



Lubricant-Engine Suitability Evaluation for Fuel Efficiency in Fishing Vessel Using Temperature and Color Degradation

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ABSTRACT

Engine performance in fishing vessel depends on the reliability and efficiency of diesel engine, in which the lubrication system plays a key role in reducing friction, controlling operating temperature, and minimizing component wear. However, field observations in small-scale fisheries indicate that many fishermen select lubricants based on habit, price, or availability rather than manufacturer specifications, which may reduce engine efficiency and increase fuel consumption. This study evaluated the suitability of three lubricants (S40, SC SAE 15W-40, and SX SAE 15W-40), each matched to a different Mitsubishi diesel engine (6D14, 6D15, 6D16) under real purse seine fishing conditions in Majene Regency, Indonesia, using engine temperature and lubricant color degradation as practical field indicators. Because operating duration varied substantially among engines (76-180 minutes per trip), fuel consumption was expressed as a rate (L hour⁻¹) for fair comparison. S40 produced the lowest, most stable rate (21.97 L hour⁻¹) and lowest final temperature (36.22°C); SC SAE 15W-40 recorded the highest rate (37.51 L hour⁻¹) despite a moderate final temperature (46.00°C); SX SAE 15W-40 showed the most fluctuating temperature (up to 50.80°C) with an intermediate rate (31.19 L hour⁻¹). Kruskal-Wallis tests confirmed significant differences among groups ($p < 0.001$). Multiple regression showed operating duration and final temperature jointly explained 30.5% of the variance in total fuel consumption ($R^2 = 0.305$, $p < 0.001$). These findings indicate that rate-based, engine-specific lubricant matching is essential for improving fuel efficiency and thermal stability in small-scale fishing vessels.

Keywords: Fishing vessels; fuel efficiency; lubricant degradation; marine engines; operating temperature

INTRODUCTION

Purse seine operations are considered the backbone of capture fisheries in Indonesia (Mirnawati 2019), especially for conventional

pelagic fishing in Majene Regency (Ihsan *et al.* 2022). The operational reliability of these vessels primarily depends on the performance



of diesel engines. In this context, the lubrication system is one of the most essential factors in mechanical efficiency, thermal stability, and avoiding unexpected wear on machinery (Xiao *et al.* 2025). However, among traditional fishermen, lubricant selection is often based on price and availability rather than engine specifications (Hidayat *et al.* 2019).

Inappropriate lubricants may elevate the engine internal friction (Kaminski 2024; Rovai *et al.* 2025). Lubricants with inappropriate viscosity may produce inadequate lubrication films. This increases the engine power and hence affects the fuel consumption (Tomanik *et al.* 2022; Rovai *et al.* 2025). Given that fuel represents the largest cost component in fishing vessel operations (Jang and Choi 2016), fuel efficiency is highly dependent on the quality and suitability of lubricants used. Improper lubricant selection can accelerate wear and significantly raise fuel expenditures, representing a major portion of total operating costs (Kaminski 2022; Kaminski 2024). In Majene, this issue is particularly critical since the average income of purse seine fishermen remains below the regional minimum wage (Manggabarani 2016), leaving little financial room for inefficient fuel use.

Conventional diagnostic indicators for lubricant degradation such as laboratory-based viscosity analysis, contaminant detection, Total Acid Number (TAN), and Total Base Number (TBN) provide highly accurate assessments of lubricant quality (Ramadhani *et al.* 2023). However, these testing methods require specialized laboratory equipment and strictly controlled conditions that are generally inaccessible to small-scale fishing communities (Hidayat *et al.* 2019). As a result, reliance on laboratory testing limits the practical ability to provide rapid, field-deployable diagnostic feedback to fishermen operating in resource-constrained environments.

To address the limitations of laboratory testing, field-based parameters such as engine working temperature and lubricant color degradation offer practical diagnostic potential for assessing in-service oil condition (Liu *et al.* 2023; Hilda *et al.* 2023; Yunardi *et al.* 2020; Honda and Hamano 2023). Progressive darkening of lubricating oil directly reflects thermal oxidation and soot contaminant accumulation generated during the internal combustion process (Lopez *et al.* 2018). Furthermore, engine surface operating temperatures exceeding standard operational

thresholds signal elevated mechanical friction and severe lubrication stress within engine components (Heredia-Cancino *et al.* 2018; Ramteke *et al.* 2022; Hilda *et al.* 2023).

