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Enhancement of thermal stability and corrosion resistance of palm oil lubricants using nonylphenol and polyethylene glycol additives

Haris Puspito Buwono*, **Aquilla Elka Ananda Kirana**
Department of Chemical Engineering, State Polytechnic of Malang, Malang 65141, Indonesia
*Corresponding author: haris.puspito@podlinema.ac.id

Abstract

Palm oil offers advantages as a lubricant due to its eco-friendliness, renewability, high viscosity index, good boundary lubrication properties, and compatibility with additives. However, palm oil is not very resistant to high-temperature changes, which limit its application in vehicle lubricants. This research aims to overcome the weaknesses of palm oil as a vehicle lubricant by adding Nonylphenol and Polyethylene Glycol surfactants at varying concentrations and evaluate thermal stability, engine operating temperature, and corrosion resistance. The quantitative experiments were conducted with palm oil blend of nonylphenol surfactant and polyethylene glycol. Formulations containing 2.5%, 5%, and 7.5% surfactant concentrations were evaluated through oven-based thermal stability testing and copper strip corrosion testing according to ASTM D4048 to determine the sulfur content in lubricating oils. From the test results, palm oil-based lubricant blends containing Nonylphenol (2.5% and 5%) and Polyethylene Glycol (PEG) (2.5% and 5%) showed a corrosion classification value of 1a, the best rating in the ASTM Copper Strip Corrosion Standard. The best engine temperature test was palm-oil-based with 5% Nonylphenol.

Keywords:
Corrosion test, lubricant, surfactant, temperature engine, temperature stability.

1 Introduction

The lubrication system in a vehicle aims to reduce the friction of moving components in the engine. Under lubrication conditions, the lubricating film protects the rubbing surfaces, plays a significant role in its formation, and controls wear behavior [1,2]. The choice of lubricant must be based on the engine specifications, as each engine manufacturer usually sets a recommended lubricant for its products. The lubricating system also helps keep the engine temperature stable, allowing the engine to operate optimally because there is no wasted power from components rubbing directly [3]. Lubricant systems also require characteristics such as appropriate viscosity, heat stability, and cooling ability to maintain engine performance [4].

Mineral lubricating oil is made from a mixture of 70-90% base oil and additives to improve performance [5]. This results in the use of mineral and synthetic oils increasing, so that environmental pollution will continue, as the properties produced by these oils are toxic to the environment [6]. In addition, the nature of lubricants derived from mineral oil cannot be renewed, so the source of mineral oil will run out.

Vegetable oil products are one of the most promising sources of renewable materials today [7]. Some example of vegetable oil is palm oil. Palm oil as a base lubricant material is more profitable because it is environmentally friendly, renewable, has a high viscosity index, good lubrication properties, especially in boundary lubrication, and dissolves readily with additives [8,9]. Based on various studies, the kinetic viscosity of palm oil ranges from 3.5 to 4.5 mm^2/s (cSt) at 40 °C, particularly in the context of its use as a raw material for biodiesel. In addition, the dynamic viscosity value of palm oil ranges from approximately 45 to 50 mPa·s under certain conditions [10].

In addition, vegetable oil exhibits superior anticorrosion properties due to its strong affinity for metal surfaces [11]. However, vegetable oil has the disadvantage of changing viscosity easily when heated; therefore, for its use as a lubricating base oil, it needs to be blended with additives. Lubricant viscosity affects engine performance, including thermal stability over a wide operating temperature range [12].

Viscosity is defined as a coefficient that indicates the degree of viscosity of a fluid. The greater the viscosity coefficient, the harder it is for the fluid to flow, and this is inversely proportional to the terminal velocity of objects falling through the fluid [13]. The higher a fluid's viscosity, the more viscous or dense it is, so it flows more slowly. Conversely, the lower the viscosity, the thinner the fluid, allowing faster flow [14]. Therefore, the addition of surfactants can improve the physical and chemical properties of cooking oil as a lubricant.

