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EXPLORING THE ANTI-WEAR AND EXTREME PRESSURE LUBRICATING PERFORMANCE OF JATROPHA OIL MODIFIED WITH NANO-ADDITIVES AND GARLIC OIL

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ABSTRACT: It is imperative to emphasize the wear-reducing and load-sustaining abilities of the lubricating oils, as they are an essential part of their operation. In this study, the anti-wear and extreme pressure (EP) performance of Jatropha oil was explored. The investigation was executed on a 4-ball tester machine according to ASTM-D-4172 and D-2783 standards. Nano-sized Molybdenum disulfide and graphene were added to the base oil, whose addition reduced the wear on the test balls but failed to improve the EP properties. However, the addition of Garlic oil elevated the EP properties of the base oil. The Last Non-seizure load and weld point of the jatropha oil was elevated by up to 3 levels, while the Load Wear index was increased by 91.88%. The Flash Temperature Parameter of jatropha oil was increased by 658% and 250% at 100kgf and 126kgf load, respectively, after the addition of 5% garlic oil. Further, the wear scars were examined under an optical microscope and FESEM, which proved that the addition of nano-additives reduced the wear of the balls during anti-wear tests at lower loads, and garlic oil reduced the wear in EP conditions and produced smoother surfaces. These improvements were attributed to the formation of tribo-films on the surfaces as characterized by the EDS analysis. It was concluded that Garlic oil could be a substantial EP additive to vegetable oils (especially jatropha oil) to lift their load-carrying capacity without hampering their environmentally friendly nature.

Keywords: Jatropha oil; Wear; Garlic oil; Molybdenum Disulfide; Graphene.

استكشاف أداء التشحيم المضاد للتآكل والضغط الشديد لزيت الجاتروفا المعدل بمضافات النانو وزيت الثوم

زاهد مشتاق و م. حنيف

الملخص من الضروري التأكيد على قدرة زيوت التشحيم على تقليل التآكل والحفاظ على الحمل، حيث إنها جزء أساسي من عملها. في هذه الدراسة، تم استكشاف الأداء المقاوم للتآكل والضغط الشديد (EP) لزيت الجاتروفا. تم إجراء التحقيق على آلة اختبار 4 كرات وفقًا لمعايير ASTM-D4172 و D-2783. تم إضافة ثاني كبريتيد الموليبدينوم والجرافين بحجم النانو إلى الزيت الأساسي، والذي قللت إضافته من تآكل كرات الاختبار لكنها فشلت في تحسين خصائص EP. ومع ذلك، أدت إضافة زيت الثوم إلى زيادة خصائص EP للزيت الأساسي. تم رفع الحمل غير المضبوط الأخير ونقطة اللحام لزيت الجاتروفا بما يصل إلى 3 مستويات، في حين تم زيادة مؤشر الحمولة بنسبة 91.88٪. تم زيادة معامل درجة حرارة الوميض لزيت الجاتروفا بنسبة 658٪ و 250٪ عند حمل 100 كجم و 126 كجم على التوالي بعد إضافة زيت الثوم بنسبة 5٪. علاوة على ذلك، تم فحص ندوب التآكل تحت المجهر البصري و FESEM، والتي أثبتت أن إضافة إضافات النانو قللت من تآكل الكرات أثناء اختبارات مقاومة التآكل عند الأحمال المنخفضة، وقلل زيت الثوم من التآكل في ظروف EP وأنتج أنعم الأسطح. تُعزى هذه التحسينات إلى تكوين أفلام تريبو على الأسطح كما تتميز بتحليل EDS. تم استنتاج أن زيت الثوم يمكن أن يكون مضافًا أَسَاسِيًّا للزيوت النباتية (خاصة زيت الجاتروفا) لرفع قدرتها على تحمل الأحمال دون إعاقة طبيعتها الصديقة للبيئة

الكلمات المفتاحية: زيت الجاتروفا؛ التآكل؛ زيت الثوم؛ موليبيديوم داسلفايد؛ الجرافين.

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NOMENCLATURE

FESEM	Field Emission Scanning Electron Microscope.
FTP	Flash Temperature Parameter.
Gar	Garlic oil.
Gr	Graphene.
JO	Jatropha oil.
LNSL	Last Non-Seizure Load.
LWI	Load-Wear Index.
M	Molybdenum disulfide.
Ra	Roughness average.
Rq	Root Mean Square Roughness.
W.P	Weld Point.
WSD	Wear Scar Diameter.