In small-scale purse seine operations in Majene Regency, fuel consumption represents the largest proportion of total operational costs, directly dictating the financial viability of local fishermen. The fishing fleet in this region primarily relies on diesel engines adapted from automotive trucks, which regularly operate under severe thermal loads and variable marine sea conditions. In field practice, fishermen typically choose lubricants based on personal habit, local availability, or market price rather than alignment with manufacturer technical specifications. Selecting improper lubricants alters fluid viscosity, which elevates internal engine friction. Selecting improper lubricants alters fluid viscosity which elevates internal engine friction, desatbilizes operating temperatures and ultimately increases fuel consumption (Kaminski 2024; Royal *et al.* 2025; Royal and Tomanik 2025). Despite the recognized financial risks of suboptimal lubrication, limited research has systematically evaluated practical field-based indicators specifically surface operating temperature and visual color degradation to assess lubricant performance in small-scale fishing vessels. Moreover, existing literature lacks empirical evaluations regarding how engine-specific lubricant matching directly impacts duration-adjusted fuel consumption rates under real fishing trip conditions. Although field parameters can be systematically recorded by fishing base technicians to generate ready-to-use advice, empirical knowledge bridging practical diagnostic indicators with actual engine-lubricant compatibility remains insufficient.

To address this knowledge gap, this study aims to evaluate the suitability of lubricant types to engine characteristics and its effect on the fuel efficiency of purse seine engines using operating temperature and color degradation as practical field indicators. The resulting findings are expected to establish actionable technical recommendations for optimizing thermal stability, enhancing fuel efficiency, and reducing operational expenditures for small-scale fisheries. To the best of our knowledge, this study provides one of the first field-based evaluations of engine-lubricant compatibility in purse seine fishing vessels by integrating thermal performance, visual lubricant degradation, and duration-adjusted fuel

consumption indicators under real operational conditions.

METHODS

Time and Location

The study was conducted between June and September 2025, involved data collection on purse seine fishing vessels in Baurung, Majene Regency, West Sulawesi, Indonesia. This location was selected because it is one of the largest fishing centers in the Majene area, especially those that use diesel-powered vessels.

Type of Research and Data Collection

This study employed a quantitative experimental design. Prior to the experiment, a preliminary field observation was conducted to identify the population of purse seine vessels operating in Baurung, Majene Regency. A total of 20 fishing vessels were recorded during this initial survey. Each vessel was documented and classified based on several operational characteristics, including vessel size, engine type and age, fishing gear configuration, engine brand, lubricant type commonly used, and operational fishing range. This preliminary observation was intended to understand the general characteristics of fishing vessel operations in the study area.

Preliminary observations indicated that most fishermen in the study area used a single lubricant type (SAE 40, API CC) for different engine models, primarily based on habit and market availability rather than manufacturer recommendations. Based on these observations, representative vessels were selected for the experimental phase. The selection aimed to represent the most common operational conditions found in local purse seine fisheries. Three vessels equipped with Mitsubishi diesel engines (6D14, 6D15, and 6D16) were chosen because these engines are widely used among fishermen in the area and reflect typical engine configurations in local fishing vessels. This approach ensured that the experimental observations reflected realistic operational conditions encountered in small-scale fishing activities.

However, differences in engine displacement, operational load, and thermal characteristics among these engine models suggest that each engine may require different lubricant performance levels. These engines are originally designed as truck diesel engines but are widely adapted for marine use

in small-scale fishing vessels in Indonesia through modification of the cooling and transmission systems. Therefore, in this experiment the lubricant type was adjusted according to the technical characteristics and operational load of each engine in order to evaluate the practical implications of engine-lubricant compatibility under real fishing conditions. Accordingly, S40 was applied to the D14 engine under standard heavy-duty conditions, SC SAE 15W-40 to the D15 engine under medium-to-heavy loads, and SX SAE 15W-40 to the D16 engine under heavy-duty operating conditions. Because each engine received only one lubricant type rather than a fully crossed combination of engines and lubricants, the results should be interpreted as an evaluation of engine-lubricant suitability under realistic field pairing, not as an isolated effect of lubricant type independent of engine.

Field observations were conducted over a 30-day period. Sampling was performed once per day for each trip. Engine temperature measurements were recorded at three stages during each operational cycle: before engine start (T_0), after 15 minutes of operation (T_{15}), and upon the vessel's return to the fishing base (T_{End}). The T_{15} measurement was selected to represent the early stabilization phase of engine operation after the warm-up period, as small marine engines typically reach a relatively stable thermal condition after several minutes of running under load. Recording temperature at this stage allows the observation of initial thermal responses associated with lubricant performance. The temperatures reported here were measured at the engine's external surface using a digital thermometer during fishing operations, rather than the internal engine, coolant, or lubricant temperature; they are therefore used as comparative indicators of relative thermal performance between lubricant types, not as absolute values of normal diesel engine operating temperature.

