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Tribological Performance of Modified Jatropha lubricant Under Reciprocating NANOVEA T 50 Tribometer for Electric Vehicles

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Abstract: In response to concerns about combustion engines' negative effect on the environment and the use of petroleum-based lubricants to address friction and wear issues, there is growing interest in the development of electric vehicles (EVs) in solving the ICEs pollution challenges. To achieve the expected performance of EVs, the use of suitable bio-lubricants is necessary. In this work, novel lubricants were formulated from jatropha oil as base lubricant using Polytetrafluoroethylene and hexagonal boron nitrate (h-BN) as additives to address the issues of friction and wear during lubrication. The investigation employed a sensitive NANOVEA T50 tribometer machine. The additives' effectiveness in enhancing tribological performance was assessed in terms of their capacity to reduce friction, wear, and load carrying ability. The substrate morphology and elemental distribution on lubricated worn surfaces was done using a scanning electron microscope (SEM) and energy dispersive x-ray (EDX). Under higher loads (25 N), blended 0.5 wt.% poly. + 0.6 wt.% h-BN reduced friction and wear, but at lower (5 N) working conditions, it performed poorly due to lack of frictional energy for the film formation. However, as compared to base jatropha oil, the 0.5 wt% poly. + 0.6 wt% h-BN provided the best friction (0.0315) and wear scar diameter (461.027 µm), among all the nano lubricants under 25 N. According to the findings, the higher the working condition if employed in EVs, the better the tribological performance of the new formulated nano lubricants, resulting in enhanced system performance.

Keywords: Jatropha oil, Polytetrafluoroethylene polymer, h-BN, lubrication, Electric Vehicle

1. Introduction

Assessment into the pollution impact during industrial combustion operations discovered that about 25% of the global CO_2 emissions are caused by fossil fuel-powered engines, including those that run on gasoline, diesel, and other fuels[1–4]. Internal combustion engines (ICEs), which run on fossil fuel, apart from non-environmentally friendly nature, also have the lowest energy conversion efficiency at 20%, leading to greater energy losses[5,6]. In addressing these global confrontations, exploration into electric vehicles (EVs) powered partially or entirely by electric driven has drawn a lot of attention recently, keeping several additional aspects in the mind of researchers[7,8]. By 2050, it is anticipated that all passenger vehicles will be zero-emission vehicles, with energy conversion efficiency of up to 60%, which can be solved via sustainability adaptation[2].

Recently, battery electric vehicles (BEV) appeared to be a promising technology that is paving the road for the environment to become carbon-free. The BEV is predicted to achieve a significant market penetration soon due to slowly advancing social acceptance mostly from the lubricating challenges[2]. It is essential that all the elements involved in the power generation process be improved to increase the vehicle's performance and efficiency, thus demanding good lubrication. The transmission fluid serves the same general purpose regardless of the type of transmission used, such as automatic stepped transmission, continuously variable transmission, or dual-clutch transmission, which is to generate hydraulic pressure, dissipate heat, and guard against wear on the metal gears and other parts[2].

However, due to some contact with the e-motor and/or other electrical parts of the car, lubricants in EVs need to have unique properties, such as better electrical insulation to prevent short -circuit, swells, cracks, etc. The operating environment for EVs can be harsh and include high temperatures, increased oxidation, and particle abrasion. The lubricants must have consistent, steady dielectric characteristics to function under these circumstances. Since copper is highly used for the majority of these components, it is crucial that the lubricant has high compatibility with copper[8)]. According to literature, corrosion that goes beyond a certain degree of potentiodynamic polarisation affects the lubricant and starts to support conductivity, which can cause a dangerous short circuit[7)].

In contrast to ICE cars, EVs are anticipated to have differing tribological performance requirements owing to its sensitivity[2)]. Among the most crucial considerations for EVs are a lubricant's thermal and electrical properties, copper corrosion, and compatibility with EVs elastomers/polymers[8)]. According to[8)], suggested that the fluids in electric vehicles require entirely different lubricating fluids, such as low viscosity, corrosion resistance, and a low conductivity tendency. To protect seals, bearings, and gears from wear and friction at speeds beyond 25,000 rpm and some low speed, proper lubrication is crucial. Lubricants' incompatibility with the explosive electrolytes in batteries and motor parts could be hazardous and dangerous. The goal of achieving higher heat transmission will also need the use of low-viscosity lubricants[9,10)]. To create new lubricants that are compatible with EV, sophisticated materials must be used. Therefore, this present research was comprehensively characterized and performed tribological analysis on a new formulated EV lubricant as to ascertain suitable application. This study employed polytetrafluoroethylene polymer and hexagonal Boron nitride (h-BN) nanoparticles to solve the challenges with friction and wear during EVs components mechanisms.

