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RESEARCH

Comparative Investigation of Lubricant Properties of Pongamia and Castor Oil Bio Lubricant Blended with (SAE20W40) Mineral Oil

Ajoy Sahu[a,*], Niharendu Saha[b]

[a]*Department of Mechanical Engineering, Assam Science & Technology University, India,*
[b]*Department of Mechanical Engineering, Assam Engineering College, India.*

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* Corresponding author:

Ajoy Sahu
E-mail: ajoys10@gmail.com

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A B S T R A C T

The present work deals with the comparative evaluation of physicochemical, rheological FTIR and tribological properties between pongamia and castor oil blended with SAE20W40 by varying their proportions ranging from 10-30% (by volume) as bio-lubricant. Among all the blends, the flash point and pour point of castor blend S4 were found to be 281°C and -19°C which can be comparable to SAE20W40. The viscosity at 40°C and 100°C and viscosity index of castor blends were approximately 100 mm²/s, 14 mm²/s and 145 respectively. FTIR analysis also confirms the presence of vital carbonyl ester functional group in castor blends with oxidation onset temperature of 243°C. The tribological studies that were carried out using pin on disc tribometer as per ASTM G99-95a standards also showed that blend S4 had coefficient of friction 0.056 at higher load which was comparable to SAE20W40. Although all the blends had low oxidation stability temperature, yet castor blend S4 showed equivalent properties with commercial lubricant SAE20W40. This confirmed its suitability as a bio-lubricant base stock, supported by its physiochemical, rheological, FTIR, tribological properties.

1. INTRODUCTION

Lubricants are essential components of modern machinery. As their name suggests, lubricants are substances applied to adjacent surfaces to ease the movement of parts, reducing friction and, consequently, heat generation. Given the paramount importance of sustainability in today's economy, resource conservation, energy efficiency, and emissions reduction have risen to the forefront of environmental concerns. In response, commercial processes have evolved, placing greater emphasis on resource preservation and a commitment to future generations. Lubricants, due to their relevance to socioeconomic and environmental sustainability, have emerged as a focal point of social awareness [1-2].

Plant seed-derived oils are non-toxic, biodegradable, and non-hazardous. They have a higher viscosity (30–80%) than mineral oil and offer better lubricity due to higher esters. They are about 95% biodegradable, much more than mineral oil, and have a 25–35% disposal rate, reducing disposal costs [3]. Vegetable oil-based lubricants are widely used in various industries, especially in the European automotive sector, as well as in metal forming, manufacturing, and journal-bearing applications [4-5]. India's rich forest resources, including affordable non-edible oils like babassu, mahua, neem, karanja, castor, and jatropha, are being explored as eco-friendly lubricant sources.

Castor seed is a type of spurge species contains approximately 45–60% of oil. The majority of this non-edible oil (80–90%) comprises hydroxylated fatty acids. Among them ricinoleic acid is predominant. These acids possess distinctive physicochemical properties such as a higher specific gravity, viscosity and also hydroxyl value [6]. The ability of castor oil to blend with methanol or ethanol has established its distinctive role in esterification processes that involve enzymes. The inhibitory impact of alcoholic substrates on lipase activity is minimal, thereby promoting the progression of the reaction [7]. Consequently, castor oil has been recognized as the preferred raw material for producing bio lubricants [8]. As it has a substantial amount of monosaturated fatty acid present so its thermal oxidative stability increases. This makes it a popular choice in industries that operate under high-temperature conditions. Castor plant can thrive in 30 different countries [9].

Pongamia pinnata, a tree that falls under the fabaceae family is renowned for its multifaceted utility, particularly as a source of lubricant [10]. The yield of kernels per tree can range from 8 to 24 kg [11]. The most valuable product produced by this tree is its seed or nut. Its versatility extends beyond providing green manure and medicinal resources [11]. The Pongamia oil has high flash point of 269°C compared to mineral oils, which typically have a flash point of around 200°C. This property not only aids in reducing emissions but also makes it an ideal choice for various applications. Additionally, this tree displays remarkable adaptability, thriving in infertile soils and diverse agro-climatic conditions. With a notably high percentage of polysaturated fatty acids and an oil yield ranging from 28% to 34% [12]. This medium-sized glabrous tree typically flourishes in moist environments along rivers and coastal areas throughout India. Moreover, it extends its distribution eastwards, particularly in the littoral regions of Southeast Asia, including Indonesia, Malaysia, Philippines and even USA [13].

Though Bio-lubricants are eco-friendly in nature, but they do come with certain limitations, including lower thermal stability which leads to oxidation and low pour point [14-15]. These can be enhanced through the incorporation of additives [16-17]. For regions with low-temperature concerns, such as tropical countries, solutions like transesterification or epoxidation can be employed to improve oxidation stability [18-19]. To make bio lubricants more sustainable and versatile, expanding the available range of viscosities is imperative [20]. Viscosity plays a critical role in determining the coefficient of friction between sliding surfaces, forming a protective film that mitigates wear. Environmentally friendly viscosity modifiers can be employed.

One notable development involves the addition of TiO_2 nanoparticles, which enhances kinematic viscosity and decreases the wear rate [21-22]. Nano-fluids containing multi-walled carbon nanotubes (MWCNT) and graphene nanoplatelets (GNP) as nanoparticles exhibit better viscosity and density [23-24]. For a blend of conventional and bio-based lubricants, ethylene-vinyl acetate (EVA) copolymer acts as a highly effective thickening agent [25]. Styrene-butadiene- styrene can also be incorporated with ethylene-vinyl acetate for enhancement of viscosity at 40°C and 100°C [26]. Additionally, ZnO and MoS_2 nanoparticles promote tribological properties [27]. Despite the advantages of bio-based lubricants over mineral-based lubricants, relatively few studies have explored their development, and their practical applications remain limited. This underscores the need for further research and innovation in the field to unlock the full potential of these sustainable lubricants.

