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Evaluation of Tribological Performances of Palm Oil-Blended Food Grade Lubrication

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ABSTRACT

Conventional industrial lubricants from mineral oil are recognized for their harmful effects on both humans and the environment. It has driven a worldwide shift to embrace food-grade lubricant due to their biodegradability, favourable viscosity, cost-effectiveness, and wide availability. This study evaluates the tribological performances of blended palm oil, assessing its suitability as an eco-friendly and efficient alternative in the industry. Although there have been numerous studies exploring the tribological performances of vegetable oils, research on the food-grade lubrication using a blend of palm oil and industrial gear oil still has potential for further improvement and advancement. Therefore, this investigation intends to measure the wear rate and coefficient of friction using the Pin-on-Disc tribometer according ASTM G-99 standard. Using industrial gear oil as the base, 15 different samples with concentrations of 0%, 15%, and 30% palm oil were tested under varying applied loads, ranging from 30N - 60N, and speeds ranging from 600 rpm - 900 rpm. Utilizing the Surftest machine SV600, both samples of S7L3P15 and S7L4P15 indicated the lowest surface roughness (Ra), which is 0.04 µm. Furthermore, the FTIR spectrometer demonstrated the presence of aliphatic hydrocarbons, olefins, and esters in the functional groups of both G70P30 and G85P15 sample oils. Beyond this point, out of 15 samples tested, 12 samples had wear rates under 50 (10^{-6}) mm³/Nm and coefficients of friction below 0.1 in the Pin on Disc test. G70P30 is the optimum biolubricant concentration because it reduces wear rate and friction more than G100P0 and G85P15. In conclusion, the blended palm oil can increase the development of biodegradable and environment-friendly lubricant oil without concerns about downgrading the tribological performances.

Keywords: Palm oil; Industrial gear oil; Pin-on-Disc; Surface roughness; FTIR

Nomenclature

ν	Absolute Kinematic Viscosity
μ	Coefficient of Friction
ΔV	Volume Loss (mm^3)

Abbreviations

FTIR	Fourier Transform Infrared Spectroscopy
ASTM	American Society for Testing and Materials

1.0 INTRODUCTION

Application of lubricant includes dissipate heat, prevent distortion, extend tool lifespan, and able to achieve smoother finishes. Manufacturing industries are researching for eco-friendly alternatives to traditional mineral oil-based lubricating fluids. Countries like the USA, Japan, Canada, Scandinavia, and various EU nations are implementing regulations to promote sustainable, biodegradable fluids for cleaner production and reduced reliance on mineral oils [1]. In processes like broaching, mineral oil-based lubricating fluids are popular due to their effective cooling and lubricating properties [2].

Most lubricants used globally are made from mineral oils because they are effective and affordable. However, they can be harmful to the environment and people's health. The type of oil and additives in these fluids affect their impact. Mineral oil-based lubricating fluids have low biodegradability and often contain chemicals to enhance performance, which can be harmful to both workers and the environment [3, 4]. In addition, mineral oil can cause long-term environmental damage [5]. This is mostly because oils derived from petroleum have a low biodegradability [6]. Mineral oil plugs soil pores, resulting in an oxygen deficit that lowers soil permeability, aeration, and water infiltration. After migrating through the soil to the nearby water reservoirs, the oil obstructs the flow of oxygen gas between the water and the atmosphere [7]. The process of failure lubrication carries a

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considerable risk of polluting the soil and water since the volatile lubricants have the potential to cloud the atmosphere [8].

People who work with these fluids can have health issues like skin cancer from contacting or breathing in the mist they create in the workplace [9]. When the oil comes into contact with the skin, it can lead to serious health problems. This can include irritating the skin or causing allergic reactions. People who are around the mist of fluids for a long time are more likely to get cancer, especially skin cancer [10]. Furthermore, an experimental study done by Elsbet et al. (2021) [11] found that giving mineral oil to mice over a long period has made their intestines more permeable, which could lead to inflammation. It also lowered their cholesterol and triglyceride levels.

Environmental laws by organizations like Occupational Safety and Health Administration (OSHA) aim to protect environment and people by discouraging mineral oil-based lubricants and harmful additives. OSHA recommends using vegetable oils as safer alternatives. This shift benefits the environment and promotes the development of biofuels and healthier lubricants [12]. Growing concerns over the harm to the environment caused by lubricants based on mineral oil have led to a global trend towards the advancement of vegetable oil as base oil [13]. Additionally, the non-renewable resource that may eventually run out in the future is mineral oil [14].

Vegetable oils are preferred because they are biodegradable, non-toxic and eco-friendly, making them safe for the environment [15]. Moreover, it has been established that vegetable oils exhibit a high viscosity index, high flash point, and low volatility [16]. Currently, there is a growing interest in biolubricants made primarily from vegetable oils because they offer reducing friction and wear properties [17]. Lubricant used in food processing areas where accidental or direct food contact is possible is food-grade biolubricants [18].

Food-grade biolubricants are designed provide protection against wear, friction, corrosion, and oxidation, while also dissipating heat and transferring power. Additionally, they are compatible with rubber and various sealing materials, and in certain instances, they enhance the sealing effect [19]. Food-grade lubricants fall into three classes: H1, H2, and H3. H1 is approved for use in food processing and has properties like being colourless, odourless, tasteless, and low in hazard potential. H2 is a biolubricant not suitable for direct contact with food. H3 primarily includes edible oils, mainly derived from vegetable sources like coconut, sunflower, canola, palm, palm kernel, soybean, rapeseed, jatropha oil, and cashew nuts [20].

One well-known biolubricant is using palm oil, which shows promise to replace mineral oil lubricants [21]. It is commonly known as palm olein and often used in cooking, but palm oil's longer hydrocarbon chains and low levels of unsaturation also have made it suitable for industrial lubrication purposes [22]. The main saturated fatty acid in palm oil is 44% palmitic acid (C16:0), which is balanced by the unsaturated fatty acids linoleic acid (~11%) and oleic acid (~39%) [23]. It is quite beneficial, particularly at the boundary lubrication stage, for the long fatty acid chains to exhibit exceptional strength within the lubricant film. As a result, the coefficient of friction is reduced due to the strong bonding and reaction of the lubricant film with metallic surfaces [24].

Malaysia is among the leading producers of palm oil globally, thanks to its favourable climate and effective management practices resulting from Research and Development (R&D) efforts [25]. As major global producer of palm oil, Malaysia has a significant advantage in making palm oil-derived lubricants because of its large-scale manufacturing capabilities at a cost-effective rate. It is commonly believed that one hectare of palm trees can produce nearly ten times more oil compared to other vegetable oil sources [26]. Biolubricants are considered eco-friendly lubricants because they do not add to carbon emissions. Experts also predict 15 to 20% increase in the biolubricant market over the next twenty years [27]. By making the most of palm oil as an alternative lubricant, Malaysia stands to gain financially while also improving the environment.

