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Research Article

Tribological Studies on AISI 1040 with Raw and Modified Versions of Pongam and Jatropha Vegetable Oils as Lubricants

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The friction and wear tests on AISI 1040 are carried out under raw, modified versions of two nonedible vegetable oils Pongam (*Pongamia pinnata*) and Jatropha (*Jatropha curcas*) and also commercially available mineral oil using a pin-on-disc tribometer for various sliding distances and loads. A significant drop in friction and wear for AISI 1040 is observed under Pongam and Jatropha raw oil compared to mineral oil, for the complete tested sliding distance and load, increasing the potential of vegetable oil for tribological applications. Stribeck curves are also drawn to understand the regimes of lubrication. Both the vegetable oils showed a clear reduction in the boundary lubrication regimes, leading to an early start of full film lubrication.

1. Introduction

Escalating prices, rapid depletion of fossil reserves as well as the stringent legislations enforced by the International authorities have enlarged the scope around the globe to explore alternative ecofriendly lubricants [1, 2]. Oils of plant origin are promising, renewable, environmental the friendly, and nontoxic fluids, pose no work place health hazards and are readily biodegradable. Vegetable oils exhibit, number of performance blessings such as natural high viscosity (30 to 80% higher than mineral oil) and excellent lubricity due to their ester functionality. These are over 95% bio degradable and thus degrade much faster than mineral oils (20 to 30%), thereby offering greater potential when it comes to reducing the cost of disposal [3]. Another important property of vegetable oils is their highflash points; for instance the flash point of Soybean oil is 326°C while mineral oils have approximately 200°C, thus reducing emissions and work place pollution. Further, biobased lubricants help to provide energy security for countries who use them and create local and regional economic development opportunities.

Vegetable-based oils are finding their applications in various sectors of industry. For instance, the automotive lubricants derived from rapeseed, soy, and sunflower oils are finding good markets in European countries [4]. Also, some of the vegetable oilbased lubricants and greases are finding their opportunities in specific applications like metal forming and working, food processing industry, machine elements, marine, locomotives, and so forth [5, 6]. Even though, the vegetablebased oils are finding their scope in various types of applications, it is meaningful to select oil for a particular application only after ascertaining the properties and behaviour. Otherwise, oil can also be selected based on the task the oil is to perform. In this context, the selected lube is expected to satisfy the basic requirements under two broad areas, namely, tribological behaviour and stability. The triglyceride structure of a vegetable oil provides these desirable qualities due to their long and polar fatty acid chains [7, 8]. It also generates high-strength lubricant films that interact strongly with metallic surfaces, reducing both friction and wear [9].

Many contributions comparing the vegetable oil performance with mineral oil performance are reported. Canola oil with boric acid showed about 30% lower friction coefficients compared to mineral oil, tested under pin-on-disc tribometer [10]. Lower magnitudes (about 35%) of wear are reported under electronized vegetable oil, tested with steel [11].

Soybean and sunflower oils showed about 25% drop in friction and wear rate when compared to mineral oil

Table 1: Fatty acid composition of Pongam and Jatropha oil.

Compound name	Pongama raw oil (%)	Jotrapha raw oil (%)
Lauric acid (C20:0)	00.30	00.40
Myristic acid (C14:0)	00.00	00.00
Palmitic acid (C16:0)	12.00	14.60
Stearic acid (C18:0)	06.70	06.60
Arachidic acid (C20:4)	01.60	00.22
Palmitoleic acid (C16:1)	00.00	01.20
Oleic acid (C18:1)	53.20	40.60
Linoleic acid (C18:2)	20.80	36.20
Linolenic acid (C18:3)	04.00	00.30

[9]. 30 percent reduction in coefficient of friction [12] is reported under sunflower oil as lubricant with coated tools compared to mineral oil. Phosphate esters with rapeseed oil exhibit about 40% reduction in friction and wear values [13, 14]. About 80% reductions in wear rate is reported for soybean and with amine phosphate as lubricant tested under tribology test rigs [15]. Soybean, canola, and sunflower oils with various oleic acid compositions, showed lower friction rates [16]. 37% drop in wear scar diameter size and about 15% decline in friction are reported when coconut oil blended with AW/EP additive [17].

