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Design and Development of Small-Scale Biodiesel Production Plant: RSM-Based Parameter Optimization

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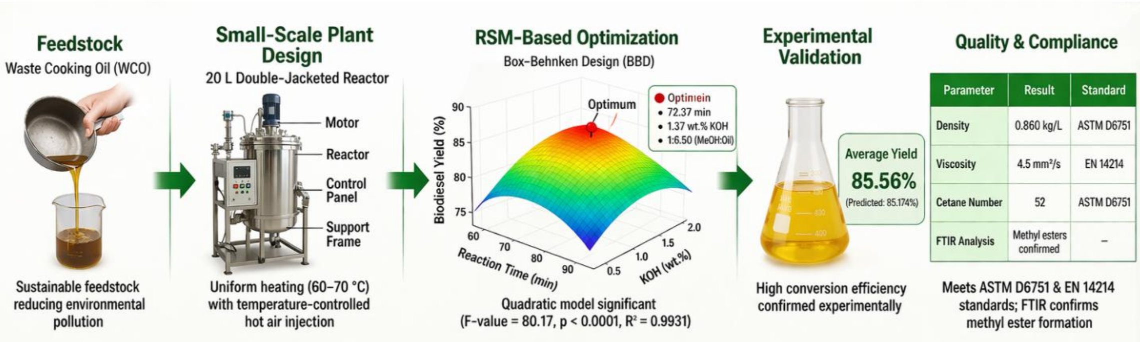
Graphical Abstract



Highlights

- A 20 L small-scale biodiesel plant was successfully designed and developed.
- The double-jacketed reactor ensured uniform heating and stable process control.
- RSM optimization achieved a biodiesel yield of up to 85.56%.
- Biodiesel properties met ASTM D6751 and EN 14214 standards.
- The system demonstrates scalable, cost-effective, and sustainable WCO utilization.

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Biodiesel; Waste Cooking Oil (WCO); Transesterification; Response Surface Methodology (RSM, Box-Behnken Design, Double-Jacketed Reactor)

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ABSTRACT

The following study outlines the development, optimization, and physicochemical characterization of a mini-biodiesel plant that uses waste cooking oil as feedstock. A 20-liter-capacity batch-type double-jacketed reactor was developed, in which hot air was injected through temperature-controlled nozzles to maintain the reactor contents at an optimum temperature (60–70°C) throughout the reaction process (esterification and transesterification). The system was constructed from stainless steel 304 to provide corrosion resistance and durability. Using Response Surface Methodology (RSM) with a Box-Behnken Design (BBD), the effects of reaction time, catalyst concentration (KOH), and methanol-to-oil molar ratio on biodiesel production were optimized. This indicated a high level of significance for the quadratic model (F-value = 80.17, $p < 0.0001$) and an R^2 of 0.9931, representing excellent predictive power. The optimum conditions were found to be 72.37 minutes and 1.37 wt. A 50% methanol ratio and a predicted conversion of 85.1744 were confirmed experimentally, with an average yield of 85.56%. The support

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frame was structurally tested and found to be mechanically sound under operational loads. The maximum stress (118.6 Pa) was at least three times lower than the material's yield strength. The biodiesel produced showed that it met all international standards (ASTM D6751 and EN 14214), and its FTIR analysis confirmed that the methyl esters were successfully formed. This integrated method is technically feasible, scalable, and cost-effective, providing a pathway for biodiesel production using WCO as a feedstock, which is expected to contribute to sustainable energy and a circular economy.

1. Introduction

The increase in the world population and industrial growth leads to a greater demand for energy worldwide, especially for fossil fuels [1,2]. According to international energy statistics, global diesel and gasoline consumption increased from 3.5 million tons in 2010 to 3.9 million tons in the 10 years ending last year, about a 12 % increase over the decade. The increasing dependence on finite hydrocarbon resources hastens the exhaustion of nonrenewable resources and substantially increases greenhouse gas emissions, atmospheric carbon accumulation, and related climate change effects [3]. Accordingly, long-term energy security and environmental sustainability now demand a transition to renewable energy sources. Among renewable options, biodiesel has attracted attention as a potential fuel because it is biodegradable, less toxic, and compatible with petroleum-powered diesel engines. Biodiesel, a fatty acid methyl or ethyl ester (FAME/FAEE) derived from biological sources, provides an alternative and renewable feedstock to decrease the dependence on petroleum-based fuel and minimize environmental pollutants [4,5].

Biodiesel with a fatty acid methyl or ethyl ester (FAME/FAEE) structure is an alternative synthetic fuel produced by a chemical reaction, primarily transesterification. This is when triglycerides from vegetable oil chemically react with short-chain alcohols (usually methanol or ethanol) in the presence of a catalyst [6,7]. Historically, feedstocks for biodiesel production have been edible oil crops such as palm, peanut, corn, and rapeseed. Nevertheless, reliance can be damaging, especially when it comes to the food vs. fuel ethical and socio-economic dilemma [8,9].