A body's operational surface can gradually lose substance due to relative motion at the surface, which is known as wear [28]. The gradual loss of material from a body's operational surface brought on by relative motion at the surface is known as wear [29]. These modifications result in changes in the thickness of the oil coating, which subsequently impacts the overall performance and reaction of the system [30]. The Archard wear equation describes the relationship between wear rate and normal load from Equation (1),

$$Q = KN/H \tag{1}$$

where N is the normal force applied to the surface (N), H is the indentation hardness of the wearing surface (N/m^2), K is the wear coefficient, and Q is the volume lost from the surface per unit sliding distance (mm^3/m). The Archard equation is restricted to a linear relationship between wear volume, material hardness, sliding distance, and normal load. The volume of material lost from the surface is directly proportional to the relative sliding distance or experiment time, provided that the K, N, and H remain constant during the wear test [31].

A force that opposes tangential motion between two surfaces in contact is called friction [32]. Guillaume Amontons (1663–1705) published the rules of friction, which stipulated that the friction force is independent of the apparent area of contact and proportional to the normal load applied [33]. The friction force, F can be stated by the basic equation (2),

$$F = \mu N \quad (2)$$

where μ is called the coefficient of friction (COF) and N is the normal load [34].

Subsequently, Bowden and Tabor developed a more comprehensive metallic friction model. According to their description, the friction force is a combination of the adhesive force (Fs) and the ploughing force (Fp) [35] from Equation (3),

$$F = Fs + Fp \quad (3)$$

During the relative motion of two contacting entities, the ploughing force is required to push the asperities of the harder surface through the softer surface, while the adhesion force is necessary to shear the junctions where adhesion occurs [36].

According to Bowden and Tabor, contact is limited to the surface asperities. This contact area, distinct from the apparent contact area and very small, is referred to as the real contact area. The real contact area, where asperities may deform, is also proportional to the applied load [37]. These result in Equation (4),

$$F = Ar\,.S + A'p \quad (4)$$

where p is the pressure to create plastic flow of the softer metal near the indentation hardness value, A' is the cross-sectional area of the ploughing track, S is the shearing strength of metallic joints, and Ar is the true contact area [38]. Asperities of the softer material undergo deformation at the contact site upon application of load, until the real area of contact becomes large enough to handle the load. N = pAr, in this case. Hence, Equation (5) can be expressed as follows,

$$F = NS/p + A'p \quad (5)$$

In the end, the coefficient of friction can be found using Equation (6),

$$\mu = F/N = S/p + A'p/N \quad (6)$$

The ploughing force for a ball-on-flat contact can be obtained as follows, as demonstrated by Bowden and Tabor. It also depends on the contact's radius of curvature (r) and ploughing track width (d) which can be derived as [39].

This study focuses on analysing the tribological performance of blended palm oil as a newly formulated biolubricant using Pin-on-Disc method. Improvements in tribological performance, such as reducing friction, enhancing wear resistance, controlling corrosion, lowering contamination, and oxidation stability, can be achieved with the appropriate blended into the base oil. The tribology of the stainless pin is evaluated in this experiment to measure the effect of the wear rate and coefficient of friction on the pin. Additionally, to further enhance the analysis and gain additional insights into the surface characteristics and chemical composition of the newly formed biolubricant, the surface roughness value and the functional group of the lubricant are obtained. These data offer significant benefits, as they allow for a comprehensive understanding of both the physical and chemical properties of the material. Surface roughness data can inform regarding the material's potential performance in various applications, while the FTIR results shed light on its molecular structure and potential reactivity. By incorporating these analyses, the research aligns closely with its primary objective of thoroughly characterizing the newly developed composition and evaluating its suitability as an eco-friendly alternative. This research could pave the way for future engineering industry studies on the maintenance of machine elements.

2.0 METHODOLOGY

The study starts with the preparation of the necessary apparatus and oil samples. Each lubricant's kinematic viscosity is then meticulously measured using the Cannon-Fenske Routine Viscometer, according to the ASTM D445-97 standard. Following this, the Pin-On-Disc method is implemented to evaluate the wear rates, coefficient of friction, and frictional force, employing the Pin-On-Disc tribometer machine in compliance with the ASTM G-99 standard. Subsequently, results are compared with expected outcomes and prior studies, providing a benchmark for assessing the new data. To further the analysis, the surface roughness of each disc specimen is measured using the Suftest machine SV600. The investigation concludes with an analysis of two types of oil which are pure industrial gear oil and a blended palm oil using Fourier Transform Infrared Spectroscopy (FTIR) to determine their functional groups. This comprehensive approach ensures a thorough evaluation of the lubricants under study.

2.1 Apparatus preparation

In order to simulate real-world sliding contact conditions, the Pin-on-Disc test disc and pin specimen materials must be chosen meticulously. Mild steel is used for the disc because of its widespread industrial use and wear properties, making it an ideal material for investigating friction. Wear and degradation can be accurately assessed with the right hardness and toughness. Thus, mild steel is ideal for automotive and industry parts. Due to its corrosion resistance and strength under stress, stainless steel is used to make the pin. These traits are crucial in food processing, medical devices, and aircraft. Surface modifications could impair test results, but this material's stability ensures accuracy. These materials provide a complete structure for studying wear and friction in engineering.

Table 1 below shows the specifications of the disc specimens used as guidelines in this study. In total, 15 mild steel disc samples were employed, each with a uniform thickness of 5 mm. The production of these disc specimens involves a precise laser-cutting process, which is used to shape the mild steel plate into perfectly flat round discs. This method ensures consistency and accuracy in the dimensions of the specimens, thereby providing reliable data for the study. The disc then undergoes finishing process to remove any residual scratches on the surface. The process is conducted by using a surface grinding machine which fits with Silicon Carbide (SiC) abrasive paper, specifically of 400-grit grade.

Four 4.5 mm diameter screw holes are created to secure the disc with screws in the disc space, ensuring it stayed in place during the Pin-on-Disc test. Additionally, one 5 mm diameter screw hole is drilled and threaded to facilitate easy removal of the disc after the Pin-on-Disc test using an M5 screw. Fig. 1 illustrates a finished disc specimen that undergoes surface grinding to achieve a flat mirror surface.