2. Materials and Method

Polytetrafluoroethylene (PTFE) powders and hexagonal Boron nitride nanoparticles were used in this study as additives. Application of jatropha bio-oil were employed as base lubricant, while the 6 mm ball is used as upper tribo-pair. These materials mentioned are purchased from Sigma-Aldrich Malaysia. According to the manufacturer, the Polytetrafluoroethylene powders and hexagonal Boron nitride had mean particle sizes of 10–44 nm and 65-75 nm, respectively. The down tribo-pair is made up of aluminum alloy (30 mm by 30mm), fabricated in the Universiti Teknikal Malaysia mechanical fabrication workshop using CNC machine with polished surface. The selected additives applied was based on their potentials in resisting corrosion and good tribological performance[11)].

2.1. Characterization of the Samples

The morphology of the samples was investigated using a scanning electron microscope (SEM) (JEOL JSM-6010PLUS/LV) powered by 100V/11 amps. Before the SEM analysis, the powdered samples were first coated for better morphology display. Alongside, EDX analysis was conducted on the samples.

Using a Gamry machine, the corrosion resistance analysis of additives was carried out. The standard three-electrode setup was used, consisting of a graphite rod as the counter electrode, a saturated calomel electrode (SCE) as the reference electrode, and a specimen with a 4 mm exposed surface as the working electrode thus pre-ground and polished. Electrolyte mediums contained physiological saline NaCl and 0.2% polymer + 0.2% h-BN, while 0.5 mV/s of voltage was scanned during tests involving potentiodynamic polarization. The samples were exposed to electrolyte to achieve stable open circuit potential (OCP) before the polarization tests. Electrochemical impedance spectroscopy (EIS) was measured at a frequency ranging from 100 kHz to 10 mHz with an amplitude of 10 mV. All the measurements were carried out at 25°C and were repeated at least three times to ensure reproducibility.

The physiochemical features such as density, viscosity, and flash point on the various samples were conducted. According to ASTM D 445 standards, the viscosity was conducted using HK-265A apparatus with capillary tube tested at 40 ºC and 100 ºC. In preparing the testing samples, base lubricant of 100 ML was used, polytetrafluoroethylene was of various fractions (0.3, 0.4, 0.5, 0.6 wt.%), while hexagonal boron nitride nanoparticles of different concentrations (0.4, 0.8, 1.2wt.%) were used. Before the test, the various additives were dispersed in 100 ml base lubricant solution using 30 min ultrasonication, separately, before blending the additives.

As illustrated in Fig. 1, SETA flash point machine was employed in this study in accordance with ASTM D3828 standard test, using butane gas. As flash point is the lowest temperature at which the lubricating oil gives off enough vapor that ignites for a moment when a tiny flame is brought near it. Therefore, it is necessary to know the lubricant flash point before using in EV to ascertain whether lubricant remains within safe operational specifications. The test requires just 4 ml of sample and introduced at upper tiny hole when the machine had heated to the desired temperature, the right button is then pressed bringing timer, at 15 sec, the line connector to butane gas is opened and ignitor is then applied to check for a flash point. At flash temperature, flash will display on the machine reading screen as seen in Fig. 1. The stated value is the average of all measurements, which were all performed at least three times to confirm the reproducibility.

