 'drop-in' aviation biofuels, driven by advances in renewable energy and the bioeconomy (Ng *et al.*, 2021). Identifying social aspects is equally important, as environmental, economic, and social sustainability are inherently interrelated (Fernando *et al.*, 2022).

Achieving social sustainability in the transition to biojet fuel necessitates a thorough identification of social elements and indicators, which serves as a foundational requirement. However, the framework for social indicators can vary depending on perspectives, temporal contexts, and regional differences (Afshari *et al.*, 2022). Renewable energy sources are anticipated to dominate future energy production, with biomass playing a pivotal role in the generation of zero-emission fuels. Among these renewable options, bioenergy, solar cells, and wind energy have been extensively studied as viable alternatives to fossil fuels, showcasing their potential to significantly reduce CO_2 emissions and contribute to sustainable energy solutions (IEA, 2017; Jamil *et al*., 2020). Biojet fuel is emerging as one of the most critical forms of renewable and green energy, with the potential to progressively replace fossil fuels in the near future through increasing its fraction in the blend. Projections indicate this fuel fraction could reach 25 % by 2020, 30 % by 2030, and 50 % by 2050 (Hassan *et al.*, 2023). Various approaches have been explored in the production of biojet fuel, with methods tailored to the raw materials used. These approaches include lipid hydro-processing, biofuels derived from alcohols, pyrolysis of biomass to convert it into jet fuel, gasification of biomass followed by the Fischer-Tropsch process, and the enhancement of biomass through hydrothermal processes. Furthermore, a comprehensive review has been conducted on the catalytic production of biojet fuels from biomass, emphasizing the potential and challenges of these technologies (Díaz-Pérez and Serrano-Ruiz, 2020). A recent report from the US Department of Energy (USDOE) highlights the chemical composition of jet fuel derived from crude oil, identifying the main types of hydrocarbons present. These include n-alkanes (straight-chain paraffins), iso-alkanes (branched paraffins), cycloalkanes (naphthenes), and aromatics, all of which fall within a carbon range of C8-C16 (Holladay *et al.*, 2020).

For Thailand, which is one of the major palm oil-producing countries, the production can be utilized in various ways, including both consumption and industrial usage. This has led to widespread palm oil production across the country (Chaiyanan *et al.*, 2021). Regarding the palm oil production situation in Thailand, the cultivation area has continuously increased. In the year 2022, the production amounted to 18,415,713 tons from a total cultivation area of 6,150,373 acres (Economics, 2022). The growing production of oil palm products has increased by-products from the refining process. One notable by-product is the free fatty acid rich palm kernel fatty acid distillate (KFAD), which is derived from the crude palm kernel oil refining process. KFAD generally holds low commercial value but offers potential as a renewable feedstock for biofuels and other sustainable applications (Thio *et al.*, 2022). KFAD is a by-product of the physical refining of crude palm kernel oil. Due to its availability and low price, KFAD is considered a cost-effective material for biodiesel production (Esan *et al*., 2022; Yeong *et al*., 2022). KFAD is a lipid material with a high free fatty acid (FFA) content, typically over 90% by weight (Halim *et al.*, 2022).

This study introduces a novel approach to biojet fuel production by integrating microwave-assisted esterification and fractional distillation using palm kernel fatty acid distillate (KFAD), a low-cost and underutilized by-product of the palm oil industry. Unlike conventional methods, this work applies a structured Box–Behnken experimental design to optimize the esterification process for maximum FAME yield and cost efficiency. Moreover, the use of activated carbon as both a microwave-absorbing

catalyst and a separation aid during microwave-assisted distillation provides a unique process intensification strategy. To our knowledge, this is the first report combining these microwave-driven methods with KFAD to produce hydrocarbons within the C8–C16 range suitable for aviation fuel applications.

Materials and Methods

Materials

Palm kernel fatty acid distillate (KFAD) was provided by New Biodiesel Co., Ltd., Tha-Chang, Surat-Thani Province, Thailand. KFAD is a by-product of the physical refining of crude palm kernel oil. Its availability and low price make it a cost-effective material (Esan *et al*., 2022; Yeong *et al*., 2022). KFAD is a lipid material with a high free fatty acid (FFA) content, contributing 92% by weight (Halim *et al.*, 2020). Methanol solution from LOBA Chemie PVT., Ltd., was of AR grade with 99.85% purity, and sulfuric acid (RCI LABSCAN LIMITED (EN)) was of AR grade with 98% concentration. Further materials used were n-hexane and KOH pellets (LOBA Chemie PVT., Ltd. (Mumbai, INDIA)). Activated carbon (AC), derived from coconut shell, was processed by crushing and sieving through a 20-mesh (0.85 mm) screen. Subsequently, the AC was dried in a hot-air oven at 105°C to ensure its moisture content was reduced to a standard value of ≤8 wt% (ASTM D2867). In the experiment, the AC was washed with water until the water was clear and then dried. The AC had a moisture content of 8.24%.