The experiment followed vessel operations over a 30-day period. Reflecting the actual operational frequency and weather-dependent conditions of the fishermen, a total of 60 observational samples were obtained, comprising 25 trips for the D14 engine, 17 trips for the D15 engine, and 18 trips for the D16 engine. The equipment used included coded sample bottles for each lubricant type, syringes for lubricant sampling, a digital thermometer for temperature measurement, a photo box to standardize lighting conditions during color observation, an ASTM D1500



color scale for determining lubricant color change, and a dipstick for measuring fuel consumption from the tank. To minimize bias from vessel motion at sea, fuel volume was measured only while the vessel was anchored, before departure and again upon return to the fishing base, with any refueling performed during the trip recorded and added to the total.

Because operating duration differed substantially among engines (35-240 minutes per trip), comparing total fuel consumption per trip directly would be biased toward shorter trips. Fuel consumption was therefore converted to a consumption rate (liters per hour of engine operation) for all descriptive and group comparisons, so that engines operating for different durations could be compared fairly. Total fuel consumption per trip was retained only as the dependent variable in the regression model described below, where operating duration was included as an explicit predictor.

Fuel consumption rate, engine temperature, and lubricant color scale were analyzed using descriptive and inferential statistical approaches. Prior to hypothesis testing, data normality and homogeneity of variance were evaluated using the Shapiro-Wilk and Levene's tests, respectively, at a significance level of 95% ($p < 0.05$). The distribution analysis revealed that the data did not strictly meet the assumptions of normality and homogeneity. Consequently, due to this unbalanced design and non-normal data distribution, the non-parametric Kruskal-Wallis H test was employed to compare the significant differences in operational duration, fuel consumption, and final engine temperatures across the three engine-lubricant groups. For the same reason, Spearman's rank correlation was used to examine the relationships between the continuous operational variables (operating duration, final temperature, and total fuel consumption), since Pearson's correlation assumes normally distributed data. Finally, Multiple Linear Regression analysis was applied to evaluate the combined influence of engine operating duration and final engine temperature on fuel consumption.

RESULTS

Characteristics of Sample Vessels

The operational characteristics of the selected sampled vessels and engines provide an overview of the typical operational conditions of small-scale purse seine fisheries in Baurung waters. The three sample vessels were equipped with Mitsubishi 6D14, 6D15, and 6D16 engines, which were estimated to have an average of five years of service. All of these sampled vessels fall in the range of 22-26 Gross Tonnage (GT), are used on average for a fishing range of 20-60 miles, are serviced monthly for lubricant changes, and utilize between 210-300 liters of fuel per trip. This uniformity in operational characteristics provides a strong basis for comparative analysis. The initial operational data of the sampled vessels are presented in Table 1.

Technical Specifications of Sample Engines

The three engine models used in this study have different technical specifications in terms of displacement and power output, although all three are high-compression, water-cooled, four-stroke diesel engines. These differences may influence engine thermal behavior, fuel consumption, and lubrication requirements during fishing operations.

Originally designed as truck diesel engines, they are widely adapted for marine use in small-scale fishing vessels in Indonesia through modifications to the cooling and transmission systems. The main technical specifications of each engine model are presented in Table 2.

Lubricant Characteristics

Three lubricant types were used in this experiment, selected according to the technical characteristics and operational load of each engine, namely S40, SC SAE 15W-40, and SX SAE 15W-40. Each lubricant has different viscosity grades and API performance classifications, which may affect lubrication performance, engine temperature stability, and fuel consumption during operation.

The technical specifications of the lubricants used in this study, including viscosity grade and API service classification, are summarized in Table 3.

Table 1 Initial operational parameters of purse seine fishing vessels equipped with Mitsubishi diesel engines (6D14, 6D15, and 6D16) in Baurung, West Sulawesi, Indonesia.

Engine Type	Engine Age	Gross Tonnage (GT)	Operating Range	Lubricant Replacement Interval	Fuel Volume per Operation	Average Refueling Duration / Engine Working Hours	Estimated Fuel Consumption
6D14	5 yrs	GT 22	20-60 mi	1 month	220 liters	24 hours	~11 L hour ⁻¹
6D15	5 yrs	GT 26	20-60 mi	1 month	210 liters	24 hours	~11 L hour ⁻¹
6D16	5 yrs	GT 24	35-40 mi	1–2 months	300 liters	8 hours	~11 L hour ⁻¹

Table 2 Technical and Mechanical Specifications of Diesel Engines (Mitsubishi 6D14, 6D15, and 6D16) Used in Fuel Efficiency Tests.