According to the pin length standard for the Pin-on-Disc machine, as shown in Table 2 below of the pin specimen specifications, the pin length should be between 23 mm and 30 mm, with a diameter ranging from 3 mm to 12 mm. This is done to avoid any errors during the experiment. Hence, a pin length of 25 mm and a diameter of 8 mm is chosen. The pin is made from stainless steel and manufactured using a CNC machine to ensure its length is precisely 25 mm.

Once all the pins have achieved a desirable flat surface, all pins undergo a polishing process to remove any scratches. Silicon Carbide (SiC) grinding paper with grits ranging from 400 to 800 is used by fixing it to a polisher rotating at a constant speed. This polishing process takes two hours to finish the 15 pins. The polishing process is performed to obtain a mirror surface on all flat pin surfaces, as illustrated in Fig. 2.

Table 1: Disc Specimen Specifications

Specifications	Description
Material	S275 Mild Steel
Material Composition	Carbon (C): 0.25% Silicon (Si): 0.50% Manganese (Mn): 1.60% Sulphur (S): 0.05% Phosphorus (P): 0.04%
Producer	Pacific Stream International Sdn Bhd
Diameter	75 mm
Thickness	5 mm
Screw Hole Diameter 1	4.5 mm
Screw Hole Diameter 2	5 mm
Type of Manufacture	Laser Cut
Finishing Method	Surface Grinding Machine

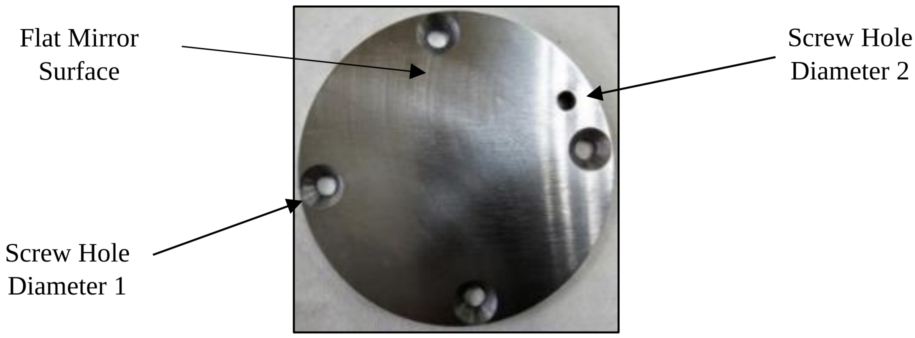

Figure 1. Finishing Disc Specimen

Table 2: Pin Specimen Specification

Specifications	Description
Material	316L Stainless Steel
Material Composition	Carbon (C): 0.03%
	Chromium (Cr): 16.0 – 18.0%
	Nickel (Ni): 10.0 – 14.0%
	Molybdenum (Mo): 2.00 – 3.00%
	Manganese (Mn): 2.0%
	Silicon (Si): 0.75%
	Nitrogen (N): 0.10%
	Phosphorus (P): 0.045%
	Sulphur (S): 0.03%
Producer	Pacific Stream International Sdn Bhd
Diameter	8 mm
Length	25 mm
Type of manufacture	CNC
Finishing method	Polishing

Figure 2. Finishing Pin Specimen

2.2 Oils preparation

The palm oil utilized in this current study is sourced from a commercial market and branded under the name Saji. Felda Global Ventures Holdings Berhad (FGV) subsidiary Delima Oil Products Sdn. Bhd. is the manufacturer of this oil. The gear oil selected for this research is a food-grade 85W140 GL-5 lubricant, specifically formulated for machinery in the food processing industry. This gear oil is engineered to perform efficiently across a broad temperature range and under high-load conditions. Its formulation ensures resilience against corrosion, oxidation, rust, and foaming, making the 85W140 GL-5 base oil versatile and suitable for diverse operational environments. The American Petroleum Institute's (API) "GL-5" classification signifies that this oil is capable of withstanding demanding conditions, further attesting to its robustness and adaptability.

The properties of base oil for the preparation of the oil samples can been in Table 3 below. The study utilizes Industrial Gear Oil 85W140 GL-5 as the base oil, which is a mineral lubricant specifically designed for mechanical transmissions. Palm oil offers excellent oxidative stability, enabling it to withstand degradation when exposed to elevated pressure and temperature [40]. Consequently, it serves as a highly efficient lubricant for machinery operating in harsh environments [41]. Previous research conducted by Subramaniam et al. (2021) [42] investigated the use of boric acid as an addition to kapok oil. The tribological characteristics of kapok oil are assessed by employing a pin on disc tribometer, and the performance is compared between pure kapok oil and kapok oil with three varying concentrations (1, 3, and 5 wt%) of boric acid.

Therefore, for this current study, three oil samples are prepared with palm oil concentrations of 0%, 15%, and 30% which can been seen in Table 4 . The total volume of each oil sample is kept constant at 1500 ml for running the pin-on-disc test.

Table 3: Properties of Base Oil

Properties	Industrial Gear Oil 85W140 GL5	Palm Oil
Density at 15℃ (kg/L)	0.907	0.890
Viscosity at 40℃ (mm^2/s)	340.0	106.8
Viscosity at 100℃ (mm^2/s)	27.0	12.07
Flash point (℃)	245	260
Pour point (℃)	-15	-4

Table 4: The Concentration of Sample Oils

Sample Oil	Gear Oil (%)	Palm Oil (%)
G100P0	100	0
G85P15	85	15
G70P30	70	30

Each oil samples concentration is prepared by measuring it using a beaker and a syringe. To calculate the volume of palm oil, Equation (7) is used,

$$V_{PO} = YX/100 \tag{7}$$

where V_{PO} is the volume of palm oil, Y is the total oil composition (1500 ml) and X is the value of concentration for one oil (0%, 15% and 30%).

Then, the blended oil samples are mixed for 10 minutes using an electronic mixer. Lastly, the blended oil samples are mixed using an ultrasonic machine. Sufficient water is required to fully submerge the containers before starting the mixing process. The ultrasonic machine is set to run for 60 minutes at a temperature of 40°C. The procedure maintains a constant temperature of 40°C to prevent potential heat damage and ensure optimal fluidity of both oils. The extended duration of 60 minutes allows sufficient time for the ultrasonic waves to permeate the entire mixture thoroughly, ensuring complete and uniform blending. This ultrasonic approach presents distinct advantages when compared to conventional mechanical mixing techniques. The result is potentially a more homogeneously blended product.

2.3 Viscosity test

After mixing the lubricant samples, it is imperative to determine the kinematic viscosity of these newly created formulations. Viscosity is a property of fluids that indicates their resistance to flow or deformation. A viscometer is to measure the flow characteristics and viscosity of fluids [43]. It is measured using a viscometer, a device widely used in different sectors to control fluid viscosity, which is crucial for maintaining high quality and performance. The viscosity index is a unitless metric that quantifies the extent to which the viscosity of a fluid changes in response to temperature fluctuations. It offers vital information on the ability of a lubricant to maintain its viscosity at various temperatures, which is crucial for evaluating its performance under diverse thermal situations.