Microwave-assisted Esterification

This study focused on the esterification of palm fatty acids obtained from the palm oil refining process using microwave irradiation, guided by a structured experimental design. The main variables investigated were the ratio of palm kernel fatty acids (PKFAD) to methanol (1:5, 1:7, and 1:9), temperature (70°C, 80°C, and 90°C), and reaction time (30, 45, and 60 min). The constant parameters, including sulfuric acid concentration, rotation speed, and microwave power, were maintained throughout the experiment. The resulting fatty acid methyl esters (FAME) were analyzed using titration to determine the %FAME yield, following the IUPAC method (1979). For titration, a 0.1 N NaOH solution was prepared by weighing 4.2 g of sodium hydroxide and dissolving it in distilled water. The volume was adjusted to 1 liter, and the solution was stored in a glass bottle. Additionally, a 1% phenolphthalein solution was prepared by weighing 1 g of phenolphthalein and dissolving it in 50 ml of 95% pure ethanol, then adjusting the volume to 100 ml with distilled water, using ethanol as the solvent.

Distillation

Distillation is a separation technique commonly utilized for purifying and separating liquid-liquid and solid-liquid mixtures. It was chosen for these experiments, and it encompasses fundamental processes and concepts such as homogeneous mixtures, boiling, evaporation, condensation, phase changes, and dissolution (Güven and Uyulgan, 2021). In this study, microwaves (MWs), which interact with materials by inducing molecular motion, mainly through dipole rotation and ion conduction, were used. This direct interaction generates heat uniformly within the material, avoiding the inefficiencies of conventional external heating, where heat must travel via conduction or convection. Therefore, microwave heating is faster, more energy-efficient, and minimizes thermal gradients. However, the potential of microwave heating is quite limited by standard microwave generators, such as magnetrons, which have a fixed frequency determined by the magnetic field strength and the structural dimensions (Lapshinov, 2021).

In prior published experiments, the temperature has been 300°C (Lam *et al.*, 2022) or 330°C (Derawi *et al.*, 2025) with a 45 min reaction time. Catalysts with inherent microwave absorption properties are versatile, functioning not only as catalysts but also as absorbents. This dual functionality eliminates the need for additional absorbents in the reaction system, thereby reducing production costs. Among carbon-based materials, activated carbon exemplifies this type of catalyst. As an absorbent, it effectively converts microwave energy into heat, which is then transferred to biomass to initiate its thermal decomposition. Additionally, polar molecules in the biomass are readily absorbed by activated carbon, and under the influence of electromagnetic fields, these molecules undergo intense motion and collisions, further enhancing the reaction process (Ren *et al.*, 2022). In this study, activated carbon, 25 wt.% (Palma *et al.*, 2020), was utilized as a catalyst to optimize these processes, ensuring efficient component separation and enhancing the quality of the resulting products. The experimental design was meticulously constructed using Design Expert Version 13, guaranteeing reproducibility and methodological robustness. Comprehensive characterization of the final products was conducted through gas chromatography (GC) at the Science Equipment Center, Prince of Songkla University, Hat Yai Campus, further validating the

effectiveness of the optimized experiment conditions.

Experimental Setup

Microwave-assisted Esterification

The esterification experiments were conducted using a multi-mode home microwave oven with a maximum power output of 800 W. A Duran vessel served as the reactor inside the microwave, equipped with a cover featuring two ports to accommodate a K-type thermocouple. This thermocouple monitored and controlled the reaction temperature throughout the process, sending an analog signal to a SHMAX temperature controller. The controller regulated a solid-state relay (SSR), which acted as an on/off switch for the microwave power supply. Additionally, the temperature controller was interfaced with a personal computer (PC) for precise monitoring and control. To ensure uniform heat transfer, the thermocouple was inserted into the reactor from the top, and the solution was agitated at a speed of 1,500 rpm.

A schematic representation of the experimental setup is provided in Figure 1. The esterification of KFAD with methanol was optimized using the Box–Behnken experimental design to maximize %FAME. Three critical factors namely sample-to-methanol ratio, reaction temperature, and reaction time, were studied at three factor levels for each, as outlined in Table 1. The esterification process was carried out in a closed batch system. KFAD is typically a light-brown, clear liquid at room temperature, though it may contain some residual solids. To achieve a homogeneous solution, the KFAD is heated to approximately 50°C and mixed with methanol in the specified molar ratios. Sulfuric acid (H_2SO_4, 98% concentration) was employed as an acid catalyst at 2 wt% of the liquid mixture. The total mixture volume was standardized to 1,000 mL per run. The prepared mixture was loaded into the Duran batch reactor, which was then placed inside the microwave to facilitate the esterification reaction. This process resulted in the production of fatty acid methyl ester (FAME). Model based optimization was employed to determine the operating conditions that would maximize %FAME while minimizing production costs. The FAME produced under the optimal conditions was subsequently subjected to a fractional distillation step for purification.

The %FFA and %FAME were determined as shown in Equations (1) and (2), respectively.

$$\%\text{FFA} = \frac{25.6 \times NaOH\ conc. \times NaOH\ (ml)}{sample\ weight\ (g)} \quad (1)$$

$$\%\text{FAME} = \frac{\%\ FFA\ before - \%FFA\ after}{\%FFA\ before} \times 100 \quad (2)$$

Distillation

The experiment utilized a multi-mode microwave oven with a maximum power output of 700 W. A quartz vessel served as the internal microwave reactor and was equipped with a three-way distillation adapter, maintained at 105°C. The first thermocouple (K-type) monitored and controlled the temperature throughout the experiment by transmitting an analog signal to the SHMAX temperature controller, which regulated a solid-state relay (SSR) acting as an on/off switch for the microwave power supply. The temperature controller was also connected to a personal computer (PC) for precise monitoring and control. A second thermocouple was attached to a borosilicate Liebig condenser, which utilized water maintained at approximately 5-8°C as a coolant.