Specification Item	Engine Model		
	6D14	6D15	6D16
Type	4-stroke, 6-cylinder diesel engine	4-stroke, 6-cylinder diesel engine	4-stroke, 6-cylinder diesel engine
Cooling System	Water-cooled	Water-cooled	Water-cooled
Valve Mechanism	Overhead Valve (OHV)	Overhead Valve (OHV)	Overhead Valve (OHV)
Cylinder Bore (mm)	110	113	118
Engine Displacement (cc)	6,557	6,919	7,545
Compression Ratio	17.5	16.0	17.5
Oil Capacity (L)	13.0	13.0	13.5
Lubricant Type	Engine oil (multi-type)	Engine oil (multi-type)	Engine oil (multi-type)
Lubricant (API)	CC or higher	CC or higher	CC or higher

Table 3 Technical specifications, performance classifications, and application suitability of tested engine lubricants (S40, SC SAE 15W-40, and SX SAE 15W-40).

Specification	S40	SC 15W-40	SX 15W-40
API Service	CF / CF-2	CF-4 / SG	CF-4 / SJ
ACEA	E2	E2	E7
Emission Standard	Pre-1998	Pre-2009	1998 and later
Key Advantages	Protection against wear, corrosion, and deposit formation	Protection against wear, corrosion, and deposits; suitable for turbocharged or non-turbocharged engines	High thermal and oxidation stability; protection against wear, corrosion, and deposits
Application Suitability	Standard heavy-duty diesel engines	Medium-to-heavy-duty diesel engines	Modern diesel engines

Fuel Consumption and Operating Duration

The fuel consumption patterns observed during fishing operations varied significantly among the engines, reflecting differences in engine capacity, operating duration, and lubricant characteristics (Figure 1). Descriptive statistical analysis (Table 4) revealed distinct differences in operational duration among the tested groups. Engines using SC SAE 15W-40 operated for an

average of approximately 76.18 minutes per trip, which was noticeably shorter than engines using S40 (averaging 180 minutes) and SX SAE 15W-40 (averaging 180 minutes).

Because operating duration differed so substantially between groups, fuel consumption was compared as a rate (L hour⁻¹) rather than as a daily total. Expressed this way, S40 showed the lowest and most stable



fuel consumption rate (averaging 21.97 L hour⁻¹), while SX SAE 15W-40 recorded an intermediate rate (31.19 L hour⁻¹) and SC SAE 15W-40 recorded the highest rate (37.51 L hour⁻¹), despite its shorter average operating duration. This pattern differs from a comparison based on total consumption per trip, in which SC SAE 15W-40 appears lowest simply because its trips were shorter; the rate-based comparison corrects for this duration bias and indicates that, per hour of operation, the D14 engine running on S40 was the most fuel-efficient of the three engine-lubricant combinations. The Kruskal-Wallis H test confirmed that the differences in fuel consumption rate among the three engine-lubricant combinations were statistically significant ($H = 15.97$, $p < 0.001$).

Engine Temperature Profiles

Temperature measurements were recorded at three stages of engine operation (T_0 , T_{15} , and T_{End}) (Figure 2). The initial temperatures (T_0) were almost identical across the different treatments (26-27°C), indicating equal engine thermal conditions before the tests. However, at the end of the operation, the engine using SC SAE 15W-40 maintained a stable final temperature of 46.00°C. The S40 exhibited the lowest final temperature at 36.22°C, whereas the SX SAE 15W-40 recorded the highest operational temperature, reaching up to 50.80°C. The Kruskal-Wallis H test confirmed that final engine temperatures also differed significantly among the three groups ($H = 46.11$, $p < 0.001$).