Previous studies have shown that surfactants can improve lubricant performance by reducing friction and increasing oxidation resistance [15]. Previous researchers have also studied that palm oil-based lubricants can maintain vehicle temperature well [16]. Other studies have also shown that adding additives to palm-based lubricants significantly improves friction and wear performance [17].

2 Research methodology

The methodology consisted of four main stages: selection of materials, fabrication of test specimens, surface preparation and dimensional measurement, and statistical data analysis.

2.1 Experimental setup

2.1.1 Thermal stability test

Lubricants are thermally tested to assess the effectiveness of additives in slowing the rate of oxidative degradation and maintaining lubricant quality [18]. Thermal tests on lubricants can determine the temperature at which they begin to decompose and the safe threshold for their use in real engine applications [19]. To determine the thermal resistance of blends of surfactants and palm oil, a series of heating tests was conducted to assess their physical and chemical stability at high temperatures. Each blend of palm oil and surfactants (Nonylphenol and polyethylene glycol) at concentrations of 2.5%, 5%, and 7.5% was heated.

This process is carried out in a closed oven with a heat-resistant container, and the temperature is kept constant. This heating process aims to simulate the operating conditions of lubricants in high-temperature engines. These tests are conducted to prevent oxidation instability in fatty acids and edible oils, as well as to use physical and chemical approaches to improve oxidative and thermal stability [20]. Thermal tests are required to determine how well a lubricant maintains its physical properties, such as viscosity and molecular stability, under extreme conditions [21].

2.1.2 Corrosion test ASTM D4048

Lubricants act as a protective barrier against corrosion of metal surfaces on engine components, especially in hot, humid environments [22]. Although lubricants are designed to protect metal surfaces, specific additive compositions can accelerate the oxidation and degradation of metals [23,24].

Corrosion tests aim to evaluate the extent to which lubricants protect metals, especially copper surfaces used in engine systems. This test is carried out according to ASTM D4048, namely the Copper Strip Corrosion Test method, which assesses the chemical reactivity of lubricants with metals by measuring changes in color and surface of copper strips.

Corrosion resistance testing of palm oil and surfactant-based lubricant blends was conducted based on the ASTM D4048 standard (Standard Test Method for Detection of Copper Corrosion from Lubricating Grease). This method is designed to evaluate the potential corrosivity of lubricants to copper, an early indicator of the corrosion tendency of metal components in machinery. In this test, a pure copper strip is used as the test medium. The copper strip was first cleaned and polished to a high gloss, then immersed in a lubricant mixture (palm oil + Surfactant). Next, the sample containing the copper strip was heated in an oven at 100°C ± 1°C for 24 hours to accelerate the chemical reaction between the lubricant and the metal.

After 24 hours, the copper strip is removed from the lubricant mixture (palm oil + Surfactant) and cleaned thoroughly using acetone. Once the strip has been adequately cleaned, its appearance is visually compared with the ASTM Copper Strip Corrosion Standards. The result of this comparison is then recorded as a number followed by a letter, in accordance with the rating ranges specified by the ASTM standard.

2.1.3 Metallography test

Metallographic testing is an analytical technique used to observe the microstructure of metals, especially changes induced by treatments such as lubrication, corrosion, and thermal and mechanical loading. In this study, the metallographic method is used to evaluate the effect of palm oil-based lubricants containing surfactants on the surface of the test metal, a copper plate previously used in corrosion testing according to ASTM D4048.

To carry out this test, a microscope is used to observe the corrosion reaction in detail that occurs on the surface of the copper strip. The use of a microscope enables the visual identification of changes in surface morphology, such as stain formation, discoloration, or damage resulting from chemical reactions between copper and the test substance. With the microscope's high magnification, the observer can determine the severity of corrosion, its distribution pattern, and the characteristics of the affected surface. This visual data is essential for analyzing corrosion test results.

2.1.4 Engine temperature measurement test

To evaluate the temperature stability of palm oil-based lubricants and surfactants, direct testing was carried out on a motorized vehicle. The purpose of this test is to determine the lubricant's ability to maintain a stable engine temperature during use. Excessively high lubricant temperatures can cause viscosity degradation, lubricant film loss, and potential engine damage [25,26]. Lubricant temperature can be strongly influenced by engine load and operating time [27].