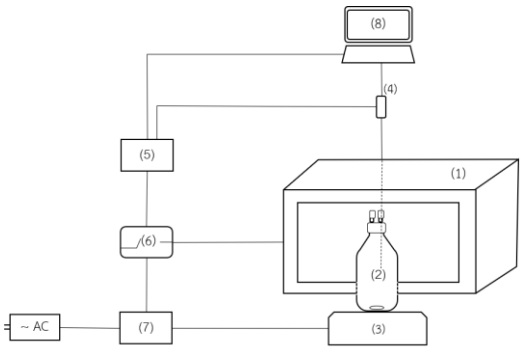

Figure 1. The experimental microwave-assisted esterification system: (1) Microwave oven, (2) Reactor, (3) Magnetic stirrer, (4) Thermocouple, (5) Temperature control, (6) Solid state relay (SSR), (7) Ammeter and (8) PC computer

Table 1. Factors and their levels applied in the Box–Behnken experimental design.

Factor	Unit	Level		
KFAD: Methanol	mol: mol	1:5	1:7	1:9
Temperature (T)	°C	70	80	90
Time (t)	min	30	45	60

The distillation vapor was directed through a receiver adapter and collected in a closed conical flask. Additionally, a third thermocouple was connected to the quartz reactor inside the microwave to monitor internal conditions. A schematic representation of the experimental setup is shown in Figure 2.

The distillation of fatty acid methyl ester (FAME) was carried out to refine the carbon chain distribution, with a particular emphasis on isolating carbon chains within the C8-C16 range, essential for producing high-quality biojet fuel. The study investigated distillation temperatures of 300°C and 330°C, while other parameters, including a distillation time of 45 min and the use of activated carbon (AC) as a catalyst at 25 wt%, were held constant. The process was conducted in a closed batch system with microwave assistance, where the reaction temperature and time were carefully controlled. AC was selected as the catalyst due to its remarkable properties, such as high thermal and chemical stability, superior thermal conductivity, and a well-structured micro- and mesoporous architecture. Furthermore, AC's availability from abundant and cost-effective precursors enhances its practicality for this application (Sultana *et al.*, 2022); moreover, it has a high dielectric loss factor, that can absorb MW energy and convert to heat in the short interval time process (Pianroj *et al*., 2016; Chuayjumnong *et al*., 2020).

A comparative analysis of biojet fuel production methods using different feedstocks is presented in Table 2. Key parameters such as feedstocks, catalysts, experimental conditions, and products obtained are emphasized, offering valuable insights into each approach's advantages and challenges. This analysis underscores the critical role of microwave-assisted processes in enhancing energy efficiency, the strategic selection of catalysts to improve reaction kinetics, and the importance of optimizing experimental conditions to maximize yield and efficiency in biojet fuel production.

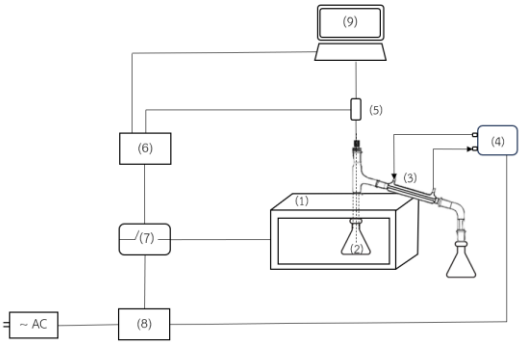

Figure 2. The experimental microwave-assisted distillation system: 1) Microwave oven, (2) Quartz reactor, (3) Condenser, (4) Pump, (5) Thermocouple, (6) Temperature control, (7) Solid state relay (SSR), (8) Ammeter, (9) PC computer

The Calculation of Total Cost of the Biojet Fuel Production

The total cost of the biojet fuel production experiment is calculated with the combination of the cost of raw materials, chemicals costs and electricity costs without the equipment costs and wages, as shown in Equations (3) and (4),

$$\text{FAME production cost (USD/L)} = \frac{(1+2+3+4)-(5)}{V.\ of\ FAME} \quad (3)$$

where (1) represents materials (PFAD) cost (in USD), (2) chemical costs are methanol and sulfuric acid (USD) per volume of FAME product (L), (3) electricity cost$_1$ is the cost of electricity used in microwave-assisted esterification (USD), (4) electricity cost$_2$ is the electricity cost used to

Table 2. Overview of biojet fuel production from various feedstocks

Sdudy	Raw material	Catalyst	Conditions	Products obtained
Vilalva (2021)	Almond oil	Homogeneous catalysts (e.g., base catalysts)	Methyl transesterification followed by atmospheric distillation (214–266°C), Vigreux column.	Lightweight biodiesel enriched with C8:0, C10:0, C12:0, and C14:0 fractions.
Said *et al.* (2022)	Microalgae oil	Optimal catalyst concentration: 2.09%	Transesterification: methanol-to-oil ratio 9.17:1, 60.49°C. Fractional distillation using rotary evaporator at 168°C and 25 mbar for 120 min.	Biojet fuel (C8-C14 hydrocarbons) isolated from AOME.
Ong *et al.* (2021)	Coconut oil	Microwave-assisted reaction	Transesterification with ethanol: ethanol-to-oil molar ratio of 9.25:1, 163.69 W microwave power, 12.66 min. Fractional distillation under vacuum (165°C, 25 mbar).	Biojet fuel (C8-C14 FAEE), optimal yield of 74.45 wt%.

evaporate methanol (USD), and (5) is methanol recovery (ml/USD).