The Cannon-Fenske Viscometer test is selected for this investigation to measure the three oil samples (G100P0, G85P15 and G70P30) according to ASTM D445-97 standard. The Cannon-Fenske tube, a U-shaped glass tube, is the main component of the capillary viscometer. The U-tube is filled with the oil sample to the prescribed level of around 20mm. A temperature-controlled bath is used with two temperature constants at 40°C and 100°C.

The accurate time (in seconds) for a consistent amount of fluid to move from one point to another within the tube, either through suction or gravity, is measured using a stopwatch. In order to measure the kinematic viscosity of the oil sample, Equation (8) is employed, utilizing the specific constant associated with the particular tube utilized. In order to ensure accuracy, the technique is repeated a minimum of three times.

$$\upsilon = Tconst\ t \tag{8}$$

where υ is the absolute kinematic viscosity, *Tconst* is the temperature constant specify to the particular tube in (℃) and t is time taken in seconds.

2.4 Tribology pin-on-disc

The Pin-on-Disc tribometer is widely used in tribology to study friction, wear, and lubrication of materials and coatings. This setup evaluates the friction and wear properties of materials and lubricants under various loads, speeds, and lubricant concentrations [44]. Wear and friction are crucial variables that must be carefully considered when designing and evaluating materials for usage in different mechanical applications. The fundamental concept is to replicate and analyse the wear and friction properties observed in actual mechanical systems when two surfaces are in relative motion. This Pin-on-Disc simulation replicates the frictional interaction between two surfaces, usually a pin and a rotating disc, with precise control over the experimental conditions. According to the ASTM G-99 standard, the pin is held vertically against the flat rotating disc at a radial distance of 20 mm under fixed load conditions in kg but at different speeds. In this study, the pin-on-disc method is utilized to measure the wear rate, coefficient of friction, frictional forces and other lubricant properties.

The Box-Behnken Design (BBD), a response surface methodology, is utilised as the optimization technique. Following the BBD recommendations, a total of 15 test conditions are prepared and tested, involving the experimental matrix including oil concentrations (0%, 15%, and 30%), speeds (600 rpm, 750 rpm, and 900 rpm), and applied loads (30N, 50N, and 60N). The following Table 5 below provides the test method and conditions for this Pin-on-Disc test. Consequently, 15 specimen pins and 15 specimen discs are used in the study. The diameter disc track used for this experiment is a constant 20 mm per disc. Each test run lasts 15 minutes per disc track. When the pin is in contact with the rotating disc tangentially, the friction occurring between the sample and the disc is measured by a sensor. The experimental tests are done within the room temperature of 25°C. The coefficient of friction, μ is calculated as the ratio of measured friction force, f to the applied normal load, N using the Equation (9),

$$\mu = f/N \tag{9}$$

The weight fastened to the tribometer's arm and subsequently moved to the pin's contact area serves as the normal load, and friction force is recorded using a force transducer. The wear rate is calculated using Equation (10),

$$Q = \Delta V/ND \tag{10}$$

where, Q is wear rate in mm^3/Nm, ΔV is volume loss is mass loss over density in mm^3, N is load in N and D is sliding distance in m. The wear rate, coefficient of friction, and frictional force obtained from this current study are meticulously compared with the results from the previous Pin-on-Disc study conducted by Tushar et al. (2023), [45].

Table 5: The Test Method and Conditions for Pin-on-Disc Test

Sample Disc	Speed (rpm)	Load (N)	Sample Oil
S7L3P0	750	30	G100P0
S6L5P0	600	50	
S9L5P0	900	50	
S7L6P0	750	60	
S7L3P15	750	30	G85P15
S6L3P15	600	30	
S9L3P15	900	30	
S7L5P15	750	50	
S7L6P15	750	60	
S6L6P15	600	60	
S9L6P15	900	60	
S7L3P30	750	30	G70P30
S6L5P30	600	50	
S9L5P30	900	50	
S7L6P30	750	60	

2.5 Surface roughness test

The surface roughness test evaluates the minute deviations of a surface from an ideal flat plane, providing a precise measure of its roughness. This evaluation is essential for understanding how surfaces interact concerning wear, friction, and lubrication. The test primarily focuses on the parameter Ra, representing the average height of surface irregularities.

A study on surface roughness conducted by Aiman et al. (2023) [46] investigated the effects of sliding speed. The results indicated that as sliding speed increases, the wear scar becomes smaller due to a reduction in surface roughness (Ra) on the lubricated block, thereby providing protection at lower speeds. A micro-pitted aluminium block has lower roughness than a smooth one. Blocks with pits spaced 2 mm apart help maintain the oil film, preventing surface roughness. The micro-pits act as oil reservoirs during the process. Thus, in this study, 15-disc specimens undergo surface roughness (Ra) measurement using a Surftest machine SV600. The Surftest machine's surface sensor slides at a constant 5 mm across each disc surface where the wear scar occurs after the Pin-on-Disc test. This surface roughness test is conducted at least three times to obtain an accurate average reading.

2.6 Fourier transform infrared spectroscopy test

Fourier Transform Infrared Spectroscopy (FTIR) is an effective analytical method for classifying and identifying chemical substances according to how well they absorb infrared light. Infrared (IR) radiation comprises electromagnetic waves with wavelengths longer than those of visible light yet shorter than microwaves. A molecule's chemical bonds have the ability to bend, vibrate, or stretch in reaction to infrared light [47]. This study employs the FTIR test on two types of oil samples: a pure industrial gear oil (G100P0) and a blended palm oil mixture (G70P30). For each sample, about 30 ml of oil is precisely measured using a syringe. A beamsplitter is used by the FTIR spectrometer to split the incoming infrared light into two distinct beams. While one beam is focused on a stationary mirror, the other is directed towards a moving mirror. The relative travel length of one beam relative to the other is altered by the oscillations of the moving mirror. An interferogram, which is a plot of intensity against optical path difference, is created when these beams recombine.

