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Analysis of Wear Behaviour of Blended Gear Oil Using Pin on Disc Experiment

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ABSTRACT

This research analysed blended palm oil and blended virgin coconut oil (VCO) as a new formulated bio lubricant utilizing pin on disc experiment. The primary objective of this project is to investigate the tribological characteristics of wear rate and coefficient of friction, as well as to examine the disc's surface morphology, following the ASTM G99 standard. The study was conducted using parameter speeds ranging from 600 rpm to 900 rpm and loads from 30 N to 60 N. Surface roughness of the disc samples was measured using a Surftest machine. The findings revealed that the lubricant with 15% Virgin Coconut Oil (VCO) content had the lowest coefficient of friction, specifically at 750 rpm and a 45 N load. The base lubricant used in this study is 85W140 GL5 gear oil, which was enhanced with blends containing 15% and 30% of Palm Oil and Virgin Coconut Oil. Additionally, the oil blend with 30% Palm Oil content exhibited the lowest wear rate, observed at 600 rpm with a 45 N load. The results, which highlight the high viscosity index, unsaturated/saturated ratio, and the low wear rate and coefficient of friction of Palm Oil and VCO, suggest that these oils are promising candidates as base fluids for lubricants in future applications. This makes them viable alternatives for various industrial uses, providing stable and favorable performance characteristics.

1. Introduction

Lubricants play a crucial role in global industrial and economic progress, primarily by mitigating friction and minimizing wear in mechanical interactions [1, 2]. The use of vegetable-based oil products stands out as a highly promising avenue for renewable energy in the current century [3]. These oils exhibit superior biodegradability compared to mineral oils, prompting increased attention towards technologies integrating them as biofuels and industrial lubricants. A growing interest has emerged in the industrial use of vegetable oil as a lubricant [4]. Moreover, it is clear that vegetable oil-based lubricants have the potential to diminish carbon monoxide and hydrocarbon outflows when utilized in inside combustion engines [5]. The application of vegetable oil as an oil is not a recent improvement.

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Over the past decade, various types of vegetable oils, including palm oil, sunflower oil, soybean oil, and castor oil, have been extensively studied. The findings suggest that vegetable oils have the potential to serve as alternatives to mineral oil across different industries [6]. Unlike pure chemical compounds with distinct melting points, vegetable oils are mixtures, meaning that at a given temperature, the sample may be entirely solid, liquid, or a combination of both [7]. Vegetable oils are particularly effective as boundary lubricants due to the high polarity of their base oils, which promotes strong interactions with lubricated surfaces. The effectiveness of boundary lubrication depends on the attraction of lubricant molecules to the surface and their potential reactions with it [8]. Among vegetable oils, palm oil stands out for its low production cost per unit and relatively simple extraction process compared to other oils. Malaysia is currently one of the world's largest producers of palm oil. The Malaysian Palm Oil Board (MPOB), formerly known as the Malaysian Palm Oil Research Institute (PORIM), has successfully produced palm oil methyl ester from crude palm oil through a transesterification process. As a result, many industrial companies are now considering using this alternative for diesel fuel, hydraulic fluids, and lubricants for engines and machinery [9].

According to Jabal and colleagues, the benefits of using vegetable oils as lubricants include their biodegradability, lower toxicity compared to petroleum-based oils, ease of production, and renewable nature [10]. The polar ester groups in vegetable oils allow them to adhere effectively to metal surfaces, providing good lubricity [11]. Erhan and colleagues have suggested that vegetable oils with high oleic content are considered viable alternatives to traditional mineral oil-based lubricants [12]. Due to their eco-friendliness, renewability, low cost, and simple manufacturing process, vegetable oils are emerging as a promising alternative, especially in light of the increasing demand for modern energy sources. As a result, recent research has focused on modifying vegetable oils to produce various synthetic mineral oils, such as lubricants, diesel, and biofuels. Additionally, innovative methods for extracting oil from biomass have been developed, including pyrolysis, fast pyrolysis, thermochemical processes, flash pyrolysis, and vacuum pyrolysis [13, 14]. In Kerala, a southern state in India, coconut oil is commonly used as a lubricant for two-stroke engines in autorickshaws and scooters, offering benefits like increased mileage, better acceleration, smoother engine operation, and reduced smoke emissions [15]. Coconut oil also possesses impressive lubricant properties, such as a high viscosity index, excellent lubricity, a high flash point, and minimal evaporative loss [16]. Among vegetable oils, palm oil is one of the most widely recognized by the industry and is currently the preferred choice for engine and machinery lubricants.

