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Enhancement of Biolubricant Production from Waste Cooking Oil using Alkali Derived from Oil-Palm empty Fruit Bunches

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ABSTRACT
This study focuses on the enhancement of biolubricant production by converting waste-cooking oil methyl esters (WOMEs) through the transesterification process. The potassium hydroxide (KOH) necessary for the transesterification was extracted from Oil-Palm Empty Fruit Bunches (OPEFB) through a multistep procedure involving cutting, sun-drying, burning, and soaking in distilled water. The resulting filtrate contained KOH at a concentration of 0.2 mol/dm³. To optimize the transesterification process, Response Surface Methodology (RSM) employing central composite design (CCD) was utilized. Three critical factors—temperature, mole ratio, and reaction time—were investigated for their influence on biolubricant yield. The study revealed that an optimal biolubricant yield of 98.5% could be achieved under the following pecific conditions: a temperature of 100°C, a mole ratio of 7:1, and a reaction time of 120 minutes. The predicted yield from the optimization correlates closely with the experimental results, indicating the efficacy of the optimization approach. Analysis of variance (ANOVA) underscored the significance of mole ratio and temperature as pivotal factors affecting biolubricant yield. This systematic investigation contributes valuable insights into the transesterification process, offering a sustainable approach to biolubricant production by utilizing waste cooking oil and KOH extracted from OPEFB. The findings provide a foundation for future research in the field of environmentally friendly lubricant synthesis.

Keywords: Transesterification; Biolubricant; Oil Palm Empty Fruit Bunches (OPEFB); Central Composite Design (CCD); Vegetable Oil; Palm Kernel Oil

1. Introduction

Fossil fuels, as their name suggests, originate from natural sources, namely organic materials of animal and plant origin. Vegetable oil, when used as a biolubricant, exhibits low volatility due to the higher molecular weight of the triglyceride molecule (Dandan et al., 2018). Mainly derived from organic sources, vegetable oils exist as free carboxylic compounds or esterified substances. They are environmentally less harmful, causing minimal pollution in the atmosphere. Vegetable oils possess excellent lubricating properties and boast a higher viscosity index. Their exceptional affinity for metal surfaces grants them anti-corrosion capabilities (Raof et al., 2022). Additionally, vegetable oils are classified as non-flammable liquids due to their high flash point (Uppar et al., 2023).

Biolubricants formulated from plant oils offer several advantages. They provide superior lubricity, leading to reduced friction losses. Their lower volatility results in decreased exhaust emissions, and they also possess a higher viscosity index (Sarma & Vinu, 2022).

However, there are some disadvantages, such as their lower oxidative stability and cold flow properties. Nevertheless, the use of additives like antioxidants can improve the performance of this product. The main raw materials for biolubricant production are vegetable oils, such as rape seed, sunflower, soybean, safflower, etc., which a mainly composed of triglycerides (Nogales-delgado& Pinilla, 2021). Vegetable oils include groundnut oil, palm kernel oil (PKO), castor oil, palm oil, coconut oil, etc.

Despite the great potential of vegetable oils as biolubricants, they are not widely commercialized due to their high heterogeneity and other undesirable physical properties related to poor oxidation stability, poor low-temperature properties, and poor viscosity indexes, among others. Considering these disadvantages, the main challenge of biolubricants is maintaining the consistent chemical composition of the vegetable oils used as starting materials to meet final application and performance specifications. Viscosity is one of the key properties of a biolubricant, as it describes the internal friction within a liquid due to molecular interactions (Cecilia et al., 2020).

Transesterification of vegetable oils is the most important initial step in producing biofuel or biolubricant. Fatty acid alkyl esters, along with glycerol, are produced by the transesterification of vegetable oils (Thangaraj et al., 2019).

Research on process optimization in various systems is currently focusing on esterification and transesterification reactions. We have chosen transesterification as the chemical pathway to produce fatty acid alkyl esters and glycerol from a combination of vegetable oils, alcohol, and a basic catalyst (Salaheldeen et al., 2021).

Generally, homogeneous chemical catalysts have several advantages, including high selectivity, turnover frequency, reaction rate, and effortless optimization of activity. In earlier research, acid, or alkali, was employed as a homogeneous catalyst. The common alkali catalysts being employed are sodium hydroxide (NaOH), sodium methoxide (CH3ONa), and potassium hydroxide (KOH). NaOH is preferred over KOH because it dissolves quickly in methanol. NaOH is considered in transesterification due to its high purity and low cost; in addition, a relatively low quantity is needed as compared to KOH (Thangaraj et al., 2019).

Transesterification of vegetable oils with different alcohols produces fatty acid alkyl esters (and glycerol) that can be used as biofuel or biolubricant. Transesterification reactions can be catalyzed by both homogenous (Fukuda et al., 2001; Lam et al., 2010) and heterogeneous (alkalines and acids) catalysts (Macario et al., 2010). In a catalytic transesterification reaction, homogenous alkali catalysts are commonly used. The alkaline catalyst mostly used is potassium hydroxide (KOH), since it decreases the tendency for soap formation compared to sodium hydroxide (NaOH). It also reduces the number of methyl esters dissolved in the glycerol phase after the reaction, thus reducing ester losses (Anusi et al., 2018).