Cost of the biojet fuel production

$$\text{Biojet fuel cost (USD/cc)} = \frac{\text{Electricity cost (Baht)}}{\text{V. of bio jet fuel (L)}} \quad (4)$$

where electricity cost is for power used in microwave-assisted distillation. It should be noted that the currency exchange rate used on 17th of January 2025 from USD to THB was 1.00:34.45.

Results and Discussion

Results

Production of FAME from Palm KFAD Using Microwave-Assisted Esterification

Optimizing Microwave-Assisted Synthesis of FAME aimed to maximize %FFA and %FAME, and minimize production cost (USD) through experimental optimization using the Box-Behnken design. The factors and their levels are shown in Table 1. The responses for %FAME and cost, summarized in Table 2, were obtained from 45 experiments, and then the results were averaged over 15 experimental runs. In these experiments, the temperature was increased from the initial state to the target temperatures of 70°C, 80°C, or 90°C (setting time ±5°C) and remained constant for the set time throughout the experiment, as shown in Figure 3.

The validation experiments conducted under the optimal conditions identified by the Box–Behnken design are presented in Table 3. These experiments were designed to verify the predicted esterification percentages and ensure the reliability of the optimization model. The experimental data closely matched the predicted values, demonstrating the robustness of the optimization approach and the reproducibility of the process under the specified conditions.

These findings substantiate the model's reliability and highlight the consistency of the microwave-assisted esterification process when operating at the optimized parameters. The maximum yield (%) of FAME from KFAD was evaluated by analysis of variance. The confidence interval was calculated at 95% ($\alpha = 0.05$) for the appropriate statistics, and the F value of the model of 13.41 indicates that the model is significant. There is only a 0.05% chance that such a large *F*-value is due to noise. The analysis was done by Design Expert 13 program as shown in Table 4. The regression models for both FAME yield and production cost, as presented in Table 4, are linear and include only the main effects of

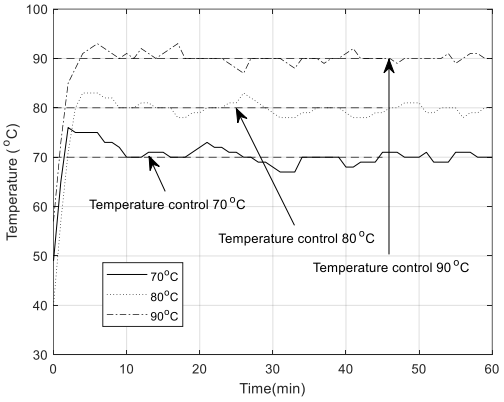

Figure 3. Temperature increase and stability in experiments

Table 3. Experimental and model-predicted results of microwave-assisted esterification under various conditions

No	Conditions			Experiment		Prediction	
	Ratio	Time (min)	Temperature (◦C)	%FAME	Cost (USD/L)	%FAME	Cost (USD/L)
1	1:5	30	80	93.55±4.49	1.58±1.29	94.72	2.76
2	1:5	45	70	94.33±2.80	1.39±4.19	94.72	2.85
3	1:5	45	90	96.75±0.49	2.10±6.53	95.78	3.35
4	1:5	60	80	95.82±1.15	2.42±5.37	95.78	3.43
5	1:7	30	70	95.58±1.12	0.99±6.95	95.44	2.76
6	1:7	30	90	96.37±1.41	1.59±2.32	96.51	3.26
7	1:7	45	80	96.55±1.32	1.56±1.65	96.50	3.35
8	1:7	45	80	97.08±0.87	1.45±4.65	96.50	3.35
9	1:7	45	80	97.52±0.55	1.71±0.42	96.50	3.35
10	1:7	60	70	96.37±1.11	1.60±11.14	96.50	3.43
11	1:7	60	90	97.16±0.93	1.95±9.19	97.57	3.93
12	1:9	30	80	97.32±0.17	1.14±8.87	97.23	3.27
13	1:9	45	70	97.58±0.28	0.98±6.43	97.22	3.35
14	1:9	45	90	97.85±0.32	1.32±2.08	98.29	3.85
15	1:9	60	80	97.73±0.26	2.03±8.70	98.29	3.94