The detector of the device converts the interferogram into digital form, generating distinct data points that correspond to the intensity at different optical path differences [48]. The data points are uniformly distributed in the temporal domain, providing accurate sampling for both types of oil. It is crucial to perform this step in order to obtain precise initial data for the following analysis. A Fourier Transform is applied to the digitalized interferogram to transform it from the time domain to the frequency domain. This transformation decomposes the interferogram into its constituent frequency components [49]. This procedure assists in determining the various chemical vibrations and bonding found in the G100P0 and G70P30 samples. The frequency-domain data is represented as an infrared spectrum, where the intensity is plotted against the wavenumber or wavelength. This spectrum illustrates the absorption of infrared radiation by each oil sample as a function of frequency [50]. The spectrum obtained from the Fourier transform undergoes further workflows, including baseline correction, smoothing, and normalization [51]. These techniques enhance the quality of the spectrum and facilitate its interpretation. By analysing the FTIR spectra, any changes can be detected in the oil's composition due to oxidation, degradation, or the formation of new compounds during the blending process or after tribological testing. This process helps to establish correlations between the oil's chemical structure and its lubricating properties, such as friction reduction and wear prevention. Furthermore, FTIR data can reveal the presence of beneficial compounds or potentially harmful contaminants, guiding the optimization of blend formulations.

3.0 RESULTS AND DISCUSSION

3.1 Viscosity

The data of the viscosity test conducted on three oil samples at 40°C and 100°C are shown in Table 6 below. The kinematics viscosity decreases significantly with the increase of palm oil concentration. For the result, the measurements are conducted at 40°C. Sample oil G100P0 exhibits the highest viscosity, with an average viscosity of 333.71 mm^2/s. Conversely, sample oil G70P30 demonstrates the lowest viscosity, measuring 77.74 mm^2/s. Sample oil G85P15 lies precisely in between these oil samples, with a viscosity of 108.05 mm^2/s. Meanwhile, the results obtained at a temperature of 100°C are observably similar to those observed at 40°C. For sample oil G70P30, the average viscosity is the lowest at 16.10 m^2/s as compared to G85P15 and G100P0, which are 17.22 mm^2/s and 20.47 mm^2/s, respectively. This indicates that higher concentrations of palm oil reduce the viscosity of the oil samples. The viscosity values indicate how the samples flow at this temperature, meaning the samples become less resistant to flow as the palm oil concentration increases.

Table 6: Viscosity Test Result at 40ºC and 100ºC.

Sample Oil	Average Viscosity at 40ºC (mm^2/s)	Average Viscosity at 100ºC (mm^2/s)
G100P0	333.71	20.47
G85P15	108.05	17.22
G70P30	77.74	16.10

3.2 Wear rate

Fig. 3 shows the wear rate graph in mm³/Nm of 15 samples based on their oil percentage concentration, speed, and applied load through Pin-on-Disc test. The highest wear rate obtained is approximately 0.0000611 mm³/Nm for the sample S6L6P15, while the lowest is around 0.0000019 mm³/Nm for the sample S6L5P30. The addition of palm oil seems to influence the wear rates significantly. The lowest wear rates are observed in sample oil G70P30 as compared to G85P15 and G100P0, indicating that the increasing of palm oil concentration may be more beneficial for reducing wear rates. Sample oil G70P30 shows a reduction in wear rates as compared to the sample oil G100P0, though some variability remains. The current study presents several biolubricants concentrations that stay well below the target wear rate of 50 (10^{-6}) mm^3/Nm. Samples S7L3P0, S6L5P0, S9L5P0, S7L6P0, S7L3P15, S7L4P15, S7L6P15, S7L3P15, S9L6P15, S7L3P30 S6L5P30, S9L530 and S7L6P30 are particularly noteworthy for their low wear rates. These compositions should be considered the best candidates for further research and potential application in bio-lubricants for food grade industries as they meet the criteria of a wear rate between 1-50 (10^{-6}) mm^3/Nm. Meanwhile, for Tushar wear rate result, the highest wear rate recorded is approximately 0.0000180 mm³/Nm for sample no. 10, while the lowest is around 0.00000114 mm³/Nm for sample no. 11. The trend wear rate current study exhibits significant fluctuations across the samples, indicating substantial variability in wear performance. In contrast, the Tushar wear rate trend is relatively stable and shows less variation as compared to the current study results.

Nevertheless, the relation between viscosity and the wear rates reveals a counterintuitive relationship. The viscosity values show a significant decrease as palm oil concentration increases. Interestingly, this trend inversely correlates with wear rate performance. While sample oil G100P0, with the highest viscosity, exhibits moderate wear rates, the G70P30 blend demonstrates the lower wear rates despite having the lowest viscosity. These findings indicate that the addition of palm oil likely enhances wear resistance through mechanisms such as improved boundary lubrication, rather than through viscosity alone. The variability in wear rates observed in the current study, contrasting with Tushar's more consistent results, further underscores the complex interaction of factors affecting wear behaviour in these bio-lubricant blends. This analysis implies that optimizing palm oil concentration in bio-lubricant formulations can lead to enhanced wear resistance even at lower overall viscosities.

Fig. 4 shows a comparison of two samples of wear rate through POD test that uses the same amount of speed and applied load which are 600 rpm and 50 N. The wear rate for the S6L5P0 condition starts high and decreases over time, eventually stabilizing. Both samples demonstrate a significant initial rate of wear when the pin initially comes into contact with the disc. This sudden increase is common as the surfaces experience first reactions and loss of material. The data points on the graph represent the wear rate at each specific moment in time, rather than being an average wear rate. The importance of stabilizing wear rates is critical, as it indicates the steady-state behaviour of the lubricant's performance after the initial run-in period. This initial high wear rate is due to the running-in period, where the contact surfaces rapidly wear down until a stable interface is formed. As the test continues, a protective film forms, reducing wear. For the S6L5P30 condition, the wear rate is significantly lower throughout the test. This suggests that adding 30% concentration of palm oil to the industrial gear oil improves lubrication, resulting in less wear. The wear rate for S6L5P30 remains stable with minor fluctuations, indicating that the mixed lubricant consistently provides a protective film that reduces wear.