Table 1. Motorcycles specification

Specifications of 150 cc Motorcycles	
Diameter X Steps	57.3 x 57.9 mm
Compression Ratio	10.6:1
Piston Diameter	57.3 mm
Maximum Power	9.3 KW / 8500 rpm
Maximum Torque	12.8 N · m / 5000 rpm

The motorcycle is run under standard operating conditions to simulate the use of lubricants in real situations. Engine temperature measurement tests were conducted at two average speeds: 40 km/h and 70 km/h. During the testing process, the engine block temperature was monitored using a thermographic (infrared) thermometer, which was constantly directed at the cylinder block. Temperature measurements were taken periodically to monitor engine temperature and assess the lubricant's ability to absorb and disperse heat generated by combustion and internal engine friction.

Fig. 1. The engine temperature test is performed by measuring the engine temperature with a thermogun.

3 Result and discussion

3.1 Thermal stability test result

In this thermal test, the focus was on two lubricant formulations: palm oil + Nonylphenol and palm oil + Polyethylene Glycol, each with varying surfactant concentrations of 2.5%, 5%, and 7.5%. During heating, all types of lubricant samples showed good stability, as shown in Table 2. All lubricant samples exhibited excellent thermal stability, comparable to that of the reference oil. There was no noticeable color change, sediment formation during the test, or any indication of damage to the physical or chemical structure of the lubricant mixture. This indicates that both Nonylphenol and Polyethylene Glycol surfactants exhibit high-temperature resistance throughout the test.

To assess long-term stability, the tested lubricant samples were transferred to plastic bottles and stored for several days. No sediment or lumps were found, as in the previous test, indicating that the lubricant's physical stability was maintained during storage. These results indicate that both surfactants have the potential to be used in the formulation of vegetable oil-based lubricants, as they maintain stability during heating and storage.

Table 2. Thermal stability test result

Thermal Stability Test Result		
No	Palm Oil (P O) + Surfactant	Condition
1	P O + Nonylphenol 2.5%	No sediment and no significant color change from the original color of palm oil. This mixture is slightly brownish.
2	P O + Nonylphenol 5%	No sediment and no significant color change from the original color of palm oil. This mixture is slightly brownish.
3	P O + Nonylphenol 7.5%	No sediment and no significant color change from the original color of palm oil. This mixture is slightly browner.
4	P O + PEG 2.5%	No sediment and no significant color change from the original color of palm oil. This mixture is brown in color.
5	P O + PEG 5%	No sediment and no significant color change from the original color of palm oil. This mixture is slightly brown.
6	P O + PEG 7.5%	No sediment and no significant color change from the original color of palm oil. This mixture is slightly brown.
7	Conventional lubricants 10W-40	No sediment and no significant color change from the original color of palm oil. This mixture is slightly brownish.

3.2 Corrosion test ASTM D4048 result

All lubricant samples formulated using palm oil with added surfactants Nonylphenol and Polyethylene Glycol showed mild corrosion, categorized under ASTM codes 1a and 1b. In the P O + Nonylphenol sample at concentrations of 2.5% and 5%, and P O + PEG at concentrations of 2.5% and 5%, get code 1a with a light orange description. This indicates that no damage or significant surface changes have occurred on the copper plate, and lubricants in this category are considered non-corrosive.

At a surfactant concentration of 7.5%, for both Nonylphenol and PEG, the lubricant showed code 1b with a dark orange description. This more pronounced color change indicates an increase in chemical reactivity, although it remains within the limits of mild corrosion according to ASTM standards.

For comparison, a conventional 10W-40 lubricant was also tested using the ASTM D4048 corrosion test method. The test results showed that this lubricant received a code 1A classification, indicating slight discoloration of the copper plate without significant corrosion. This classification indicates that the Fastron lubricant retains good corrosion resistance and meets automotive lubricant standards for protecting metal components.