As the largest CPO producer in the world, Indonesia faces a serious trade-off: as demand for and production of biodiesel have increased, using CPO to produce biodiesel could affect the domestic cooking oil supply, leading to negative price volatility and social consequences [10,11]. In this respect, the utilization of non-food-industry waste for biomass production has been proposed as a more environmentally friendly option. Moreover, within these resources, waste cooking oil (WCO) is an attractive feedstock that already aligns with a sustainable approach to biofuels production. It is circular and provides solutions to waste problems while developing renewable energy [12,13]. Waste cooking oil (WCO) is often improperly disposed of by commercial facilities such as restaurants, hotels, and schools, as well as households, which is harmful to the environment. Improper disposal of WCO could result in significant ecological problems, including clogging of water drainage systems, contamination of water bodies through eutrophication, degradation of soil quality, and the emission of detrimental airborne pollutants when incinerated without controls [14,15]. The commercial tap industry in Indonesia alone produces 157 million liters of potential WCO annually, excluding contributions from households. Instead, WCO is not just a byproduct but also a promising feedstock for sustainable renewable energy processes. Producing biodiesel from WCO is an attractive option for both environmental pollution control and economic benefits [16]. This all helps create jobs, encourage local entrepreneurship, and promote efficient resource use. It also pertains to a key concept of the circular economy: upgrading low-value waste into high-value commodities, closing loops in urban resources, and supporting development towards a more sustainable, climate-proofed energy system [17,18].

Indonesia has taken the lead globally under its national biodiesel program, with the B35 standard requiring a 35 % biodiesel blend with 65% diesel [19,20]. The success of such a program will depend on the availability of local raw materials, technological development, and friendly policies. In the present scenario, it is a strategic solution to process waste cooking oil (WCO), as shown previously: this raw material is low-cost and available in large quantities, and its use aligns with sustainability criteria [20,21]. The production of biodiesel from WCO is a carefully controlled process. It starts with filtering out solid particles, then treating chemically to reduce the acid number (FFA). Lastly, the principal converting reactions are esterification and transesterification. In this process, triglycerides are transformed into methyl esters (biodiesel) when treated with methanol and a base catalyst like sodium hydroxide (NaOH), while glycerol is obtained as an important co-product [22,23].

This study introduces a new technique for designing, improving, and analyzing a biodiesel manufacturing process using waste cooking oil (WCO) as an environmentally friendly feedstock. The study was developed in two interconnected stages to construct an indirectly heated batch reactor with a 20 L processing volume, suitable for both esterification and the systematic optimization of catalyzed reaction parameters using response surface methodology (RSM) according to a Box-Behnken design. The main feature of the reactor is an indirect heating method with controlled hot-air injection through dedicated ports to ensure uniform temperature control during the reaction—thereby improving thermal stability, process efficiency, and energy savings. For maximizing the efficiency of the conversion, important process factors, including methanol-to-oil molar ratio, catalyst concentration, and reaction time, were studied and optimized. The biodiesel produced was characterized physically and chemically in accordance with the requirements of the ASTM D6751 and EN 14214 standards.

2. Materials and Methods

Critical components were manufactured from stainless steel (SUS304) due to its corrosion resistance to moisture, organics, and chemically reactive media. Its high chemical resistance to traditional alcohol-based reactants, as well as to many by-products and fuel components, and its relatively low risk of material degradation, contamination-induced corrosion, or failure guarantee process integrity, reliable operation, and cost-effective long-term system performance [24,25].

Table 1. Properties of Stainless Steel (SUS304)

Properties	Value	Unit
Density	8000	kg/m^3
Young's Modulus	193	GPa
Poisson's Ratio	0.29	-
Yield Strength	206	MPa
Tensile Strength	517	MPa
Melting Point	1400 – 1450	°C
Thermal Conductivity	16.2	W/m.K.

2.1 Design Specification

The development of the overall design system architecture began by defining crucial design specifications, which served as a primary point of reference throughout the concept development phase. By imposing the correct size of all the building blocks for operating and containing the working fluid is guaranteed. Table 2 summarizes the main design specifications of the biodiesel production plant.

Table 2. Specification of Biodiesel Plant

Parameter	Specification
Process Flow	Degumming, Esterification, and Transesterification
Capacity	20 L
Material	Stainless Steel 304
Reactor Type	Batch Jacketed Reactor
Heating System	Indirect Heating
Heating Media	Hot Air
Heating Elements	Electric Heat Gun
Agitator System	Top Entry Agitator
Agitator Type	Paddle Agitator

2.2 Design of a Small-Scale Pilot Biodiesel Production Plant

The biodiesel plant and its components were designed using SolidWorks 2022 and Ansys 2021. The system is capable of processing various seed oils, allowing flexibility to adapt existing biodiesel production processes while also accommodating raw materials and recovering by-products. Each tank in the system—including the oil tank, reactor, methoxide tank, pure water tank, washing/conditioning tank, pure biodiesel tank, wastewater tank, and glycerol tank—has a capacity of 20 L. The configuration of the small-scale pilot biodiesel production plant is illustrated in Figure 1.