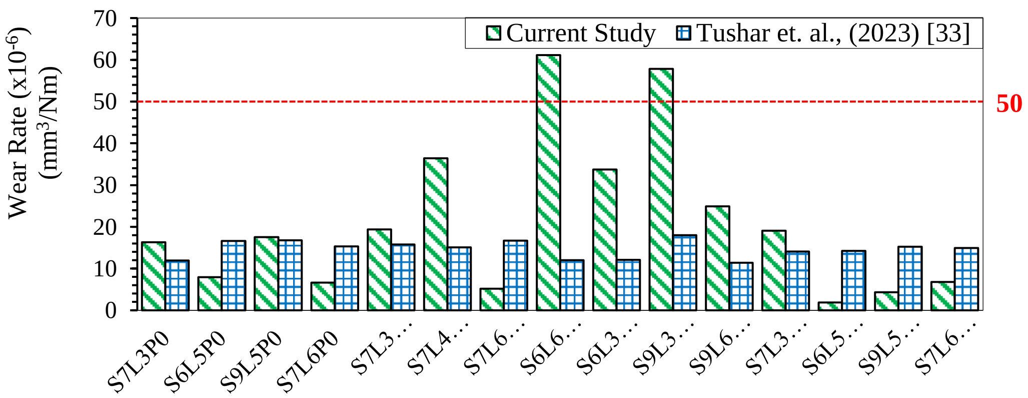

Figure 3. Wear Rate vs. Sample

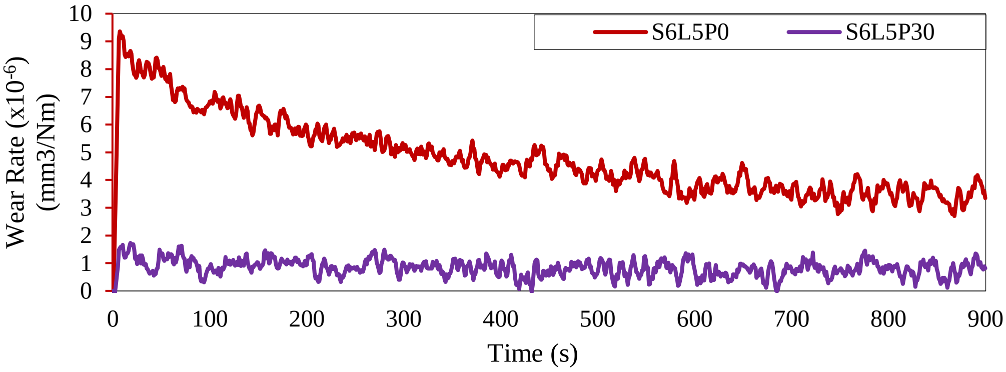

Figure 4. Wear Rate vs. Time

3.3 Coefficient of friction

Fig. 5 presents a comprehensive comparison of the coefficient of friction (COF) across 15 samples tested using the Pin-on-Disc method, revealing significant insights into the tribological performance of various blended palm oil formulations. The data exhibit a wide range of COF values, indicating the complex interplay between oil composition, speed, and load conditions. The highest recorded COF is approximately 0.10083200 for sample S7L6P30, which notably exceeds the desired performance criteria. This outlier suggests that this particular blend, likely with 30% palm oil concentration, may have suboptimal lubrication properties under specific conditions, indicating that it may require additional refinement or may not be appropriate as bio-lubricants in their current compositions. In contrast, several samples, particularly those labelled as S7L4P15, demonstrate remarkably low COF values approaching zero. This exceptional performance indicates that certain blends, especially those with a moderate palm oil concentration of 15%, can achieve superior friction reduction under specific operating parameters. The base oil samples (G100P0) generally exhibit moderate COF values, as exemplified by S9L5P0 with a coefficient of 0.0895555, serving as a benchmark for comparison with the blended formulations. The addition of palm oil to the base lubricant yields varied effects of COF, revealing a non-linear relationship between palm oil concentration and friction reduction. Samples with 15% palm oil (G85P15) consistently show very low COF values, suggesting an optimal concentration for minimizing friction across a range of speed and load conditions. However, increasing the palm oil concentration to 30% (G70P30) generally results in higher COF values, indicating a potential threshold beyond which additional palm oil may adversely affect the lubricant's performance. This could be attributed to changes in the oil's viscosity at higher concentrations. The stark contrast between the current study's results and those reported by Tushar is noteworthy. While the present study shows significant fluctuations in COF across samples (ranging from near 0 to 0.10083200), Tushar's [33] data exhibits much greater consistency, with COF values falling within a narrower range of 0.0335 to 0.0411. This discrepancy underscores the importance of standardized testing protocols and highlights the potential impact of subtle variations in experimental conditions or blend formulations on tribological performance. These insights are essential for applications in industries where the maintenance of low friction is vital, such as in food-grade machinery, to ensure the efficiency and durability of equipment.

Two samples of COF through Pin-on-disc test applied at the same speed and load (600 rpm and 50 N) are compared in Fig. 6 below. When the pin first comes into contact with the disc, both samples show a high coefficient of friction. This sudden spike is the characteristic of the surfaces' early modifications and material removal. The data points on the graph show the immediate coefficient of friction, not an average value. The importance of stabilising COF values is significant since they show the lubricant's steady-state performance after the initial run-in time. The COF for the S6L5P0 condition stays stable around 0.04 throughout the test, indicating that pure industrial gear oil provides consistent lubrication and reduces friction effectively. For the S6L5P30 condition, the COF starts higher at about 0.08 and remains stable for a while before decreasing significantly around the 600 s mark. The initial high COF is due to the initial interaction between palm oil and industrial gear oil. The decrease around the 600 s mark indicates a transition in the lubrication regime. It is likely that wear particles from the surfaces have been split out and either embedded into the lubrication film or ejected from the contact zone, before it settled into a more stable regime.