Pongam and Jatropha are nonedible and plentifully available vegetable oils in Indian scenario. Currently, the oils are being used for the production of biodiesel. Due to their higher monosaturates (oleic acid) in their fatty acid composition (Table 1) and higher thermal and oxidative stability, they are projected as potential lubricants for wide range of operations. Oxidative stability is an important property to be considered for the consistent formation of oil layer at operating temperature for the whole life of the oil. These facts highlight the potential of vegetable oils as good lubricants.

The steel, AISI 1040, is a proven material for the manufacture of different components of machine and plentifully used in many other manufacturing industries also.

The motive of the present work is to bring out the enormous potential of vegetable oils to be used in manufacturing sector as straight cutting oils or lubricants. This has gained more importance in the light of the recent restrictions made by world leaders like OSHA, HOSH, EPA, and so forth, where in, they have suggested to come out with replacements for mineral oils, which are most environmentally friendly and also are depleting. Also, there is a large consumption of cutting oils/lubricants for the manufacturing sector.

In the present study, the two raw oils and their chemically modified versions are tested for physicochemical properties. These raw, modified versions of the vegetable oils and two commercially available mineral oils are used as lubricants to conduct friction and wear tests on AISI 1040 using pin-on-disc tribometer. Experiments are conducted for different loads and sliding distances. The tribological performance of the two materials with vegetable oils and with mineral oils is compared. Further, the Stribeck curves are also drawn with all these oils to analyse the onset of full fluid film.

2. Methodology

2.1. Oil Modification. The raw vegetable oils have certain limitations like low thermo-oxidative stability [18]. This problem is addressed by various methods, namely, reformulation of additives, chemical modification, and genetic modification of the oil seed [2]. In the present work, chemical modification methods such as epoxidation [19] and transesterification [20] are used to modify the structure of two raw oils. After the modifications, their polyunsaturated C=C bonds are eliminated in the oil structure and the thermo-oxidative stabilities are enhanced.

Pongam raw oil (PRO) is modified into Pongam methyl ester (PME) and epoxidized Pongam raw oil (EPRO). Similarly, Jatropha raw oil (JRO) is altered to Jatropha methyl ester (JME) and epoxidized Jatropha raw oil (EJRO). Further, Pongam methyl ester (PME) and Jatropha methyl ester (JME) are modified into epoxidized Pongam methyl ester (EPME) and epoxidized Jatropha methyl ester (EJME), respectively.

2.2. Physicochemical Properties. The physicochemical properties of mineral, raw, and modified vegetable oils such as viscosity (ASTM D 445), viscosity index, (ASTM D 2270), flash point (ASTM D 92), pour point (ASTM D97), iodine values, and others are tested as per the standards (Table 2).

The result show that, the viscosity of epoxidized Pongam and Jatropha oils is increased by about 20% compared to their raw versions. This is attributed to high molecular weight and more polar structure in the epoxidized oils than their raw versions [19]. A marginal increase in viscosity index is seen under EPRO and EJRO. However, about 30% and 37% increase in viscosity index under EPME and EJME, respectively, are observed compared to their raw versions. Further, about 30% drop in flash point under both EPME and EJME are seen. The modification slightly improved the low temperature property (pour point) of the oils.

The epoxidation of the two oils is also confirmed by the reduction in iodine values, an indicator of unsaturation. EPRO, EPME, EJRO, and EJME show about 75%–80% drop in iodine values compared to their raw versions. The material composition of AISI 1040 is also ascertained (Table 3).

2.3. Friction and Wear Tests. Experiments are conducted on AISI 1040 steel pins of 8 mm diameter under the mineral, raw, and modified versions of the two vegetable oils using a pin-on-disc tribometer. Friction and wear tests are conducted with the wear track diameter of 100 mm and sliding speed of 4.2 m/s and for the loads 70 N, 100 N, 150 N, and 200 N. The volumetric wear and coefficient of friction for various distances of 1.25 km, 2.50 km, 3.75 km, 5.00 km, 6.25 km, and 7.5 km and loads are determined. The variation of coefficient of friction as well as wear as a function of sliding distance for different loads and oils are drawn.