The objective of the study is to evaluate the feasibility of utilizing renewable resources for the production of bio-lubricants. These resources are

plant based oils, namely castor (Ricinus communis) and karanja (Pongamia pinnata). Different ratios (by volume) of these oils were mixed with a base lubricant (SAE 20W40) to obtain the blends. The physiochemical properties of blended bio-lubricants along with the associated tribological characteristics were analyzed. Friction and wear analysis were also carried out with the blends of Pongamia and Castor oil with SAE 20W 40 using a pin-on-disc tribometer at two different loads.

2. MATERIALS AND METHODS

2.1 Lubricant sample preparation

The seeds of pongamia and castor were collected locally and oven dried at a temperature of 60°C for 6 hours. After that the seeds were unshelled and kernels were again oven dried for 12 hours at a temperature of 60°C. The reported mean particle size and seed-to-solvent ratio of kernels for optimal oil yield were 0.1-0.8 mm and 1:6 respectively [28]. In this study, the kernels were dried first then grounded and then sieved to a size of 0.6 mm. Oils were extracted from the ground masses of both the seeds with the help of Soxhlet extractor using n-hexane (99% AR) as solvent. After the extraction, solvent from the extract was removed with the help of rotary vacuum evaporator (IKA, RV-3V, Germany). The extracted oils were then filtered and weighed to determine the yield of extraction. The yield of both the oils was calculated using Eq. 1

Table 1. Pongamia and Castor blends with their proportions.

Sample name	Sample	Volume of oil (in %)	Volume of SAE20W40
S1	pongamia blend-10	10	90
S2	pongamia blend-20	20	80
S3	pongamia blend-30	30	70
S4	castor blend-10	10	90
S5	castor blend-20	20	80
S6	castor blend-30	30	70

$$\text{Yield of oil} = \left(\frac{\text{mass of oil}}{\text{Mass of the sample}}\right) \times 100\% \qquad (1)$$

After extracting both the oils, different ratios (by volume) of pongamia and castor were mixed with base lubricant SAE20W40 to obtain the blends. For each sample, three different blends were prepared by mixing bio oil with base oil in the ratio of 10, 20 and 30 per cent by volume as represented in Table 1. The mixtures were prepared by using magnetic stirrer for thirty minutes with a rotational speed of 1000 rpm (revolutions per minute). The mixtures were stored in air tight containers to avoid contamination of the samples.

2.2 Thermal property analysis

The fire and flash points of the blended samples were determined in accordance with ASTM D-97 standards using a Cleveland open cup apparatus. The pour points of pongamia and castor blends were measured following ASTM D 97. For this, a cylinder containing 50 ml of the oil sample was surrounded by a cooling medium. The pour point is defined as the temperature at which the sample ceases to flow, and it was measured with an accuracy of ±1 °C. Density (kg/m^3) determination as also obtained using pycnometer.

2.3 Rheological properties

The viscosity of the lubricants was determined using an Anton Paar's Modula compact Rheometer (MCR-102) within a temperature range of 40°C to 100°C, with a shear rate of 10-1500 s^{-1} following ASTM D-445 standards. The measurement setup employed a cone-and-plate geometry in accordance with ISO 3219 standards. The cone and plate with cone angle 1^0, had a diameter of 40 mm. Each measurement utilized a sample volume of less than 1 ml. Temperature variations were managed through a flange ring that leveraged the Peltier effect, enabling control over both temperature increases and decreases. Each sample underwent three measurement trials, and the average viscosity was calculated. The viscosity index (VI) was determined based on ASTM D 2270-10, 2016 as the chosen standard using Eq. 2 [29]

$$V.I = \left[\frac{\{(antilogN)-1\}}{0.00715}\right] + 100 \qquad (2)$$

where $N = \left(\frac{logH-logU}{logY}\right)$

Where U and Y indicates kinematic viscosity (mm^2/s) of considered oil at 40°C and 100°C respectively. H denotes the kinematic viscosity (mm^2/s) measured at 40°C of an oil with a viscosity index of 100, having an equivalent kinematic viscosity at 100°C as the oil under evaluation.

2.4 FTIR analysis

Fourier transforms infrared (FT-IR) spectroscopy is a technique that can be used to determine structural characteristics of biolubricants [30]. The produced biolubricants were performed on Agilent Cary Win-360 FT-IR Spectrometer. All the analyses were conducted with the wave number set in the range of 4000-650 cm^{-1}.

2.5 Oxidation stability analysis

The thermo-gravimetric analysis (TGA) method was considered an effective approach in determining oxidation stability. In this process the mass loss was monitored during a programmed temperature process. It actually indicates the oil's shelf life under normal atmospheric conditions. The analysis was conducted using a thermal gravimetric analyzer (TGA) instrument manufactured by Mettler Toledo (model TGA2). For this the a 25–600°C temperature range was considered. The heating rate was 10 °C/min with a sample weight of 10– 11 mg. The analysis was carried out under pure oxygen (O_2) atmosphere.

2.6 Tribological property analysis

The tribological testing of samples were conducted using a Ducom Pin-On-Disc Tribometer in accordance with ASTM G99-95a standards. This test aimed to determine key parameters such as frictional force, wear, and the coefficient of friction. The results obtained from these tests were then utilized to analyze and identify the best-performing blend among all the samples. A digital weighing balance was utilized to determine weight loss of the pin by recording its weight before and after usage. Low coefficient of friction and low wear are the desired properties.

The pin material was low carbon steel with 10 mm of diameter and 30 mm of height. The disc was made up of high carbon alloy steel EN31 having a diameter of 80mm and thickness of 10 mm. The load on the pin was varied from 50 N to 100 N for each blended sample. Few drops of each sample were added at a constant interval of time. The rotational speed for the pin was selected at 1100 revolutions per minute and a wear track diameter of 60 mm. Duration of each test was 600 seconds. Prior to each test, the contact surfaces of the pin specimen were polished using emery paper of 1000 grit size (SiC) and after that it was cleaned with acetone. The test results were then analyzed for determining the best performing blend among all the test samples.

