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Application of Response Surface Methodology (RSM) for Optimizing the Food Grade Bio Lubricant

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ABSTRACT

With growing global concerns about the production of environmentally friendly lubricants, efforts to develop vegetable oil-based alternatives to mineral oil-based lubricants are gaining growth. However, the properties of vegetable oil-based lubricants such as poor low-temperature behaviour, low oxidative stability and poor thermal stability are concerning for industrial gear lubricant applications. Although the number of researches of using vegetable oil-based as an alternative lubricant, the scientific research for industrial gear oil application have not been studied adequately. As a result, the purpose of this study is to investigate the friction coefficient and wear rate of the blended oil using a pin-on-disc test experiment and then compare it to food grade oil, with the hope that the findings will assist the food industry in improving their machinery. Response Surface Methodology (RSM), a Box- Behnken Design approach, has been employed to optimize the lubricant characterization based on the results. The effects of three independent variables—load, speed, and additive concentration—on the coefficient of friction and wear rate have been investigated in this study. The number of tests has been reduced to 15 using this RSM methodology. At the speed of 600 RPM, 30 N load and 30% concentration concluded the lowest predicted wear rate was -38.1986 m3 /m. These results showed that blending palm oil with gear oil can increase the development of biodegradable and environment-friendly lubricants without concerns about downgrading the tribological performance.

1. Introduction

Numerous industries use lubricants, mostly in automotive and industrial settings, including the production of consumer and commercial vehicles. In order to keep a mechanical system functioning smoothly for a long time, lubricants are designed to reduce friction, wear, and heat between contacting surfaces in relative motion as well as passive resistance of stationary parts [1]. Based on how they physically appear, they can be categorized as solid (Teflon, graphite), liquid (oils), or semi-solid (grease, silicon gels). Lubricants are frequently utilized in industrial settings as hydraulic fluids, metalworking fluids, grease, general industrial oils (such as compressor, refrigeration, and turbine

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oils), and process oils (such as transformer, rubber, and printing ink oils) [2]. Mineral base oils and synthetic base oils are the two primary categories of base oils [3]. Base oils, which are frequently made with a variety of oil formulations that are added ranging from 1% to 30% of the oil volume, determine the overall qualities of a lubricant [4]. By adding substances like antioxidants, viscosity modifiers, anti-wear agents, and pour point depressants to the base oil, the new formulation of blended oil is used to enhance the base oil's current properties or to give the base oil new properties [5]. Each lubricant has various performances and properties, but they all have base oil as their common fundamental ingredient [6]. This study focuses on gear oils, which are created to safeguard the critical gearbox parts (such as gear teeth, bearings, and seals). In order to convert the speed and torque between rotating components, gearboxes are used. Frequently, high loads, a wide range of operating temperatures, and a variety of environmental conditions must be tolerated by gears and bearings [7]. Due to intense operating temperatures that put essential elements under stress to the point of failure, gearbox failure frequently results in machine downtime. There also resides the purpose of gear oils, which are designed to withstand harsh operating conditions. Today's industrial gear oils have to adhere to the following basic criteria: 1) Appropriate viscosity, 2) Oxidative and thermal stability, 3) Solid load-carrying capacity, 4) Demulsibility, or the capacity to shed water, 5) Resistance to foaming, and 6) Protection against rust and corrosion [8]. There are considerable financial losses as a result of downtime for maintenance and repairs [9]. When operating under high load, low speed conditions that cause micro-pitting, gears and rolling element bearings may come into direct touch with other metal surfaces [10]. The ultimate goal of the majority of companies includes the development of new, higher-quality lubricants due to the rising demand for lubricants [11]. Due to rising concerns over the manufacturing of environmentally friendly lubricants around the world, they began to replace lubricants that were based on mineral oil with those that were based on vegetable oil to achieve this. The new industrial gear formulation aims to place more of an emphasis on cost savings while extending lubricant life and increasing gearbox efficiency. It is not a recent finding that vegetable oils are employed in the lubrication industry; in India, two-stroke engines are lubricated using coconut oil [12]. Vegetable oil has several benefits over mineral oil, including being biodegradable, non-toxic, renewable, and reasonably priced. Additionally, vegetable oil is superior to mineral oil-based because it has a higher viscosity index, better lubricity, a higher flash point, and lower evaporative loss in nature [13]. Due to its high production rate, which can meet the need for lubricating oil with a vegetable base, palm oil has emerged as a viable renewable resource in Malaysia [14]. Numerous studies have been conducted to examine how well palm oil performs when compared to commercial lubricants. The findings demonstrate that palm oil creates lower coefficients of friction and establishes strong lubricant film stability [15]. A previous study on the properties of palm fatty acid distillate combined with mineral oil found that the lowest coefficient of friction was achieved by blending 20% total mass of palm oil [16]. Aiman and his partner looked into the production of palm oil blended with semi-synthetic oil, whereas Bari and his colleagues examined the use of palm oil as a biodiesel engine and hydraulic fluid [17]. The findings of all the study on palm oil have been positive, and its use in engineering has a promising future. It has been demonstrated that palm oil performs well as a lubricant, which raises the possibility of replacing it with mineral-based oil lubricants.