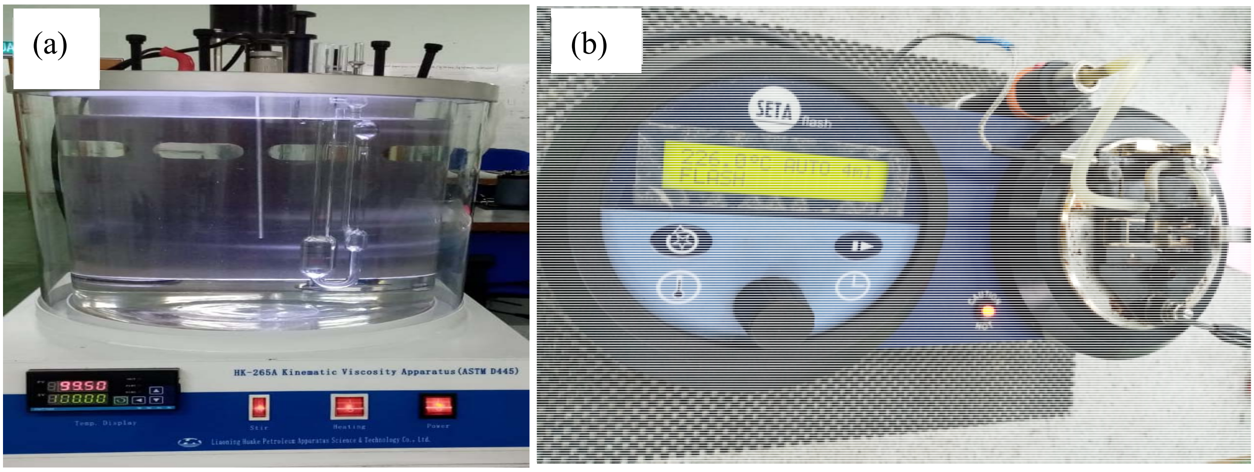


Fig. 1: Image of viscosity apparatus (ASTM D445) (a) and SETA machine (b) for lubricant flash point.

2.2 Frictional Analysis

The purpose of this testing is to determine the formulation's efficacy in decreasing friction and wear that is produced by sliding operations under internally generated heat. Since EVs are made up of different mechanisms that come into contact with each other during operation, a proper lubricant is required to control the frictional heat created in order to avoid high friction and wear. Del Río et al.,[12], investigated the effectiveness of lubricant tribological enhancement using magnetic nanoparticles, Nd alloy compared to trimethylolpropane trioleate base. In comparison to TMPTO, the Nd alloy compound nano dispersion had the highest tribological performance, with decreases in friction and WSD of 29% and 67%, respectively. The experimental work was performed in the Laboratory Green Tribology and Engine Performance Research Group (G-TriboE), Universiti Teknikal Malaysia Melaka. The tribological testing employed sensitive NANOVEA tribometer (ASTM G133-05) as shown in Fig. 2. The NANOVEA tribometer is a modern tribometer that uses a sharp chaotic waveform with numerous noise signals, covers all readings, regardless of their size. Other than the heat produced by the frictional process, no heat is applied during the processes. The NANOVEA tribometer is connected to a system monitor for collection of coefficients of friction (COF) and wear rate data's, followed by analysis.

The operation is by reciprocating mode, employing ball and flat materials according to Shahabuddin et al.,[13], whereby moving ball (steel) will be sliding on a stationary flat (aluminum). Before each test, various elements for the analysis were ultrasonically washed using acetone followed hot air for final dry, thus performed before and after each run. Base oil of 100 ml was used in the study before blending with additives. During the testing, stroke of 5 mm, and 100 rpm of speed was used. To avoid some external influence in accordance with machine usage, the system was closed to keep the operation at room temperature. The working conditions like applied load, testing aluminum materials and time duration are presented in Table 1. At the end of each testing, the flat was analyzed on the wear effect using SEM machine, while profilometer machine was used for wear track profiles/surface roughness analysis of lubricated flat specimens.

Table 1: Experimental working condition and tribo-pair parameters.

Parameters	Value	Property	Ball Spacemen	Flat specimen
Speed (rpm)	100	Test position and motion	Upper and reciprocating	Lower and fixed
Stroke (mm)	5	Designed	As purchased	to smoothest
Time duration (min)	15, 30	Hardness (range), Hv	700-900	29.0 - 96.0
Load (N)	5, 10 and 20	Tensile strength, MPa	2240	0.700 - 1600
Lubricants	Jatropha	Young's modulus, GPa	$2.1*10^{11}$	$69*10^{6}$
Additives	PTFE and h-BN	Surface roughness	Mirror-finish	$0.05 \leq Ra \leq 0.090$ μm
Samples Con. (wt.%)	0.3, 0.4, 0.5, 0.6 for polymer 0.4, 0.8, 1.2 for h-BN	Poisson's ratio	0.3	0.31–0.34

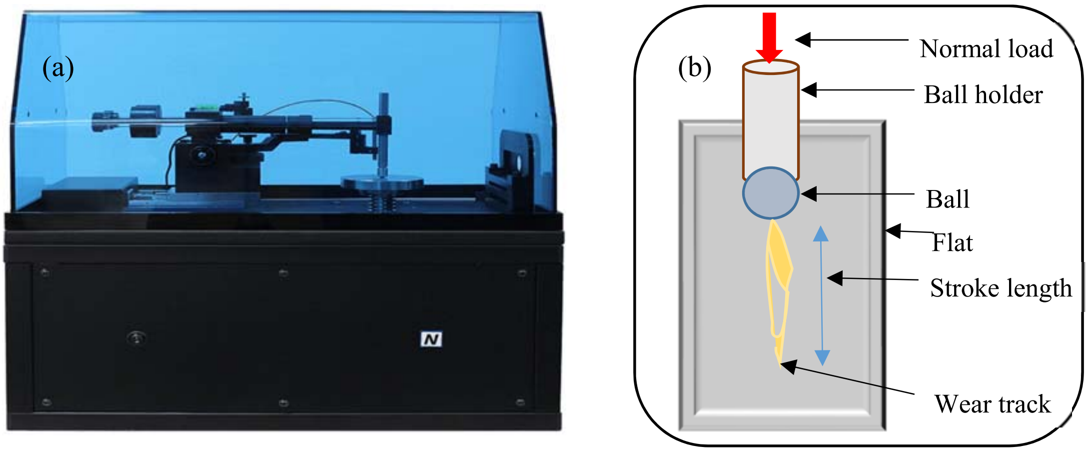


Fig. 2: Image of sensitive NANOVEA tribometer (a) and tribo-pairs mechanism (b)