Table 2. Percentage of uncertainty associated with various parameters for pongamia and castor blends.

Parameters	Instrument used		Uncertainty	% Uncertainty
Density	Pycnometer with thermometer AS-R- Analytical Balance		±0.01 ml and ±0.2°C (thermometer) ±0.0001 g	0.595
Pour point	Cloud and Pour point apparatus		±0.1°C	1.49
Flash Point	Cleveland open cup tester		±0.5°C	0.579
Kinematic Viscosity	Anton Paas Viscometer	40°C	±0.05	0.0191
		100°C		1.167

2.7 Uncertainty analysis

Uncertainties or errors can occur in experiments due to various factors such as instrument selection, environmental conditions, observations etc. Since the devices used in this study had different levels of accuracy, the parameters measured with these devices also contained errors. Therefore, it was necessary to investigate the effect of measurement errors on these results. The uncertainities were determined using the method followed by Mohammadfam et.al. 2020 [31]. If R is a function of experimental variables such as x_1, x_2, x_3, …, x_n, the following relation is used to calculate the measurement error of the parameter x_i:

$$U_{Ri} = \frac{x_i}{R}\frac{\partial R}{\partial x_i}u_{x_i}$$

where xi is the measurable quantity and u_{xi} the measurement error. The maximum error of parameter R is calculated by combining the error of each parameter x_i using the following equation:

$$U_R = \pm\left\{\left(\frac{x_1}{R}\frac{\partial R}{\partial x_1}u_{x_1}\right)^2 + \left(\frac{x_2}{R}\frac{\partial R}{\partial x_2}u_{x_2}\right)^2 + \cdots + \left(\frac{x_n}{R}\frac{\partial R}{\partial x_n}u_{x_n}\right)^2\right\}^{\frac{1}{2}}$$

The overall uncertainity of these experimental results is calculated by taking the squareroot of the sum of all individual uncertainity associated with the parameters. Thus the value obtained is ±2.049%, so the accuracy of the results can be accepted within±3%.

3 RESULTS AND DISCUSSION

3.1 Physico-chemical properties

In this study the physic-chemical properties of the blended biolubricants measured were density, fire point, flash point, pour point and cloud point. As shown in Table 3, the density of the blended samples was measured at room temperature. It is the ratio between mass of sample to its volume at same temperature. S1, S2 and S4 samples have approximately same density when compared with standard SAE20W40. The pour point is a crucial characteristic for bio lubricants intended for use in countries with low-temperature climates. As presented in Table 3, the pour points of castor blends were lower than that of pongamia blends. This variation is attributed to the presence of polyunsaturated fatty acids. Although all the three castor blends have comparable pour point value with SAE20W40, sample S4 stands closely with it which can be considered as preferable blend ratio with respect to pour point [32]. The flash point of all the blends was found to be much higher than that of the standard lubricating oil. A higher value of the flash point indicates a low tendency for evaporation and enhances resistance to fire hazards during operation [32].

Table 3. Physicochemical properties of pongamia, castor, SAE20W40 and their blends.

Sample Name	Density (kg/m³)	Flash Point (°C)	Pour Point (°C)
S1	895	269.1	-16
S2	897	267	-15
S3	903	264.4	-15
S4	899	281	-19
S5	907	273	-17
S6	915	265.2	-17
Pongamia	924	248	-3
Castor	966	234	-5
SAE20W40	887	240	-20

3.2 Rheological properties

The rheological properties of any lubricants is a crucial characteristic to measure from an engineering perspective. These properties were characterized by examining the relationship between shear rate and shear stress. Shear rate is the rate at which fluid layers or lamina move past each other. On the other hand, shear stress is the force per unit area. The viscosity of a fluid represents the relationship between shear stress and shear rate, providing insights into how the lubricant behaves under different flow conditions [30]. Understanding these rheological parameters is essential for optimizing the performance of lubricants in engineering applications. High viscosity always stands as an essential requirement for good quality lubricant [32]. For industrial applications, the recommended viscosity ranges between 5-15 mm²/s at 100 °C which can be comparable with commercial lubricants. Maintaining the appropriate viscosity is essential for ensuring the optimal performance and longevity of lubricated systems in various industrial settings [33]. Table 4 shows the kinematic viscosity at 40°C, 100°C and viscosity index of all the blended samples along with the SAE20W40. From the Table 4 it can be said that all the castor blends were comparable in all three mentioned aspects when compared with standard lubricant. And also implies that the viscosity temperature relation has less influence at high temperature.

Table 4. Rheological properties of pongamia, castor, SAE20W40 and their blends.

Sample Name	Kinematic viscosity (mm²/s)		Viscosity Index
	at 40°C	at 100°C	
S1	93.877±0.610^{B}	13.367±0.153^{B}	143.05
S2	84.777±0.502^{C}	12.817±0.135^{C}	149.744
S3	80.780±0.354^{D}	12.177±0.155^{D}	146.968
S4	100.1±0.656^{D}	14.25±0.261^{B}	145.29
S5	102.48±0.452^{C}	14.38±0.210^{B}	142.79
S6	104.91±0.390^{B}	13.96±0.241^{B}	134.88
SAE20 W40	104.81±0.301^{B}	14.417±0.11^{B}	140.73
Castor	238.2±0.755^{A}	19.253±0.248^{A}	91.26
Pongamia	38.963±0.235^{E}	8.567±0.208^{E}	203.55

Data are expressed as mean ± standard deviation (S.D.).
A, B, C, D, E means that do not share a letter are significantly different.