Viscosity is crucial for lubricants as it determines the level of friction between moving surfaces and whether a sufficient layer can be formed to prevent solid-to-solid contact and wear. To minimize variations in friction due to temperature changes, it's preferable for lubricants to have consistent viscosity. Therefore, fluids are typically rated by their viscosity index [17]. The collective findings of various researchers confirm that palm oil demonstrates favourable results and holds promise for extensive use in engineering applications. Additionally, it has been substantiated that palm oil exhibits commendable performance in terms of lubrication, suggesting its potential to diminish reliance on mineral-based oil lubricants. Numerous researchers have provided evidence supporting the dependability of palm oil, as exemplified in studies such as the one conducted by [18]. As per their assessment, palm oil possesses the capability to meet the requirements for vegetable-based lubricants. They aim to assess the feasibility of palm oil as a lubricant in cold work applications, specifically in the forward plane strain extrusion process. The experimental findings indicate that palm oil exhibits satisfactory lubrication performance compared to paraffinic mineral oil and offers advantages in reducing the extrusion load.

In this investigation, friction and wear assessments were performed using a Pin-on-disc type Tribometer according to the ASTM G99 standard, a laboratory device. The Tribometer consists of a driven spindle and chuck to secure the rotating disc, a lever-arm mechanism for retaining the pin, and additional components that allow for controlled loading of the pin specimen against the rotating disc specimen. The wear track on the disc exhibited a circular pattern, and the Tribometer was equipped with a friction force measuring system (using a load cell) to determine the coefficient of friction. Blended palm oil was specifically selected in this study to assess the sensitivity of the test methods to lubricant conditions [19]. However, to fully comprehend the effectiveness of vegetable oils as lubricants, it is crucial to understand how variations in fatty acid composition influence their ability to reduce friction, form protective films, and resist wear [20]. Vegetable oils have the potential to replace petroleum-based oils, offering environmental benefits, renewability, lower toxicity, and outstanding lubricating properties such as a high viscosity index, effective lubricity, and low volatility. As a result, there is increasing demand for vegetable oil-based lubricants in various environmentally conscious industrial applications.

This research aims to examine the tribological properties of newly formulated bio-lubricants, specifically blended palm oil and virgin coconut oil (VCO). Vegetable oils are good because they break down naturally and can be renewed, but they also have problems like not working well in cold temperatures, and they can break down when exposed to heat and oxygen. These issues can result in the formation of insoluble deposits due to certain components in the oils. This study involves testing 15 samples of blended palm oil and VCO mixed with 85W140 GL5 gear oil. The wear rate and friction characteristics of a mild steel disc are assessed using a pin-on-disc machine according to the ASTM G99 standard. The surface roughness is measured with a Surftest machine SV600, and the friction coefficient is then calculated from the computer. The goal of this paper is to analyse the tribological characteristics of blended palm oil and virgin coconut oil (VCO) by evaluating their wear rate, coefficient of friction, and surface roughness.

2. Methodology

2.1 Preparation Oil Sample

In this study, 85W140 GL5 Gear Oil was used as the base oil. This mineral lubricant is versatile and resistant to oxidation, rust, corrosion, and foaming, making it suitable for a wide range of applications, including use in cold climates due to its low pour point. Its excellent "Extreme Pressure" properties provide outstanding wear protection, making it ideal for heavy-duty hypoid transmissions, gearboxes, and rear axles. Table 1 presents its properties. Safety measures and personal protective equipment were employed when handling the oil. There is potential to enhance its biodegradability and environmental friendliness.