Transesterification of vegetable oils with lower alcohols like methanol, ethanol, etc. produces 'biodiesel', while with higher alcohols, C8 to C14 synthesizes 'biolubricants' (Bilal et al., 2013).

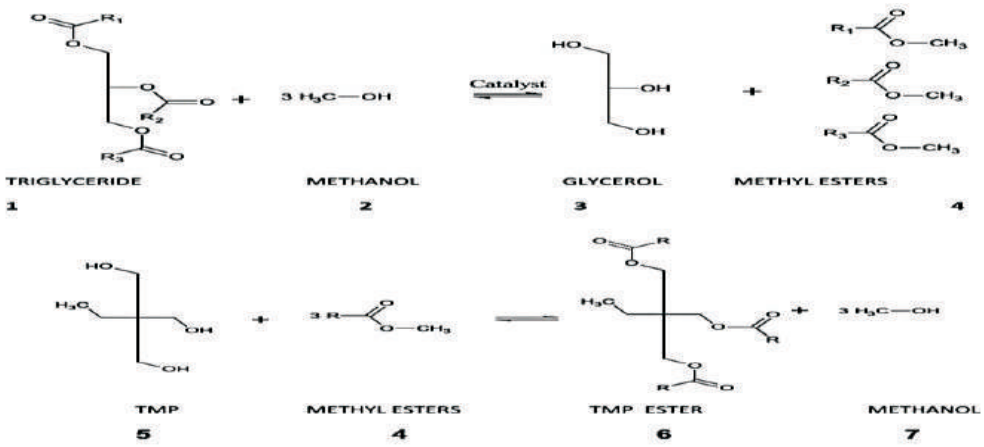

Figure 1: Transesterification reaction stoichiometry (Koohikamali et al., 2012).

The aim of this study is to experimentally investigate the production of biolubricant from waste cooking oil (WCO). The objectives of the study are the preparation of potassium hydroxide (KOH) from the dried OPEFB, the design of the experiment using Design-Expert software for optimization of production yield, as well as the characterization of the biolubricant produced.

2. Materials and Methods

2.1 Materials

The necessary materials for this research include waste cooking oil (WCO), which was procured from a local restaurant in Nigeria. Oil-palm empty fruit bunches (OPEFB) were purchased from the local market. The esterification process involves using ethanol as the alcohol, which reacts with palm kernel oil (PKO). The catalyst employed was potassium hydroxide derived from palm bunch ash. The reaction took place within PET bottles. Essential equipment and apparatuses used encompass a viscometer, weighing balance, heater, thermometer, glass spatula, funnel, Bunsen burner, Whatman filter paper, retort stand, separator funnel, Erlenmeyer flask, measuring cylinder, beaker, masking tape, and PET bottles for storage.

2.2 Methods

2.2.1 Preparation of Ash from Oil Palm Empty Fruit Bunches

The waste from oil palm empty fruit bunches was cut into small pieces and exposed to sunlight for 6 to 10 days. After sun-drying, the materials were burned in open air to create charred remains. These ash samples were finely ground into small particles. The resulting sample was placed in a crucible and vigorously heated using a Bunsen burner for a minimum of 80 minutes. This process aimed to achieve a finer particle size. The finely-ground material was then dissolved in distilled water in standard beakers, the mixture was stirred with a glass spatula. The solution obtained was filtered using Whatman filter paper, resulting in a solution of potassium hydroxide. The concentration of this solution was determined through titration using a known standard acid concentration.

2.2.2 Production of biolubricant

The waste cooking oil (WCO) was subjected to filtration and heating to eliminate water and potential contaminants that could influence the experiment. In a PET bottle, potassium ethoxide was produced by combining potassium hydroxide and ethanol. A different PET bottle was utilized to contain the waste cooking oil (WCO), into which the previously prepared potassium ethoxide was introduced. The bottle was sealed tightly and agitated vigorously by shaking. This mixture was then heated, keeping the temperature below 78°C, which is ethanol's boiling point, for 30 minutes. The resulting mixture was transferred from the PET bottle to a separating funnel, supported by a retort stand to allow settling. Phase separation became evident after 10 minutes. The distinct components, specifically the upper layer of ethyl ester (biodiesel) and the lower layer of impure glycerol, were gathered by carefully guiding them into appropriately labeled measuring cylinders. For the ethyl ester production, the obtained product was heated to 70°C in a water bath, followed by the addition of a potassium hydroxide base catalyst solution at a concentration of 0.9 g/mol. After a 10-minute interval, 20 g/mol of propane 1, 2 diol was added to the reaction vessel. The reaction proceeded for 2 hours at 80°C. The mixture was then allowed to cool to room temperature before being transferred into a separating funnel. Propane 1, 2 diol trimester (biolubricant) is collected as the lower viscous layer. The entire procedure was repeated with varied input parameters (temperature, mole ratio, and time) for WCO. A design layout from the Design-Expert software was used for 20 experimental runs to examine the influence and interactions of process variables on the response. The percentage yields of KOH, ethyl ester, and biolubricant were calculated using equations 1, 2, and 3, respectively.