1. INTRODUCTION

The consumption and scarcity of energy are on the all-time rise. The condition of shortage of fossils is inevitable in the future due to its present rapid exhaustion (Wang et al., 2020). Tribological losses are a major source of energy losses, and there is a dire need to minimize their level to save energy in various industries (Tahir et al., 2018). Lubrication plays a major role in reducing friction and wear by forming a film between the mating parts and preventing their direct contact (Yazawa et al., 2014). A majority of the lubricants available in the market are petroleum-based products. They provide good lubrication but are not biodegradable and eternal. They contribute to pollution, and their demand needs to be reduced by introducing environmentally friendly lubricants like vegetable oils (Shafi & Charoo, 2021). Vegetable oils have been under the spotlight of research for the last couple of decades for their impeccable lubricating properties. We can say that they are a sure-shot-cure to mitigate the universal problem of swift crude oil depletion (Owuna et al., 2020; Woma et al., 2019). Very vast research has concluded that vegetable oils can make as good lubricants, and their properties can be ameliorated by mixing desirable types of additives like anti-friction and anti-wear additives, nanoparticles, extreme pressure additives, etc. (Chan et al., 2018; Hernández-Sierra et al., 2019; Panchal et al., 2017; Zainal et al., 2018). Jatropha oil has staggering tribological potential, and it has been proved to be a viable option to replace mineral oils by numerous studies. The lubricating properties of jatropha oil have been improved by adding various types of additives (Mushtaq & Hanief, 2021b, 2021a, 2021c; Talib et al., 2019, 2021). There are a number of different types of additives available which can enhance the performance of base lubricants, and care needs to be taken in selecting the best and most suitable one. If the nano-sized additives are added to a lubricant, then it is called a nano-lubricant. The friction and wear-reducing capacities of the nano-lubricants are much better as compared to the base oils (Kotia et al., 2018). Recent research has suggested that additives like Graphene and MoS_2 are good options for lubricant additives to reduce friction and wear (Berman et al., 2014; He et al., 2020; Lin et al., 2011; Meng et al., 2020; Wu et al., 2018). The addition of graphene nanoparticles was reported to boost the tribological properties of vegetable oils and decrease the coefficient of friction and wear scar diameter (Kiu et al., 2017). It has been proved that MoS_2 and Graphene nanoparticles, when added in the mixed form, are very effective in reducing friction and wear even better than when added individually (Gong et al., 2017; Xu et al., 2015). Garlic oil is a natural plant oil that is also used nowadays as a liquid additive to enhance the properties of lubricants. It has been reported to enhance the extreme pressure properties of base oils by a considerable amount and elevate their weld point (Li et al., 2014). Garlic oil was added to palm oil and coconut oil, and the extreme pressure properties of the mixed lubricants were examined on a four-ball tester. It was observed that the mixed lubricants gave better performance than the mineral oil (Chikezie & Ossia, 2018). Garlic oil improved the oxidative stability and pour point of the coconut oil and converted it into a much better performing lubricant without harming its non-hazardous nature (Kumar et al., 2021).

The impact of the combination of Graphene and MoS_2 additives on the anti-wear behaviour of jatropha oil has not been tested yet. Also, the effect of garlic oil on the EP properties of jatropha oil still remains to be investigated. Hence, the current study emphasizes the anti-wear and extreme pressure properties of jatropha oil. Nano-sized Molybdenum disulfide (M) and Graphene (Gr) were added in the assorted form in the ratio of 1:1 in weight percentages of 0.1 to 0.4%. The above nano-lubricants were reported to reduce the Wear Scar Diameter of the test balls during ASTM-D4172 tests. However, they did not elevate the weld points of the test lubricants during ASTM-D2783 tests. Hence, pure garlic oil was added in 1% to 5% by volume to the jatropha oil because of its biodegradable nature. It showed promising results and improved the extreme pressure properties of the jatropha oil, and elevated the weld points. Hence, it can be summarized that the addition of nano-additives improves the anti-wear properties of the jatropha oil, and the garlic oil boosts the extreme pressure properties and makes it resist more load.

2. MATERIALS AND METHODOLOGY

2.1 Equipment and the tribo-pairs

A Four-ball tester (as shown in Figure 1) was employed to conduct the anti-wear and extreme pressure experiments with 52100 chromium steel balls of 12.7mm diameter as tribo-pairs. Both the equipment and the test balls were delivered by Ducom Instruments

Pvt. Ltd. The physical properties of the test balls are given in Table 1. A Four-ball tester consists of a steel cup in which three test balls are accommodated in a triangular shape, with all three making contact with each other, as shown in Figure 2. Then the pot is filled with the test lubricant so that all three balls are completely submerged in it. The 4th ball is gripped in the upper part, which is rotated with the help of a motor. The 4th ball is then pressed against the rest of the three balls in the form of an equilateral tetrahedron such that it makes point contact with all three balls simultaneously. The steel cup is also connected to an electrical heater and a temperature sensor to maintain a constant temperature according to the requirement of the experiment. The operating parameters are fed through computer software equipped with the machine, and after attaining the desired parameters like load and temperature, the test is started. As the upper ball is pressed and rotated against the three lower balls, it causes a scar on each of them. The diameter of the three scars on the lower balls is measured and then averaged, and this value signifies the lubricating capabilities of the test lubricant used in the steel cup.

2.2 Synthesis of bio-lubricants

The base oil used in this study was vegetable oil-based jatropha oil, whose fatty acid combination is shown in Table 2, while its physicochemical properties are presented in Table 3. The nano-additives of Molybdenum disulfide and graphene were procured from a reliable supplier, and their properties are given in Table 4. The lubricants were synthesized by adding different proportions of additives as percentages of weights. Both the nano-additives were mixed in the ratio of 1:1 and added by weight from 0.1% to 0.4% after weighing on a highly accurate weight balance. The nano-lubricants then produced were subjected to 6 hours of ultrasonication to ascertain the homogeneous dispensation of nanoparticles before starting the experiments. Figure 3 shows the prepared nano-lubricant samples of jatropha oil mixed with nano-additives at different percentages. However, the pure Garlic oil was used as an extreme pressure additive and was added to the pure jatropha oil by volume percentages from 1% to 5%. The magnetic beads were submerged in the test tube containing the mixtures and were stirred for 2-3 hours on a magnetic stirrer. All the lubricant samples were placed in separate test tubes.