Table 1
Properties of base oil, Palm Oil, VCO

Properties	85W140 GL5 gear oil	Palm oil	Virgin coconut oil (VCO)
Density at 15°C (kg/L)	0.907	0.890	0.920
Viscosity at 40°C (mm^2/s)	340.0	106.80	27.82
Viscosity at 100°C (mm^2/s)	27.0	12.07	7.07
Flash point (°C)	245	260	225
Pour point (°C)	-15	-4	23

Given that Malaysia is a leading producer of palm oil, this research advocates for its use or incorporation into industrial applications. Palm oil exhibits high oxidative stability, meaning it resists degradation under high pressure and temperature, making it an excellent lubricant for machinery operating in extreme conditions. Consequently, this study involves blending palm oil with the base oil and analyzing its tribological properties.

Virgin coconut oil (VCO) is extracted from new coconut meat utilizing cold pressing or wet processing, protecting its common purity and useful compounds. Rich in medium-chain fatty acids, particularly lauric corrosive, it is effectively digestible and gives speedy vitality. VCO moreover contains antioxidants like phenolic compounds and vitamin E and has antimicrobial properties. It is evident or slightly cloudy when fluid, solidifying below 76°F (24°C), and features a pleasant coconut aroma and flavour. Highly stable with a long shelf life, VCO supports digestion, metabolism, skin and hair health, and heart health, making it versatile for both culinary and personal care uses [21]. Consequently, this study blends VCO with the base oil and examines its tribological properties in Table 1.

According to [22, 23], who investigated the use of palm oil as a substitute for mineral oil in CI engines, the optimal blending concentrations were identified as 20% PFAD and 25% palm oil, respectively. Building on these findings, this experiment prepared oil samples with palm oil and VCO concentrations ranging from 0% to 30%. The experiment included 15 lubricant samples with varying concentrations: four samples with 0%, four samples with 15%, and seven samples with 30% for both palm oil and VCO. The concentrations tested were 0%, 15%, and 30%, with 0% representing pure base oil without any added palm oil or VCO. A total of 1500 ml of mixed oil samples were prepared for each concentration to conduct the pin-on-disc test, along with 10 ml for the viscometer test. The oil mixtures were measured using beakers and syringes, then blended using a bench-top ultrasonic cleaner set at 55°C for 30 minutes. The volumes of palm oil and VCO were calculated using Eq. (1) and the oil composition as outlined in Eq. (2).

$$V_{VCO/PO} = Y \frac{X}{100} \quad (1)$$

where $V_{VCO/PO}$ represents the volume of virgin coconut oil and palm oil, Y is the total volume of the mixed oil (1500 ml) and X is the percentage composition of one type of oil (0%, 15%, 30%).

$$V_{Base} = (1500\ ml - V_{VCO/PO}) \quad (2)$$

where V_{Base} is the total volume of the base oil before being blended with palm oil or VCO.

2.2 Experimental Apparatus

2.2.1 Preparation pin and disc

The study on wear and friction utilized a flat-ended pin and a flat disc. The pin was made of stainless steel, while the disc was made of mild steel. The pin, measuring 8 mm in diameter and 5 mm in length, was polished using a polishing machine. The disc, with dimensions of 75 mm in diameter and 25 mm in thickness, was finished with a grinder. Stainless steel, with a density of 7.54 g/cm³, and mild steel, with a density of 7.68 g/cm³, were selected due to their strength, durability, and toughness. These materials are ideal for wear and friction tests because they are hard and resistant to deformation. The surfaces were polished to a high degree of smoothness, with a roughness of less than Ra 0.1 µm, to ensure even contact during the tests [24]. Figure 1 shows the dimensions and shapes of the stainless-steel pin and mild steel disc used. This setup ensures reliable data on wear and friction, which is crucial for evaluating the performance of lubricants and the interaction of materials in machinery.