Table 3. Corrosion test ASTM D4048 result

Picture							
Palm Oil + Surfactant	P O + Nonylphenol 2.5%	P O + Nonylphenol 5%	P O + Nonylphenol 7.5%	P O + PEG 2.5%	P O + PEG 5%	P O + PEG 7.5%	Conventional lubricants 10W-40
ASTM code	1a	1a	1b	1a	1a	1b	1a
Color	Light orange	Light orange	Dark orange	Light orange	Light orange	Light orange	Light orange

3.3 Metallography test result

Based on microscopy test results, in the palm oil-based lubricant sample containing 2.5% nonylphenol, the corrosion spread pattern is quite wide from a single starting point. However, there was no significant discoloration on the surface of the copper strip, indicating that although corrosion occurred, the chemical reaction did not cause any noticeable visual changes to the material. Meanwhile, in the sample with 5% Nonylphenol added, the photomicroscopic results showed that the spread of corrosion on the copper surface was significantly limited. As with the 2.5% concentration, no discoloration was observed on the copper. This indicates that increasing the concentration of Nonylphenol has the potential to improve the lubricant's chemical stability with copper and to limit the rate or spread of corrosion.

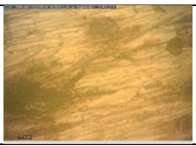
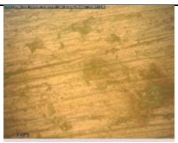
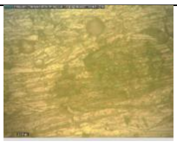
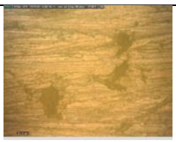
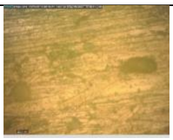
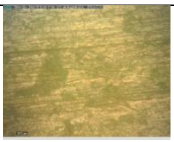
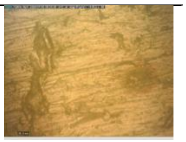
In the palm oil sample containing 7.5% nonylphenol, microscopic observations show that corrosion spreads extensively across the surface of the copper strip, starting from a single point and extending to the surrounding area. In addition, there is evident discoloration of the copper strip, indicating a chemical reaction between the lubricant and the metal.

The palm oil-based lubricant sample with 2.5% PEG (Polyethylene Glycol) showed, under a microscope, minimal corrosion spread on the surface of the copper strip. There was no indication of a significant chemical reaction between the lubricant and the metal, indicated by the absence of color change or surface damage on the copper strip. Meanwhile, in the sample with 5% PEG, the corrosion spread was still very minimal, but a mild chemical reaction was observed on the copper surface. This is indicated by a faint color change, suggesting a chemical interaction between the lubricant component and the copper material. Although no extensive damage occurred, these results indicate that increasing the PEG concentration can affect the lubricant's chemical stability towards the metal, although the corrosion effect remains relatively low.

In the palm oil sample containing 7.5% PEG, microscopic observations revealed that the corrosion spread more extensively on the surface of the copper strip. Additionally, a distinct chemical reaction was observed, indicated by noticeable changes in both color and surface texture of the copper. These findings suggest that at higher PEG concentrations, the lubricant's chemical stability in contact with copper decreases, thereby facilitating more intense chemical interactions and accelerating corrosion.

As a comparison, a conventional SAE 10W-40 lubricant was used. Based on microscopic observations, the spread of corrosion on the copper strip was found to be minimal. Furthermore, no discoloration or signs of chemical reaction were detected on the copper surface. These results indicate that the conventional lubricant exhibits good chemical stability toward copper and provides adequate corrosion protection under the same test conditions.