Figure 1. Four-ball tester.

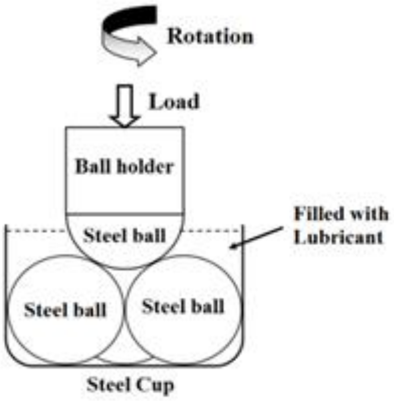

Figure 2 Schematic Diagram.

Table 1. Physical properties of the tribo-pairs.

S. No	Physical Properties	52100 Cr steel ball
1.	Hardness (HRC)	63 - 66
2.	Elastic Modulus (GPa)	190 - 210
3.	Density (g/cm^3)	7.81
4.	Poisson’s Ratio	0.29
5.	Melting Point (^{o}C)	1424
6.	Tensile Strength (MPa)	2240
7.	Yield Strength (MPa)	2030

Table 2. Fatty acid combination of Jatropha oil

S.No.	Fatty acids	Composition (%)
1.	Myristic acid C14:0	1.2 - 1.6
2.	Palmitic acid C16:0	15 - 16
3.	Stearic acid C18:0	9 - 10
4.	Oleic acid C18:1	40 - 42
5.	Linoleic acid C18:2	31 - 34
6.	Arachidic acid C20:0	0.3 – 0.6

2.3 Experimental procedure

The anti-wear (A/W) tests were conducted on the four-ball tester according to ASTM-D4172 standards. The operating conditions associated with it are: Load = 392 N, temperature = 75°C, RPM = 1200 and time = 3600 seconds (1 hour). Four 52100 chromium steel balls were used for each test, and all of them were washed thoroughly with acetone before the tests to remove any contamination. The three balls were placed in the steel cup, and it was filled with the test lubricant. The upper ball was pressed against these lower three balls by applying the load and other parameters. As soon as the desired level of parameters was reached, the test was started. The test stopped spontaneously after the completion of the given time. Each sample of nano-lubricants was tested for its anti-wear properties by filling the steel cup with them one by one. After completing the test, the test lubricant was displaced, and the balls were removed and washed again with acetone. Then the wear scars on the lower three balls were examined and measured under an optical microscope and FESEM. The size of the scars gave the anti-wear performance of the test lubricant.

The Extreme Pressure (EP) tests determine the load sustaining capacity of the test lubricant and give the maximum load it can withstand before causing failure. The EP tests were conducted on the same machine under the ASTM-D2783 standard. The operating conditions associated with it are: Load = varying from 6kgf to 800kgf, temperature = 27°C ±2, RPM = 1760 ±40, and time = 10 seconds. Starting from the lower loads, the load was increased step by step and continued until the seizure of the four balls took place. The balls and the test lubricant are not reusable and can be used only in one test. Hence they need to be replaced after every test. The balls were cleaned with acetone before each test to remove any unwanted particles from the surface. The lubricant samples with mixed nano-additives (0.1 to 0.4 wt.%) and garlic oil (1 to 5 vol.%) were tested alternately for their extreme pressure capabilities under different loads until their seizure occurred. Their weld points were noted down, and the scars produced on the balls were examined and measured under an optical microscope and FESEM. In case of any discrepancy, the ambiguous tests were repeated three times to bring more transparency.

3. RESULTS AND DISCUSSIONS

3.1 Anti-Wear tests

The one-hour anti-wear tests were performed according to ASTM D-4172 standards using a four-ball tester. The balls were lubricated with Jatropha oil with and without additives.

Table 3. Physicochemical properties of Jatropha oil.

S.No.	Properties	Jatropha oil
1.	Density (g/cm^3)	0.918
2.	Kinematic Viscosity at 40°C	47 - 54 cSt
3.	Kinematic Viscosity at 100°C	9 -10 cSt
4.	Viscosity Index (VI)	180 - 186
5.	Flash point (°C)	186°C
7.	Pour point (°C)	8°C

Table 4. Properties of Nano-additives.

Specifications	Graphene	Molybdenum Disulphide
Formula	C	MoS_2
Appearance	Grayish Black powder	Black powder
Purity	>99%	99.9%
Odour	Odorless	Odorless
Thickness/APS	5 – 10 nm	80 – 100 nm
Length	5 – 10 micron	-
Density	4.2 g/cm^3	5.06 g/cm^3
Melting point	3650°C	1185°C
Molecular weight	12.01 g/mole	160.07 g/mole

Figure 3: Nano-lubricants prepared from Jatropha oil.