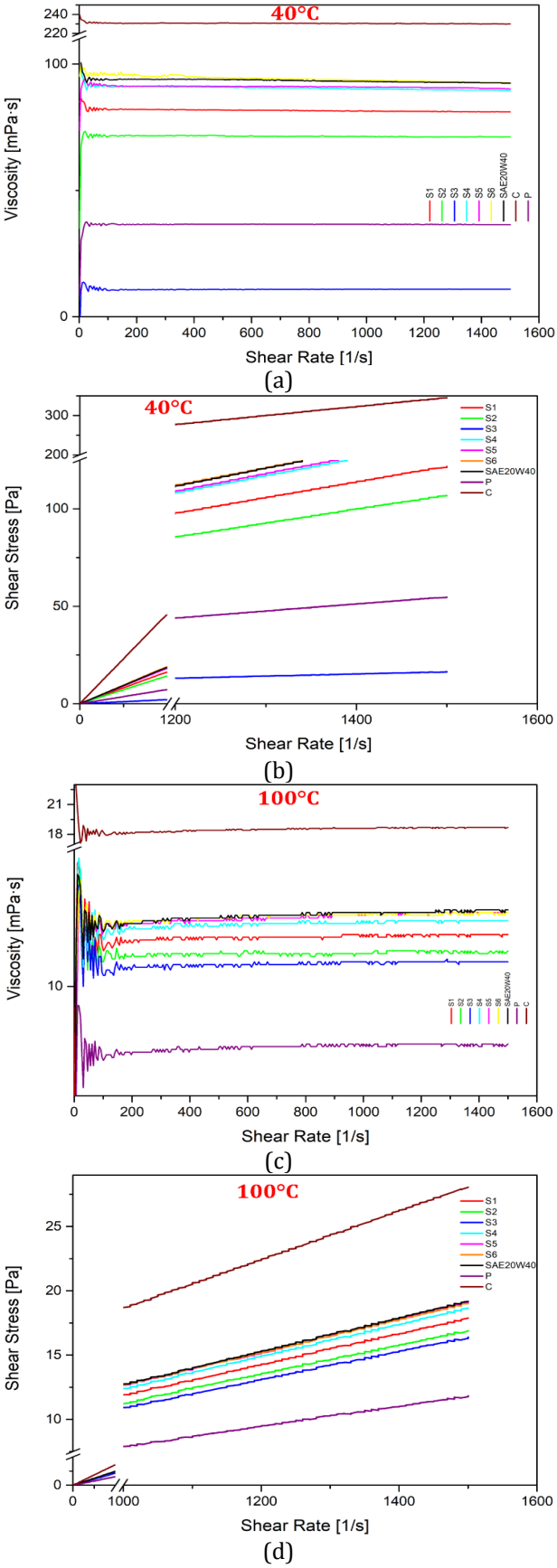
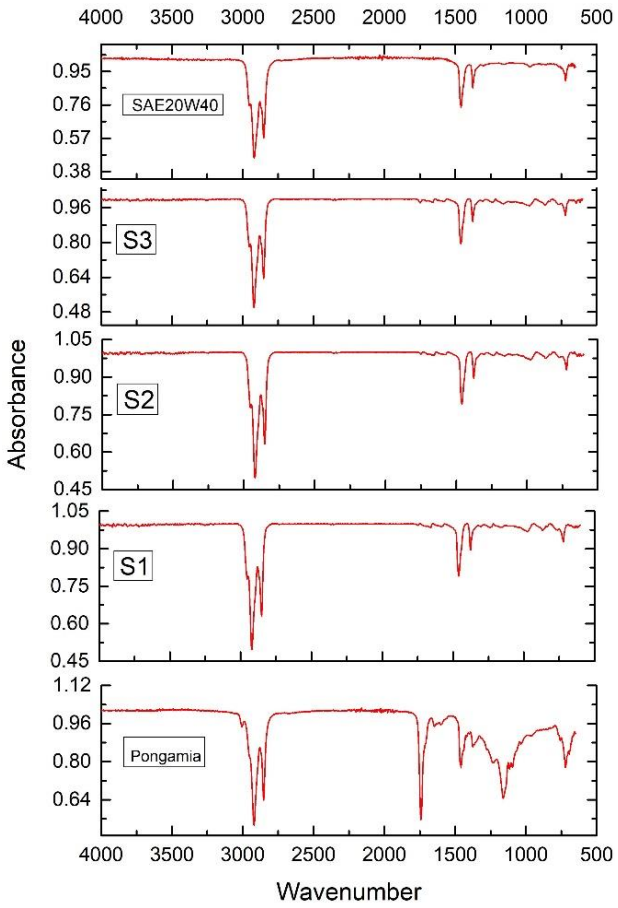


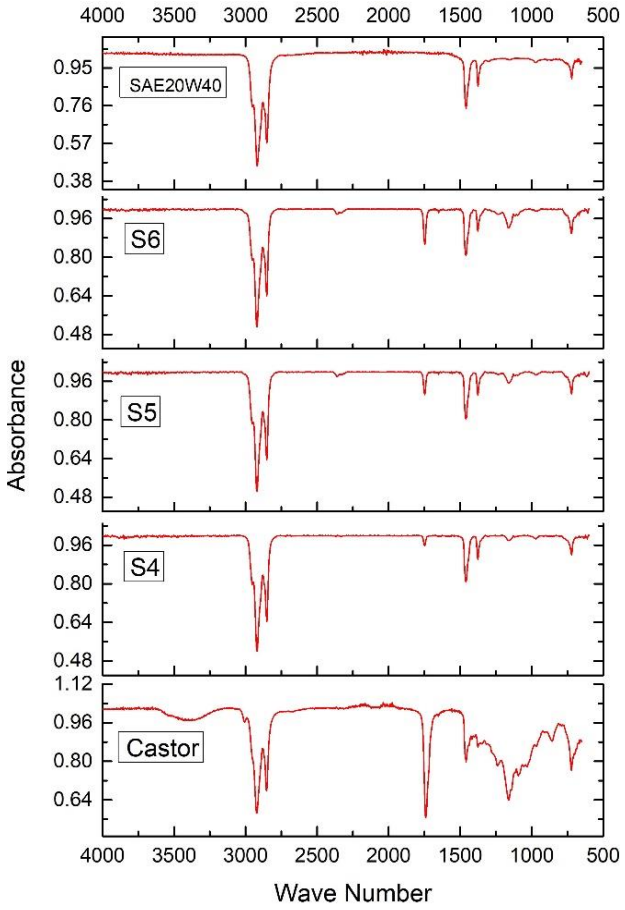
Fig. 1. (a) Dynamic viscosity vs shear rate (b) Shear stress vs shear rate at 40°C (c) Dynamic viscosity vs shear rate (d) Shear stress vs shear rate at 100°C of pongamia, castor, SAE20W40 and their blends.