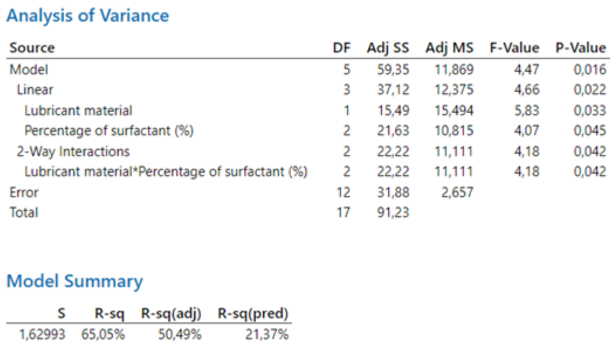
Table 4. Metallography test result

Picture							
Palm Oil + Surfactant	P O + Nonylphenol 2.5%	P O + Nonylphenol 5%	P O + Nonylphenol 7.5%	P O + PEG 2.5%	P O + PEG 5%	P O + PEG 7.5%	Conventional lubricants 10W-40

3.4 Engine temperature measurement test result

Temperature data collected from direct testing on motorcycles is then processed using Minitab software. Data processing was carried out using factorial analysis to evaluate the effect of each treatment factor, namely the type of lubricant sample and vehicle speed, on engine working temperature.

Using Minitab, the analysis results are displayed as ANOVA (Analysis of Variance) tables, regression coefficient tables, and p-values used to test hypotheses. The use of this factorial method provides a clearer, more comprehensive picture of the simultaneous effects and interactions among variables, enabling stronger conclusions about the thermal performance of palm oil lubricants compared to conventional lubricants.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	59,35	11,869	4,47	0,016
Linear	3	37,12	12,375	4,66	0,022
Lubricant material	1	15,49	15,494	5,83	0,033
Percentage of surfactant (%)	2	21,63	10,815	4,07	0,045
2-Way Interactions	2	22,22	11,111	4,18	0,042
Lubricant material*Percentage of surfactant (%)	2	22,22	11,111	4,18	0,042
Error	12	31,88	2,657		
Total	17	91,23			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1,62993	65,05%	50,49%	21,37%

Fig. 2. Results of the ANOVA test on vehicle engine temperature at 40 km/h

Based on the ANOVA results shown in the figure above, the overall regression model is significant (P-value = 0.016), indicating that the independent variables (type of lubricant, surfactant concentration, and their interaction) simultaneously have a significant effect on the response variable. The lubricant type factor showed a significant effect on the test results (P-value = 0.033), indicating that the selection of palm oil-based lubricant type and the additives used significantly affected final results, such as temperature, thermal stability, and corrosion resistance. This is in line with the nature of palm oil, which still needs to be modified through the addition of additives to improve its performance as a vehicle lubricant.

The surfactant percentage factor has a near-significant effect (P-value = 0.045). Variations in surfactant percentage can affect lubricant stability, particularly in mixing and homogeneity between surfactants and palm oil. One of the test results showed a significant interaction between lubricant type and surfactant percentage (P-value = 0.042). This indicates that the effect of surfactant addition in lubricants is always linear or uniform, but rather depends on the type of lubricant used.

Based on the Model Summary, the R² of 65.05% indicates that about 65% of the variation in the response variable is explained by the model. The lower Adjusted R² of 50.49% indicates that, after accounting for the number of variables in the model, the actual contribution of these variables to the response variable is only about 50%. The predicted R-squared of only 21.37% indicates that the model has very low predictive ability for new data. The S-value of 1.62993 reflects the average deviation between the predicted and actual values. The considerable S value indicates that the model's prediction error rate is also high.