Fig. 1. Pin and disc

2.2.2 Viscometer

A viscometer is an instrument utilized to measure the flow characteristics and viscosity of fluids. In tribology and oil studies, viscosity is regularly highlighted as the foremost basic property of a base oil. But why is viscosity so imperative for a machine's oil? In case the viscosity is as well low, it may lead to wear due to direct contact between moving inner parts. Alternately, in case the viscosity is too high, the machine would need to apply more exertion to overcome the lubricants inside resistance to flow. Hence, understanding the viscosity of the base oil and how it changes with distinctive operational or natural conditions is essential.

For this study, a capillary (glass) viscometer test was selected due to its availability and effectiveness. The primary component of a capillary viscometer is a U-shaped glass tube, specifically the Cannon-Fenske routine viscometer. Each tube in this viscometer has a specific temperature constant, as outlined in Table 2. The Cannon-Fenske 300-series viscometer was used to measure viscosity at 40°C, while the 150-series was employed for viscosity measurements at 100°C. The U-tube is filled with the oil sample up to a designated level and immersed in a temperature-controlled bath set to 40°C and 100°C, respectively. Figure 2 shows the configuration of the oil level. Using a stopwatch, the time (in seconds) for a fixed volume of fluid to flow from one level to another within the tube, driven by suction or gravity, was recorded as shown in Figure 3. The kinematic viscosity of the oil sample was calculated using equation (2), with the constant specific to the tube provided in Table 2. To ensure accuracy, the procedure was repeated at least three times. These procedures adhere to the ASTM D445-97 standard for Gravity Flow U-shaped Glass Tube Capillary Viscometers [25].

$$\upsilon = T_{const}\ t \tag{3}$$

where υ represents the absolute kinematic viscosity, T_{const} is the temperature constant specific to the particular tube (℃) and t is the time taken in seconds.

Table 2
Cannon- Fenske routine viscometer specification

Size tube	Serial number	40℃ constants	100℃ constants	Kinematic viscosity range
150	259D	0.03199	0.03185	7 to 35
	P982	0.3602	0.03586	7 to 35
	J140	0.2467	0.2456	50 to 250
300	59W	0.24427	0.24454	50 to 250
	60W	0.23374	0.23406	50 to 250

Fig. 2. Cannon-Fenske viscometer

Fig. 3. Viscosity

Table 3 shows the result of blended oil based on the Eq. (2) and Cannon-Fenske routine viscometer.

Table 3
Viscosity of blended oil

Temperature	Kinematic viscosity (mm^2/s)				
	Gear oil	Blended 15% conc. palm oil	Blended 30% conc. palm oil	Blended 15% conc. VCO	Blended 30% conc. VCO
40	133.71	108.13	77.74	102.13	74.97
100	20.47	17.24	16.10	16.93	14.16

2.2.3 Pin on disc machine

This test is conducted using a pin-on-disc tribotester machine as shown in Figure 4 connected to a controller that displays data on a computer, adhering to the ASTM G99 standard. Several conditions were established before starting the experiment: speeds range from 600 rpm to 900 rpm, the load ranges from 30 N to 60 N with 15 N increments, and each sample is run for 30 minutes. In this experiment, the controller provides data on wear and frictional force. The pin-on-disc machine is equipped with an LVDT sensor which capable of detecting the wear rate of both the pin and the disc.

In this setup, a cylindrical pin is placed against a rotating circular disc under a load. To conduct experiments using the pin-on-disc instrument, two specimens are needed: a disc and a pin, both of standard dimensions. The standards and dimensions of the disc for experimentation with the pin-on-disc instrument are pin diameter range 2 mm to 10 mm while, disc specimen diameter range 30 mm to 100 mm and disc specimen thickness range 2 mm to 10 mm. Table 4 detailed the condition and parameter of pin on disc used.