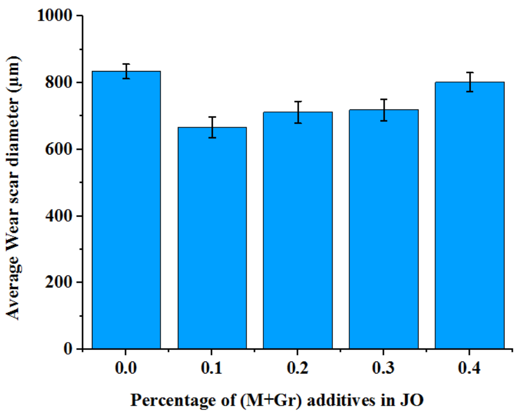

Figure 4: Average Wear Scar Diameter (WSD) of test balls.

The additives were MoS_2 nanoparticles and Graphene nanoflakes mixed in the ratio of 1:1 in the different weight percentages of 0.1 to 0.4%. An Optical microscope and FESEM were used to examine the worn-out lower balls and measure the diameters of their respective wear scars produced after the tests. The three values of diameters were averaged to get the average wear scar diameter (WSD). Figure 4 displays the average WSD of the tests recorded on the test balls lubricated with different mixtures. The average WSD of test balls, when lubricated with pure jatropha oil, is 833.413 µm. The diameter recorded is within the range of WSD (510 µm – 870 µm) allowed for commodity oils (Cermak et al., 2013). However, as the nano-additives were added to the oil, the anti-wear properties reportedly got improved, and the average WSD was reduced. The minimum average WSD was reported at 0.1% concentration of nano-additives. The average WSD of Jatropha oil with 0.1%M+Gr was 633.291 µm, as shown in Figure 4. It is clearly evident that the introduction of nano-additives resulted in lowering the size of the wear scar. The jatropha oil reported an improvement of 24.01% in reducing the wear at 0.1% of activation. Hence, 0.1% was found to be the optimum percentage of additives for minimum WSD. This improvement in the anti-wear properties of jatropha oil can be related to the intrusion of nano-additives inside the peaks and valleys and decrease the surface roughness of the surface. Moreover, the additives are more prone to chemically react with the metallic surface, lubricant and the environment. This reaction gives rise to a protective layer on the surface and safeguards the tribo-pairs from being worn out rapidly. The combination of the two nano-additives was used in this research because it has been reported in the literature that the combination of MoS_2 and Graphene additives performs more effectively as anti-wear additives than when they are used separately. The graphene delays the oxidation of MoS_2 and helps it stay along the surface for a much longer time during a sliding operation. While as, the MoS_2 helps the graphene stay along and not let break up into fine and weak particles (Gong et al., 2017; Xu et al., 2015, 2018).

Figure 5 shows the low-magnification (10x) optical and high-magnification (3000x) FESEM images of the wear scars on the test balls lubricated with different mixtures. Figures 5(a, b) show the wear scar on the ball at low and high magnifications when it was lubricated with pure jatropha oil. A large number of abrasive furrows can be seen spread all over the scar in Figure 5(a), indicating abrasive ploughing as the dominant wear mechanism. Figure 5(b) shows the material removal and deposition caused by the abrasive action. After the intrusion of the nano-additives by 0.1 wt%, the scar diameter is reduced to a great extent, and less intense grooves can be seen in Figure 5(c). The grooves are also less deep and not widespread, giving somewhat less-ploughed area at the top and bottom, which reduces the total wear. Figure 5(d) shows a comparatively smoother surface with few fine lines of abrasion. The deposits of nano-additives on the surface can also be seen as black marks in the above image. This clearly indicates that the jatropha oil performed better after the intrusion of MoS_2 and graphene nano-additives and reduced the wear of the test balls to a large extent. This improvement is attributed to the formation of a protective film due to the tribochemical reaction between the nanoparticles and the metallic surface. This film prevents direct and intense rubbing between the balls and restricts the wear.

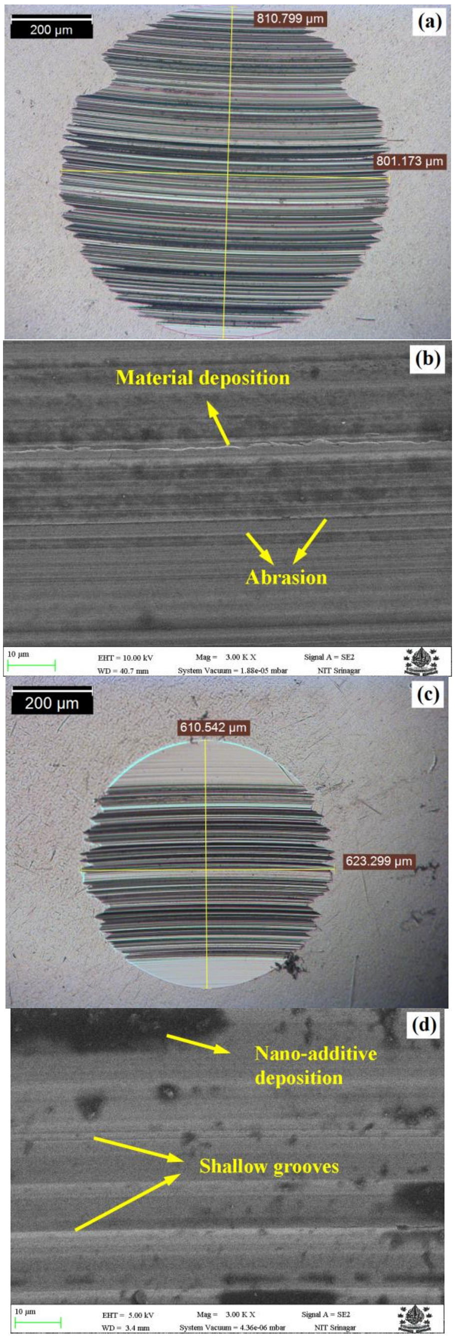

Figure 5: Optical and FESEM images of wear scars on balls lubricated with (a, b) Pure JO (c, d) JO + 0.1% M+Gr.