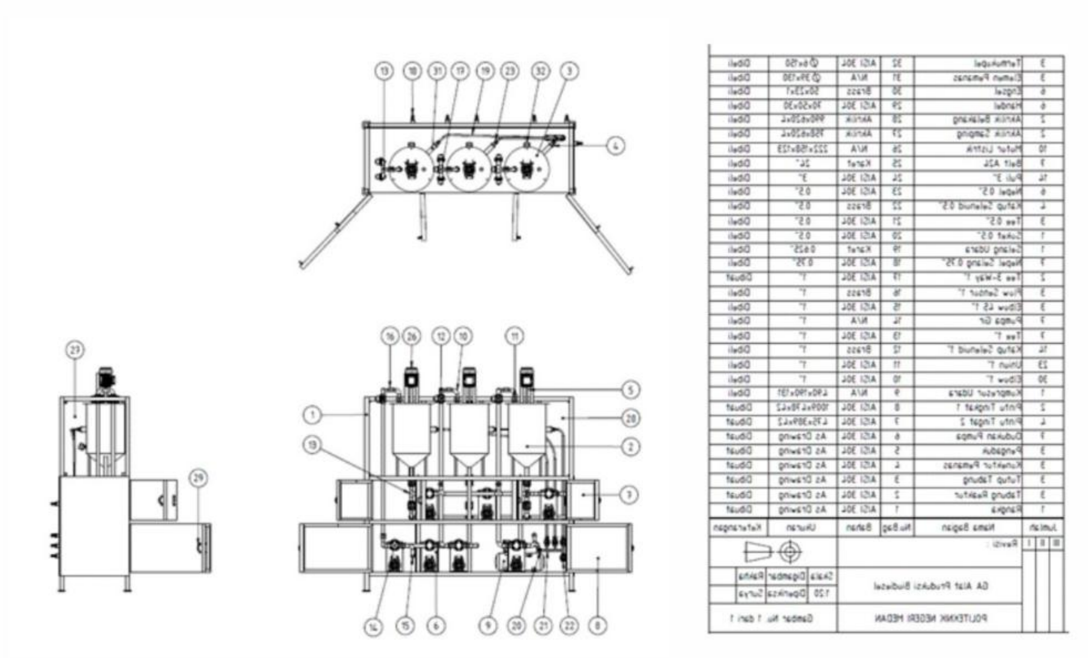

Figure 1. The solid-work biodiesel plant design

2.3 Main Components: Biodiesel Reactor

The design consists of a hybrid configuration integrating a conical section with a cylindrical section, which together enhance mixing efficiency and facilitate complete discharge of the reaction mixture. The dual-jacketed design includes an inner and outer concentric tube arrangement. The inner jacket is the main reaction chamber, where reactants, such as waste cooking oil (WCO) and methanol, are contained, and the annular space between the outer and inner jackets serves as a heat-transfer passage for hot air. Such indirect heating allows for an accurate, even temperature that can be maintained constant throughout the reaction medium, which is important for achieving an efficient conversion. The double-jacketed reactor has the following benefits over the single-jacketed reactor in terms of process stability and energy transfer, as it prevents the local hot spots from forming, which results in uniform mixing between two immiscible phases.

2.4 Description and analytical models for the design of the mini biodiesel production plant

The small biodiesel plant is composed of several integrated components, including a double-jacketed reactor and a structural support frame. The reactor serves as the primary processing unit for esterification and transesterification, while the frame provides mechanical stability, load distribution, and safe support for reactors, agitators, and auxiliary equipment during operation.

2.4.1 Double Jacket Reactors

The volume of the double-jacketed reactor tube was calculated systematically to achieve a designed processing capacity of 20 L per batch. Such calculation is crucial for limiting the reactor to the designed, established volumetric capacity so that process consistency, safety, and efficiency can be maintained during the performed chemical reactions, e.g., esterification and transesterification. The methodology used basic geometric equation 1:

$$V = \pi \times r^2 \times t \quad (1)$$

where V represents the volume, π (pi) is a mathematical constant approximately equal to 3.14159, r is the radius of the circular base, and t is the height (or length) of the cylinder. While the conical section was calculated as following equation 2:

$$V = \frac{1}{3} \times \pi \times r^2 \times h \quad (2)$$

where V is volume, π is a dimensionless number equal to about 3.14159, r is the circular base radius of the cone, and h is the height of the cone from the base to the apex; The ultimate reactor dimensions were then calculated to fit within the specified volume of the reaction mixture while staying within planned parameters and were predicted to allow for reproducible biodiesel production under constant thermal and mixing conditions.

2.4.2 Frame

The structural frame functions as the primary load-bearing element of the mini biodiesel plant, supporting the reactor vessels, motors, and auxiliary equipment during operation. Structural strength, stress, and bending moment analyses are essential to ensure the frame can safely withstand static and dynamic loads, prevent excessive deformation, maintain dimensional stability, and guarantee long-term mechanical reliability under continuous operating conditions [26].

2.4.2.1 Structural strength analysis

The structural frame, which serves as the foundation of the small biodiesel plant, supports the reactor vessels, motors, and auxiliary equipment. For long-term mechanical reliability in continuously operating parts, the frame must be designed to absorb static and dynamic loading safely, maintain bending deflection within serviceability limits, and maintain dimensional stability within shrinkage/creep limits.

2.4.2.2 Stress

Stress, a primary mechanical property, is the force per unit area of internal resistance created in a material as it bears an external load and is essentially a description of how forces are distributed over a cross-section. It is defined by the equation 3:

$$\sigma = F/A \quad (3)$$

where σ denotes stress, F is the applied force (in Newtons, N), and A is the cross-sectional area over which the force acts (in m^2).