Table 4. ANOVA for the response surface regression models of FAME (%) from KFAD

Source	Sum of squares	df	Mean squares	*F*-value	*P*-value
FAME (%)					
Analysis of variance					
Model	17.12	3	5.71	13.41	0.0005
Residual	4.68	11	0.425		
Lack of fit	4.21	9	0.4679	1.98	0.3799
Pure error	0.4718	2	0.2359		
Total	21.81	14			
Fit statistics					
Stc. Dev.	R^2	Adjusted R^2	Predicted R^2	Mean	C.V. %
0.6525	0.7853	0.7267	0.6023	96.50	0.6761
Cost (USD)					
Analysis of variance					
Model	2262.84	3	754.28	16.32	0.0002
Residual	508.33	11	46.21		
Lack of fit	468.46	9	52.05	2.61	0.3076
Pure error	36.88	2	19.94		
Total	2771.17	14			
Fit statistics					
Stc. Dev.	R^2	Adjusted R^2	Predicted R^2	Mean	C.V. %
6.80	0.8166	0.7665	0.6218	54.70	12.43

the independent variables: KFAD-to-methanol molar ratio (R), reaction temperature (T), and reaction time (t). The analysis reveals that the molar ratio (R) has the most significant positive effect on FAME yield-higher methanol concentrations promote more efficient esterification. Reaction temperature and time also contribute positively but to a lesser extent. For production cost, the molar ratio exhibits a strong inverse relationship, where increasing methanol lowers the cost, likely due to improved conversion efficiency. In contrast, higher temperature and longer reaction time increase energy consumption, thus raising production costs. Interaction and quadratic effects were not included in the final models, indicating that the response trends are adequately explained by linear relationships within the tested parameter range. These findings validate the use of a simplified linear model for practical optimization and economic analysis of biojet fuel production from KFAD.

The average total energy consumption for FAME production at the experimental points was also recorded. A linear model was used to predict the FAME percentage, and the cost, as shown in Equations (5) and (6).

$$\text{FAME}\ (\%) = 86.24838 + 0.626875R + 0.053375T + 0.0355t \quad (5)$$

$$\text{Cost}\ (\text{USD}) = -18.555 - 4.33375R + 0.861625T + 0.77025t \quad (6)$$

Here, R is the molar ratio of PFAD to methanol, T is the reaction temperature and t is the reaction time.

Model-based predictions of FAME yields from KFAD are illustrated in Figure 4. According to model prediction, the optimal esterification conditions for maximizing FAME yield were identified as 80°C, a 1:9 KFAD-to-methanol molar ratio, and 30 min, achieving a predicted yield of 97.23%. However, experimentally, the highest yield was 97.73% at 60 min. In contrast, the most cost-effective conditions were at 70°C for 45 min, which provided a high yield of 97.58% at the lowest cost of 0.98 USD/L. Figure 4(b) depicts the relationship between the regression model predictions and the actual experimental results for FAME yields from KFAD. The coefficient of determination (R^2) was 0.7853, indicating a moderately strong correlation between the model and experimental outcomes. This analysis highlights the reliability and predictive accuracy of the regression models under the specified conditions.

The predicted cost of FAME (fatty acid methyl ester) production from KFAD, as based on the model, is depicted in Figure 4(c). The flag points on the graph represent the optimal conditions predicted for achieving the maximum yield. According to the results, the production cost for the highest yield of FAME is approximately 1 USD per cc and Figure 4(d) illustrates the relationship between the regression model predictions and the actual experimental data for FAME yield from KFAD. The coefficient of determination (R^2)

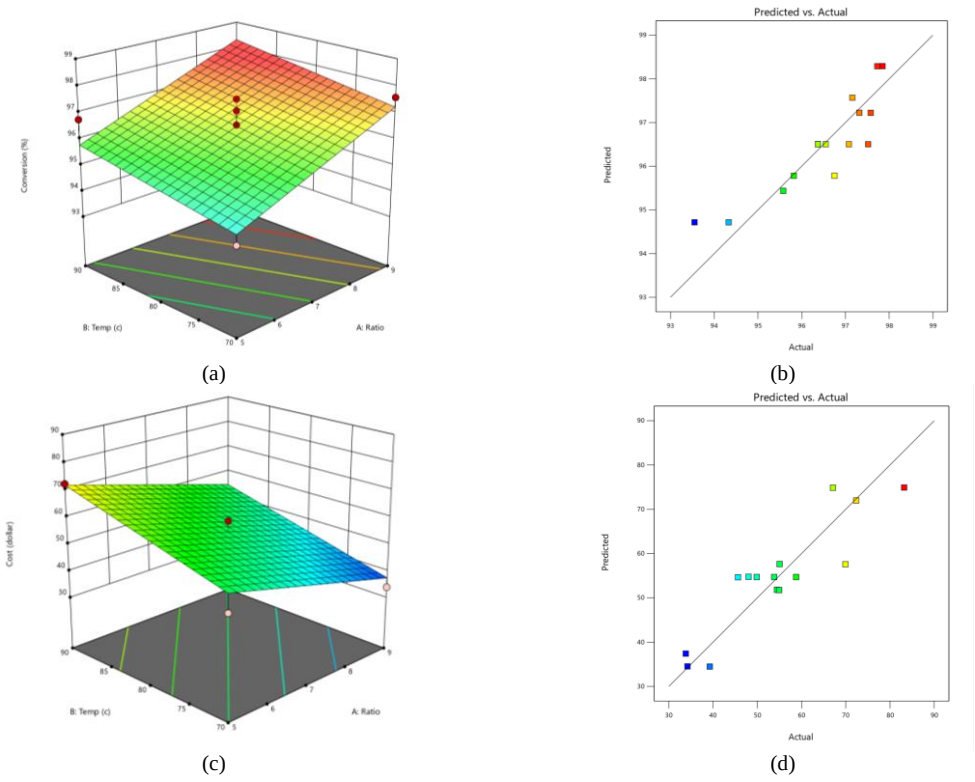

Figure 4 (a) Response surface plot for predicted FAME yield from KFAD under varying temperature, KFAD: methanol ratio, and time, (b) predicted vs. actual comparison for FAME yield from KFAD with regression model, (c) response surface plot for predicted FAME production cost from KFAD under varying temperature, KFAD: methanol ratio, and time, and (d) predicted vs. actual comparison for FAME production cost from KFAD with regression model

was 0.8166, which indicates a relatively strong correlation between the predicted values from the model and the experimental results. This analysis underscores the reliability and predictive accuracy of the regression model when applied under the specified experimental conditions.