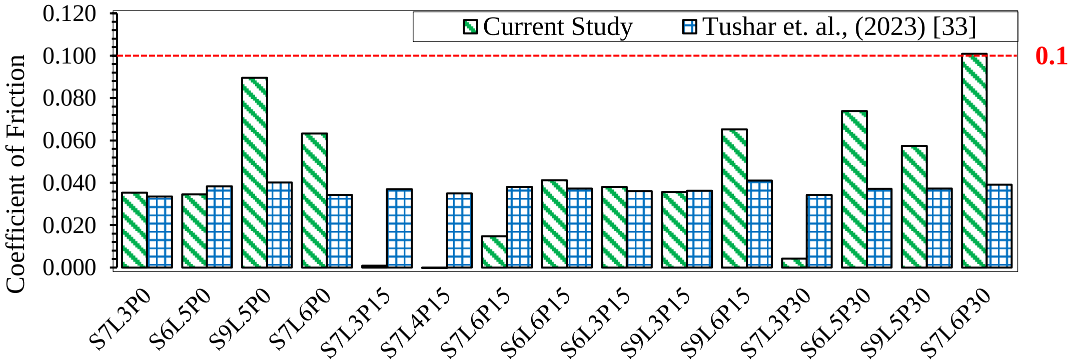

Figure 5. Coefficient of Friction vs. Sample

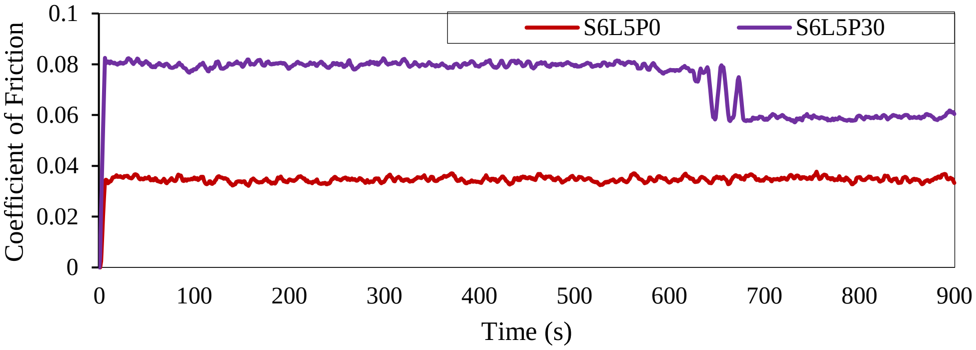

Figure 6. Coefficient of Friction vs. Time

3.4 Surface roughness

The graph in Fig. 7 shows the relationship between the average surface roughness (Ra) and various disc samples. The surface roughness value (Ra) is typically associated with the cleanability and hygienic state of surfaces that comes into contact with food. Both the European Hygienic Engineering and Design Group and the American Meat Institute (AMI) advise that the Ra value should not exceed 0.8 µm [52]. The surface roughness evaluations of all the sample discs are significantly lower than the recommended maximum of 0.8 µm. This shows that each specimen satisfies the hygienic requirements for surfaces in contact with food, guaranteeing their ease of cleaning and decreased susceptibility to contaminants.

Sample discs S7L3P15 and S7L4P15 exhibit the lowest surface roughness value of 0.04µm as shown in Fig 7. These samples likely benefit from optimal conditions that minimize surface roughness. Additionally, sample oil G85P15 indicates that an optimum concentration of palm oil demonstrates mostly the lowest surface roughness among the disc samples as compared to G100P0 and G70P30. Sample discs S6L5P30 and S7L6P30 show the highest surface roughness value of 0.34µm. The increasing trend in surface roughness with higher sample identifiers could be linked to the varying palm oil concentration. Sample discs with higher palm oil concentration involves sample oil G70P30 which tends to have higher surface roughness as compared to G85P15 and G100P0, indicating that excessive palm oil may lead to a rougher surface.

The correlation between surface roughness (Ra) and coefficient of friction (COF) results provides crucial insights into the tribological performance of blended palm oil lubricants. Samples S7L3P15 and S7L4P15, which exhibit the lowest surface roughness of 0.04 µm, also demonstrate exceptionally low COF values approaching zero, indicating an optimal blend that minimizes both wear and friction. This trend is consistently observed in sample oil G85P15 (15% palm oil), suggesting that moderate palm oil addition achieves the best balance of surface protection and lubrication. In contrast, sample oil G70P30 (30% palm oil) tends to have higher surface roughness and COF values, with S7L6P30 showing the highest Ra of 0.34 µm and COF value of 0.10083200. This correlation implies that excessive palm oil may lead to increased wear and friction, possibly due to changes in viscosity or film-forming properties.

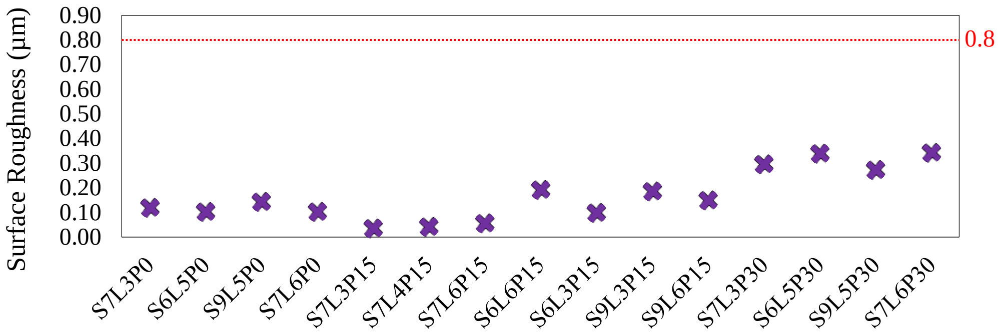

Figure 7. Surface Roughness vs. Sample Disc

3.5 Fourier transform infrared spectroscopy

The Fourier Transform Infrared Spectroscopy (FTIR) spectra of the blended palm oil of G70P30 and the pure industrial gear oil of G100P0 reveal the data of their chemical concentrations and functional groups. Comparing these spectra indicates how blending influences the oil's molecular structure and properties. Both spectra cover the wavenumber range of 4000 cm^{-1} to 600 cm^{-1}. In contrast, the industrial gear oil of G100P0 mainly contains aliphatic hydrocarbons which can be seen in Fig. 8. It shows distinct peaks at approximately 3000-2850 cm^{-1}, which correspond to the stretching of C-H stretching, and at 1465-1375 cm^{-1}, which correspond to the bending of CH_2 and CH_3 groups. Additionally, there is a characteristic peak at around 720 cm^{-1}, which corresponds to the rocking vibrations of long-chain methylene groups.

Mineral oil consists of a complex mixture of hydrocarbons that are primarily made up of aromatic and saturated aliphatic hydrocarbons. In mineral oil, the aliphatic hydrocarbons can range from short-chain alkanes like octane and hexane to long-chain alkanes like dodecane, hexadecane, and even tetracosane or more [53]. Due to their unique chemical structures, such as peroxide bonds, many aliphatic compounds are more resistant to biodegradation. Because of their resistance, they may accumulate in the soil and pose long-term environmental risks [54]. Certain aliphatic hydrocarbons have the ability to dissolve in water and can move into groundwater, which has the potential to pollute water sources. Their toxic and carcinogenic qualities make them potentially hazardous to human and animal health. Compounds like benzo[a]pyrene and naphthalene have the ability to build up in the food chain, which can lead to health risks for people [55].

Several functional groups have been found for the sample blended palm oil of G70P30 as shown in Fig. 9. Olefins exhibit characteristic peaks at approximately 3100-3000 cm^{-1}, according to C-H stretching, and at 1650-1600 cm^{-1}, corresponding to C=C stretching. Esters exhibit prominent peaks at around 1740-1720 cm^{-1} for C=O stretching and 1250-1050 cm^{-1} for C-O stretching. Peaks in the range of 2950-2850 cm^{-1} (C-H stretching) and 1465-1375 cm^{-1} (CH_2 and CH_3 bending) are indicative of aliphatic hydrocarbons. The FTIR analysis of sample oil G70P30 will yield similar results to sample G85P15 due to the presence of palm oil concentration in the mixture.