3.2 Extreme Pressure (EP) tests

The EP tests were conducted according to the ASTM-D2783 standards on a four-ball tester. The steel cup was lubricated with different mixtures of jatropha oil and additives. After the tests, the diameter of the scars produced on the lower three balls was measured on an optical microscope. The average WSD recorded at different loads and lubricant mixtures as compared with the Compensation scar diameters (CSD) are compiled in Table 5. It is observed that the WSD for jatropha oil increases with the increase in load. After adding the garlic oil, the WSD increased with the increasing load but at a slow speed as compared to the base oil. The WSD of jatropha oil was reduced by 76.47% after adding 5% garlic oil at a load of 100kgf. When the WSD is within the 5% limits of the CSD, then it is called the Last Non-Seizure Load (LNSL). The LNSL for pure jatropha oil was found to be 50kgf, and the load at which the four balls get welded (Weld Point) was recorded as 160kgf. However, after adding garlic oil from 1 to 5 vol.%, both LNSL and Weld points got elevated, as presented in Table 5. The LNSL of jatropha oil got elevated to 63kgf and 100kgf at 1% and 5% addition of garlic oil, respectively. Further, the weld point of jatropha oil increased to 250kgf and 315kgf at 1% and 5% garlic oil, respectively. The Load-Wear Index (LWI) of the lubricant mixtures was also calculated following the ASTM-D2783 standards and is plotted in Figure 6. The LWI of pure jatropha oil was recorded as 26.671. However, it was observed that the LWI increased after the addition of garlic oil. The maximum improvement in LWI was 51.177, as recorded with the addition of 5% garlic oil. Hence, it was concluded that the garlic oil elevates LNSL, Weld point as well as LWI of jatropha oil. However, it is also reported that the addition of nano-additives had no effect on any of the extreme pressure properties of the jatropha oil.

3.3 Wear Analysis

The high magnification (3000x) FESEM image of the test ball lubricated with pure jatropha oil at 126kgf is shown in Figure 7(a). It is observed from this figure that the main wear mechanism has shifted to adhesion at a higher load. Large cracks and heavy material removal by adhesion can be seen in Figure 7(a). It specifies that the lubricant film produced without any additive is not durable and is easily breached, especially at higher loads. This allows severe engagement between the asperities of the two surfaces and results in material removal and the formation of cracks on a large scale. Figure 7(b) shows the FESEM image of the test ball lubricated with jatropha oil + 5% Garlic oil at 200kgf. The addition of garlic oil to the jatropha oil minimizes the adhesive wear between the contacting surfaces and gives a much smoother surface, as shown in Figure 7(b). The surface has very small cracks and adhesive marks. It proves the effectiveness of garlic oil in minimizing the wear between the sliding surfaces. After the addition of garlic oil to the jatropha oil, a much smoother surface is produced even at a higher load of 200kgf. This study agrees with the results experienced by several researchers that garlic oil is a very effective extreme pressure additive that improves the lubricity of the lubricant and reduces the wear between the sliding surfaces. It has the capability to form protective tribo-films from the oxides, sulphates, and sulphides of iron. The low-molecular-weight sulphides present in the garlic oil react much readily with the metallic surfaces to form a protective layer. The unsaturated double bond enhances the adsorption of the film on the metallic surface, thereby making it more effective in restricting the direct metal-to-metal contact and minimizing the wear (Gasni et al., 2019; Jesbin & Mahipal, 2021; Li et al., 2014).

Table 5. Load versus WSD for various lubricant mixtures.

Load (kgf)	CSD (mm)	Pure JO	JO+1% Gar	JO+3% Gar	JO+5% Gar
50	0.36	0.37 (LNSL)			
63	0.39	0.51	0.37 (LNSL)		
80	0.42	1.73	0.98	0.42 (LNSL)	
100	0.46	2.04	1.77	1.03	0.48 (LNSL)
126	0.5	2.23	2.46	1.66	0.91
160	0.54	W.P	2.55	2.12	2.08
200	0.59		2.93	2.29	2.12
250	0.63		W.P	3.68	3.14
315				W.P	W.P

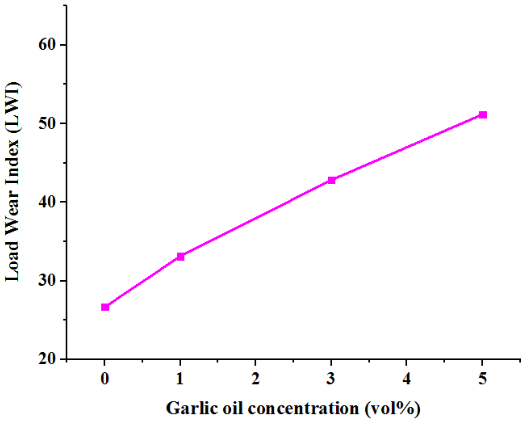

Figure 6: Load wear Index for different lubricant mixtures.