2.4.2.3 Bending Moment

The bending moment is a major structural parameter that represents the internal moment induced in a beam or structural member by external forces or loads that cause bending deformation. It is the algebraic sum of moments due to all forces acting to one side of a particular cross-section about that section. The bending moment M at a point along a beam can be calculated using the equation 4:

$$M = F \times d \quad (4)$$

where M is the bending moment, F is the applied force (in N), and d is the lever arm distance (m)

2.5 Biodiesel Production

The production of biodiesel from waste cooking oil (WCO) involves a multi-step process of degumming, esterification, and transesterification to efficiently convert high-acid feedstock into fatty acid methyl esters (FAME). In the first degumming step, 20 L of WCO containing phospholipids and other impurities is heated to 60 °C and mixed at 800 rpm for 15 min in Reactor A to homogenize the oil. This is followed by the addition of phosphoric acid (2 %v/v), and the solution is then agitated again for 30 minutes under the same conditions to allow gum coagulation. This mixture is then left to stand for 4 hours to allow hydrated phosphatides to sediment. The purified upper oil layer is decanted, filtered, and washed with distilled water at 40 °C, then dried under vacuum at 60 °C for 30 min to eliminate any remaining water and prevent subsequent oxidation. Subsequently, due to the high free fatty acid (FFA) content, esterification is carried out in Reactor B: the oil is reacted with methanol (methanol to oil ratio = 6:1), catalyzed by sulfuric acid (H_2SO_4, 1-2 %wt. Figured out how to work like this: KH, then flushed with water (% (not KOH) at 60 °C for 1-2 hours while stirring vigorously. This process lowers the FFA content to under 1 % before they are subjected to transesterification. Base-catalyzed transesterification is then carried out in Reactor C using either 1 or 1.5 wt.% of KOH (Appendix A) (6:1 molar ratio) in methanol at 60–65 °C for 1.5 h. After 6 hours of phase separation into glycerol (bottom phase) and biodiesel (top phase) (Figure 2), the crude biodiesel is washed with warm water (50 °C), vacuum-dried, and filtered to obtain the final product meeting ASTM/EN specifications. The yield of methyl ester (biodiesel) produced from waste cooking oil (WCO) in this study was calculated using Equation 5 [27].

$$\text{WCO Methyl esters yield (\%)} = \frac{\text{weightof WCO methylester (g)}}{\text{weight of WCO oil (g)}} \times 100\% \quad (5)$$

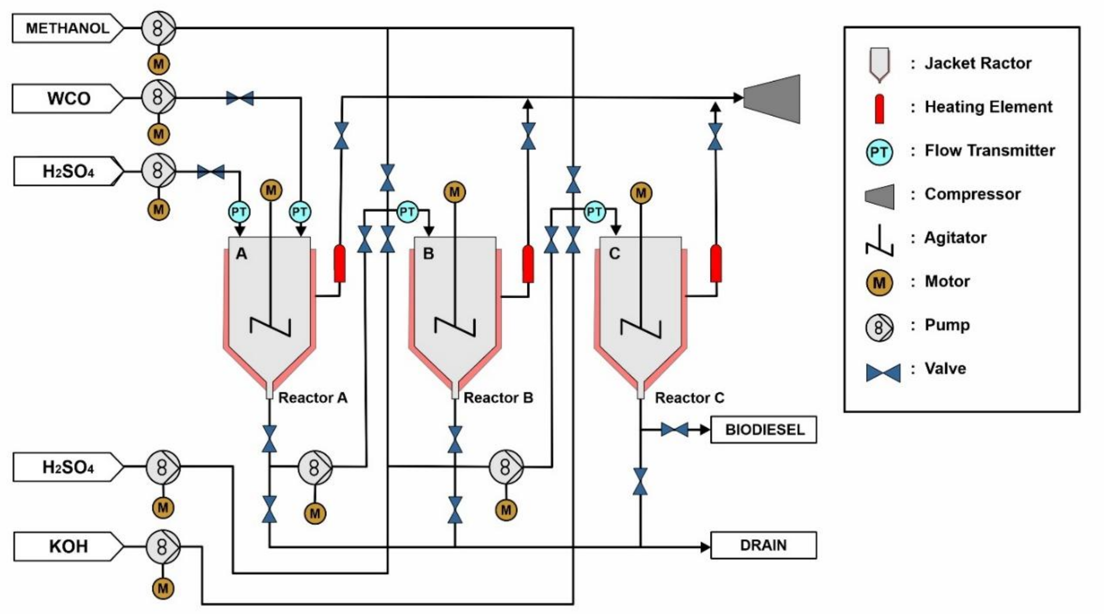

Figure 2. The schematic diagram of the biodiesel production plant

2.6 Optimization of Biodiesel Production

The experimental design was set up using Design-Expert® software (version 11, Stat-Ease Inc., Minneapolis, USA). The Box-Behnken experimental design was used to determine the influence of process parameters on oil conversion yield. The second-order regression model is described in the equation 6:

$$Y = \beta_0 + \sum_{j=1}^{n} \beta_j \beta_j + \sum_{j=1}^{n} \beta_{jj} \beta_{j^2} + \sum_{i=1}^{j-1} \sum_{j=2}^{n} \beta_{jj} x_i x_j + \varepsilon \quad (6)$$

Y denotes the response variable; β0 indicates the intercept coefficient; βi, βii, and βij are the regression coefficients; and xi and xj represent the independent variables in presented Table 3 [28].

Table 3. Levels of parameters based on Box Behnken design

Parameters	Unit	Level	
		Minimum	Maximum
T_m = Time	Minute	45	75
C_t = Catalyst	%	1	1.5
M_t = Methanol	wt.%	30	50

2.7 Properties of biodiesel WCO methyl ester

In this study, biodiesel obtained from waste edible oil methyl ester (WCOME) via high-pressure hot-air spraying, based on a cavitation-assisted transesterification process, was produced to report and compare its physicochemical properties with those of conventional diesel fuel. The level of important parameters, including kinematic viscosity at 40 °C, density at 15 °C, acid value, and flash point, was determined using ASTM D6751 and EN 14214 standards [29].