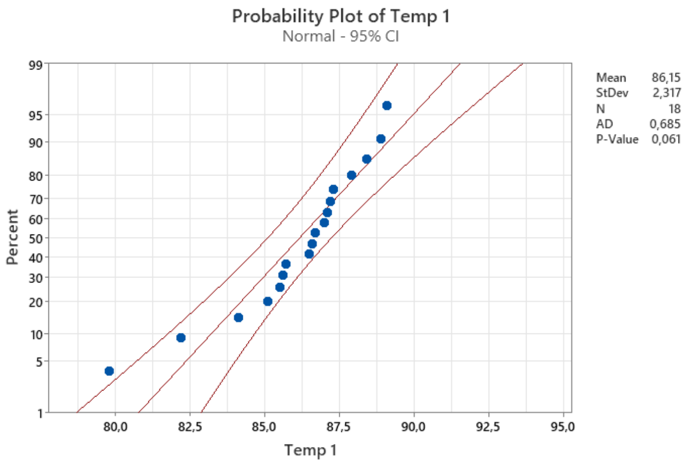
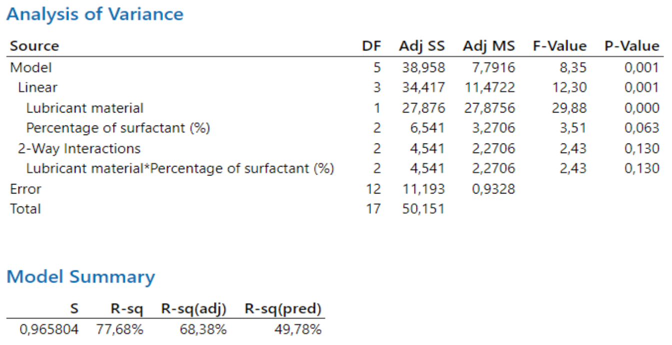


Fig. 3. Probability plot engine temperature at 40 km/h

The analysis showed that the mean temperature was 86.15°C with a standard deviation of 2.317. In the Probability Plot, the temperature data points follow the diagonal line, which represents a normal distribution. Most of the points are within the 95% confidence interval limits shown by the two red curved lines. This shows that the data distribution is quite consistent with a regular distribution pattern.

The p-value obtained is 0.061, which is above the significance limit of 0.05. Based on the normality test criteria, if the p-value is greater than 0.05, the data is considered normally distributed. Thus, it can be concluded that the temperature data in this study do not deviate significantly from normality and thus fulfill the assumption of normality.



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	38,958	7,7916	8,35	0,001
Linear	3	34,417	11,4722	12,30	0,001
Lubricant material	1	27,876	27,8756	29,88	0,000
Percentage of surfactant (%)	2	6,541	3,2706	3,51	0,063
2-Way Interactions	2	4,541	2,2706	2,43	0,130
Lubricant material*Percentage of surfactant (%)	2	4,541	2,2706	2,43	0,130
Error	12	11,193	0,9328		
Total	17	50,151			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0,965804	77,68%	68,38%	49,78%

Fig. 4. Results of the ANOVA test on vehicle engine temperature at 70 km/h

From the data above, the regression model has a P-value of 0.001, indicating that the overall model is significant. This indicates that the combination of independent variables, namely lubricant type and surfactant concentration, has a significant influence on the observed response variable. The lubricant type factor contributes most dominantly to the model, indicated by a P-value of 0.000. This value indicates that different types of lubricants, especially palm oil-based formulations with certain surfactants added, significantly affect lubricant performance.

Meanwhile, the surfactant percentage factor (%) shows a P-value of 0.063, which is slightly above the 0.05 significance threshold. This indicates that the surfactant percentage has a near-significant influence, or is marginally significant.

Based on the Model Summary output, the R² value of 77.68% indicates that about 77% of the variation in the response data can be explained by the model. The lower Adjusted R² of 68.38% indicates that, when the number of variables in the model is taken into account, the model's ability to explain data variation decreases slightly. The predicted R-squared of 49.78% indicates that the model's predictive ability remains moderate. The S-value of 0.965804 indicates the average deviation between the model's predicted and actual values.