3. Results and Discussion

3.1 Characterization of samples used.

The sample morphology was conducted in line with previous works[14,15]. Fig. 3 (a), (b) and (c) exhibit the SEM micrographs of the Polytetrafluoroethylene powder, wear h-BN and 0.25 wt.% by 0.25 wt.% of mixed polymer and h-BN, respectively, showing the distribution and morphology of the various samples. According to the EDX, Polytetrafluoroethylene (a1) sample displayed the element of carbon, fluorine. On the side of h-BN (Fig. (b1)), elements of boron and nitrogen were seen while under combination as in Fig. 3 (c1), revealed carbon, fluorine, nitrogen, and boron. However, Zirconium (Zr) element came from the coating material during the testing.

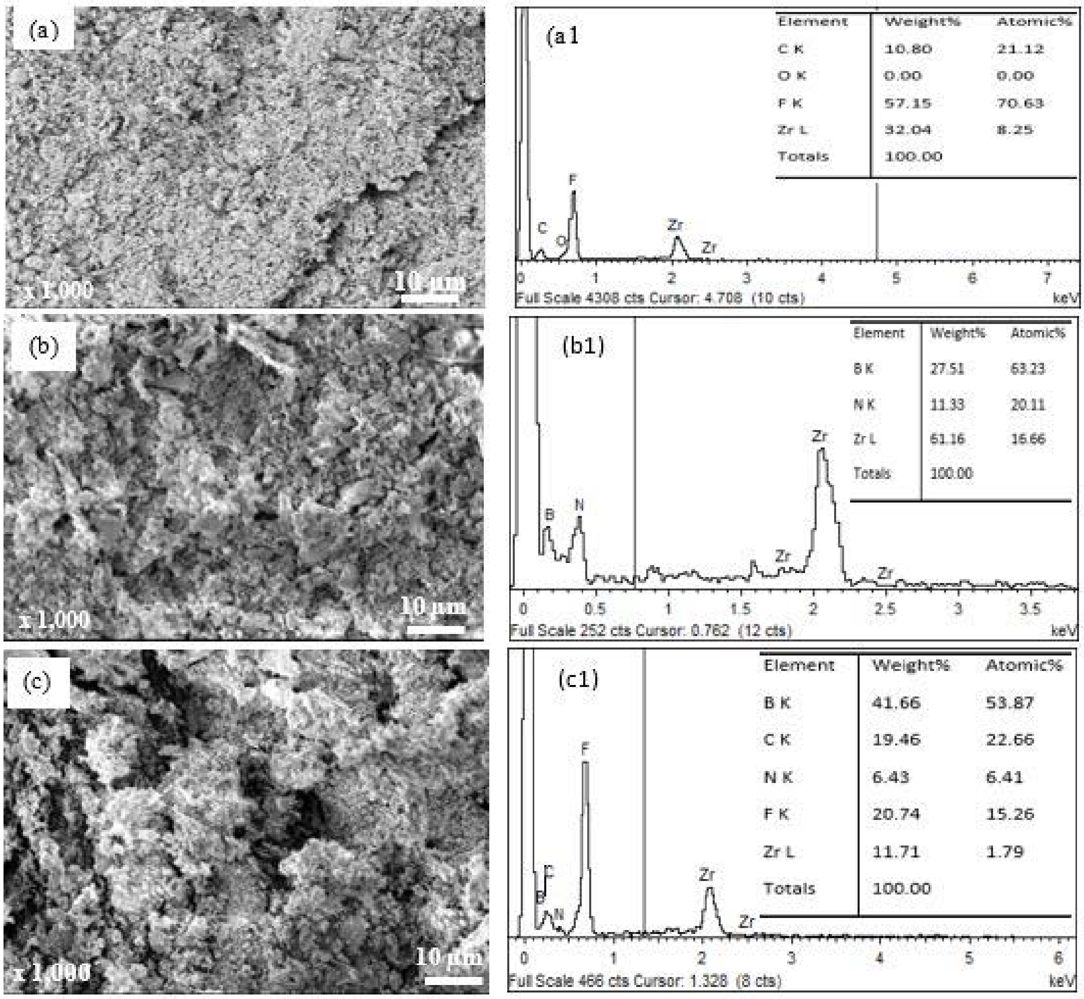


Fig. 3: SEM and EDX results of Polytetrafluoroethylene (a-a1), h-BN (b-b1) and mix (c-c1).