Distillation of Biojet Fuel

The distillation of biojet fuel was carried out using microwave-assisted distillation to separate fatty acid methyl esters (FAME) into hydrocarbons of specific chain lengths. This process aimed to optimize the carbon chain distribution for biojet fuel applications, focusing on two temperature settings, 300°C and 330°C, with a fixed processing time of 45 min. Activated carbon (25 wt%) was employed as a catalyst to enhance reaction kinetics and separation efficiency due to its excellent thermal conductivity, stability, and micro- mesoporous structure. The separation targeted carbon chains within the C8-C16 range for biojet fuel. The product yield(%) of biojet fuel at the distillation temperatures 300°C and 330°C was 10.52% and 10.38%, respectively; moreover, the production cost (USD/mL) was 0.317 and 0.322. In terms of cost efficiency, distillation at 300°C was slightly more economical, when compared to 330°C. This difference highlights the advantage of operating at lower temperatures, which require less energy and better utilize the catalytic properties of activated carbon. The results emphasize the thermal stability of mid-chain hydrocarbons and the importance of maintaining optimal temperature conditions for achieving high yields and cost-efficient biojet fuel production.

The products were analyzed using Gas Chromatography with a Flame Ionization Detector (GC-FID) under the following conditions: equilibration time of 1 min; oven program set to an initial temperature of 140°C for 5 min, then increased at 10°C/min to 210°C for 5 min, and finally ramped at 20°C/min to 250°C for 8 min, with a total run time of 27 min. The system operated at an initial pressure of 7.5495 psi, a flow rate of 1 mL/min, an average velocity of 22.534 cm/sec, and a holdup time of 2.2188 min. The flow program was maintained at 1 mL/min throughout the run. The front detector parameters included a heater

set to 300°C, H_2 flow at 30 mL/min, airflow at 300 mL/min, makeup flow at 25 mL/min, and an active flame and electrometer.

At 300°C, the analysis revealed a product distribution predominantly in the C8-C16 range, which constituted 79.38% of the total peak area. However, at 330°C, the distribution shifted, with the C8–C16 range decreasing to 72.65% of the total area. At 300°C, the bagged area percentage is higher than at 330°C, even though both temperature setpoints require the same distillation time of 45 min. This can be attributed to the thermal stability of mid-chain hydrocarbons (C8-C16) at lower temperatures, which prevents excessive thermal degradation. At 330°C, the elevated temperature accelerates the decomposition and evaporation of shorter chained hydrocarbons, leading to a broader hydrocarbon distribution outside the target C8-C16 range. Additionally, the catalytic activity of activated carbon might differ at these temperatures, further influencing the selectivity and yield of the targeted hydrocarbon fractions, as shown in Figure 5.

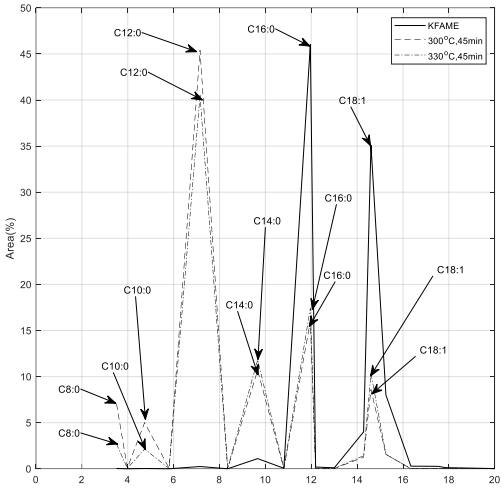

Figure 5. Hydrocarbon yield distribution at distillation temperatures 300°C and 330°C with a residential time of 45 min

Discussion

The production of fatty acid methyl ester (FAME) and its refinement through distillation into biojet fuel demonstrates the effectiveness of microwave-assisted processes in biofuel production. For the esterification stage, experimental results closely matched model predictions, with FAME yields reaching up to 97.23% under optimal conditions (a 1:9 KFAD-to-methanol molar ratio, 80°C temperature, and 30 minutes reaction time). The regression model exhibited a moderately strong fit (R^2 = 0.7853), indicating reliability in predicting experimental outcomes. This high level of correlation suggests that the model effectively captures the relationship between experimental variables and the %FAME yield. Notably, the predicted cost for FAME production was validated, demonstrating a strong correlation between predicted and experimental results (R^2 = 0.8166). These findings emphasize the precision of the Box-Behnken design in optimizing biofuel production processes.