Table 2: Physicochemical properties of raw and modified oils.

Properties	Pongam raw oil	Epoxidized Pongam raw oil	Epoxidized Pongam methyl ester	Jatropha raw oil	Epoxidized Jatropha raw oil	Epoxidized Jatropha methyl ester	Mineral oil (MRO)
Kinematic viscosity at 40°C (cSt)	53.65	65.41	20.15	35.36	63.65	11.22	33.00
Kinematic viscosity at 100°C (cSt)	13.90	20.17	11.50	11.70	19.97	07.07	12.00
Viscosity index	163.58	171.08	219.00	177.23	178.10	225.36	185.21
Total acid value (mg KOH g^{-1})	00.73	00.18	00.13	05.91	01.28	00.05	1.75
Flash point (0°C)	268.00	270.00	190.00	284.00	310.00	180.00	160
Pour point (0°C)	02.00	02.00	−02.00	−05.00	−06.00	−03.00	00.00
Iodine value (mg l g^{-1})	80.44	20.21	21.41	101.44	20.00	22.00	06.50

Table 3: Compositions of AISI 1040.

Contents	C	Si	Mn	P	S
Percentage	0.444	0.130	0.702	0.026	0.017

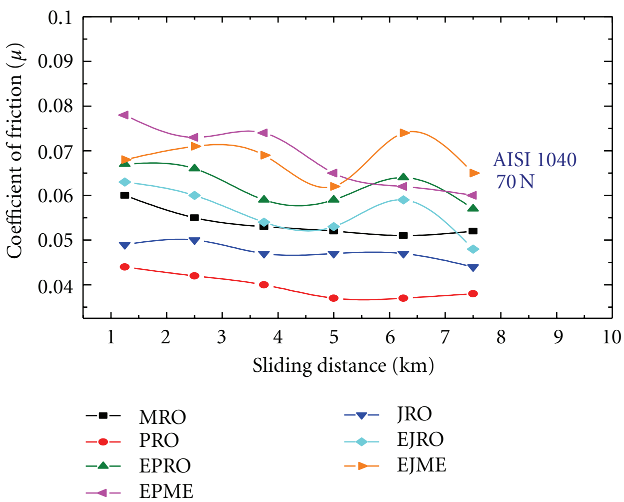

Figure 1: Variation of coefficient of friction with sliding distance for 70 N.

3. Analysis of Results

3.1. Friction Behaviour of AISI 1040. Figure 1 represents the variation of coefficient of friction with sliding distance for 70 N load. It is seen that about 50% drop in co-efficient of friction values under Pongam raw oil for the complete range of sliding distance tested when compared to mineral oil. However, under its epoxidized versions, EPRO and EPME, about 10% and 15% increase in friction respectively is observed compared to mineral oil. Further, under Jatropha raw, about 15% drop in the friction coefficient is seen compared to petroleum oil. On the other hand, marginal increase in friction is observed under EJRO and about 10% increase is noticed under EJME compared to mineral oil.

Low friction coefficients are seen under Pongam, Jatropha raw, and their versions of oils except EPRO for 100 N

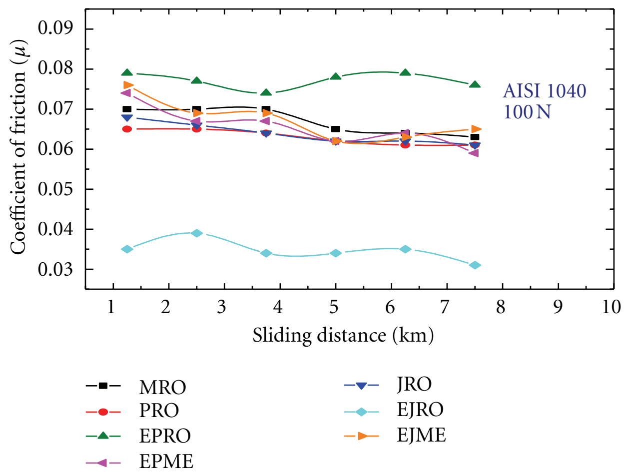

Figure 2: Variation of coefficient of friction with sliding distance for 100 N.

load (Figure 2). About 10% drop is seen under all versions except EJRO and EPRO. EJRO show about 40% lower friction compared to mineral oil. However, EPRO show marginally higher values of friction.