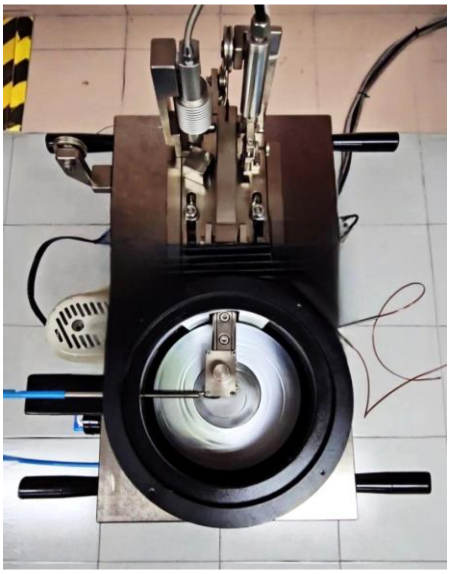

Fig. 4. Pin on disc machine

Table 4
The condition and parameter of pin on disc for palm oil (PD) and VCO (VC)

Oil sample	Speed (rpm)	Load (N)	Palm oil composition (%)
PD1	750	30	0
PD2	600	45	
PD3	900	45	
PD4	750	60	
PD5	750	30	15
PD6	750	45	
PD7	750	60	
PD8	600	60	
PD9	600	30	
PD10	900	30	
PD11	900	60	
PD12	750	30	30
PD13	600	45	
PD14	900	45	
PD15	750	60	
VC1	750	30	0
VC2	600	45	
VC3	900	45	
VC4	750	60	
VC5	750	30	15
VC6	750	45	
VC7	750	60	
VC8	600	60	
VC9	600	30	
VC10	900	30	
VC11	900	60	
VC12	750	30	30
VC13	600	45	
VC14	900	45	
VC15	750	60	

2.2.4 Surface roughness test

After the experiment, a Surftest Machine SV600 was used to measure the surface roughness at the surface of the disc. This machine is a precise tool utilized for evaluating surface roughness, providing crucial data for quality assurance, manufacturing, and product enhancement. Employing advanced technology, it accurately captures surface profiles, ensuring reliability and precision in measurements. Using the Surftest Machine SV600 involves setup, surface preparation, parameter selection, stylus placement, measurement commencement, result review, data analysis, documentation, and machine maintenance. Adhering to manufacturer guidelines is essential for optimal performance. Ensure measurements are taken at least thrice on areas where the highest values are anticipated, ensuring compliance with specified limits across the entire surface.

Fig. 5. Surftest machine SV600

3. Results

In the pin-on-disc experiment, the parameters for palm oil and VCO were observed and measured. The coefficient of friction is derived from the friction torque recorded by the test machine, while the surface roughness is measured using the Surftest Machine SV600.

3.1 Wear Rate

The wear results from previous studies and the experiment using palm oil and VCO inputs are illustrated in Figure 6. Based on literature data, the maximum specific wear rate is 1.67 x 10^{-5} mm^3/Nm, while the minimum is 1.0 x 10^{-6} mm^3/Nm [26]. For palm oil inputs, the highest wear rate recorded is 5.78 x 10^{-5} mm^3/Nm, and the lowest is 1.9 x 10^{-6} mm^3/Nm. For virgin coconut oil (VCO) inputs, the maximum wear rate is 2.536 x 10^{-4} mm^3/Nm, with the minimum being 5.1 x 10^{-6} mm^3/Nm. An analysis of the wear rate chart reveals that most values for palm oil and VCO exhibit significant variations, similar to those observed in literature. Both palm oil and VCO are highly effective as lubricants due to their unique properties. Palm oil contains natural fatty acids that form a protective layer on surfaces, significantly reducing friction and wear. It is also stable at high temperatures, making it ideal for various industrial applications. VCO, with its medium-chain fatty acids, provides excellent lubrication and reduces wear. Its high oxidative stability ensures it remains effective under heat, making it suitable for high-temperature applications. These characteristics make both oils valuable for lubrication purposes.