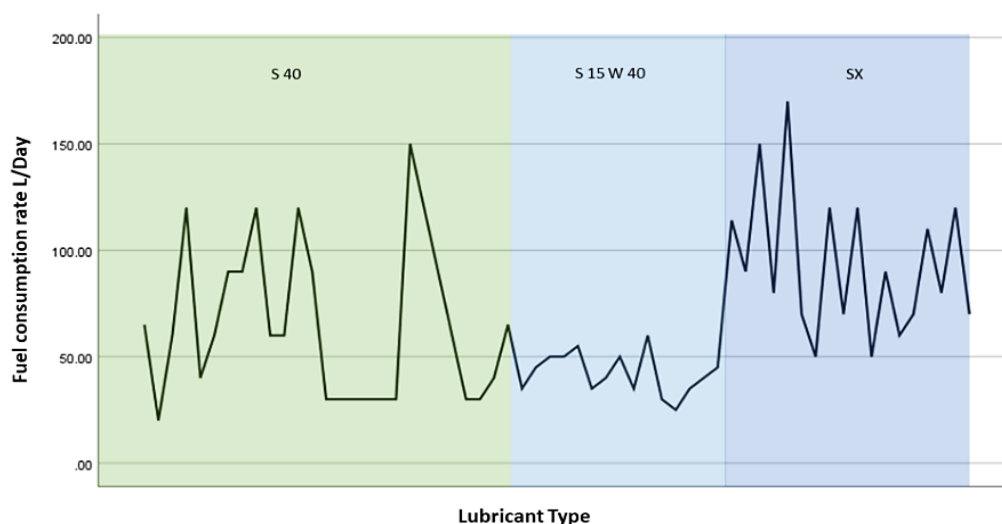


Figure 1 Fuel Consumption patterns (L hour⁻¹) of three diesel engines (6D14, 6D15, and 6D16) under different lubricant conditions during fishing operations.

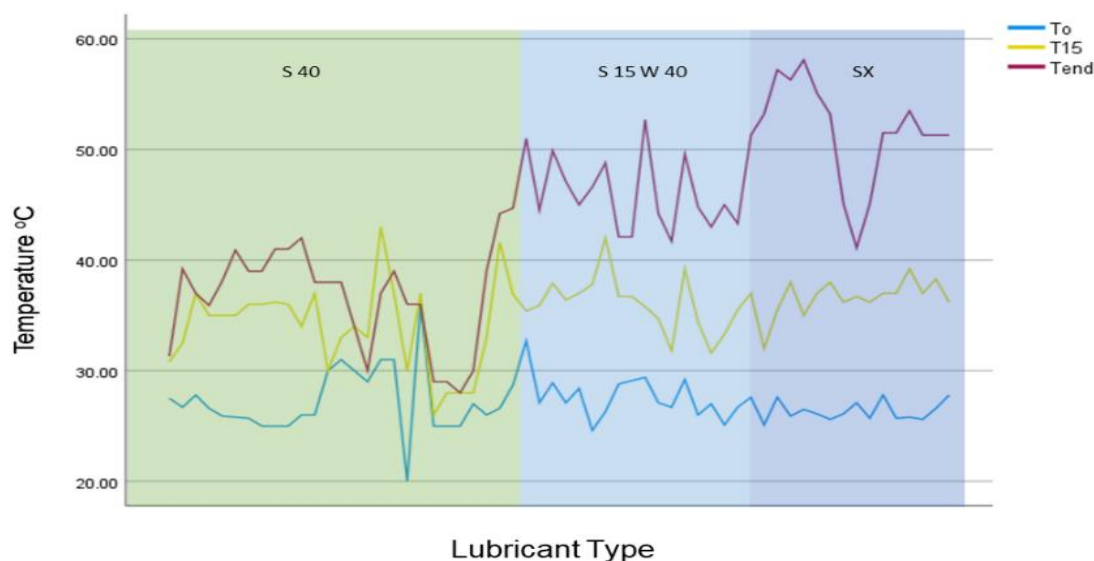


Figure 2 Engine temperature profiles of Mitsubishi 6D14, 6D15, and 6D16 measured at three operational stages (T_0 , T_{15} , and T_{End}) during fishing operations.

Descriptive Statistical Results

Descriptive statistical analysis was conducted to summarize the operational performance of each engine-lubricant combination. The variables observed included engine operating duration, fuel consumption, engine temperature at three operational stages (T_0 , T_{15} , and T_{End}), and lubricant color degradation based on the ASTM D1500 color scale.

The results indicate clear variations in operating duration, fuel consumption, and temperature profiles among the three engine-lubricant combinations (Table 4). Engines using SC SAE 15W-40 operated for an average of approximately 76.18 minutes per trip, shorter than engines using S40 and SX SAE 15W-40 (both averaging 180 minutes). Despite the shorter duration, the SC SAE 15W-40 recorded the highest fuel consumption rate (37.51 L hour⁻¹), while S40 recorded the lowest and most stable rate

(21.97 L hour⁻¹) and SX SAE 15W-40 an intermediate rate (31.19 L hour⁻¹). The Kruskal-Wallis H test confirmed that the differences in operational duration, fuel consumption rate, and final engine temperatures across the three engine-lubricant combinations were all statistically significant ($p < 0.001$).