An electrochemical test is conducted to investigate the corrosion properties of the additives in a solution with copper material. Fig. 4 shows the images of the solution under different tests. Under Nacl solution with copper material indicated the corrosion effect on the rod thus changes the color of the solution as shown in Fig. 4 (a). With the inclusion of the additives, a little change was found on the solution unlike investigation without additive, revealing the corrosion resistance as presented in Fig. 4 (b). The results on the potentiodynamic polarization curves are shown in Fig. 4 (c and d). Copper rod in Nacl solution alone as shown in Fig. 4 (c) demonstrated reactions, displaying at higher negative zone unlike Fig. 4 (d) which indicated that the E_{corr} of copper rod in Nacl solution with h-BN + Polymer is more noble, which means that the selected additives could decrease the Ecorr value, thus good for EVs lubrication. A more negative potential indicates a positive thermodynamic reaction trend. The current study's observations demonstrate that the corrosion behavior of the solution containing h-BN and polytetrafluoroethylene was determined to be within the required corrosion threshold, which will resolve the conductivity and short circuit issues. This is similar with previous research presentation[16].

The kinematic viscosities of base jatropha oil and blended at various concentrations of additives under temperature of 40 and 100°C are presented in Table II, along with the corresponding density and viscosity index. The illustration shows how increasing temperatures result in a decrease in the kinematic viscosity of every tested lubricant. This is similar to reported literatures[17,18]. Obviously, inclusion of polymer demonstrated the polymeric tendency of replenishing base lubricant viscosity loss compared base jatropha. However, the effect was less under 0.3 wt.%, also, the performance under 0.6 wt.% was close to that of 0.5 wt.%. The effect of h-BN on base jatropha was not much pronounced compared with the polymer samples. The outcome from the combination of the selected additives enhances the viscometric performance of the formulation thus yielding synergetic impact. At high temperatures, the lubricants loses its viscometric properties, showing lesser values as a result of the thermal impact[19,20].

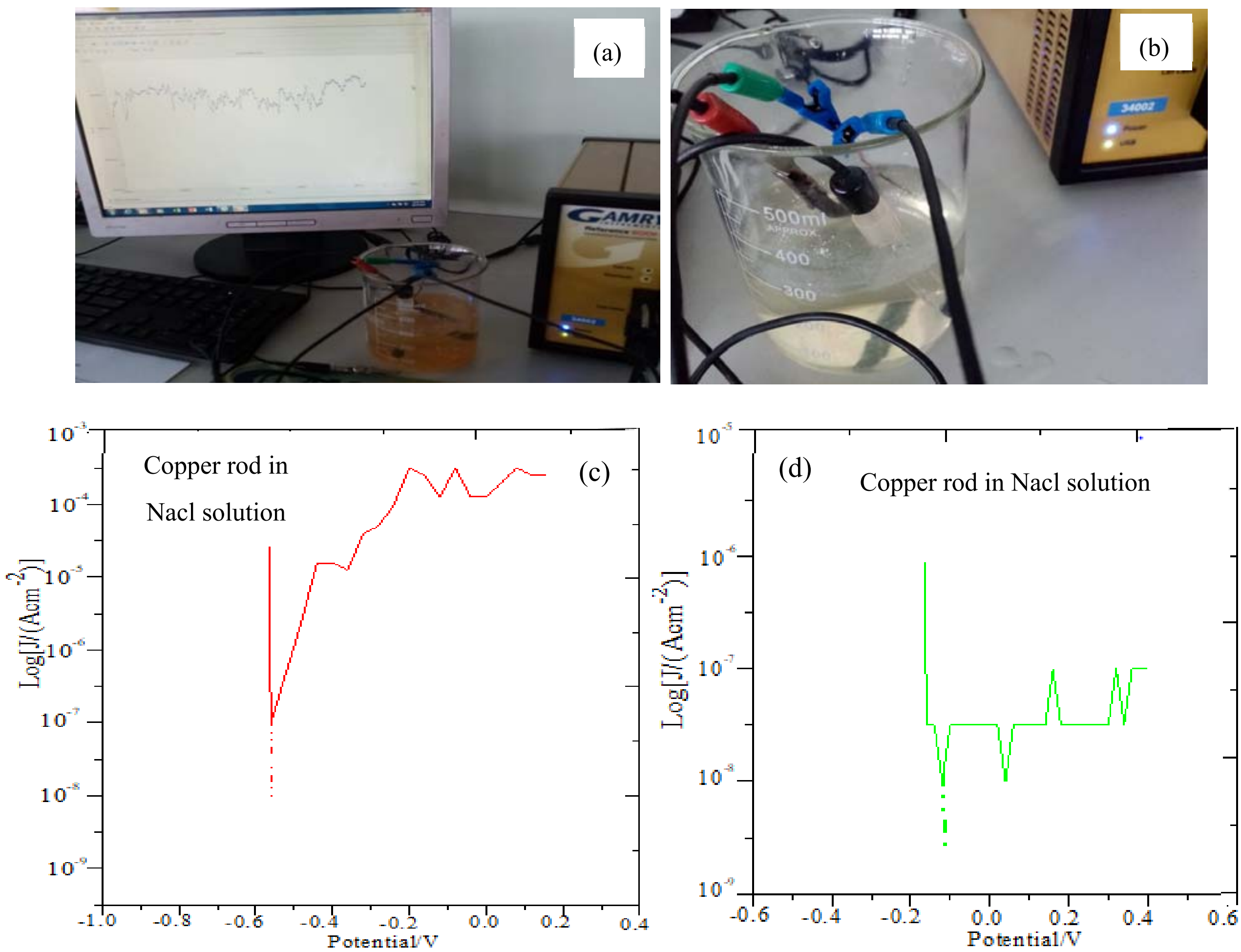
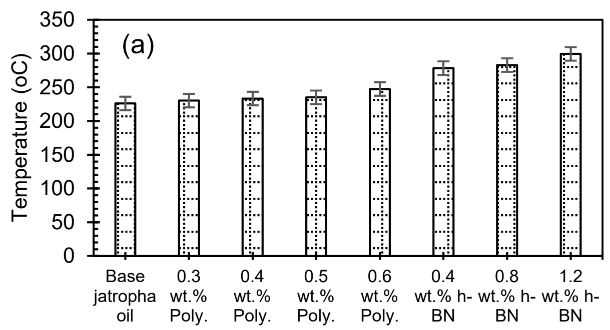