In the distillation process, the target was to refine FAME into hydrocarbons within the C8-C16 range for biojet fuel applications. Experimental results highlighted a higher 79.38% yield of hydrocarbons at 300°C compared to 72.65% at 330°C, for the same reaction time of 45 min. This result underscores the thermal stability of mid-chain hydrocarbons, which are more susceptible to degradation at higher temperatures. The use of activated carbon as a catalyst enhanced the separation efficiency by stabilizing thermal and catalytic conditions. However, while yields at 300°C were slightly higher, the overall hydrocarbon recovery remained low (10.52% at 300°C and 10.38% at 330°C), indicating room for further optimization. The stronger selectivity of the 300°C condition also resulted in marginally lower energy costs compared to 330°C. These results highlight the importance of balancing reaction conditions to achieve both cost efficiency and product quality in biojet fuel production.

Conclusions

This research optimized biojet fuel production from palm kernel fatty acid distillate (KFAD) through innovative microwave-assisted esterification and distillation methods. The optimal conditions based on model-predicted maximum yield for the esterification process were identified as a molar ratio of KFAD to methanol of 1:9, a reaction temperature of 80°C, and a reaction time of 30 min, yielding a high fatty acid methyl ester (FAME) conversion rate of 97.23%. However, the most cost-effective condition was at 70°C for 45 min, which provided a high yield of 97.58% at the lowest cost of 0.98 USD/L. The distillation process further refined FAME into hydrocarbons within the C8-C16 range, achieving a 79.38% yield at a temperature of 300°C, which was higher than the 72.65% yield observed at 330°C. These findings highlight the importance of precise temperature control to maximize product quality and minimize

thermal degradation. The cost analysis revealed that operating at 300°C during distillation was slightly more economical than at 330°C, further supporting the adoption of lower-temperature processes. However, the overall yield of hydrocarbons suitable for aviation fuel applications (10.52% at 300°C and 10.38% at 330°C) suggests room for improvement in process optimization to enhance yield while maintaining cost efficiency. This study demonstrated the advantages of microwave-assisted techniques in enhancing energy efficiency and precision, offering a sustainable and economically feasible approach to producing renewable aviation fuels. The findings provide a valuable contribution to the global transition toward sustainable energy solutions for the aviation sector.

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References

Afshari, H., Agnihotri, S., Searcy, C., and Jaber, M.Y. (2022). Social sustainability indicators: A comprehensive review with application in the energy sector. Sustainable Production and Consumption, 31:263-286. https://doi.org/10.1016/j.spc.2022.02.018

Akram, F., ul Haq, I., Raja, S.I., Mir, A.S., Qureshi, S.S., Aqeel, A., and Shah, F.I. (2022). Current trends in biodiesel production technologies and future progressions: A possible displacement of the petro-diesel. Journal of Cleaner Production, 370:133479. https://doi.org/10.1016/j.jclepro.2022.133479

Chaiyanan, S., Niyomtoon, I., Porntaveewat, W., Sooksai, N., and Chaiyanan, S. (2021). Effuent management of palm oil factory with ozone treatment befire biogas production. Phranakhon Rajabhat Research Journal: Science and Technology 16(2):45-56.

Chuayjumnong, S., Karrila, S., Jumrat, S., and Pianroj, Y. (2020). Activated carbon and palm oil fuel ash as microwave absorbers for microwave-assisted pyrolysis of oil palm shell waste. RSC Advances, 10(53):32058-32068. https://doi.org/10.1039/D0RA04966B

Derawi, D., Razak N.A.A., Saadon, N.S., Bar, N.A., and Taufiq-Yap, Y.H. (2025). Conversion of palm fatty acid distillate to bio-jet fuel-range hydrocarbons over bimetallic NiCo/SBA-15-NH2 catalyst. Fuel, 380:133192. https://doi.org/10.1016/j.fuel.2024.133192

Díaz-Pérez, M.A. and Serrano-Ruiz, J.C. (2020). Catalytic production of jet fuels from biomass. Molecules, 25(4):802. https://doi.org/10.3390/molecules25040802

Dujjanutat, P. and Kaewkannetra, P. (2020). Production of bio-hydrogenated kerosene by catalytic hydrocracking from refined bleached deodorised palm/palm kernel oils. Renewable Energy, 147:464-472. https://doi.org/10.1016/j.renene.2019.09.015

Economics, OoA. (2022). Oil palm production information. Retrieved from https://palm.dit.go.th/Production.aspx

Esan, A.O., Smith, S.M., and Ganesan, S. (2022). A non-conventional sustainable process route via methyl acetate esterification for glycerol-free biodiesel production from palm oil industry wastes. Process Safety and Environmental Protection, 166:402-413.

Fernando, Y., Halili, M., Tseng, M.-L., Tseng, J.W., and Lim, M.K. (2022). Sustainable social supply chain practices and firm social performance: Framework and empirical evidence. Sustainable Production and Consumption, 32:160-172. https://doi.org/10.1016/j.spc.2022.04.020

Güven, N.A. and Uyulgan, M.A. (2021). Linking the representation levels to a physical separation and purification method in chemistry: Understanding of distillation experiment. Journal of Pedagogical Research, 5(3):80-104. https://doi.org/10.33902/JPR.2021370703

Halim, S.F.A., Chang, S.H., and Morad, N. (2020). Extraction of Cu(II) ions from aqueous solutions by free fatty acid-rich oils as green extractants. Journal of Water Process Engineering, 33:100997. https://doi.org/10.1016/j.jwpe.2019.100997

Halim, S.F.A., Morad, N., Shahadat, M., and Chang, S.H. (2022). Palm kernel fatty acid distillate-based bulk liquid membrane for Cu(II) separation: Design and its operating parameters. Journal of Water Process Engineering, 47:102646. https://doi.org/10.1016/j.jwpe.2022.102646

Hassan, S., Attia, N., El Diwani, G., Amin, S.K., Ettouney, R., and El-Rifai, M. (2023). Catalytic hydrocracking of jatropha oil over natural clay for bio-jet fuel production. Scientific Reports, 13(1):13419. https://doi.org/10.1038/s41598-023-40500-2

Holladay, J., Abdullah, Z., and Heyne, J. (2020). Sustainable Aviation Fuel: Review of Technical Pathways. U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, p. 1-81.