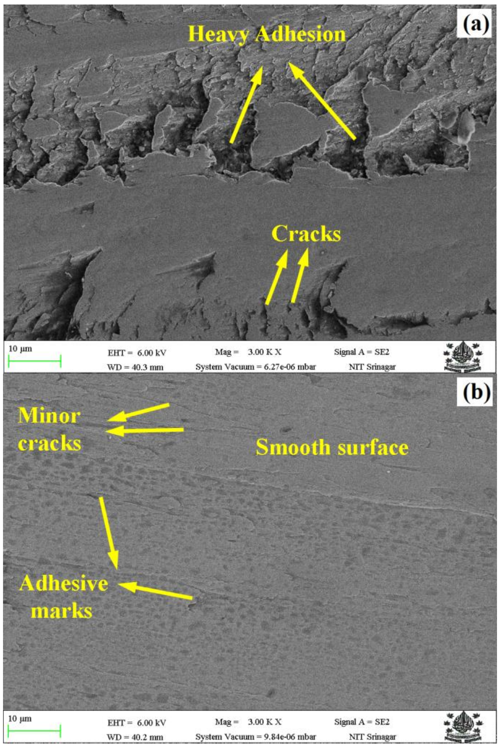

Figure 7. FESEM of wear scars on balls lubricated with (a) Pure JO at 126kgf (b) JO + 5% Gar at 200kgf.

3.4 3D Topographic Analysis

The surface topographic analysis of wear scars was conducted using a 3D profilometer with a non-contact lens from Rtec Instruments, USA. The 3D view, texture pattern, and the roughness parameters (Ra, Rq) of the wear scars were also revealed. The roughness parameters were calculated at three different places of a wear scar, and then the three values were averaged. Figure 8 shows the 3D view, texture pattern, and the roughness parameters of the wear scar on the test ball lubricated with pure jatropha oil at 126kgf load. Figures 8(a) and 8(b) clearly show the deep crests and troughs depicting large wear and rough surface when the balls are lubricated with jatropha oil without additives. It means the lubricating film is breached, causing severe wear to the tribo-pairs. Figure 8(c) gives the values of roughness parameters recorded at three different places of the wear scar.

The averaged values of Ra and Rq are 7.663 and 10.7733, respectively. The high values of Ra and Rq signify the high roughness of the wear scar. Figure 9 corresponds to the wear scar lubricated with Jatropha oil + 5% Garlic at 200kgf. After the intrusion of the garlic oil, the wear on the tribo-pairs is restricted up to a large extent, as evident from Figures 7 (a, b). Figure 9(a) displays a less rugged surface as compared to Figure 8(a). Also, the peaks and valleys observed in Figure 9(b) are of lesser depth as compared to Figure 8(b).

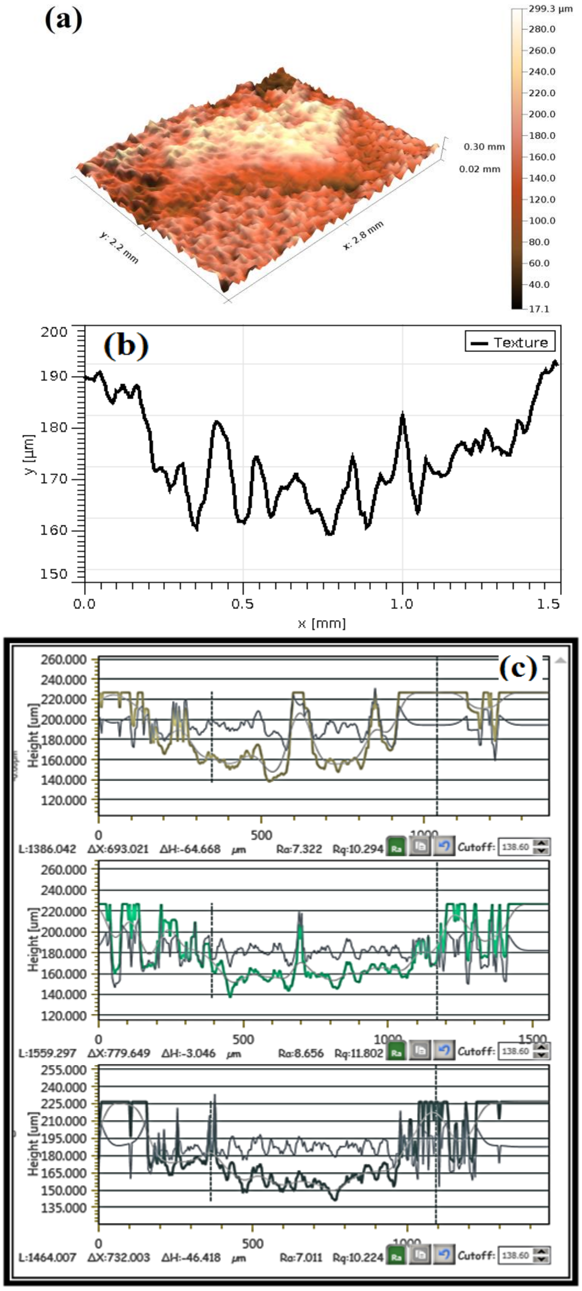

Figure 8: 3D topographic analysis of the wear scar lubricated with pure JO at 126kgf load (a) 3D image (b) Texture pattern (c) Roughness parameters.