Figure 1b and 1d represented the relationship between shear stress (Pa) and shear rate (s^{-1}) at temperatures of 40°C and 100°C, respectively. The letter 'P' indicated pongamia oil, while the letter 'C' indicated castor oil. The observation from the figures revealed that shear stress increased linearly with an increase in shear rate. This linear relationship between shear rate and shear stress was consistent within the temperature range of 40-100°C, providing evidence of Newtonian behavior for all oil samples. Additionally, Figures 1a and 1c illustrated the variation of dynamic viscosity (mPa-s) concerning shear rate (s^{-1}). In this case, viscosity was observed to remain relatively constant over the shear rate range of 100-1500s^{-1}. However, when comparing with the standard SAE 20W40, only castor blend samples closely followed the profile of SAE 20W40. Consequently, castor oil can be considered as a blending oil with SAE 20W40.

3.3 FTIR Spectroscopy analysis

Fourier Transform Infrared Spectroscopy (FTIR) analysis was employed to identify the functional groups present in the blended samples.





(b)

Fig. 2. FTIR analysis of (a) pongamia, SAE20W40 and their blends (b) castor, SAE20W40 and their blends

Figure 2a represents the FTIR analysis of pongamia blends. C-H stretching vibrations at 2912 and 2850 cm^{-1} suggested the presence of alkanes. The presence of alkenes was indicated by a peak between 1666 cm^{-1} and 1580 cm^{-1}, corresponding to C=C stretching vibrations. The presence of alcohols was shown by the detection of O-H stretching vibrations at 1371cm^{-1}. Peaks in the interval of 977-721 cm^{-1} indicate the presence of aromatic compounds.

Figures 2b shows the FTIR analysis of castor blends. The stretching vibrations of alkanes were observed at 2912 and 2850 cm^{-1}. In the absorption spectrum ranging from 1454 to 1379 cm^{-1}, bands with asymmetric and symmetric vibrations indicated the presence of alkene (C = C) groups in the bio-lubricants. The presence of alcohols and aromatic compounds was indicated by the peaks at 1371 cm^{-1} and 977-721 cm^{-1} respectively.

Notably, castor blends exhibit a characteristic peak at 1751 cm^{-1}, indicating stretching vibrations associated with carbonyl ester functional groups present in the oil. The strong absorption peak at 1751 cm^{-1}, attributed to the C=O stretching of the ester group, confirms its presence in the blend. Additionally, a two-band peak ranging from 1163 cm^{-1} to 1225 cm^{-1} corresponds to the C-O stretching mode of the C-OH group in esters. As reported by *Ghosh et.al., 2018* these functional groups, identified by these bands, play a significant role in enhancing the qualities of bio-lubricants as a suitable alternative [34].

3.4 Oxidation stability analysis

The thermal behavior of all the oil samples in oxygen atmosphere were presented in Fig. 3. It includes the typical TGA mass loss curve and the differential thermal gravimetric (DTG) curve with respect to temperature ranging from 25-600 ^{0}C. The curves of all the samples displayed in figure exhibits similar trend. It also showed involvement of multiple events, thus indicating comparable thermal mechanisms were at play in the degradation processes.

In TGA analysis, a crucial parameter was the onset temperature, specifically the first stage temperature at where 2% of weight loss occurred [35], as indicated by previous research [36]. The onset temperature for pongamia and castor blends along with SAE20W40 were shown in Table 5. It can be seen that castor blends S4, S5, S6 exhibits slightly better oxidation stability than pongamia blends S1, S2, S3. Although previous research suggested that onset temperature with 200 ^{0}C possessed good thermal stability [37]. But the presence of hydroxyl group in both the pongamia and castor blends showed better than 200^{0}C [38]. When compared with SAE20W40, castor blends S4 comes close to it in respect of onset temperature.

Table 5. Oxidation onset temperature of pongamia and castor blends with SAE20W40.

Sample name	Oxidative onset temperature (^{0}C)	Method
S1	235.667	TGA
S2	230.167	TGA
S3	235.0	TGA
S4	243.5	TGA
S5	236.83	TGA
S6	242.167	TGA
SAE20W40	272.0	TGA