Fig. 4: Images of the solution changes on copper in Nacl solution (a) and solution with h-BN + Polytetrafluoroethylene (b): Potentiodynamic polarization curves of copper in Nacl solution (c) and solution with h-BN + Polytetrafluoroethylene (d).

Table 2: Density, Kinematic viscosity and viscosity index of the various samples.

Lubricants	Density	Kinematic viscosity (mm^2/s)		Viscosity
		@ 40 °C	@ 100 °C	Index
Base Jatropha	0.903	83.7	19.7	259.86
0.3 wt.% Polymer	0.917	85.1	20.1	261.33
0.4 wt.% Polymer	1.105	88.4	22.5	283.06
0.5 wt.% Polymer	1.113	88.9	23.2	289.92
0.6 wt.% Polymer	1.121	90.3	23.3	287.32
0.4 wt.% h-BN	0.907	83.7	19.9	262.36
0.8 wt.% h-BN	0.931	83.9	19.8	260.66
1.2 wt.% h-BN	1.005	84	19.9	261.53
0.5 wt.% Poly. +0.5 wt.% h-BN	1.136	87.1	23.3	296.07
0.5 wt.% Poly. +0.6 wt.% h-BN	1.142	88.6	23.5	294.30
0.5 wt.% Poly. +0.7 wt.% h-BN	1.146	88.8	23.6	294.98
0.5 wt.% Poly. +0.8 wt.% h-BN	1.151	88.9	23.5	293.48

The flash point of the base jatropha oil and the blended additives lubricants are shown in Fig. 5. The mentioned lubricant property is very important, as these lubricants have been used recently in compressors used for compressing highly inflammable refrigerants like hydrocarbons. The flash points were found to increase by the addition of additives as presented in Fig. 5 (a). On individual additive, 0.5 wt.% poly. (237.5) and 0.8 wt.% h-BN (282.9) yielded maximum values. This demonstrated improvement by 4.32% and 6.35% for 0.5 wt.% polymer and 0.8 wt.% h-BN, respectively when compared with base jatropha lubricant. On investigating the combination of various additives as in Fig. 5 (b), observed that flash points increase with increase in concentration, therefore good for EVs application. The higher flash point was owing to the improved thermophysical characteristics and stability of the polymer nanoparticles and h-BN nanoparticles. The highest value was found with 0.5 wt.% poly. + 0.8 wt.% h-BN, thus improved by 2.35% when compared with base jatropha lubricant.