PRO shows about 60% drop in friction for the load 150 N (Figure 3) compared to mineral oil. Also, EPRO and EPME exhibit about 35% and 40% lower friction, respectively, compared to under mineral oil. Further, JRO, EJRO, and EJME follow similar trend with 35% drop in friction compared to petroleum oil.

Figure 4 shows the variation of coefficient of friction with sliding distance for 200 N. About 20% and 13% drop in friction is seen under PRO and EPRO, respectively, compared to mineral oil. On the other hand, EPME exhibits about 30% lower friction. Further, JRO and EJRO show the trend similar to PRO and EPRO. However, under EJME, marginally lower frictional values are seen compared to mineral oil.

The lower friction values under the two vegetable raw oils are attributed to their polar nature and viscosity properties. Significant reductions under vegetable oils can be due to the fact that, the thin surface film that develops in boundary lubrication is formed by the adsorption of polar compounds

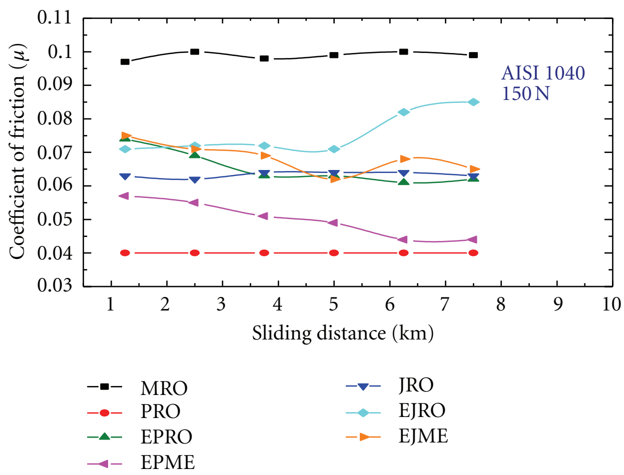

FIGURE 3: Variation of coefficient of friction with sliding distance for 150 N.

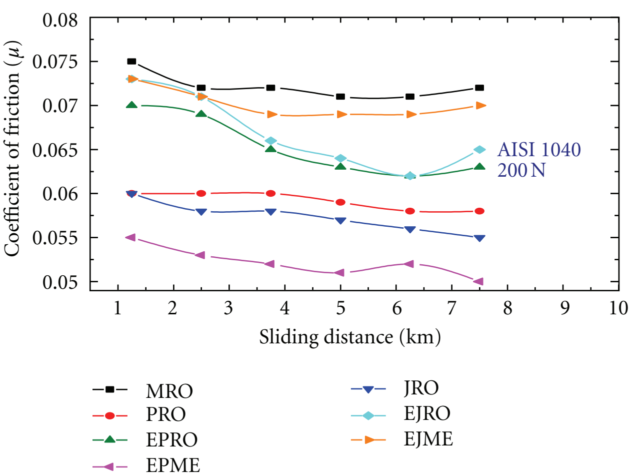

FIGURE 4: Variation of coefficient of friction with sliding distance for 200 N.

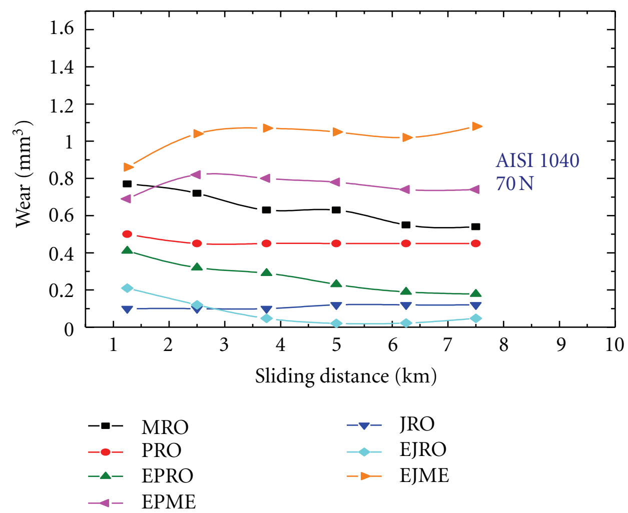

FIGURE 5: Variation of wear with sliding distance for 70 N.