The corresponding average values of Ra and Rq are 4.966 and 6.274. After the addition of 5% garlic oil to jatropha oil, there was a reduction of 35.2% and 41.7% in Ra and Rq, respectively, representing a significant improvement in the surface roughness of the wear scar. The results of the 3D profilometer analysis depict that the addition of garlic oil to jatropha oil is beneficial in terms of reducing wear and the surface roughness of the wear scar. After the addition of garlic oil, a much smoother surface with fewer and smaller peaks, less Ra and Rq, is obtained. These results are in full agreement with the wear analysis on FESEM, as shown in Figure 7.

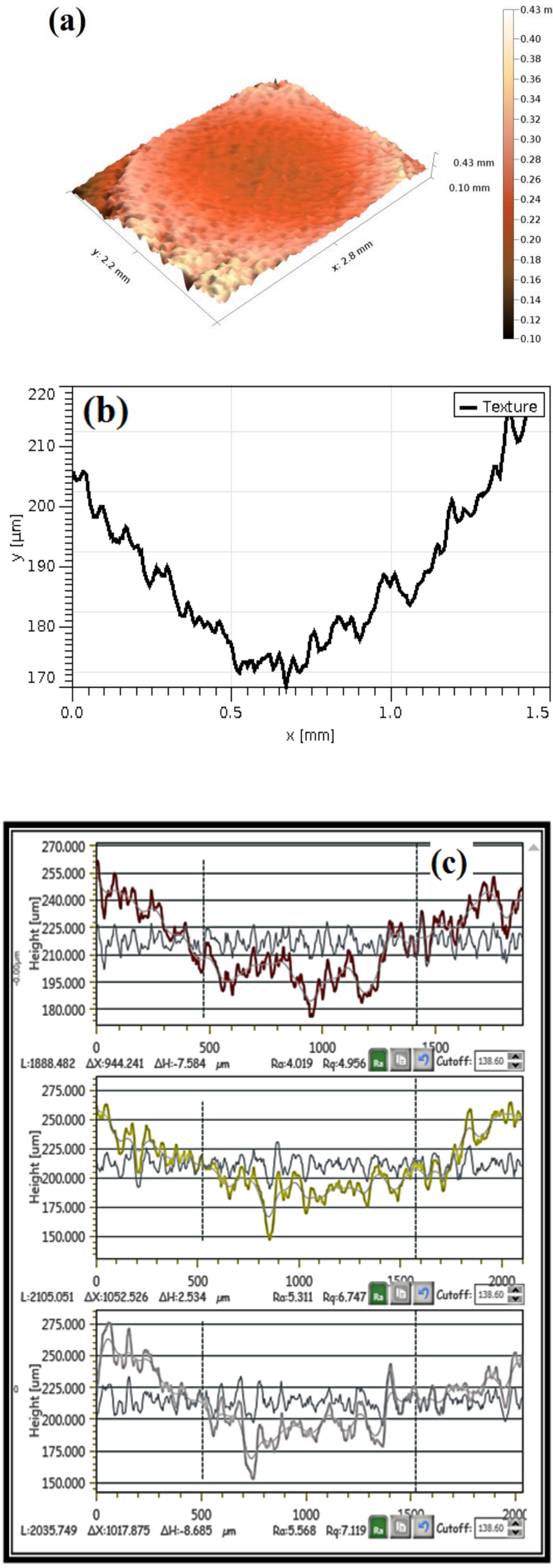

Figure 9: 3D topographic analysis of the wear scar lubricated with JO + 5% Gar at 200kgf load (a) 3D image (b) Texture pattern (c) Roughness parameters.