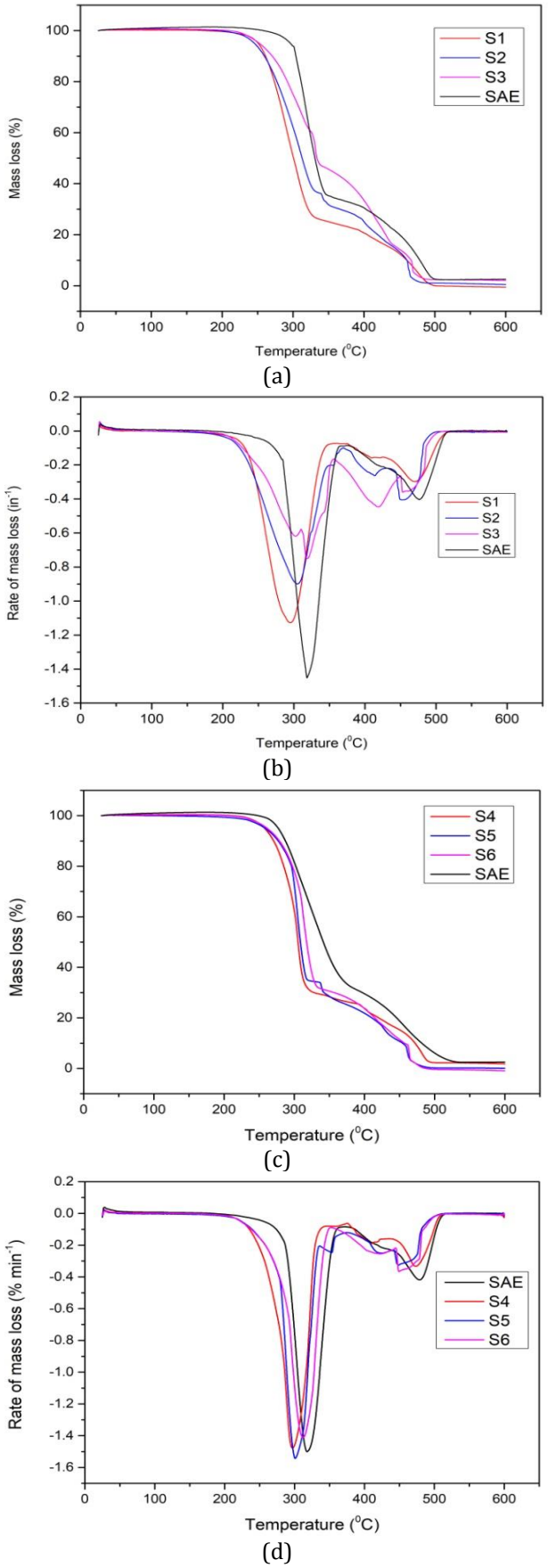


Fig. 3. (a) TG and (b) DTG profiles of pongamia blends and SAE20W40 (c) TG and (d) DTG profile of castor blends and SAE20W40

The DTG curves are derived from typical TGA mass loss curves with respect to heating temperature. They show the rate of weight reduction and are primarily employed to analyse processes and differentiate various stages of the reaction. From the DTG curve of pongamia blends as presented in Fig 3b, three oxidation stages with peaks were observed at the temperature of 295 ^{0}C, 408 ^{0}C, 469 ^{0}C for S1, 304^{0}C, 413^{0}C, 453^{0}C for S2 and 301^{0}C, 417^{0}C,452^{0}C for S3 respectively. For the castor blends as presented in Fig 3d the three oxidation peaks were seen at the temperature ranges from 296^{0}C, 410 ^{0}C and 474^{0}C for S4, 301^{0}C, 423^{0}C, 448^{0}C for S5 and 312^{0}C, 424^{0}C, 449^{0}C for S6 respectively. For standard lubricant SAE20W40 these three peaks were seen at 318^{0}C, 422^{0}C and 477^{0}C respectively. The peak observed in the first stage was regarded as the most significant, as it indicated the initial degradation process of triglycerides [39]. In this phase, the formation and accumulation of peroxides occurred through the reaction with oxygen [40]. Therefore, this stage was crucial in determining the thermal stability of oils [41]. In this ground castor blends were found more prominent to pongamia blends with respect to SAE20W40.

3.5 Tribological properties

A set of experiments were performed to determine frictional characteristics of the sliding pair using a pin on disc tribometer. The lubricants, including all the blended samples and SAE20W40, were applied between the contact surfaces at room temperature for a sliding distance of 2072 meter. To record the frictional data generated by the pin on disc controller, the win ducom software has been used.

The variation of the coefficient of friction (CoF) with respect to time for 50 N and 100 N loads is represented in Figure 4a and 4b respectively. Initially, a significant CoF variation occurred, due to the roughness associated with the sliding pair, hence high asperity constant generates which results additional force of friction [41,42]. In the preliminary run, the film of lubrication didn't develop sufficiently, leading to the breakdown of the deposited layer and a clean pin and disc metallic contact surface appeared. Due to this the bonding force between the contact surface increased. After a particular duration, rubbing generated a consistent fluid film, which led to an increase in partial load-carrying capacity to a certain extent. This resulted in the smoothing of the friction surface and a reduction in the variation of the coefficient of friction.