Palm oil has been utilized in numerous industrial applications and has some advantages in mechanical applications. Lubrication in mechanical applications, particularly in machinery operations, is one of the advantages of palm oil [18]. It has a high level of oxidative stability and an evenly distributed ratio of high and low components with low molecular weight that have high boundary lubrication capabilities, reducing wear and friction in equipment. When palm oil is utilized as a lubricant in mechanical applications, wear reduction, friction, and load carrying capacity all significantly improve [19]. Additionally, due to its superior lubricating and combustion properties, palm oil has been utilized as a feedstock for biodiesel in automotive engines, which has grown in popularity as a replacement for mineral-based diesel fuel. Similar annual energy outputs to mineral diesel fuel are produced by palm oil biodiesel, but with less hydrocarbon and particle emissions. It has also been demonstrated that using sustainable palm oil instead of traditional fossil fuels reduces greenhouse gas emissions from the manufacture of biodiesel. With the addition of palm oil, the study of industrial gear oil aimed to resemble food-grade oil [20]. Use of the blended oil must be appropriate and secure for the food sector. From prior research, there is still lack of study and data explaining the using of palm oil as bio lubricant replacement and is it suitable for replacement of food grade oil in food industry. However, it has been shown that mixing vegetable oils, like palm oil, with mineral engine oil reduces the coefficient of friction when compared to the states of the oils when it is entirely pure [21]. The goal of this research is to examine the properties of lubricating oils that have been combined with palm oil. The following goals can help to attain the study's goal in utilizing the box-Behnken Design, and more specifically the Respond Surface Method (RSM), optimize the mixed oil characterization, and also to calculate the rate of wear, frictional force, and coefficient of friction.

2. Methodology

Due to the fact that the factorial arrangement does not include any points at the corners of a cubic region, as well as the fact that the resulting design may be rotated, the box-behnken design was chosen to conduct the tests. Experimental designs allow for the execution of a limited number of experiments and the creation of regression models. For three-level full factorial designs, BBD is a component of response surface method design, which is far more effective than central composite design. Every 1 concentration required 1 set of pin and disc, 5 loads and 4 different speeds. From 140 combinations of experiment, it has been reduced to 15 combinations through optimization method as per Table 1.

Table 1
Number of optimized runs

Name	Speed (rpm)	Load (N)	Palm oil Composition (%)
BPO 1	900	50	15
BPO 2	900	30	30
BPO 3	750	10	30
BPO 4	900	30	0
BPO 5	600	30	0
BPO 6	750	50	30
BPO 7	600	10	15
BPO 8	750	30	15
BPO 9	750	30	15
BPO 10	600	30	30
BPO 11	750	30	15
BPO 12	600	50	15
BPO 13	750	10	0
BPO 14	750	50	0
BPO 15	900	10	15

3. Results

3.1 Regression Model Wear Rate

A pin-on-disc experiment's outcome or data are often referred to as the experimented result. To research friction, wear, or other related phenomena, a pin-on-disc test places a pin in controlled contact with a revolving disc. Depending on the characteristics being measured, such as data on friction coefficient, frictional force, and wear rate, the precise outcome can differ. Three variables are used to predict the value of wear rate by using the Box Behnken Design as per in Table 2.

Table 2
Predicted wear rate result

Name	Speed (rpm)	Load (N)	Palm oil Composition (%)	Wear (Micron) [m^3/m]
BPO 1	900	50	15	-22.0611
BPO 2	900	30	30	61.3446
BPO 3	750	10	30	-15.5799
BPO 4	900	30	0	-11.2725
BPO 5	600	30	0	21.7744
BPO 6	750	50	30	-10.6698
BPO 7	600	10	15	-10.6698
BPO 8	750	30	15	-22.8795
BPO 9	750	30	15	-15.4589
BPO 10	600	30	30	-38.1986
BPO 11	750	30	15	13.1865
BPO 12	600	50	15	-0.3476
BPO 13	750	10	0	-11.1856
BPO 14	750	50	0	2.1900
BPO 15	900	10	15	-10.6698

The relationship between the response variable which is coefficient of friction (COF) and the three independent variables (load, speed, concentration) are shown in Eq. (1) which the estimated regression model for COF with uncoded variables.