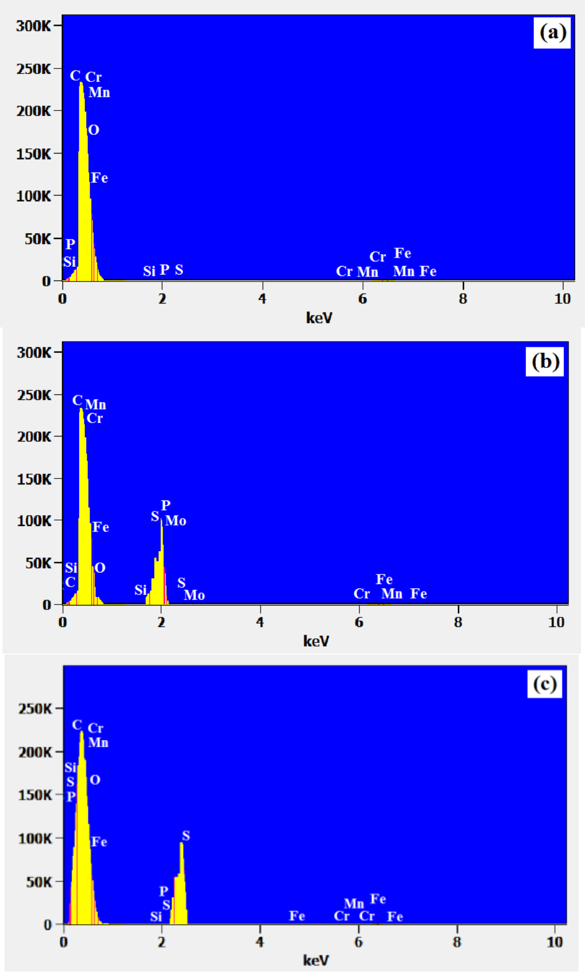

Figure 10: EDS analysis of wear scars lubricated with (a) pure JO (b) JO + 0.1% M+Gr (c) JO + 5% Gar.

Table 6. EDS elemental composition of wear scars lubricated with different mixtures (Weight %).

Element	Pure JO	JO + 0.1% M+Gr	JO + 5% Gar
Molybdenum	-	12.71	-
Sulfur	0.24	2.6	5.18
Carbon	3.2	8.15	1.3
Oxygen	15.2	9.23	25.3
Iron	79.57	66.4	63.88
Silicon	0.321	0.298	0.28
Chromium	1.22	1.12	1.15
Phosphorus	0.02	0.32	2.79

3.5 EDS Analysis

Figure 10 shows the EDS analysis of the wear scars lubricated with the jatropha oil with and without additives. The elemental composition present in the wear scars is given in Table 6. It is observed from Figure 10(a) that Molybdenum is absent in the scar when it is lubricated with pure jatropha oil. Table 6 shows that the major components are iron and oxygen with small amounts of sulfur, silicon and carbon. Figure 10(b) represents the EDS of wear scar lubricated with jatropha oil and nano-additives. In Figure 10(b), Molybdenum is present, and the content of carbon is also increased due to the presence of graphene, as shown in Table 6. This depicts the presence of Molybdenum disulfide and graphene nano-additives necessary for the tribo-film formation. The EDS of wear scar lubricated with Jatropha oil mixed with garlic oil is presented in Figure 10(c). Molybdenum can again be found absent in this figure. While as, Table 6 shows the reduced content of carbon and the presence of higher contents of sulfur, oxygen and phosphorus. This is a clear indication of the formation of oxides and sulfides on the surface of the wear scar due to the high content of sulfur in the garlic oil, which promotes the creation of the protective tribo-film and restricts the wear between the sliding surfaces.

3.6 Flash Temperature Parameter (FTP)

FTP is a criterion used to determine the critical temperature exceeding which the lubricating film suffers a breakdown at given conditions. It specifies the effectiveness of the lubricant. The higher the value of FTP, the stronger the lubricating film and the better the lubricant. It depends on the WSD and the load and can be calculated following the IP-239 Standard, 1986, (Lane, 1957) from the equation below

$$\text{FTP} = \text{Applied Load} / (\text{WSD})^{1.4}$$

The FTP values observed for different lubricants at different loads are compiled in Table 7. It is observed that the FTP of the additized oils is greater than the base oil. The FTP of jatropha oil increases from 36.85 to 279.42 after the addition of 5% garlic oil at 100 kgf. Hence, it can be outlined that the addition of garlic oil elevates the FTP of the jatropha oil and boost the lubricity.

Table 7. Flash Temperature Parameter calculations.

Load (kgf)	Pure JO	JO+1% Gar	JO+3% Gar	JO+5% Gar
50	201.13	209.00		
63	161.71	253.43	235.42	
80	37.13	82.29	269.48	
100	36.85	44.96	95.94	279.42
126	40.99	35.73	61.97	143.78
160		43.14	55.87	57.38
200		44.40	62.69	69.84
250			40.34	50.37

4. CONCLUSION

The following conclusions can be drawn from the current study:

1. Graphene and MoS_2 nano-additives reduce the wear scar diameter of the test balls but do not improve the extreme pressure properties of the jatropha oil. The lowest wear scar is observed with 0.1% of the nano-additive concentration.
2. Garlic oil improves the extreme pressure properties of jatropha oil by elevating the LNSL and weld point, increasing the LWI, and reducing the wear of balls at high loads. The LNSL of the jatropha oil was increased by 1 to 3 levels, while the weld point was elevated by 2 to 3 levels after the addition of garlic oil. The LWI of jatropha oil increased from 26.671 to 51.177.
3. The wear analysis on FESEM revealed that adding garlic oil to jatropha oil minimized the wear and produced smoother surfaces at 200kgf load as compared to the surfaces lubricated with pure oil at 126kgf load. The 3D topographic analysis showed that the inclusion of garlic oil in the jatropha oil lowered the wear and surface roughness. It produced much smoother surfaces and decreased the values of Ra and Rq.
4. EDS analysis of the wear scars confirmed the presence of nano-additives and the formation of the tribo-film on the surface. The presence of sulfide and oxide films was detected on the wear scars lubricated with jatropha oil mixed with garlic oil.
5. The FTP of jatropha oil was elevated to a large extent after the addition of garlic oil.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding this article.

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