Lubricant Color Degradation

Visual observation of lubricant degradation using the ASTM D1500 color scale showed that while SC 15W-40 initially exhibited a lighter color (value 1.5) compared with S40 and SX 15W-40 (value 2.5), all three lubricants experienced the same extent of deterioration after engine operation (Figure 3). Regardless of the engine type, all lubricants reached a value of 8.0 (dark black), indicating significant degradation due to thermal exposure and combustion by-products.

Table 4 Descriptive statistics of operational duration, fuel consumption, thermal dynamic phases, and ASTM D1500 lubricant color degradation across evaluated engine–lubricant pairings.

Lubricant	Stats	Duration (min)	Fuel consumption ((L hour ⁻¹))	Initial temp (°C)	Temp after 15 min (°C)	Final temp (°C)	Color degradation (ASTM)
S40 (D14)	Mean	180.00	66.20	27.16	33.62	36.22	8.00
	Min	120.00	20.00	20.00	26.00	28.00	8.00
	Max	240.00	150.00	36.00	43.00	42.00	8.00
	Std Dev	30.00	37.84	3.11	3.83	4.25	0.00
SC 15W-40 (D15)	Mean	76.18	43.24	27.86	36.58	46.00	8.00
	Min	35.00	25.00	24.60	31.60	41.70	8.00
	Max	180.00	65.00	32.70	42.00	52.70	8.00
	Std Dev	35.69	10.74	1.84	2.78	3.34	0.00
SX 15W-40 (D16)	Mean	180.00	93.56	26.36	36.39	50.80	8.00
	Min	180.00	50.00	25.10	32.00	41.10	8.00
	Max	180.00	170.00	27.80	39.20	58.10	8.00
	Std Dev	0.00	33.74	0.90	1.73	4.93	0.00

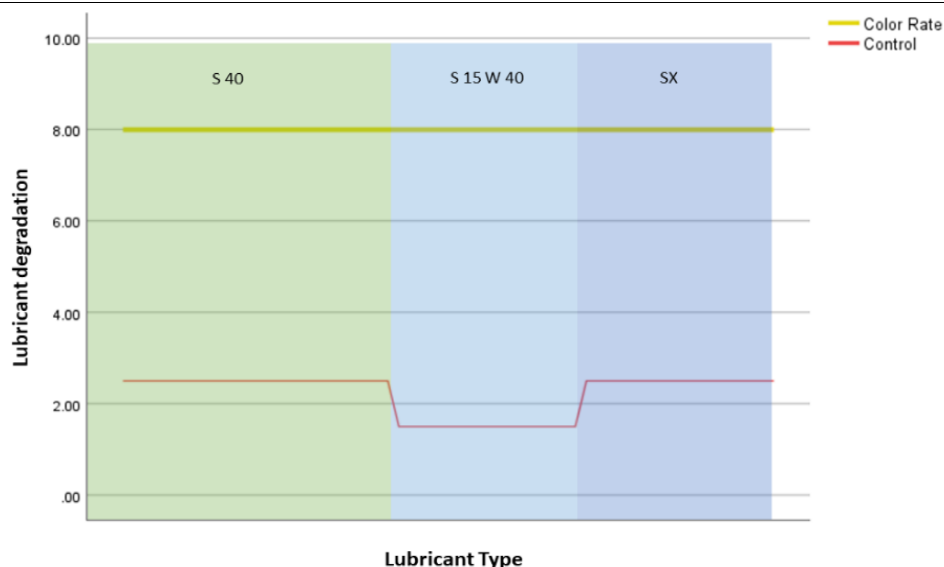


Figure 3 Lubricant Color Comparison based on the ASTM D1500 Color Scale.



Relationships Between Operational Variables

Spearman's rank correlation analysis was conducted to examine the relationships between operational variables, including engine operating duration, total fuel consumption per trip, and final engine temperature (T_{End}), given that the data did not meet the normality assumption required for Pearson's correlation.

The results demonstrated that total fuel consumption had a positive and significant relationship with engine operating duration ($p = 0.506$, $p < 0.001$), confirming that longer trips result in higher total fuel use. The correlation between final engine temperature (T_{End}) and total fuel consumption was weaker and only marginally significant ($p = 0.225$, $p = 0.084$).