$$\% \text{ yield of KOH} = \frac{Mass of KOH obtained}{Mass of ash taaken} \times 100 \quad (1)$$

$$\text{The yield of ethyl ester} = \left(\frac{V_0}{V_s}\right) \times 100 \quad (2)$$

where Vp is the volume of product, and Vs is the volume of sample oil used for the synthesis

$$\% \text{ yield of biolubricant} = \left(\frac{V_0}{V_s}\right) \times 100 \quad (3)$$

2.3 Design of the Experiment

Central composite design (CCD) was used to study the effect of transesterification reaction variables and subsequent process optimization. This method is suitable for fitting quadric surfaces, which helps to optimize the effective parameters with the least number of experiments and analyze the interaction between the parameters. To describe the effects of temperature, time, and mole ratio on the yield of biolubricant, batch experiments will be conducted based on the Central Composite Design. The coded values of the process parameters will be determined by the following equation:

$$x_i = (X_i - X_0)/\Delta X_0 \quad (4)$$

Where xiis the coded value of the ith variable, Xiis the uncoded value of the ith test variable and X0is the uncoded value of the ith test variable at the centre point. A second-order polynomial equation will be used to express the biolubricant yield (Y) as a function of the independent variables.

$$Y = b_0 + \sum_1^k = {}_1 b_i X_i + \sum_1^k = {}_1 b_{ij} X_i^2 + \sum_j^k b_i X_i X_j + e \quad (5)$$

Where Y is the response factor (% yield), i and j denote linear and quadratic coefficients respectively, b0 is the intercept, bi is the first-order model coefficient, k is the number of factors and e is a random number.

3. Results and Discussion

3.1 Analysis of transesterification product

The independent variables' levels are listed in Table 1. Regression analysis using a second-order polynomial was conducted to estimate the response function, and the Design Expert 11 software was used for this purpose. Additionally, ANOVA was performed to assess the model's adequacy. Response surfaces were generated to examine the individual and interactive effects of temperature, time, and mole ratio (with high and low values) on the biolubricant yield.

Table 1: Factors levels of independent variables

Factor	Name	Units	Level	Low Level	High Level	- alpha	+ alpha
A	Temperature	°C	95.98	80	100	52.7283	187.272
B	Molar Ratio		6.30934	3	7	1.63641	8.36359
C	Time	minute	141.447	120	200	92.7283	227.272

3.2 Model Fitting and Analysis of Variance (ANOVA)

The optimization of the transesterification reaction for biolubricant production was carried out using the Central Composite Design (CCD). The study focused on three essential independent variables: temperature, time, and mole ratio, while the percentage yield of biolubricant served as the response (dependent) variable to develop the empirical model. The goal was to identify the best conditions for achieving the highest biolubricant yield. The CCD typically involves six centre runs and 2(n) axial runs, where n represents the number of factors. In this research, a total of 20 experiments were conducted, including 6 central points, and the randomization of experiments aimed to avoid systematic errors. The analysis resulted in the suggestion of a quadratic model from the CCD module, as the CCD setup does not have enough runs to support a full cubic model, making the cubic model aliased. The statistical significance of the model was assessed using P-values, and the model summary and lack of fit tests for the biolubricant synthesis are presented in Tables 3, 4, and 6.

Table 2: Central Composite Design arrangement and response

Run	Factor A	Factor B	Factor C	Response	Run	Factor A	Factor B	Factor C	Response
1	90	5	160	96	11	90	5	160	93
2	90	8.36359	160	50	12	90	1.63641	160	96
3	73.1821	5	160	90	13	90	5	227.272	83
4	90	5	160	94	14	80	3	120	98
5	90	5	160	92	15	90	5	160	96
6	106.818	5	160	83	16	90	5	92.7283	93
7	80	3	200	80	17	100	3	200	98
8	80	7	200	75	18	100	7	200	98
9	90	5	160	91	19	100	3	120	98
10	80	7	120	80	20	100	7	120	98.5

Table 3: Summary of P-values for Biolubricant Synthesis

Source	Sequential P-value	Lack of Fit P-value	Adjusted R^2	Predicted R^2	Remark
Linear	0.0056234	0.001147838	0.4473211	0.1875554	Suggested
2FI	0.610573444	0.000812547	0.4056997	-0.1812423	
Quadratic	0.139531007	0.00114194	0.5427252	-0.8146496	
Cubic	0.225778207	0.000600341	0.6661423	-20.43138	Aliased

Table 4: Summary of model statistics

Source	Std. Dev.	R^2	Adjusted R^2	Predicted R^2	PRESS	Remark
Linear	8.667954	0.534586	0.4473211	0.1875554	2098.494	Suggested
2FI	8.988415	0.593373	0.4056997	-0.1812423	3051.075	
Quadratic	7.884403	0.759329	0.5427252	-0.8146496	4687.127	
Cubic	6.736911	0.894571	0.6661423	-20.43138	55355.91	Aliased