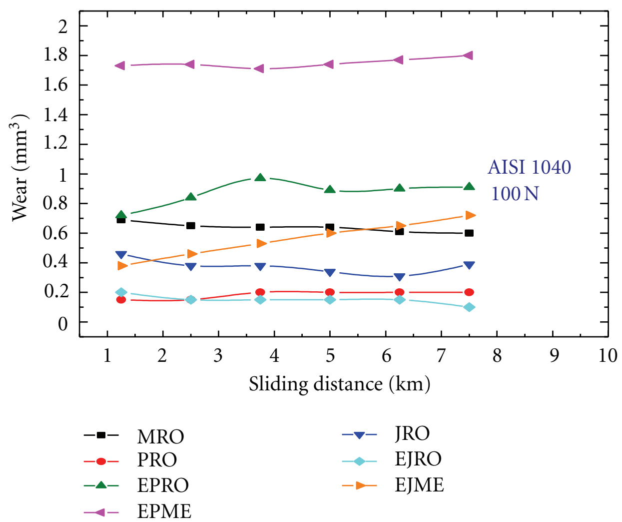

FIGURE 6: Variation of wear with sliding distance for 100 N.

at the metal surface of the mating pair or by chemical reaction of the lubricant at the surface. Since boundary lubrication by fatty acids is associated with the adsorption of the acid by dipolar attraction at the surface, they are capable of reducing the friction between the surfaces. Further, the oleic acid composition play, a vital role in reducing the friction coefficient largely when compared to linoleic and linolenic acids. Higher oleic acid composition is desirable for lower friction [21].

PRO show lower frictional values due to its polar in nature and presence of little higher oleic acid composition in the structure compared to JRO and its versions. However, epoxidized versions of Pongam oil have higher viscosity, leading to higher friction at low loads. On the other hand, as the load and temperature increases, a tribochemical reaction film could be formed on the frictional surface. The three member oxirane ring could form polyester or polyether material due to tribo-polymerization, which is tribologically effective to reduce friction [22].

3.2. Wear Behaviour of AISI 1040. Figures 5, 6, 7, and 8 show the variation of wear with sliding distance. The two raw oils show lower wear values compared to mineral oil for the complete tested sliding distance irrespective of load.

On the contrary, their epoxidized ester versions exhibit higher wear values, particularly at lower loads. The wear patterns observed here follow the same trend under friction measurement.

PRO shows 65%–98% drop in wear for various loads. EPRO exhibits 65%–70% lower wear at lower loads and 35%–95% lower values of wear at higher loads. EPME show 20%–90% higher wear under lower loads and contrast results are seen under higher loads.

JRO shows 50%–98% reduction in wear for the tested loads. EJRO exhibits maximum reduction in wear in the range 75%–98% for the tested loads. Further, under EJME, the material wears more at lower loads but, reduction in wear is seen at higher loads.

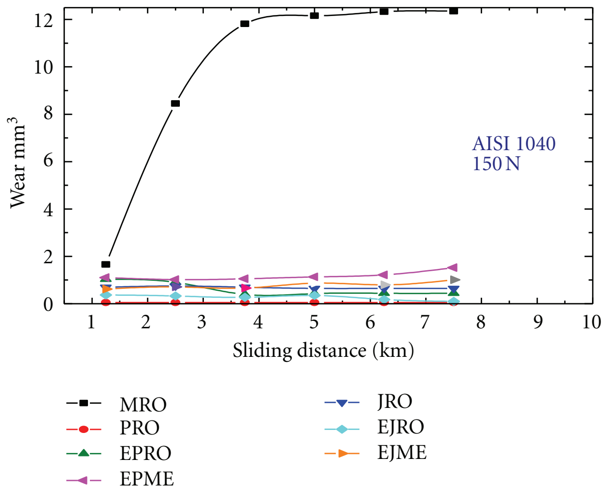

Figure 7: Variation of wear with sliding distance for 150 N.