Regression Equation in Uncoded Units:

$$\text{Predicted Wear Rate} = 248 - 0.87\,A + 0.62\,B + 5.83\,c + 0.000727\,A*A - 0.0339\,B*B + 0.0373\,c*c + 0.00069\,A*B - 0.01221\,A*c + 0.0490\,B*c \tag{1}$$

A good fit model should yield an R^2 of at least 0.8. The result shows that the value of R^2 obtained is 0.6162 which also almost a good fit model. The results of the ANOVA and the estimated regression coefficient are shown in Table 3 and Table 4, respectively. The analysis of variance findings in Table 4 reveals that the interaction term p-value also as low as 0.070. The estimated regression coefficient for these results, as shown in the Table 3, indicates that since the p-values of squared terms for speed are relatively low while the load and concentration of additives are slightly high, respectively 0.276 and 0.334. The coefficient for the squared terms in this context is only demonstrated to be significant where this component significantly affects the wear rate. The only interaction that indicates statistically significant values for the interaction effects is that between speed and additive concentration.

Table 3
Estimated regression wear rate of palm oil as additives

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.005	0.108	0.05	0.963	
speed	0.1533	0.0661	2.32	0.068	1.00
load	0.0063	0.0661	0.09	0.928	1.00
concentration	0.0932	0.0661	1.41	0.218	1.00
speed*speed	0.1405	0.0973	1.44	0.208	1.01
load*load	-0.1191	0.0973	-1.22	0.276	1.01
concentration*concentration	0.1040	0.0973	1.07	0.334	1.01
speed*load	0.0084	0.0935	0.09	0.932	1.00
speed*concentration	0.2145	0.0935	2.29	0.070	1.00
load*concentration	0.0307	0.0935	0.33	0.756	1.00

Table 4
Analysis of variance (ANOVA) result for acquired model

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	0.620807	0.068979	1.97	0.235
Linear	3	0.257931	0.085977	2.46	0.178
speed	1	0.188097	0.188097	5.38	0.068
load	1	0.000314	0.000314	0.01	0.928
concentration	1	0.069519	0.069519	1.99	0.218
Square	3	0.174750	0.058250	1.67	0.288
speed*speed	1	0.072852	0.072852	2.08	0.208
load*load	1	0.052369	0.052369	1.50	0.276
concentration*concentration	1	0.039957	0.039957	1.14	0.334
2-Way Interaction	3	0.188126	0.062709	1.79	0.265
speed*load	1	0.000283	0.000283	0.01	0.932
speed*concentration	1	0.184074	0.184074	5.26	0.070
load*concentration	1	0.003770	0.003770	0.11	0.756
Error	5	0.174828	0.034966		
Lack-of-Fit	3	0.174788	0.058263	2886.18	0.000
Pure Error	2	0.000040	0.000020		
Total	14	0.795635			

This pareto charts shows that the which factors is significantly affect the standardized effect. The Pareto Chart of the standardized effects for Wear Rate in Figure 1 below shows that the interaction between AC which A (Speed) and C (concentration) are high same as the interaction in Pareto Chart of the standardized effects for Coefficient of Friction. However, for this Pareto chart the interaction that are relatives low is between AB which is the squared term.

The accuracy of the ANOVA analysis must be verified in order to generate a suitable model and confirm the ANOVA validity. It is possible to assess whether or not the population being sampled is normally distributed using normal probability plots of the residual. Figure 2 shows four residual graphs with various interactions, including the correlations between the residuals and fitted value, the frequency and residuals, and the residuals and observation. They appear to be clustered around the red line which supports the idea that the residuals are normally distributed, according to the graph. The presumption of normality for this graph also corrects.