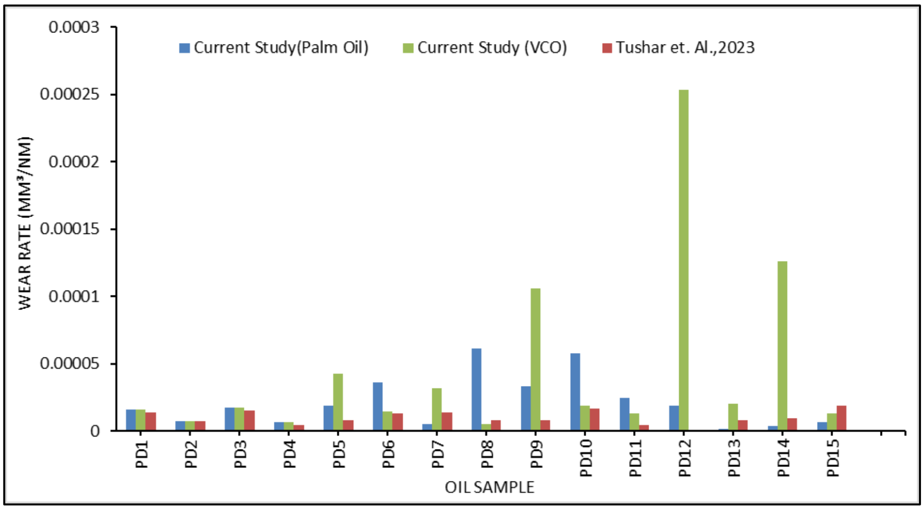

Fig. 6. Wear rate vs oil sample

3.2 Coefficient of Friction (COF)

The coefficient of friction (COF) results for 15 trials with different independent parameters are shown in Figure 7. Literature-based data indicates that COF values generally range from a minimum of 0.025 to a maximum of 0.041. However, when analyzing palm oil, the COF results vary significantly, with the highest value recorded at 0.100832 and the lowest at -0.0002. This suggests a wider range of performance under the test conditions. In contrast, virgin coconut oil (VCO) exhibits a COF range with a maximum of 0.100993 and a minimum of -0.039082. These variations highlight the unique frictional properties of palm oil and VCO, emphasizing their potential applications based on the specific requirements of various mechanical systems. The analysis of COF results indicates that most of the values for both palm oil and VCO show variations that are slightly higher than those reported in the literature. This implies that the frictional properties of both oils align closely with established data, affirming their reliability and effectiveness as lubricants.