3. Results and Discussion

3. 1 Measurement

Measurement of the physical dimensions of the reactor tank revealed a cylindrical section measuring 18.5 cm inside diameter and 50 cm height, or a volume of 53.7 L (full cylinder); a bottom section measuring 13 cm height with the same base diameter of 18.5 cm, or an additional 4.565 L, providing a total reactor volume of 58.265 L, corresponding well with the intended operational design of the setup being three parallel batches of up to 20 L per cycle (Figure. 3a). The structural mass of the reactor system was calculated individually, where the outer and inner tubes made up 11.89 kg and 8.72 kg, respectively, resulting in a total core tank mass of 20.61 kg. This is supplemented by a top cover (2.4 kg) and a mixing impeller (0.54 kg) for each reactor unit, resulting in an empty mass per unit of 23.55 kg. Each reactor is loaded with 40 L of reactant mixture waste cooking oil (~16 kg) and methanol (~15.8 kg) during operation, which brings the mass per reactor to 55.35 kg under operating conditions. Separating into three reactor units paired with individual drive motors (3.52 kg/unit), the dry mass of the entire system totals 70.65 kg (same force: 70.65 N). Now, the dynamic weight measured is 166.05 kg if we fill all the things in the plane so that the static load will be 166.05 kg, just the weight under gravitational conditions. This data is critical for structural and mechanical integrity evaluations of the support frame (Figure. 3b).

This resulted in a total support cross-sectional area of 1.4 m², which was then used to assess the support frame's stress. The stress under maximum full load of 118.6 Pa is much lower than the yield stress of hollow iron (205–215 MPa), indicating that the structure has a large safety factor and will not deform permanently. Additionally, a bending-moment analysis was conducted to assess how the load was distributed throughout the frame. In the case of an empty reactor unit (motor + cover), the force for one reactor unit is 27.07 N, and the distance between units is 0.5 m; the maximum bending moment is expected at the half-span, which results in a value of 58.87 Nm. The outcomes indicate that the frame design can evenly and safely distribute the load without causing the material to exceed its elastic limit. In conclusion, the structural analysis of this biodiesel reactor system has determined the optimal design, which meets the criteria for strength, stability, and reliability required for long-term laboratory or small-scale industrial operations. The constructed biodiesel plant is shown in Figure 4.

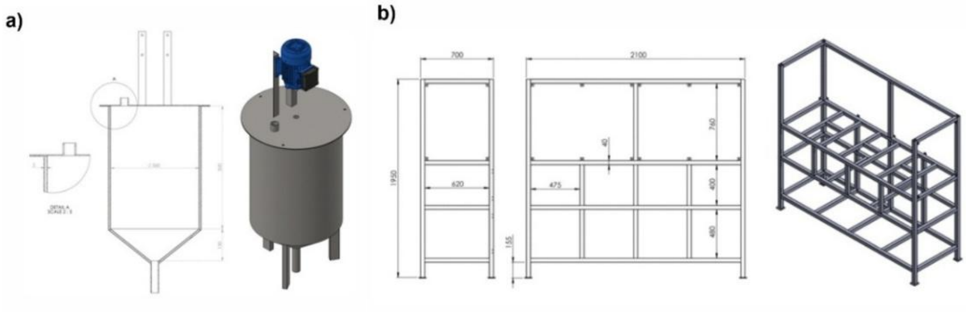

Figure 3. Solid work design a) Double-jacket reactor and b) frame

Figure 4. Completed biodiesel production plant

3. 2 Optimization of the transesterification process variables using BBD-RSM

This study optimized the methanol-to-oil ratio, KOH catalyst concentration, and reaction time to maximize the yield of WCOME. A total of 15 experimental runs were conducted based on the Box-Behnken design in this study (Table 4). The quadratic model was identified as the optimal choice based on the significance of its terms and lack of aliasing, as indicated in the program's fit summary. This section compiles the key statistical indicators to determine the most appropriate starting point for the final model selection (Table 5).

Table 4. Experimental design generated using Box-Behnken design

Run	Time	Catalyst	Methanol	Experimented Yield	Predicted yield
1	45	1.25	50	74.4	74.8
2	45	1	40	72.2	72.3
3	60	1	30	78.9	79.3
4	60	1	50	82.2	81.8
5	75	1	40	81.7	81.6
6	60	1.25	40	81.2	81.5
7	75	1.25	50	84.4	84.9
8	45	1.25	30	73.6	73.1
9	60	1.5	30	80.7	81.1
10	60	1.25	40	81.4	81.5
11	60	1.25	40	81.8	81.5
12	75	1.5	40	83.5	83.4
13	60	1.5	50	83.2	82.8
14	45	1.5	40	73.2	73.3
15	75	1.25	30	82.8	82.5

Table 5. Model statistics obtained by RSM-BBD

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2	
Linear	0.0001	0.0202	0.7849	0.6779	
2FI	0.9919	0.0137	0.7077	0.2779	
Quadratic	0.0007	0.1623	0.9807	0.9004	Suggested
Cubic	0.1623		0.9946		Aliased

The experimental data were analyzed using multiple regression techniques, which revealed that the quadratic response surface model provided the most accurate predictions. Therefore, this quadratic regression model was employed to estimate the yield of WCOME as follows (Eq. (7)):

$$Y = -2.18333 + 1.87611\, Tm + 30.1333\, C_t - 0.250833\, M_t + 0.0533333\, T_m C_t + 0.00133333\, T_m M_t - 0.08\, Ct\, Mt - 0.0139259\, T_m^2 - 10.9333\, Ct^2 + 0.00466667\, M_t^2 \quad (7)$$