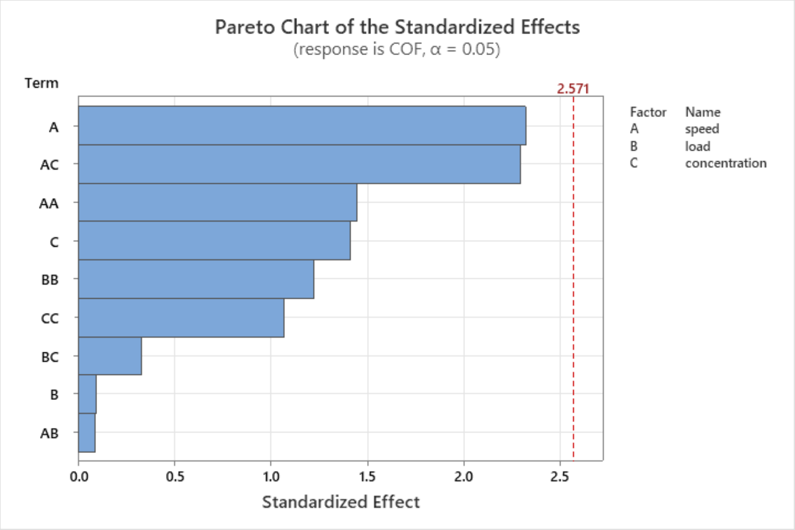


Fig. 1. Pareto chart for wear rate

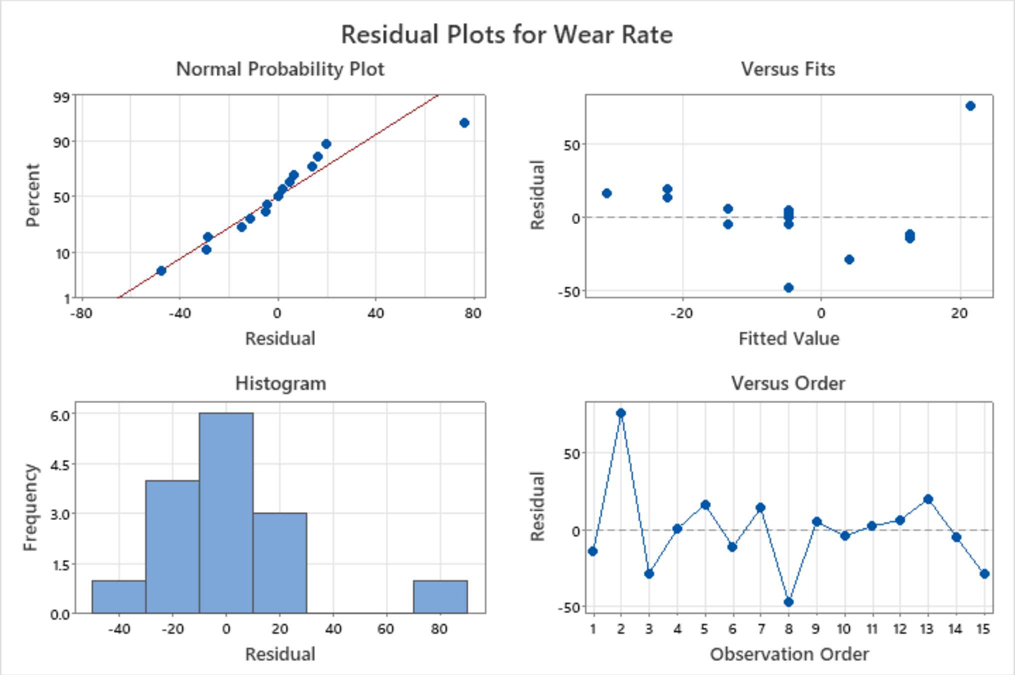
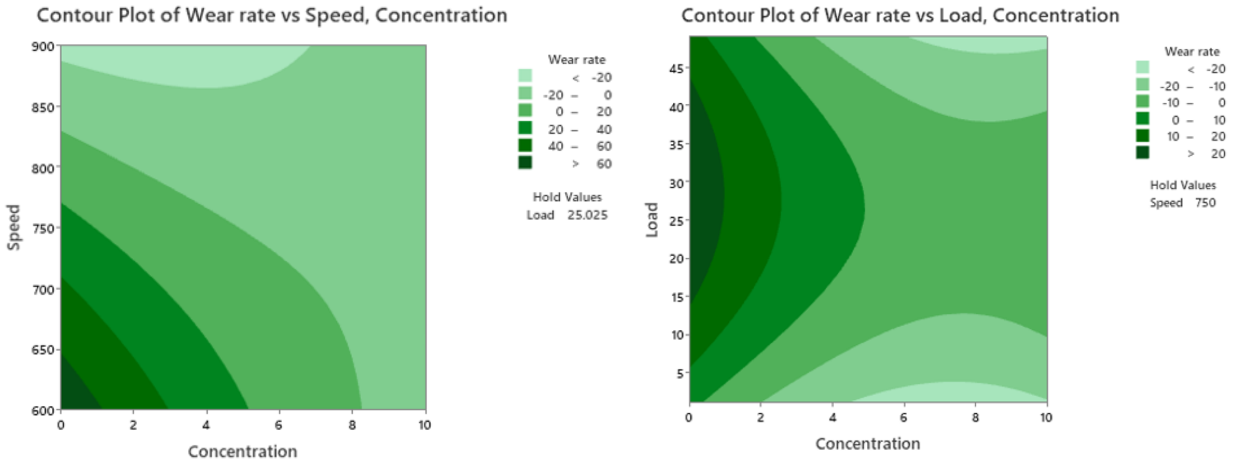