Multiple Linear Regression Analysis

To further evaluate the combined effects of operational parameters, a multiple linear regression analysis was performed using total fuel consumption per trip as the dependent variable, with operating duration and final temperature (T_{End}) as predictors. Total consumption, rather than the rate, was used as the dependent variable here because regressing a rate on its own duration component ($\text{rate} = \text{total} \div \text{duration}$) would introduce a mathematical, non-substantive association between the predictor and the outcome.

The regression model produced a coefficient of determination (R^2) of 0.305, indicating that operating duration and final engine temperature simultaneously explain 30.5% of the variance in total fuel consumption per trip. The analysis of variance (ANOVA) resulted in a highly significant F-value ($F = 12.51$, $p < 0.001$), confirming that the overall regression model provides a statistically robust explanation of fuel usage.

The regression coefficients revealed that both variables were significant predictors of fuel consumption. Operating duration had a highly significant positive effect ($\beta = 0.357$, $p < 0.001$), consistent with the correlation result above. Final engine temperature (T_{End}) also emerged as a significant predictor ($\beta = 1.411$, $p = 0.011$) once operating duration was controlled for, even though its simple correlation with total consumption was only marginal. This indicates that, for a given operating duration, engines running hotter tend to consume more fuel in total, a relationship that is consistent with the rate-

based finding that SC SAE 15W-40, which ran at a moderate-to-high temperature, also had the highest hourly consumption rate.

DISCUSSION

Lubricant Performance in Different Engine Types

The experimental observations demonstrate that differences among specific engine-lubricant pairings were associated with variations in operational performance of purse seine fishing vessels equipped with different diesel engine models. Once fuel consumption is expressed as a rate rather than a daily total, the descriptive statistics show that the D14 engine running on S40 achieved the lowest and most stable fuel consumption rate ($21.97 \text{ L hour}^{-1}$), together with the lowest and most stable final engine temperature (36.22°C). In contrast, the D15 engine running on SC SAE 15W-40 recorded the highest consumption rate ($37.51 \text{ L hour}^{-1}$), despite operating for a shorter average duration per trip, while the D16 engine running on SX SAE 15W-40 showed an intermediate rate ($31.19 \text{ L hour}^{-1}$) combined with the highest and most fluctuating operating temperature (up to 50.80°C). However, the observed differences cannot be attributed solely to lubricant type because each lubricant was evaluated on a specific engine model without a fully crossed experimental design. Therefore, the results represent the combined performance of specific engine-lubricant pairings under realistic fishing operations rather than the independent effect of each lubricant formulation. Differences in engine displacement, mechanical characteristics, operational load, and duty cycle may also contribute to the observed variations in fuel consumption and thermal responses. S40 paired with the 6D14 engine achieved optimal performance

These differences are associated with variations in engine displacement, mechanical efficiency, and lubricant viscosity characteristics. However, because each engine model was evaluated with only one lubricant type, the individual contribution of lubricant properties and engine characteristics cannot be completely separated. Therefore, the observed differences should be interpreted as the combined response of each engine-lubricant pairing under actual fishing conditions. Crucially, lubricant viscosity dictates engine performance by minimizing friction through the formation of protective films between components (Raisin *et al.* 2016). Proper lubrication reduces internal

friction between moving parts, thereby improving energy transfer efficiency and lowering fuel consumption. Conversely, lubricants with viscosities that do not align with engine performance characteristics can increase engine load and reduce operational efficiency (Rovai *et al.* 2025; Hagga *et al.* 2025). In this study, the S40–D14 pairing showed the most favorable combination of lower fuel consumption rate and lower final temperature among the evaluated combinations. However, this observation does not indicate that S40 independently outperformed other lubricants because engine characteristics and operating conditions may also contribute to the observed differences. , suggesting that within the range of engines and lubricants tested, matching a simpler, higher-viscosity oil to a smaller, lighter-duty engine can be more fuel-efficient in practice than assigning a premium multigrade oil to a larger-displacement engine under heavier load, even though the latter carries a higher nominal performance classification.

Engine Temperature Dynamics During Operation

Engine temperature is a critical indicator of thermal stability and mechanical efficiency. The temperature profiles recorded in this study show a gradual increase from the initial engine condition (T_0) to the operating phase (T_{15}), followed by further temperature changes toward the end of the fishing trip (T_{End}). This behavior is typical for marine diesel engines, where temperature stabilization occurs as lubrication circulation and combustion processes reach steady operational conditions.