A class of hydrocarbons called olefins, or alkenes, is distinguished by having at least one carbon-carbon double bond (C=C) in their molecular structure. Because of the double bond, these molecules are unsaturated, meaning they contain fewer hydrogen atoms than their saturated counterparts, or alkanes [56]. Formulations that maintain a consistent viscosity across a broad temperature range can be achieved by utilising olefins, particularly in the synthesis of lubricants that are precisely defined. This stability is essential for guaranteeing that lubricants operate effectively in both high and low temperatures, thereby improving their overall reliability and efficacy [57]. When compared to conventional petroleum-based additives, olefins perform better as lubricants due to their improved adsorption to metal surfaces and enhanced oxidative stability. Higher molecular weight compounds may also be formed as a result of oxidative reactions, and these compounds can enhance viscosity and stability in general [58].

Organic molecules known as ester compounds are produced during the esterification process, which is the reaction of an alcohol with a carboxylic acid that releases water. When discussing oils, particularly edible oils, the term "esters" mostly refers to fatty acid esters, which are the main building blocks of triglycerides [59]. Through the formation of a protective film on surfaces, esters effectively provide lubrication, thereby reducing friction and abrasion [60]. In applications such as internal combustion engines, this function is particularly critical, as it can result in less energy consumption and improved fuel efficiency by reducing friction. The environmental impact of esters is greatly influenced by their biodegradability. As industries shift towards more environmentally friendly options, the use of biodegradable lubricants helps reduce the ecological consequences related to the disposal and spillage of lubricants [61].

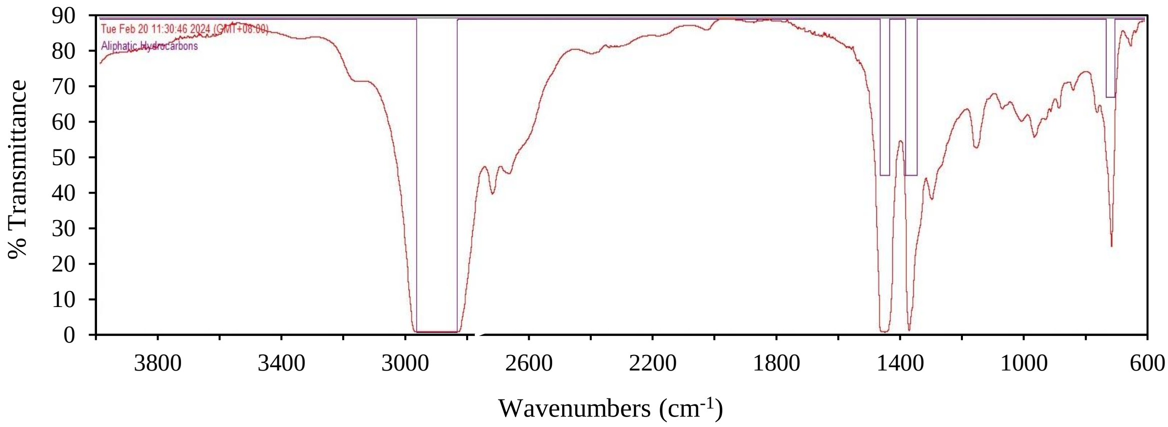

Figure 8. FTIR of Pure Industrial Gear Oil (G100P0)

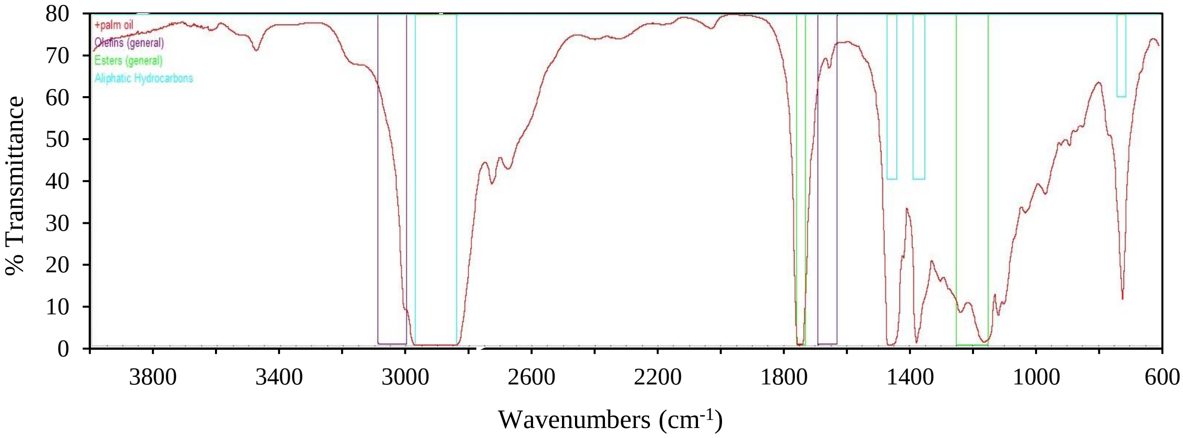

Figure 9. FTIR of Blended Palm Oil (G70P30)

4.0 CONCLUSION

In conclusion, this study investigated the tribological performances of different concentration palm oil in blend with industrial gear oil as a new food-grade lubrication oil on wear rates, coefficient of friction, surface roughness and chemical functional group. In the context of wear rate and coefficient of friction, 12 out of 15 samples exhibited a wear rate under 50 (10-6) mm^3/Nm and a coefficient of friction less than 0.1 through the Pin on Disc test. However, the G70P30 sample oil is considered the best bio-lubricant concentration because it optimally reduces both wear rate and coefficient of friction as compared to G100P0 and G85P15. This demonstrates enhanced machine elements longevity with improved lubrication and wear protection due to the addition of concentration palm oil. Meanwhile, sample discs S7L3P15 and S7L4P15, with the lowest surface roughness, demonstrate that the G70P30 sample oil is the best-optimized palm oil concentration for the optimal range of speed and load, which are 700 rpm and 30-40N. This indicates that machine elements operating within this range of speed and load will have smoother surfaces when in metal-to-metal contact. Lastly, the sample oils G70P30 and G85P15 contain additional esters and olefins in their chemical functional groups, compared to the G100P0 sample oil, which only has aliphatic hydrocarbons. Esters are known for their excellent lubrication properties, high thermal stability, and biodegradability. They help reduce friction and wear, contributing to better performance in lubricants. Additionally, olefins can enhance the viscosity index and oxidation stability of lubricants, making them more effective over a wider range of temperatures and more resistant to degradation over time. Beyond this point, this blended palm oil as biolubricant or food grade lubricant could pave the way for future engineering industries with its good lubrication properties, environmental benefits, and potential for improved performances.

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