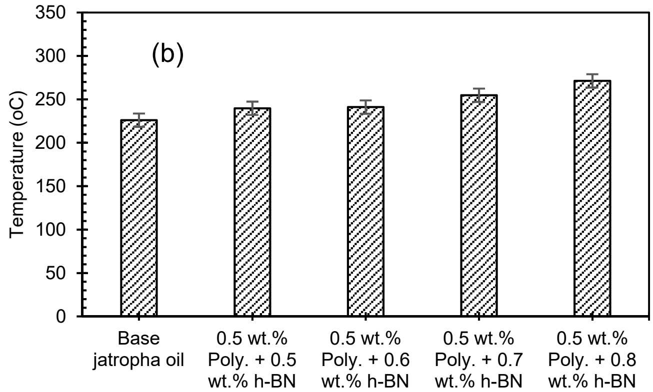


Fig. 5: Flash point of various lubricants (Single additives(a); combined additives (b)).

3.2 Frictional Analysis

Fig. 6 depicts the results of COF and wear rate for various modified jatropha lubricants in comparison with unmodified jatropha oil under 10 N and sliding length of 5mm. Analyzing the COF generated during operation, base jatropha lubricant recorded the lowest COF (0.011), however inclusion of polytetrafluoroethylene additives ranges from 0.012-0.014 under polymer, whereas h-BN ranges from 0.016-0.019 as illustrated in Fig. 6 (a). This shows that addition of both additives individually had no enhancement on the lubricant performance. This could be the inability of the operation to generate frictional energy which would help in tribo-film formation [20,21]. The poor performance was also suspected to come from viscous nature of the lubricant leading to sliding drag since the machine is sensitive and recommended less viscous lubricant likewise EVs lubricants [9]. Though, the samples of polytetrafluoroethylene exhibited better COF performance than h-BN when compared to unmodified jatropha oil. The COF percentage increment of the additive's lubricant against base lubricants are presented in Table III.

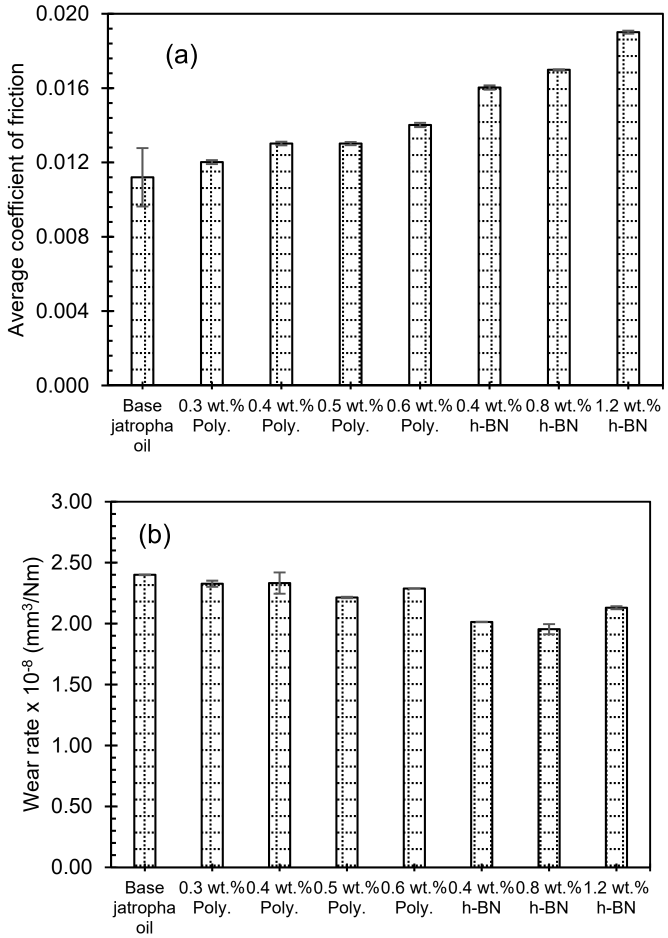


Fig. 6: Results of avg. COF (a) and wear rate (b) of the various individual additives under10 N and sliding stroke of 5mm.

Under wear rate, inclusion of additives demonstrated wear rate reduction as shown in Fig. 6 (b). The performance was suggested to be from penetration of nanoparticles on the sliding region thereby preventing much direct sliding contact[22]. Unmodified jatropha lubricant yielded a wear rate of 1.68 *(10^{-9} mm^3/N/m). Obviously, the use of h-BN revealed better performance in terms of wear rate reduction compared to polytetrafluoroethylene, taken base jatropha as reference. 0.8 wt.% h-BN gives the best performance 1.59 *(10^{-9} mm^3/N/m), while 0.6 wt.% and 0.4 wt.% poly. yielded the worst results with equal value 1.66 *(10^{-9} mm^3/N/m). The percentage reduction on the lubricants wear rate are shown in Table 3.