Table 5: ANOVA for Biolubricant

Source	Sum of squares	Df	Mean square	F Value	P-value
Model	1961.299462	9	217.922162	3.50561	0.03178
A-Temperature	8.426405188	1	8.42640519	0.13555	0.72042
B-Molar ratio	1371.570305	1	1371.57031	22.0638	0.00085
C-Time	8.06E01	1	0.8060896	0.01297	0.91159
AB	69.03125	1	69.03125	1.11047	0.31677
AC	63.28125	1	63.28125	1.01798	0.33679
BC	19.53125	1	19.53125	0.31419	0.58746
AA^2	6.336630063	1	6.33663006	0.10193	0.75609
BA^2	425.8658014	1	425.865801	6.8507	0.02571
CA^2	0.254032538	1	0.25403254	0.00409	0.95029
Residual	621.6380376	10	62.1638038		
Lack of Fit	600.3047043	5	120.060941	28.1393	0.00114
Pure Error	21.33333333	5	4.26666667		
Cor Total	2582.9375	19			

Std. Dev. = 7.88; Mean = 89.13; C. V. = 8.85%; PRESS = 4687.13.
R^2 = 0.7593; Adjusted R^2 = 0.5427; Predicted R^2 = -0.8146; Adeq precision = 7.6750

Table 6: Lack of fit test for Biolubricant synthesis

Source	Sum of squares	df	Mean square	F-Value	P-value	Remark
Linear	1180.801367	11	107.345579	25.15912	0.001148	Suggested
2FI	1028.957617	8	128.619702	30.145243	0.000813	
Quadratic	600.3047043	5	120.060941	28.139283	0.001142	
Cubic	250.9825042	1	250.982504	58.824024	0.0006	Aliased
Pure Error	21.33333333	5	4.266666667			

The ANOVA results for Biolubricant from WCO are presented in Table 6. In this case, B and B^2 were significant model terms while the regression F-value of 3.51 implies that the model was significant which was validated by the P-values of less than 0.05. There is only a 3.18% chance that an F-value this large could occur due to noise (Bzovsky et al., 2022). The test for the accuracy of the regression models, the significance of individual model coefficients and the lack of fit test were carried out using the same statistical package. The P-values were used as a tool to check the significance of each of the coefficients, which in turn were necessary to understand the pattern of the mutual interactions between the test variables (Gwise et al., 2021). Hence, the higher the F-test value and the smaller the P-values, the higher the significance of the corresponding coefficient (Zawawi et al., 2022). Adeq Precision measures the signal-to-noise ratio. A ratio greater than 4 is desirable. The ratio of 7.675 indicates an adequate signal (Yuan et al., 2019). This model can be used to navigate the design space. The coefficient of regression R^2 was used to validate the fitness of the model equation.

The biolubricant produced from WCO yielded a high R^2 value of 0.7593, indicating that 75.93% of the response variability could be explained by the model. This suggests that the model's ability to predict experimental data was considerably satisfactory. The quadratic model equation (3) was derived after removing non-significant terms for the transesterification from WCO.

The equation in terms of coded factors allows making predictions about the response based on different levels of each factor. In a regression equation, a positive sign for an independent variable indicates that an increase in that variable will lead to an increase in the response, while a negative sign suggests a decrease in the response (Razak et al., 2018). Thus, higher temperature, time, and mole ratio will result in an increased percentage yield. Time and temperature have a more significant impact on the response increment, as indicated by their higher coefficients.

To validate the model, normal plots of residuals for WCO production (Figure 2) and predicted vs. actual plots (Figure 3) were examined to check the distribution of residuals. The close distribution of points along the straight lines signifies a strong relationship between experimental and predicted response values. These plots also confirm the adequacy of the chosen model for predicting the response variables in the experimental values.