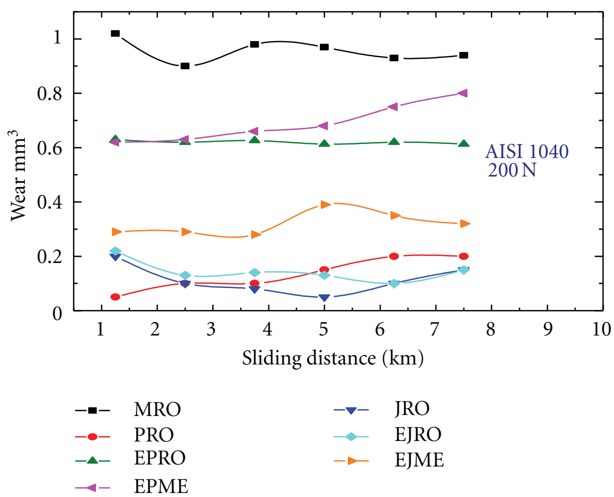

Figure 8: Variation of wear with sliding distance for 200 N.

More wear resistance under Pongam and Jatropha oils is observed. It is attributed to high oleic acid composition in the oils, which generates stronger adsorption on metal surfaces and produces greater lateral interaction between the ester chains [23]. Stronger adsorption capability is reported with high oleic acid content in the fatty acid composition of a vegetable oil [24]. Further, epoxidized Pongam and Jatropha forms produce polyester material due to tribo-polymerization, which reduces wear significantly, specifically at higher loads.

3.3. Stribeck Curve. Stribeck curves represent the regimes of lubrication and would throw some light on the possibility of expanding the borders of the film lubrication ranges (when moving from the right to the left over the Stribeck curve), the film lubrication will stay longer and support higher loads and in unloading cycle (moving from left to the right), the change from boundary lubrication to film lubrication will occur earlier [11]. Stribeck curves are drawn for various coefficient of friction (μ) and loads (P), keeping speed (N) and viscosity (Z) constant; Figure 9 represents the Stribeck curves for AISI 1040 under various lubricant modes.

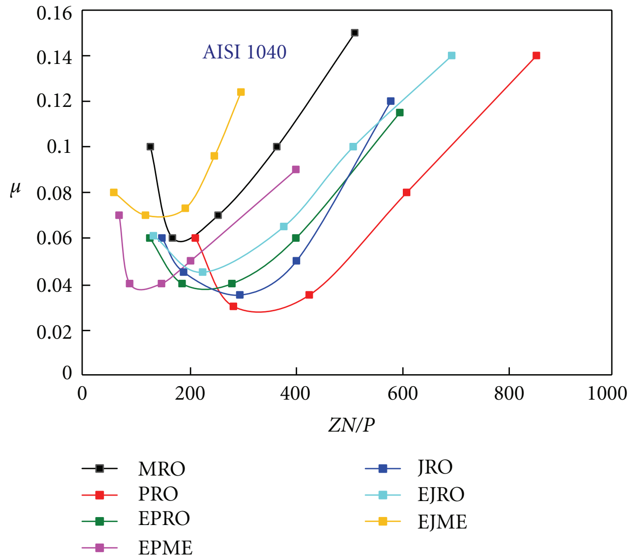

Figure 9: Stribeck curves for AISI 1040.

Early full film formation is seen under both the vegetable oils and their versions compared to petroleum oil. This is clearly observed as the Stribeck curves for the vegetable oils are shifted towards the left. The Stribeck curve under EPRO and EPME show about 30% shift towards left and similar trends are seen under Jatropha and its versions.

Pongam and its epoxidized versions of oils are found to be better for AISI 1040 among the two vegetable oils as they generate early full film and produce low friction.

4. Conclusions

A comparative study reveals a significant reduction in friction and wear for AISI 1040 under Pongam and Jatropha raw oils compared to mineral oil. However, their modified versions of both oils exhibit slightly higher friction at low-load operations.

Pongam, Jatropha and epoxidized Jatropha raw oils offer more wear resistance for the tested sliding distances and loads compared to petroleum oil.

Both Pongam and Jatropha oils show a promising trend of extension of film lubrication with reduction in boundary lubrication regimes compared to mineral oil.

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