The ANOVA for the quadratic model (Table 6) indicates that the model is highly significant and hence suitable for describing the relationship between the process variables and the response. The full model is highly significant (F = 80.17, $p < 0.0001$), indicating that the regression is statistically significant and that the model provides a satisfactory fit to the experimental data. As a result, reaction time (T_m) is obviously the most important (F-value = 566.97, $p < 0.0001$, and the highest F-value), confirming the dominant effect of the factor on the response. The catalyst concentration (C_t) and the methanol-to-oil ratio (T_m) also have large linear effects, with p-values of 0.0189 (C_t) and 0.0041 (T_m), respectively. In comparison, the interaction terms (Tm, Mt, and C_tT_m) are not significant, suggesting that the factors are largely independent over the range tested. The T_m^2 factor is highly significant (p = 0.0001), and a well-defined curvature exists, which justifies the use of a quadratic model, while the methanol ratio and catalyst concentration quadratic terms are not significant. The fit test (p = 0.1623) also indicates good model fit (not shown). In addition, the three coefficients (namely, R^2 = 0.9931, adjusted R^2 = 0.9807, and predicted R^2 = 0.9004) and an adequate precision value (26.7017) indicate that the model fits perfectly and has excellent predictive ability.

Table 6. ANOVA results for the quadratic model

Source	Sum of	df	Mean	F-value	p-value	
Model	241.95	9	26.88	80.17	< 0.0001	significant
T_m - Time	190.13	1	190.13	566.97	< 0.0001	
CT - Catalyst	3.92	1	3.92	11.69	0.0189	
M_t - Methanol	8.41	1	8.41	25.06	0.0041	
$T_m C_t$	0.1600	1	0.1600	0.4771	0.5205	
$T_m M_t$	0.1600	1	0.1600	0.4771	0.5205	
$C_t M_t$	0.1600	1	0.1600	0.4771	0.5205	
T_m^2	36.25	1	36.25	108.10	0.0001	
C_t^2	1.72	1	1.72	5.14	0.0727	
M_t^2	0.8041	1	0.8041	2.40	0.1822	
Residual	1.68	5	0.3353			
Lack of Fit	1.49	3	0.4967	5.32	0.1623	not significant
Pure Error	0.1867	2	0.0933			
Cor Total	243.62	14				
R^2						0.9931
Adjusted R^2						0.9807
Predicted R^2						0.9004
Adeq Precision						26.7017

3.2.1 Three-dimensional response surface plot of WCOME conversion

A comprehensive analysis of the biodiesel production process from waste cooking oil was conducted using three-dimensional response surface plots to visualize the interactive effects of key operational parameters on methyl ester yield. As shown in the three-dimensional response surface plots in Figures 5a–5c, the nonlinear and interactive effects of (a) catalyst and time, (b) methanol-oil and time, and (c) methanol-oil and catalyst on biodiesel yield are well established, and they corroborate that a quadratic model can accurately describe the transesterification process. Yield grows steeply as a function of reaction time in part (a) (i.e., from 45 min to ~65–70 min), reflecting the progressive conversion of the triglycerides, and thereafter the surface flattens, indicating the approach to equilibrium, where further extension yields diminishing returns. Simultaneously, the increase in yield is attributed to the catalytic sites and increased kinetics from the loading of the catalyst (1.0–1.36 wt%); however, the diminishing returns of loading (excessive added catalyst (>1.4 wt%)) lead to an overall reduction in gains due to viscosity and mass-transfer restrictions [26]. This strong synergistic effect between time and catalyst is evidenced by the clear curvature and orientationally elliptical contour lines, with both optimal yield domains found at higher times (≈84.5 min) and moderate-to-high catalyst contents (≈1.36 wt%). As we can see in Figure (b), both the reaction time and the methanol ratio have a positive effect on the yield, which is in accordance with Le Chatelier's principle, whereby the equilibrium can be driven toward the formation of the ester by having an excess of methanol. Still, the lesser curvature of the methanol axis suggests decreasing marginal returns at large ratios, presumably due to difficulties with phase separation, alcohol recovery, and emulsion stability. The near-parallel contours indicate that the effects are largely independent, suggesting that enough residence time is necessary before there is enough methanol enrichment to take advantage [30]. The comparatively flatter response surface for catalyst vs. methanol in Figure (c) further verifies little interaction between these two factors, as indicated by mild curvature and widely spaced contours, confirming that they contribute additively, not synergistically.