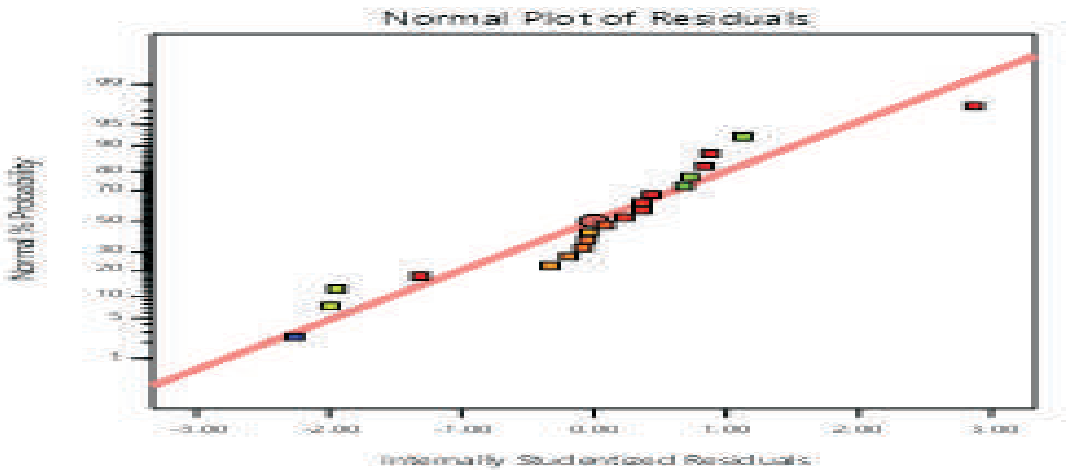

Figure 2: Normal plot of residuals

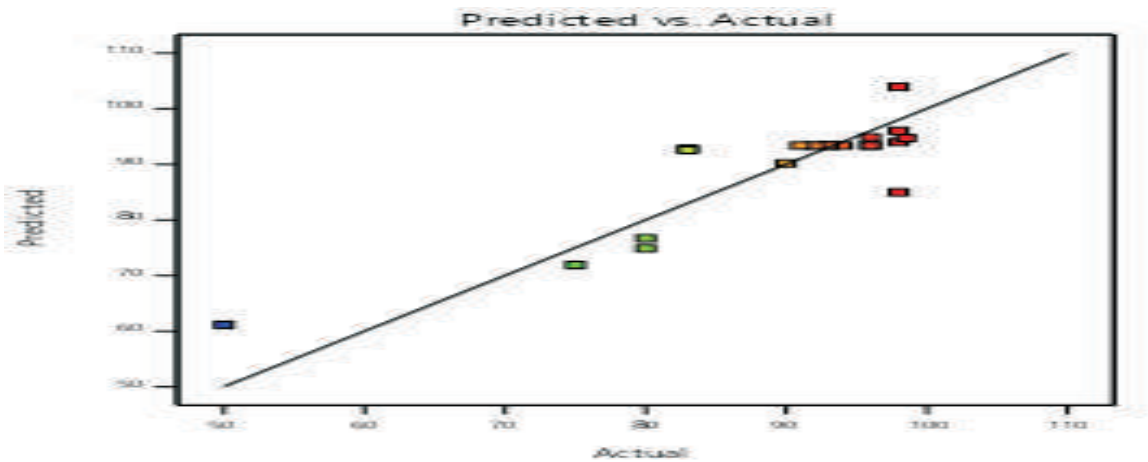

Figure 3: Predicted vs Actual plot

3.3 Effect of process parameter on transesterification reaction

Response surface plots were created to illustrate the interactions between the two factors for the three reaction parameters: temperature, time, and mole ratio. The yield ranged from 50% to 98.5% in the plots.

3.3.1 Effect of mole ratio and temperature on transesterification reaction

In Fig. 3, the plots demonstrate how the temperature and mole ratio impact the biolubricant production from WCO while keeping the time fixed at 2 hours and 40 minutes.

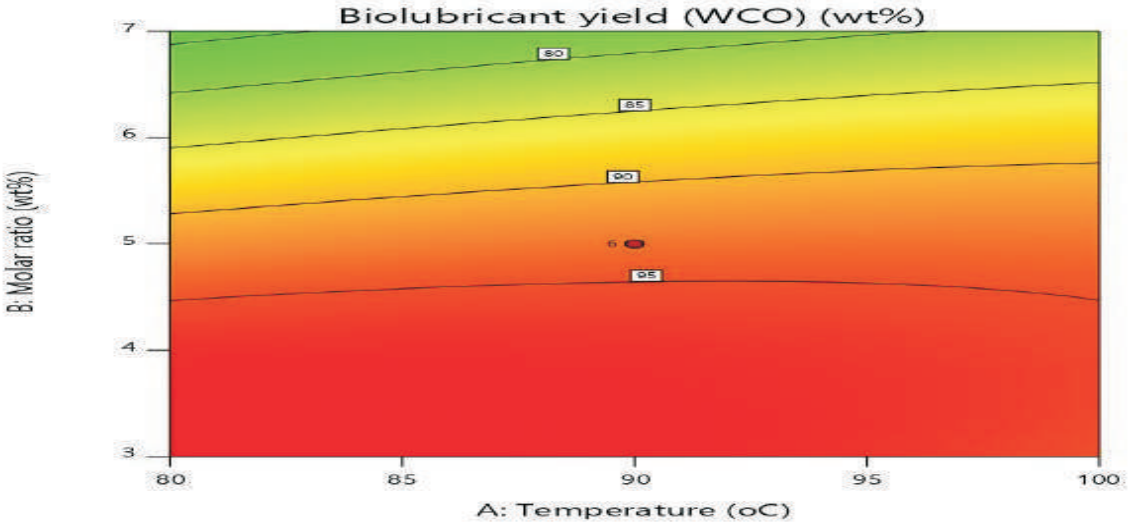

Figure 4: Surface plot for the effect of temperature and mole ratio

3.3.2 Effect of time and temperature on transesterification reaction

Figure 5 shows the plots of the effect of temperature and time at a fixed mole ratio of 5:1 for WCO.