Fig. 2. One-way ANOVA: Wear rate (Micron) versus concentration (ml)

3.2 Response Surface Methodology Analysis

The three factors in this study—speed, load, and oil mixture concentration—that influence wear rate as follows. Through the application of the Response Surface Methodology (RSM) technique, the response surface can be visually represented through the use of surface and contour plots. By employing varied concentrations of the oil mixture, discrepancies were detected when the speed and load were taken at their midway values, which were 750 RPM and 25.025, respectively.

In Figure 3, at load of 25.025 N wear rate decreases as the concentration of the oil sample increases. The region of the lowest coefficient of friction being indicated with the light green colour. Theoretically, high speeds have the potential to increase surface friction, which would raise wear rates. At a speed of 600 RPM to 650 RPM, the region with the highest point value of the coefficient of friction is exceeding 0.02% of additive. The wear rate offers important insights into the material's resistance to wear and aids in assessing how well various coatings, lubricants, and surface treatments work to minimise wear. Longer component lifespans and improved wear resistance are typically indicated by lower wear rates.



(a) (b)

Fig. 3. Contour Plot of wear rate against concentration (a) Speed and (b) Load

3.3 Optimization Plot of Wear Rate

At a region of 0% additive and a speed of 706rpm, the optimisation for low friction of a 1N/10N load was observed. The 10ml (0.67%) additive region with the optimal speed of 706rpm was where the optimisation zone for high friction of 49.050N/50N was observed. The optimum wear rate condition shows that the minimum value of wear rate also shows at the speed of 706rpm, 1N/10N load, and concentration of additive of 16.96ml corresponded to -33.759 as in Figure 4.

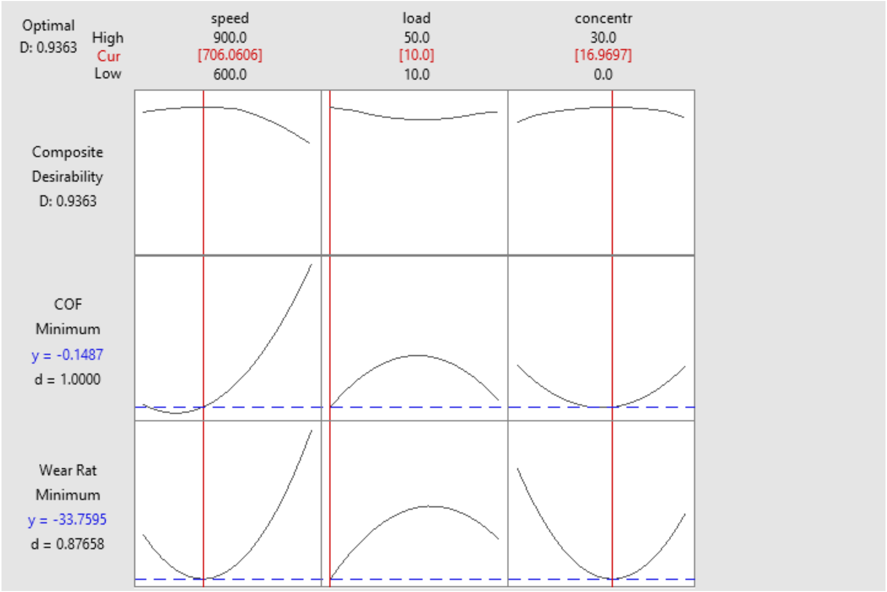


Fig. 4. Response optimization values of wear rate

4. Conclusions

A preliminary investigation has been done to see if incorporating palm oil into industrial gear oil could affect friction coefficient and wear rate. The major characteristic among the three independent variables, according to the ANOVA study's findings, is speed, which has a bigger impact than load and additive concentration. Additive had some effect on values. The low friction optimum for the 30N load was seen at a region of 30% additive and a speed of 600rpm. The ideal wear rate condition revealed that at a speed of 706 rpm, a load of 10N, and an additive concentration of 16.96 ml, However, when palm oil was added to the industrial gear oil, negligible COF was attained in the 706 RPM range.

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