IEA. (2017), Energy Technology Perspectives 2017, IEA, Paris https://www.iea.org/reports/energy-technology-perspectives-2017, Licence: CC BY 4.0

Jamil, U., Khoja, A.H., Liaquat, R., Naqvi, S.R., Omar, W.N.N.W., and Amin, N.A.S. (2020). Copper and calcium-based metal organic framework (MOF) catalyst for biodiesel production from waste cooking oil: A process optimization study. Energy Conversion and Management, 215:112934. https://doi.org/10.1016/j.enconman.2020.112934

Lam, J.E., Mohamed, A.R., Lup, A.N.K., and Koh, M.K. (2022). Palm fatty acid distillate derived biofuels via deoxygenation: properties, catalysts and processes. Fuel Processing Technology, 236:107394. https://doi.org/10.1016/j.fuproc.2022.107394

Lapshinov, B. (2021). Temperature measurement methods in microwave heating technologies. Measurement Techniques, 64(6):453-462. https://doi.org/10.1007/s11018-021-01954-w

Lim, M., Luckert, M.M., and Qiu, F. (2023). Economic opportunities and challenges in biojet production: A literature review and analysis. Biomass and Bioenergy 170:106727. https://doi.org/10.1016/j.biombioe.2023.106727

Negm, N.A., Zahran, M.K., Abd Elshafy, M.R., and Aiad, I.A. (2018). Transformation of *Jatropha* oil to biofuel using transition metal salts as heterogeneous catalysts. Journal of Molecular Liquids, 256:16-21. https://doi.org/10.1016/j.molliq.2018.02.022

Ng, K.S., Farooq, D., and Yang, A. (2021). Global biorenewable development strategies for sustainable aviation fuel

production. Renewable and Sustainable Energy Reviews, 150:111502. https://doi.org/10.1016/j.rser.2021.111502

Ong, M.Y., Nomanbhay, S., Kusumo, F., Raja Shahruzzaman, R.M.H., and Shamsuddin, A.H. (2021). Modeling and optimization of microwave-based bio-jet fuel from coconut oil: investigation of Response Surface Methodology (RSM) and Artificial Neural Network Methodology (ANN). Energies, 14(2):295. https://doi.org/10.3390/en14020295

Palma, V., Barba, D., Cortese, M., Martino, M., Renda, S., and Meloni, E. (2020). Microwaves and heterogeneous catalysis: A review on selected catalytic processes. Catalysts, 10(2):246. https://doi.org/10.3390/catal10020246

Pianroj, Y., Jumrat, S., Werapun, W., Karrila, S., and Tongurai, C. (2016). Scaled-up reactor for microwave induced pyrolysis of oil palm shell. Chemical Engineering and Processing: Process Intensification, 106:42-49. https://doi.org/10.1016/j.cep.2016.05.003

Ren, X., Ghazani, M.S., Zhu, H., Ao, W., Zhang, H., Moreside, E., Zhu, J., Yang, P., Zhong, N., Bi, X., (2022). Challenges and opportunities in microwave-assisted catalytic pyrolysis of biomass: A review. Applied Energy 315:118970. https://doi.org/10.1016/j.apenergy.2022.118970

Said, Z., Nguyen, T.H., Sharma, P., Li, C., Ali, H.M., Nguyen, V.N., Pham, V.V., Ahmed, S.F., Van, D.N., Truong, T.H., (2022). Multi-attribute optimization of sustainable aviation fuel production-process from microalgae source. Fuel, 324:124759. https://doi.org/10.1016/j.fuel.2022.124759

Sultana, M., Rownok, M.H., Sabrin, M., Rahaman, M.H., and Alam, S.N. (2022). A review on experimental chemically modified activated carbon to enhance dye and heavy metals adsorption. Cleaner Engineering and Technology, 6:100382. https://doi.org/10.1016/j.clet.2021.100382

Thio, CW, Lim, W.H., Md. Shah, U.K., and Phang, L.-Y. (2022). Palm kernel fatty acid distillate as substrate for rhamnolipids production using Pseudomonas sp. LM19. Green Chemistry Letters and Reviews 15(1):83-92. https://doi.org/10.1080/17518253.2021.2023223

Vilalva, J.B. (2021). Produção de ésteres leves derivados de óleo de amêndoa de macaúba para potencial aplicação como biocombustível de aviação. Universidade Estadual Paulista (Unesp), 58p.

Yeong, S.P., Chan, Y.S., Law, M.C., and Ling, J.K.U. (2022). Improving cold flow properties of palm fatty acid distillate biodiesel through vacuum distillation. Journal of Bioresources and Bioproducts, 7(1):43-51. https://doi.org/10.1016/j.jobab.2021.09.002