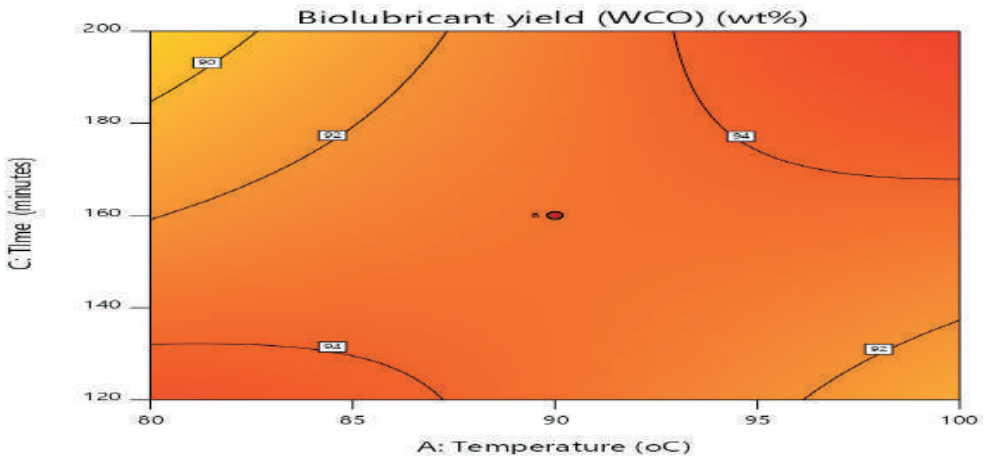

Figure 5: 2D surface plot for the effect of temperature and time

3.3.3 Effect of time and mole ratio on transesterification reaction

Figure 6 shows the plots of the effect of mole ratio and time at a fixed temperature of 90°C for WCO.

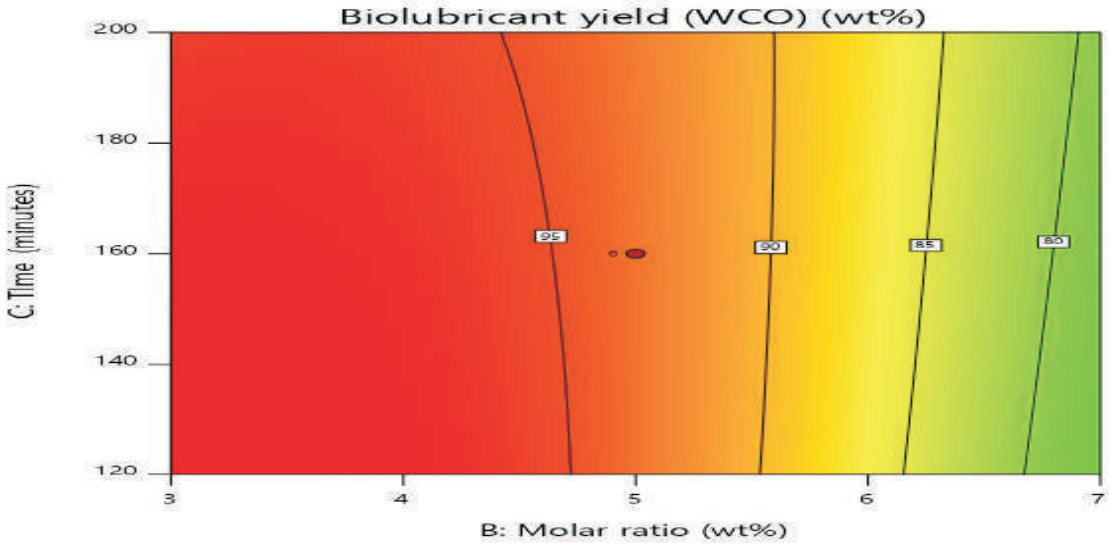

Figure 6: 2D surface plot for the effect of mole ratio and time

Figures 7, 8, and 9 display response surface contours, representing graphical outcomes of interactive effects. The optimal values observed were 96% for PKO and 98.5% for WCO, surpassing the highest calculated values based on the experimental design. The surface plot, depicting the conversion of biolubricant concerning molar ratio and temperature, indicated maximum conversions of 96% for PKO and 98.5% for WCO, obtained from the contour plot at the highest values of molar ratio and temperature.