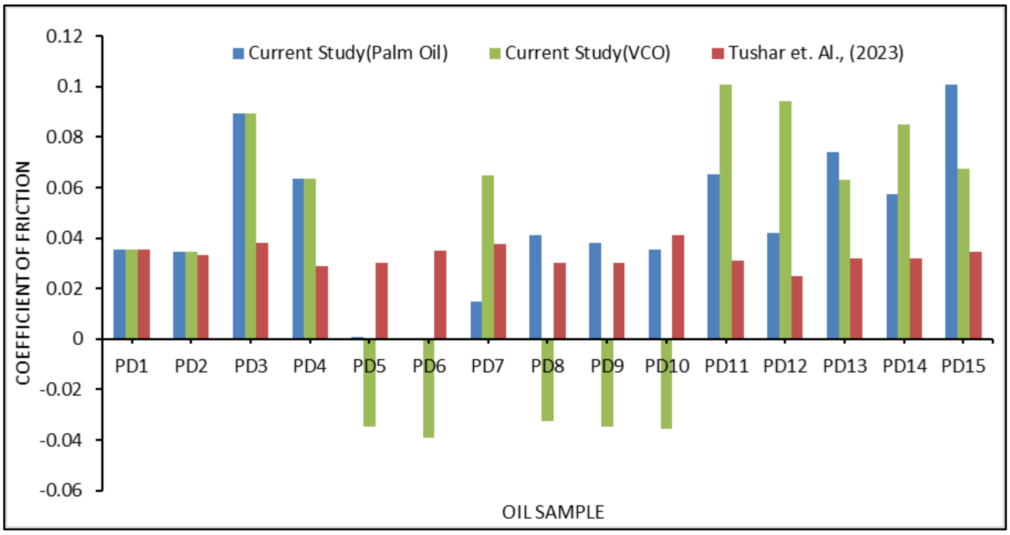

Fig. 7. Coefficient of friction vs oil sample

3.3 Surface Roughness

Wear rate, coefficient of friction (COF), and surface roughness are interrelated factors that significantly influence the performance of mechanical systems. Surface roughness, which refers to the variations in a surface's texture, directly affects the COF; smoother surfaces generally exhibit lower COFs due to reduced interactions between surface asperities. Higher COF often leads to increased wear rates because of the greater frictional forces and material interactions involved. Effective lubrication, such as that provided by virgin coconut oil (VCO) or palm oil, can fill in surface asperities, thereby reducing both surface roughness and COF, which helps lower wear rates. Enhancing tribological performance by optimizing surface roughness through appropriate material selection and treatment is essential for ensuring the efficiency and longevity of mechanical systems. Figure 8 presents the data collected for palm oil and VCO. From the data, the highest surface roughness value is observed with virgin coconut oil (VCO) at 0.5 µm on disc sample 10, with a 15% concentration, a load of 30 N, and a speed of 900 rpm. The lowest surface roughness value is recorded for palm oil at 0.04 µm, which occurs on two-disc samples, disc 5 and disc 6. Both discs have the same concentration and speed, 15% concentration and 750 rpm, but different loads of 30 N and 15 N, respectively.

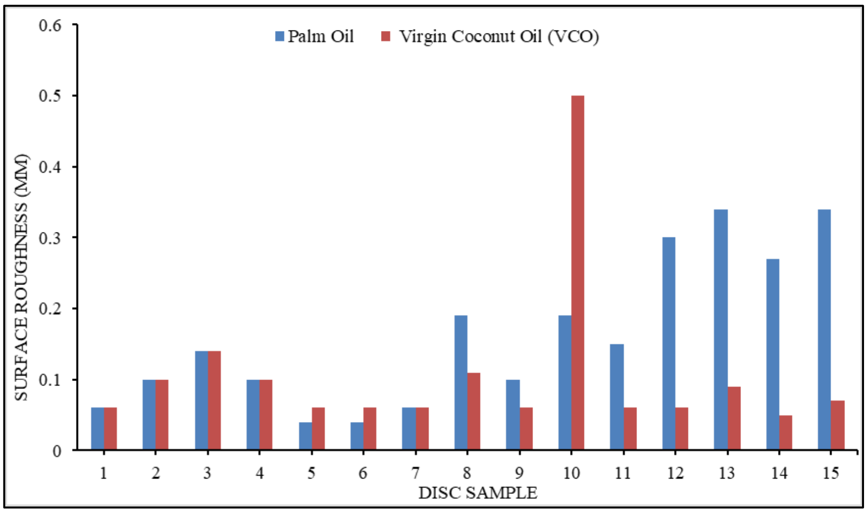

Fig. 8. Surface roughness vs disc sample

4. Conclusions

This study aimed to assess the impact of adding palm oil and virgin coconut oil to industrial gear oil on the wear rate, coefficient of friction (COF), and surface roughness of the oil samples. Factors such as operational speed, applied load, oil concentration, and viscosity were critical in influencing these outcomes. Viscosity tests conducted at temperatures of 40°C and 100°C revealed that pure gear oil had the highest viscosity, whereas a 30% concentration of virgin coconut oil had the lowest viscosity. While no single sample was found to be optimal for both COF and wear rate, certain samples demonstrated better individual values for these parameters. Sample PD13, which contained 30% palm oil, had the lowest wear rate at 0.0000019 mm^3/Nm, indicating that higher concentrations of palm oil could significantly reduce wear rates. On the other hand, sample PD6, consisting of virgin coconut oil (VCO), recorded the lowest COF at -0.039082. Regarding surface roughness, the blended VCO samples consistently exhibited low values, with disc samples 5 and 6 having the lowest Ra of 0.04 µm.

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