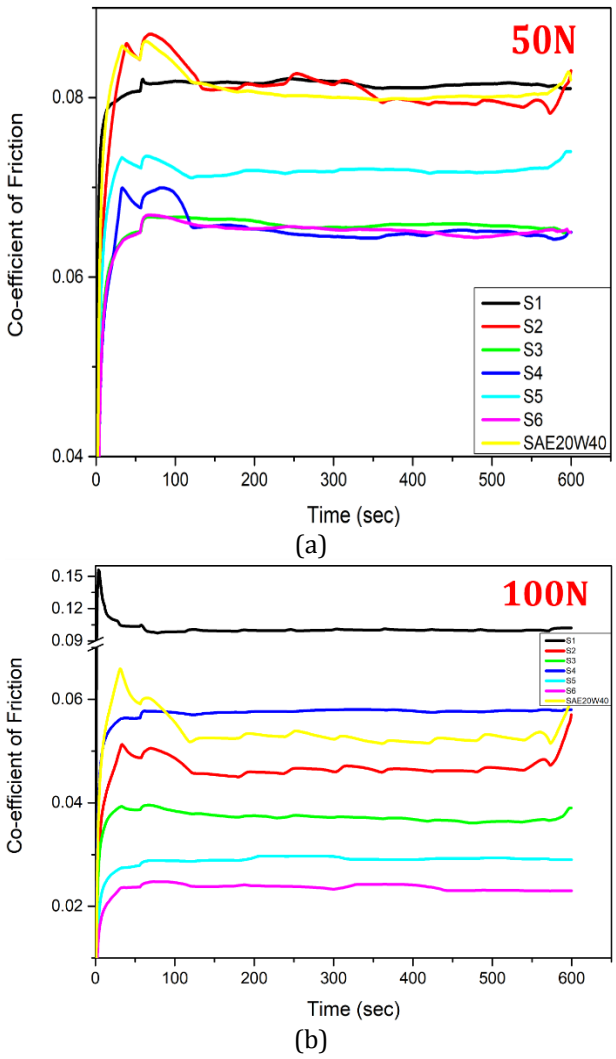


Fig. 4. Variation of coefficient of friction with time at 28°C (a) for 50N and (b) for 100N.

Vegetable oils contains saturated, monounsaturated, and polyunsaturated fatty acids due to which bio-lubricants exhibit better tribological properties [43]. This implied a comparable CoF for all the blends with standard SAE20W40. However, castor blends showed better tribological behavior than pongamia blends for both loads because castor oil is rich in ricinoleic acid, a fatty acid with a hydroxyl group that enhanced film formation on metal surfaces. The hydroxyl group in ricinoleic acid increased the polarity of castor oil, which led to the formation of a strong lubricating film and enhanced the ability to adhere to metal surfaces. This strong film helped in reducing friction and wear more effectively than the fatty acids present in pongamia oil. It could be seen from figure 4a and 4b that pongamia blends S1, S2, and S3 showed more variation of CoF than castor blends S4, S5, and S6.

The TGA analysis revealed that castor blends had better oxidation stability than pongamia blends. This meant they could retain their lubricity at higher temperatures and resist oxidation, preventing the formation of corrosive substances that could affect tribological behavior.

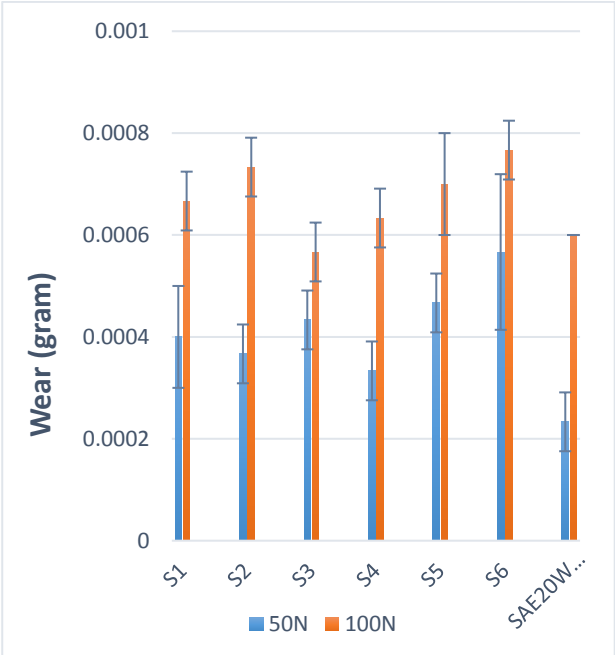


Fig. 5. Variation in weight loss of all the blended samples at 50N and 100N load

For the study of wear behavior, the pin's loss of weight was determined by estimating its weight (g) pre and post experiment with an electronic weighing machine maintaining an 0.0001 g accuracy. Figure 5 compares the pin's weight loss under two different loading conditions for seven different lubrication conditions: six with the bio-lubricants samples under study and the last one is a control sample of SAE 20W40. All the tests were carried out at room temperature.

At 50 N loads, wear was similar for pongamia blends S1 and S2, while it increased slightly for S3 blend. However, for castor blends S4, S5, and S6, a consistent increase in wear was observed with the higher proportion of castor oil. For the 100N load, wear patterns were consistent across all blends except for S3 and S6. The wear was higher for 100N load than 50N.

This is obvious as increased load generates higher frictional heat on the surface, leading to thermal softening as well as plastic deformation. Consequently, the material's strength decreased, leading to an increased wear rate [44,45].

The image captured from the microscope at 100 μm scale for analyzing the worn surfaces of the pin are shown in figures 6-9. After each time of pin on disc experiment, the contacted pin surface with disc was analyzed using optical microscope. From figure 6, 7, 8 and 9 it can be seen that when the load was increased from 50N to 100N, the pin surfaces become smoother. This occurs because the increased applied force leads to the formation of a wear debris layer, which then disintegrated into smaller pieces. The subsequent reduction in size leads to smoothing of the contact surfaces between the pin and disc as they roll over each other [46]. It can be seen from figure 6 and 7 that the pin face for Pongamia blends at 50N load do not show smoother surface. Although smoothness increases for 100N load, but they were no comparable to SAE20W40. On the other hand, the pin face smoothness for castor blends were better than pongamia blend as seen from figure 8 and 9. The severity of wear scars correlates with poorer lubrication [47]. The presence of ester group in castor blends as detected by FTIR analysis can significantly improve the wear resistance of mechanical systems [43]. The polar nature of ester strongly adheres the metal surfaces and its inherent lubricity helps in reducing wear and ensure smoother movement between surfaces [48]. Ester-based lubricants also resist hydrolysis, maintaining their effectiveness in the presence of water, which can otherwise promote wear and corrosion [48]. From the analysis of both (variation of COF with time and wear behavior) the results, it can be stated that castor blends have better tribological behavior over pongamia blends. Given these wear behaviors, blend S4 emerges as the most suitable option among all and exhibits similar wear behavior with standard SAE20W40.