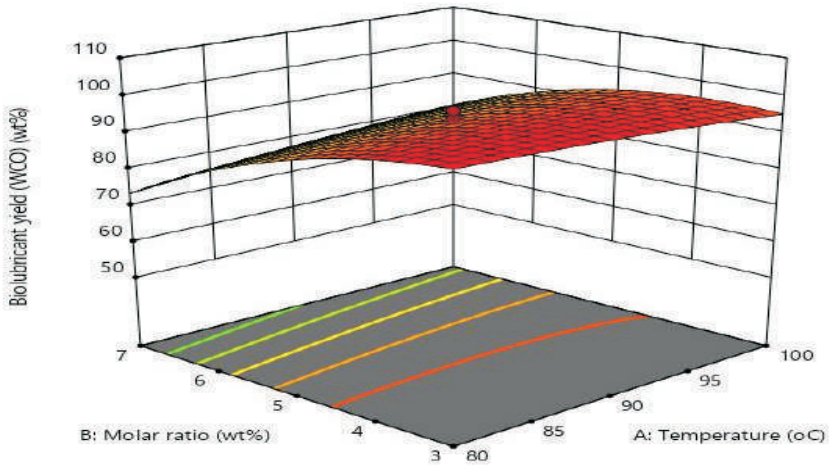

Figure 7: Surface and contour plot between mole ratio and temperature against Biolubricant yield

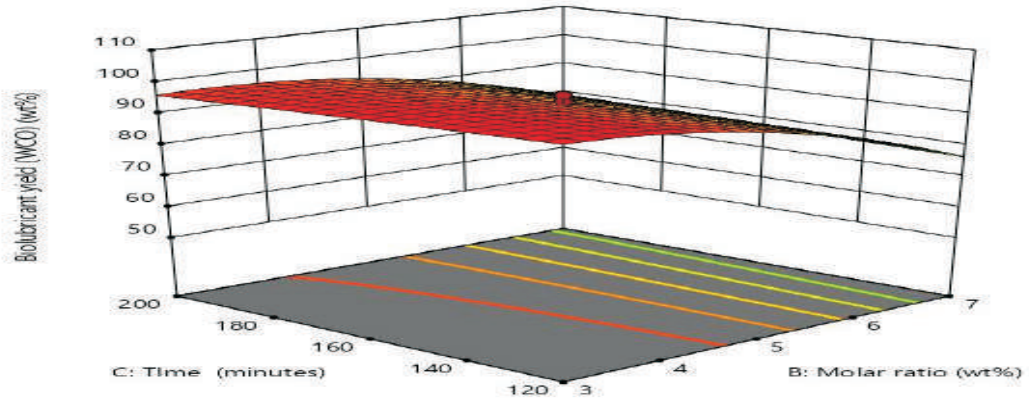

Figure 8: Surface and contour plot between molar ratio and time against Biolubricant yield

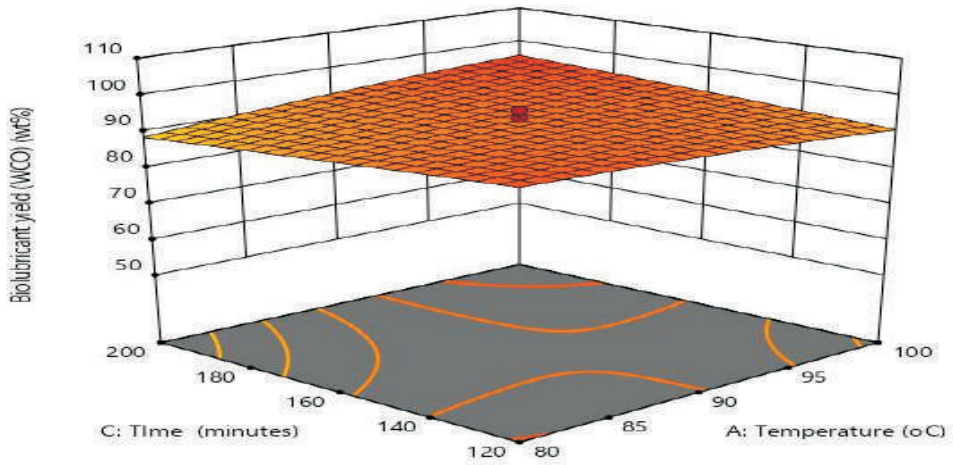

Figure 9: Surface and contour plot between time and temperature against Biolubricant yield

The response surface plots (Figures 6-8) displayed a distinct peak, indicating that the optimal conditions for achieving maximum yield were well within the design boundaries. From the 3D plots, it was evident that the conversion increased with higher temperatures and mole ratios. When observing the effect of temperature, the yield rose with an increasing mole ratio before reaching a plateau; on the other hand, at lower temperature values, the trend followed a parabolic path. Keeping the molar ratio constant, increasing the temperature enhanced the yield until a certain point where further increments did not lead to a significant increase in yield.

The 3D response demonstrated that the synthesis of biolubricant increased with higher FAME concentrations. Thus, the maximum biolubricant conversion was achieved at a high mole ratio. This outcome was attributed to the stoichiometry of transesterification, which necessitates a 3:1 ratio of FAME and propane 1,2 diol as a result of the reaction involving the conversion of one ester and alcohol into another ester and alcohol. Consequently, having an excess of FAME drives the reaction closer to completion. Therefore, a higher FAME concentration led to greater biolubricant conversion in a shorter time, as depicted in Figure 7.

A higher biolubricant yield is strongly favoured when employing a high molar ratio, along with a specific reaction time (C) and temperature (A). The molar ratio is a critical variable in the transesterification process for biolubricant synthesis.