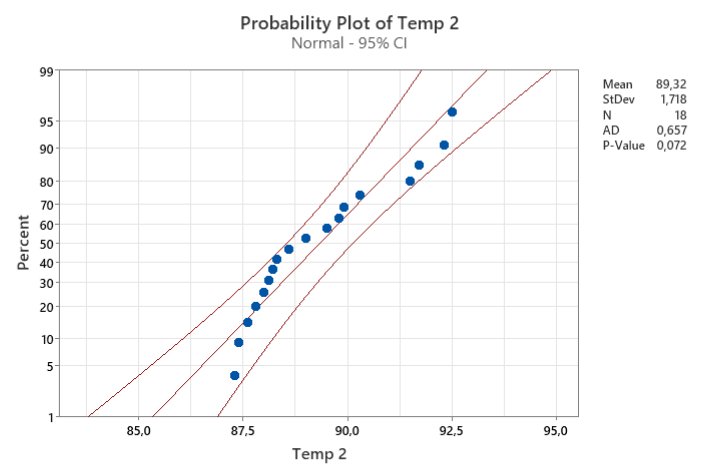
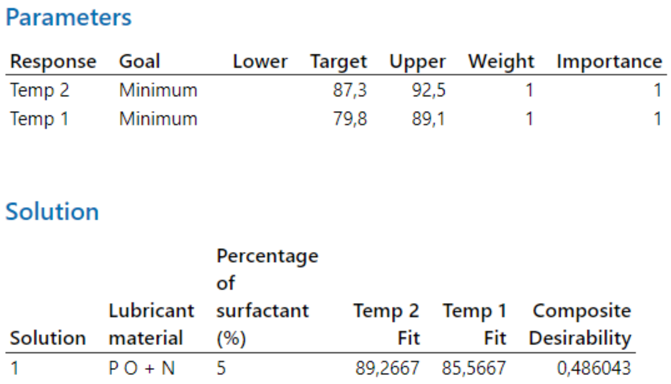


Fig. 5. Probability plot engine temperature measurement test at 70 km/h

A normality test was conducted on the temperature data 2 to determine whether the data followed a normal distribution, a prerequisite for parametric statistical analysis. Based on the Probability Plot displayed, temperature data 2 has an average (mean) value of 89.32°C with a standard deviation of 1.718. The number of samples used is 18.

On the graph, the temperature data points are scattered around the diagonal line, which represents a normal distribution, and most points lie within the 95% confidence interval, as depicted by the two red curved lines. This indicates that the data distribution does not deviate significantly from normality.

The test yields a p-value of 0.072, which is greater than the significance threshold of 0.05. Therefore, the null hypothesis (H_0) that the data are normally distributed cannot be rejected, indicating that the temperature data can be considered normally distributed.



Parameters

Response	Goal	Lower	Target	Upper	Weight	Importance
Temp 2	Minimum		87,3	92,5	1	1
Temp 1	Minimum		79,8	89,1	1	1

Solution

Solution	Lubricant material	Percentage of surfactant (%)	Temp 2 Fit	Temp 1 Fit	Composite Desirability
1	P O + N	5	89,2667	85,5667	0,486043

Fig. 6. Comparison of engine temperature measurement test based on ANOVA test results 1 & 2

The optimization analysis results in the figure show that the objective of the test is to minimize two responses, namely Temperature 2 and Temperature, which can be interpreted as the lubricant's operating temperature under certain conditions. The target parameters are set within the temperature range, with equal weight and importance (1:1), meaning that both parameters are considered equally important in determining lubricant performance. From the solution results generated by Minitab software, the best lubricant formulation was palm oil + nonyphenol with a 5% surfactant concentration.

4 Conclusion

This study demonstrates that adding the surfactants Nonylphenol and Polyethylene Glycol (PEG) to palm oil-based lubricants significantly enhances their performance. All formulations exhibited good thermal stability, with no discoloration or sediment formation after heating and storage. Engine temperature testing further confirmed that the incorporation of surfactants has a substantial effect on reducing operating temperature, with the 5% Nonylphenol formulation producing the lowest engine temperature and comparing favorably with the conventional lubricant 10W-40. This formulation shows enhancement of heat transfer capability compared to the other formulations. Overall, the combination of palm oil and surfactants results in a lubricant that is thermally stable, non-corrosive, and capable of maintaining lower engine operating temperatures, making it a strong candidate for development as an environmentally friendly lubricant alternative with performance approaching that of conventional lubricants. However, the study was limited to short-term thermal and corrosion evaluation and further investigation is required.

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