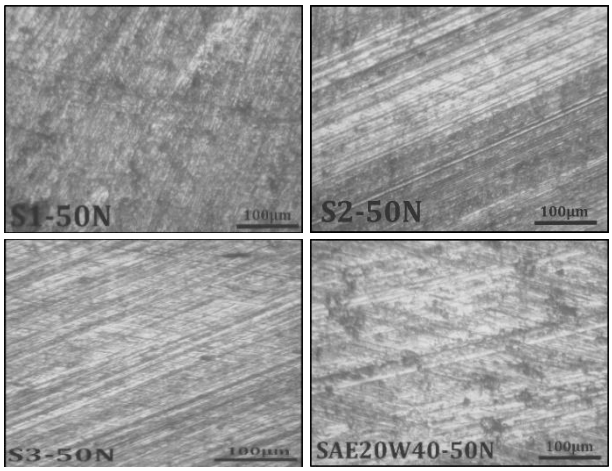


Fig. 6. Microscale images of worn pin surfaces lubricated with S1, S2, S3, and SAE20W40 under 50N load

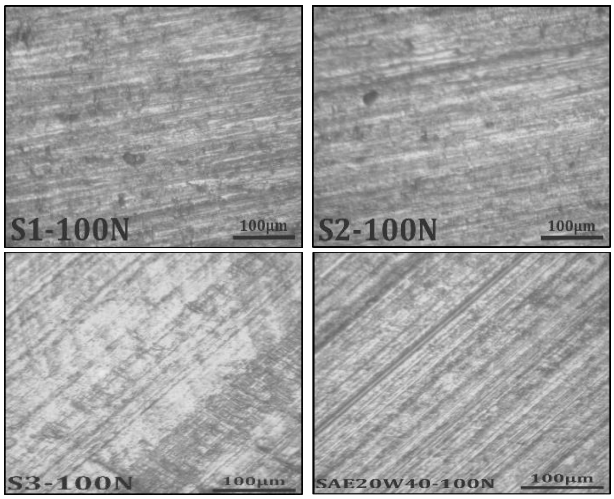


Fig. 7. Microscale images of worn pin surfaces lubricated with S1, S2, S3, and SAE20W40 under 100N load.

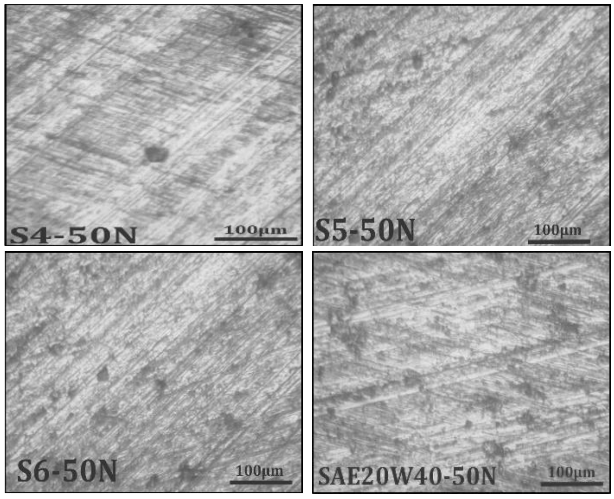


Fig. 8. Microscale images of the worn pin surfaces lubricated with S4, S5, S6, and SAE20W40 under 50N load.

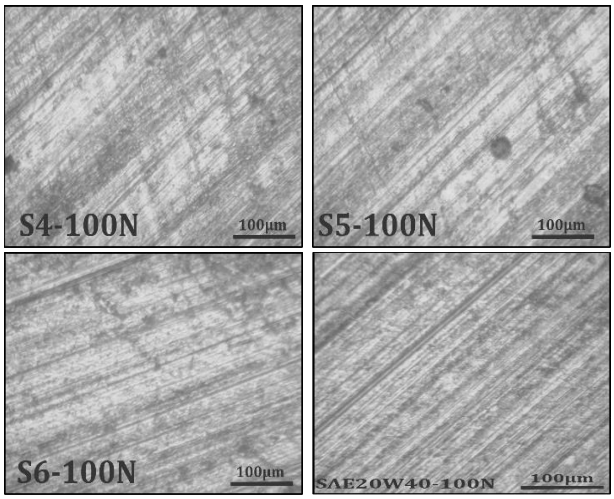


Fig. 9. Microscale images of the worn pin surfaces lubricated with S4, S5, S6, and SAE20W40 under 100N load.

4. CONCLUSIONS

In the present study, pongamia oils and castor oils were extracted chemically by using soxhlet extractor. These oils were then blended with SAE20W40 by varying proportions ranging from 10 – 30% (by volume). Three samples each from pongamia oil S1, S2, S3 and castor oil S4, S5, S6 were prepared. After that their physiochemical, rheological, FTIR analysis, Thermo oxidation stability and tribological studies were carried out. The following were the conclusions that have been drawn from the experimental results.

- Among all the prepared samples, castor blend S4 which contains 10% of castor oil shows lower pour point. As pour point is crucial property for the bio lubricants which were intended to use in cold climate countries. The value of Flash point for S4 blend was recorded as higher among all the samples which is a required property for fire hazards enhancement.
- The rheological studies suggest that castor blends have better rheological properties than pongamia blends. The kinematic viscosity (mm^2/s) of castor blend S4 and S5 at 40 ^{0}C and 100 ^{0}C of temperature were comparable to that of SAE20W40.
- From the FTIR analysis it can be said that castor blends possess carbonyl ester functional groups which is necessary for the production of bio lubricants.
- The TGA analysis indicates that the oxidation onset temperature of castor blend S4 and S5 were comparable to SAE20W40.
- Tribological studies (variation of COF with time and wear behavior) suggested that castor blends have better tribological behavior than pongamia blends. Blend S4 shows similar wear behavior with standard SAE20W40.

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ORCID iDs

Ajoy Sahu 0009-0009-9108-2614
Niharendu Saha 0009-0003-2738-1106

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