According to the 3D response surfaces, an increase in reaction temperature leads to a higher biolubricant yield while reducing the required reaction time. However, increasing the reaction time at a low-temperature level does not enhance the catalytic activity. On the other hand, higher temperatures improved the dispersion of catalyst particles in the liquid medium, leading to better mass transfer between the reactants. The contour plot indicates that a higher biolubricant yield is favoured by increasing the reaction temperature while maintaining a low or intermediate level of reaction time.

Moreover, the 3D response surface demonstrated that elevating the reaction temperature results in an increased biolubricant yield while reducing the required reaction time. However, after approximately 3 hours of reaction, extending the reaction time does not significantly impact the yield. Additionally, higher temperatures improved the dispersion of catalyst particles in the liquid medium, leading to enhanced mass transfer between the reactants. The contour plots also indicated that a higher biolubricant yield is favoured by a higher temperature level with a low to intermediate reaction time.

3.4 Process variable optimization and validation

Table 7 displays the results of optimization and validation for biolubricant synthesis. Predicted responses were generated using a point prediction node within the optimization node of the CCD module at a consistent temperature with fixed molar ratios of reactants. The specified temperature range was set between 80°C and 100°C. The molar ratio of reactants was adjusted between 4 and 6, and the designated time ranged between 2 hours and 3 hours and 20 minutes. The highest biolubricant yield from WCO within the experimental range was found to be between 50% and 98.5%.

Table 7: Optimization/Validation of results

Parameter	Optimum operating condition
Temperature (°C)	100
Time (min)	120
Mole ratio	7:01
Yield (optimum) wt%	98.5
Yield (validated) wt%	87.3701

3.5 Lubricating properties of biolubricant

The viscosity of a lubricant is widely regarded as one of its crucial properties. If the viscosity does not match the specific requirements for a particular component and application, the lubricant will be ineffective in providing proper lubrication. This mismatch can result in significant damage and potential equipment failure. Specifically, the kinematic viscosity at 40°C was measured for the biolubricant produced from WCO, and the results are presented in Table 8.

Table 8: Kinematic viscosity, cSt

Experimental Runs	Viscosity	Experimental Runs	Viscosity
1	22.5	11	29.5
2	24.5	12	24.2
3	20.2	13	21.3
4	29.1	14	25.4
5	28.9	15	24.1
6	27.8	16	24.3
7	26.6	17	27.2
8	29.4	18	28.7
9	29.6	19	29.3
10	23.1	20	35.2

Various kinematic viscosities have been reported by different authors for different bio-based lubricants at 40°C. Such reports include 39.7 cSt and 54.1 cSt for TMP esters of palm kernel oil and palm oil (Fadzel et al., 2018). and 43.9 cSt for TMP esters of Jatropha curcas oil (Abobatta, 2019). Furthermore, when compared with the ISO VG 32 standard specification for light gear lubricant, the properties of the optimum biolubricants for WCO met the stipulated specification.

Table 9: EN standard and ISO VG of Biolubricant produced (Shaba et al., 2018; Tarbuka et al., 2017)

Parameters	WCO	EN 16751 European BD Standard	ISO VG32
% Yield	98.50%	-	-
Viscosity at 40°C	35.2 (cSt)	3.5	>28.8
Flash Point (°C)	198	>120	204
Pour Point (°C)	10	0.860.90	<-10
Cloud Point (°C)	-5	-	-
Density(kg/cm³)	0.924	-	-
Specific Gravity	0.93	5	-

The WCO-based biolubricant exhibits promising characteristics for low-temperature applications. With a low pour point of 10°C and a cloud point of -5°C, it remains fluid in extremely cold environments. The high flash point of 198°C ensures safety during use. The measured density of 0.924 kg/cm³ and a specific gravity of 0.93 indicate a light composition (Deering et al., 2022; Reeves, 2013).

4. Conclusion

In conclusion, the application of the Response Surface Method (RSM) through Central Composite Design (CCD) proved to be highly effective in optimizing the synthesis of propane 1,2-diol-based biolubricant from waste cooking oil (WCO). Through a systematic exploration of reaction temperature, mole ratio, and reaction time, the study successfully identified and fine-tuned the key parameters influencing transesterification reaction yield. The utilization of a polynomial quadratic model allowed for accurate predictions of the maximum yield and optimization of reaction conditions. The model pinpointed the optimal settings, advocating for a reaction temperature of 100°C, a mole ratio of 7:1, and a reaction time of 120 minutes. Subsequent experimentation under these conditions yielded an impressive WCO biolubricant with a substantial actual yield of 98.5 wt%. The analysis of variance (ANOVA) underscored the pivotal role of the mole ratio and temperature in influencing the biolubricant yield. This comprehensive approach not only enhanced our understanding of the transesterification process but also provided practical insights for achieving optimal results in the synthesis of biolubricants from waste cooking oil. These findings position the biolubricant as a competitive and eco-friendly option, warranting further exploration in specific applications and industries.

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