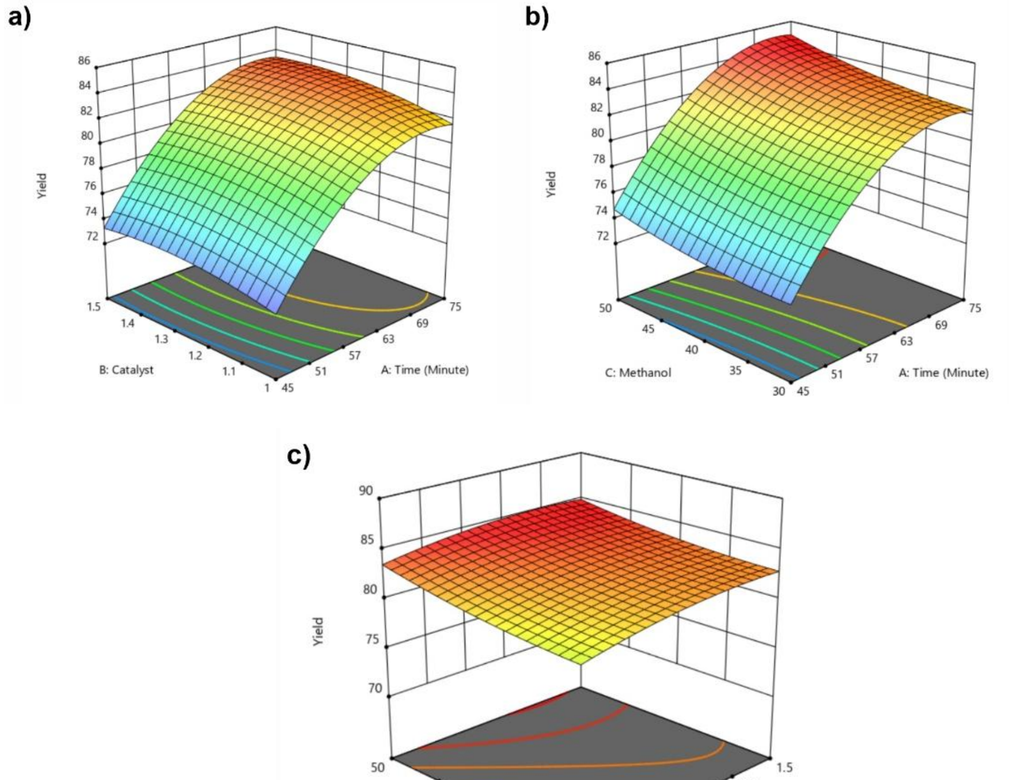

Figure 5. Surface plot illustrating (a) catalyst and reaction time, (b) methanol-oil and reaction time, and (c) methanol-oil and catalyst

3.2.2 Validation of the predicted WCME optimum yield

The WCOME yield was confirmed through three repeated trials, as shown in Table 7. Under optimal conditions with a methanol-to-oil molar ratio of 50 % and a KOH catalyst concentration of 1.37 wt%, the model predicted, using Design-Expert® v11 (Stat-Ease Inc., Minneapolis, USA), that the maximum waste cooking oil methyl ester (WCOME) yield was 85.174 % and the reaction time was 72.37 minutes. Measured values were 84.53 %, 84.42 %, and 84.73 % across three experimental replicates, giving a mean of 84.56 %. The predicted yield is 85.174 %, and the mean absolute error is 0.614 %, which is a very small value. A small standard deviation (0.157) also indicated high reproducibility. The proximity between the predicted and experimental yields confirms the reliability and likely precision of the quadratic RSM model for optimizing biodiesel production. To conclude, these results confirm the utility of RSM as a powerful optimization approach and highlight the model's particular strength in accurately predicting maximum yields within experimental reproducibility.

Table 7. Validation of WCOME modeled yields.

Run	Measured yield (%)
1	84.53
2	84.42
3	84.73
Mean	84.56
Modeled yield (%)	85.174
Mean Absolute Error (%)	0.614
Standard deviation	0.157

3. 3 Analysis of WCOME

The FTIR spectrum displays several typical absorption bands confirming that the analyzed oil is biodiesel, i.e., FAME (methyl esters of fatty acids) [31]. The WCOME analysis was conducted using Fourier transform infrared (FTIR) spectroscopy. Figure 6. The strong absorption bands around 2923 and 2853 cm^{-1}, respectively, are attributed to the asymmetric stretching ($–CH_2–$) and symmetric stretching vibrations of aliphatic C–H groups ($–CH_3$), suggesting the presence of long-chain fatty acid moieties, which are characteristic constituents in biodiesel. A strong, intense band at around 1742 cm^{-1} is assigned to the ester carbonyl (C=O) stretching vibration, a clear sign of transesterification, and can be used to confirm the formation of ethyl esters from triglycerides. In the fingerprint region, bands at approximately 1462 and 1379 cm^{-1} can be assigned to bending vibrations of $–CH_2–$ and $–CH_3$ groups. These further confirm the aliphatic ester species in biodiesel. The absorption between 1244 and 1016 cm^{-1} is assigned to the C–O stretching vibrations of ester linkages, further confirming that m-ethyl ester was obtained. In addition, the clear peak at around 722 cm^{-1} can be attributed to rocking vibration of long-chain methylene groups, as the same mechanism is reported in biodiesel from vegetable oils (vegetable oil/animal fat). Taken together, the spectral features of these biodiesels are in good agreement with published FTIR profiles of standard biodiesel, confirming that the above oil is rich in FAMEs and has been fully converted to potential biodiesel through the transesterification process.