The operational temperatures reported in this study refer to the external surface temperature of the engine measured during fishing operations, rather than the internal engine, coolant, or lubricant temperature. They were therefore used as comparative indicators to evaluate the relative thermal performance of different lubricant types under similar operating conditions, rather than as absolute values of normal diesel engine operating temperature. Within that comparative frame, the S40-lubricated engine maintained the lowest average final temperature (36.22°C), consistent with its lower fuel consumption rate, while the SX SAE 15W-40-lubricated engine recorded the highest and most fluctuating temperature, reaching up to 50.80°C. The effectiveness of lubrication plays a paramount role in regulating these thermal conditions, acting as a vital coolant (Chuepeng and Saipom 2018;

Capone and Gianfrani 2025). Inadequate lubrication performance leads to increased thermal loads, which negatively affects engine durability and operational efficiency.

Lubricant Degradation and Operational Implications

Visual observations of lubricant degradation using the ASTM D1500 color scale showed that all lubricant types experienced noticeable degradation after engine operation. Although SC 15W-40 initially exhibited a lighter color (value 1.5) compared to S40 and SX 15W-40 (value 2.5), all three lubricants reached the maximum degradation level (value 8.0 - dark black) after the operation phase.

This color degradation is primarily associated with the accumulation of soot particles, oxidation products, and other contaminants generated during the combustion process. The oil acts as a cleansing medium that removes impurities from engine parts, leading to increased contamination (Rimpung and Gunung 2022). Furthermore, prolonged exposure to high operational temperatures accelerates the oxidation processes, where the darkening of the oil serves as a primary visual indicator of declining lubricant quality (Hadi *et al.* 2021). This underscores the importance of timely lubricant replacement to prevent excessive wear on engine components.

The Relationship Between Operational Variables and Fuel Efficiency

The statistical analysis clarifies the interaction between operational variables and fuel efficiency. The Spearman correlation analysis demonstrated a positive and significant relationship between engine operating duration and total fuel consumption ($p = 0.506$, $p < 0.001$), reflecting the logical premise that longer operational periods naturally result in higher total fuel usage during fishing trips.

More importantly, the multiple linear regression analysis successfully isolated the combined influence of operating duration and engine temperature on fuel consumption. The model confirmed that these variables explain 30.5% of the variance in fuel consumption ($R^2 = 0.305$, $p < 0.001$). A key finding from this regression model is that, once operating duration is statistically controlled, final engine temperature emerges as a significant predictor of fuel consumption ($p = 0.011$), even though its simple correlation with consumption was only marginal.



Taken together with the rate-based comparison, these results indicate that both operating duration and thermal load matter for fuel use, but they do not always favor the same lubricant. Higher operating temperatures, as seen in the SX 15W-40 group, are associated with increased mechanical resistance and reduced combustion efficiency, elevating fuel use and operational costs (Kaminski 2024; Rovai *et al.* 2025). At the same time, the SC 15W-40 group shows that a moderate operating temperature does not by itself guarantee the lowest hourly fuel consumption; engine size, load, and duty cycle also play a substantial role. Therefore, selecting the appropriate lubricants must be based on the specific engine's performance characteristics and realistic operating conditions, evaluated using rate-based indicators, rather than on the lubricant's nominal performance grade alone (Achmat *et al.* 2024).

CONCLUSION

1. The 6D14 + S40 combination produced the lowest fuel consumption rate (21.97 L hour⁻¹) and the most stable final temperature (36.22°C). The 6D15 + SC SAE 15W-40 combination recorded the highest consumption (37.51 L hour⁻¹), while the 6D16 + SX SAE 15W-40 combination exhibited the greatest temperature fluctuations (reaching 50.80°C). However, this efficiency is the result of the combined performance of the engine and the lubricant, not just the lubricant's contribution alone
2. Operating duration and final engine temperature significantly influenced 30.5% of the variance in fuel consumption ($R^2 = 0.305$, $p < 0.001$), with higher engine temperatures proven to increase fuel consumption.
3. All lubricants reached maximum color darkening (ASTM D1500 scale: 8.0), confirming that visual color change is an effective rapid indicator in the field for detecting sludge accumulation and thermal degradation.

SUGGESTION

We recommend that future research test each type of lubricant on all engine types to statistically separate the independent effects of lubricant characteristics from those of engine specifications. Furthermore, the use of field indicators such as surface temperature

and color degradation (ASTM D1500) needs to be validated through periodic laboratory analysis (such as viscosity testing, TAN/TBN, and particle contamination testing) to confirm the accuracy of rapid on-site diagnostics. Finally, the integration of a holistic economic analysis that accounts for hourly fuel savings, lubricant prices, and effective service life is highly recommended to provide concrete, measurable, and financially beneficial engine maintenance guidelines for small-scale fishermen.

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