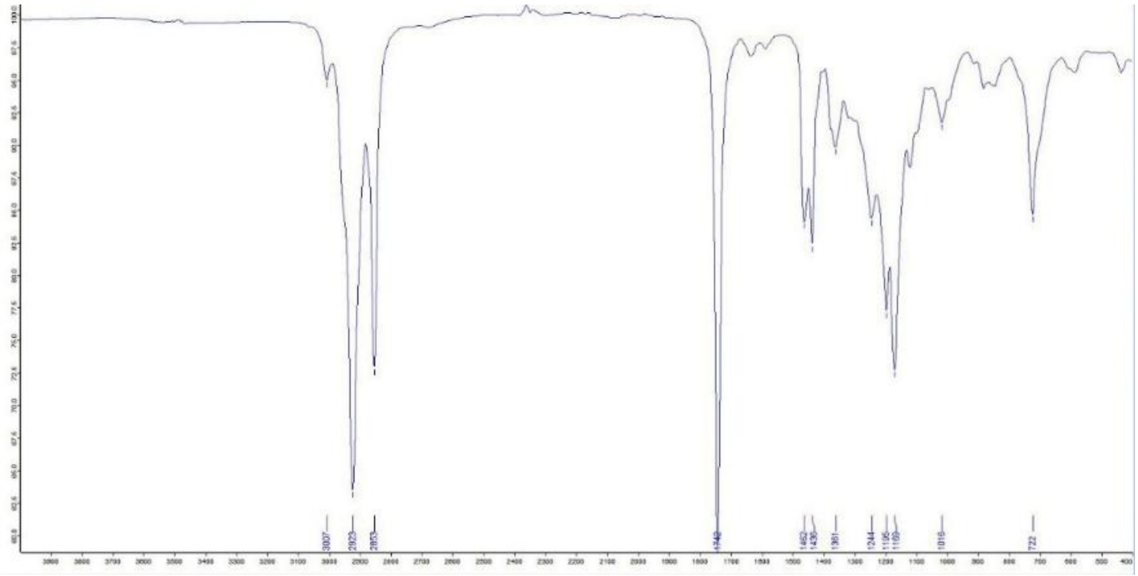

Figure 6. Spectral analysis (FTIR) of WCOME

A detailed comparative evaluation of the physicochemical properties of optimized WCOME (Figure 7) with international biodiesel standards (ASTM D6751 and EN 14214), conventional diesel, and specification limits are summarized in Table 8. The kinematic viscosity of WCOME (4.55 mm^2/s, 40 °C) is well within the ASTM (1.9–6.0 mm^2/s) and EN (3.5–5.0 mm^2/s) ranges for optimal atomization behavior: sufficiently low to ensure fine droplet generation required for supporting the combustion process yet high enough to provide the needed lubricity and prevent fuel leaks in the injection system, an important requirement to avoid premature wear in high-pressure common rail engines. The density (831.4 kg/m^3 at 15 °C) is below the lower EN limit (860 kg/m^3) but still well within the wider ASTM-compatible (880 kg/m^3 nominal) range; this indicates a slightly higher volumetric energy density per mass DAH, although there is a slight loss in mass C values energy density, both well within the normal ranges and characteristic of unsaturated WCO-derived FAMEs, and engine performance is not compromised. The flash point (≥157.6 °C) is well above ASTM (≥100 °C) and EN (≥120 °C) minimal, confirming superior handling safety and low fire risk in storage and transport; the acid number (0.451 mg KOH/g) also falls below the stringent 0.5 mg KOH/g threshold, suggesting an only minimal presence of residual free fatty acids and a negligible occurrence of catalyst carryover and concomitant, low corrosivity toward copper and steel components in fuel systems. Together, these results confirm that the WCOME meets or exceeds all critical fuel specifications, demonstrating its technical readiness as a direct drop-in replacement for fossil diesel in unmodified compression-ignition engines.

Table 8. Physicochemical properties of WCOME with optimum process variables

Property	Unit	ASTM D6751 Limit	EN14214 Limit	Diesel	WCOME
Kinematic viscosity @ 40°C	mm^2/s	1.9-6.0	3.5-5.0	2.96	4.55
Density @ 15°C	Kg/m^3	880	860-900	846.1	831,4
Flash point	°C	100-170 min	>120	75.5	157.6
Acid number	Mg KOH/g	0.5 max	0.5 max	0.017	0.451

Figure 7. Waste Cooking Oil Methyl Ester (WCOME)

4. Conclusion

The present study successfully illustrated the conceptual description, synthesis, and optimization of a small-scale biodiesel production plant based on WCO as a sustainable, circular feedstock. The results showed that the batch-type, forced circulation double-jacketed reactor was constructed from stainless steel 304 for better corrosion resistance and satisfactory mechanical properties, with an indirect hot air heating system, which ensured a uniform thermal control functioning well below its material limits (as determined by structural and stress analysis) and was suitable for long-term use in the laboratory and pilot plant. The Box–Behnken design of RSM was used to optimize the process, revealing that the reaction time was the most influential parameter, followed by catalyst concentration and the methanol-to-oil molar ratio, with a high predictive accuracy (R^2 = 0.9931) for the quadratic model. Results from the experimental examination indicated that, under optimal conditions, the system would have an MEB of 85 %. FTIR studies indicated the formation of methyl esters from fatty acids, confirming the successful completion of the transesterification reaction, while physicochemical analysis confirmed that the produced biodiesel met both ASTM D6751 and EN 14214 requirements. Overall, the results confirm that the mini biodiesel plant is technically feasible and a viable, cost-effective solution for converting WCO into high-quality biofuel with a low capital investment, while being compliant with sustainable power generation and circular economy requirements.

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CRediT Authorship Contribution Statement

Surya Dharma and Siti Maretia Benu: Conceptualization, Methodology, Investigation, Data Curation, Writing Original Draft, Writing – Review & Editing, and Visualization; Jovian Zefanya Richard Chrisardo Silalahi: Investigation, Data Curation and Formal Analysis; Rahmawaty and Rihat Sebayang:, Methodology, Formal Analysis, Ulfa Hasnita, Heru Pranoto and Mohamad Ali Ahmad: Formal Analysis.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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