Table 3: COF percentage increament/reduction of the various lubricants used under 10N.

Lubricants	**COF (%) increment**	**Wear rate (%) reduction**
0.3 wt.% poly.	-9.09%*	1.78%
0.4 wt.% poly.	-18.18%*	1.19%
0.5 wt.% poly.	-18.18%*	2.97%
0.6 wt.% poly.	-27.27%*	1.19%
0.4 wt.% h-BN	-45.45%*	4.16%
0.8 wt.% h-BN	-54.54%*	7.14%
1.2 wt.% h-BN	-72.72%*	5.35%

To confirm the tribological response of the two additives on jatropha lubricant, the two additives were further blended selecting the bast range of performance under individual use to ascertain their synergistic or antagonistic effect. Fig. 7 presents the various average COF that emerged against the used loads for all the investigated lubricants compared to the unmodified jatropha base oil. Obviously, the samples demonstrated similar behavior on the graph trends as presented in Fig. 7 (a and b). It was observed that under lower loads of 5 N and 10 N, unmodified jatropha gave better COF but displayed higher COF at higher load (20N) as shown in Fig. 7 (a). According to the results, the formulation performed better under higher load than lower operating conditions when compared to the base lubricant.

Under 5 N, the unmodified jatropha yielded COF of 0.0108, while at 10N produced 0.011. At 20 N revealed the highest COF of 0.0128, thus stands as the maximum COF in the entire analysis. This revealed poor performance of modified jatropha under lower working condition, thus recommended its application on EVs at higher working conditions. The poor performance from samples of additive could be inability to generate frictional enegy that will lead in the formation of tribo-film at the sliding zone. Good formation of tribo-film causes contact separation/less friction leading to low COF according to Kerni et al.,[20]. Among the modified jatropha samples, 0.5 wt.% + 0.6 wt.% h-BN gave the best results except under 5 N, were 0.5 wt.% poly. + 0.5 wt.% h-BN performed better. The percentages COF increment or reduction from the use of the various lubricants are listed in Table 4.

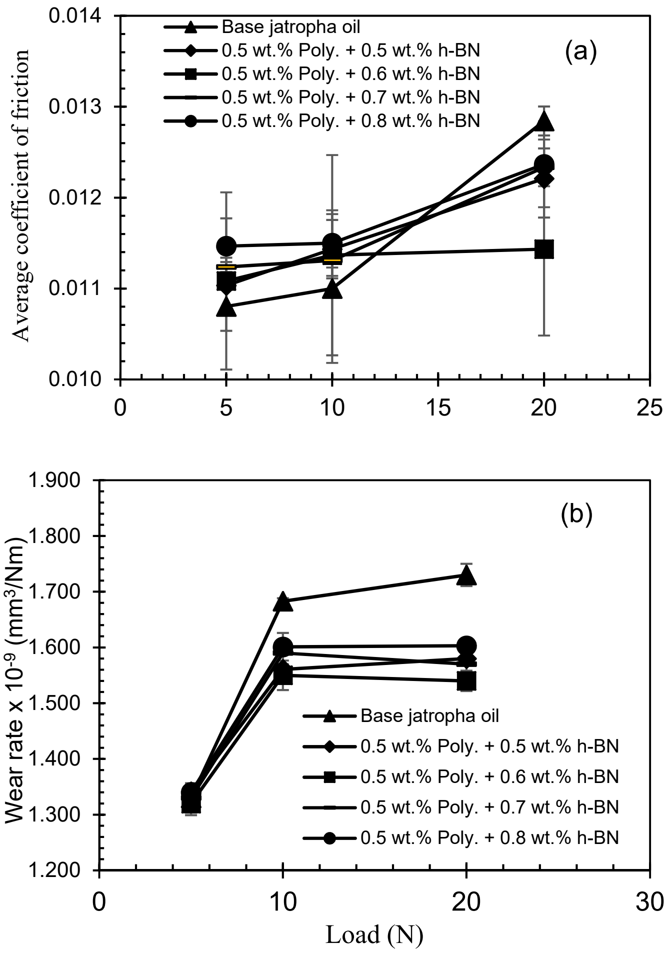


Fig. 7: Results of avg. COF (a) and wear rate (b) of the various lubricants under different loads (5 N, 10 N, 20 N) and sliding distance of stroke of 5 mm.

Evaluating the lubricants' effectiveness towards wear rates as seen in Fig. 7 (b). The addition of additives to jatropha oil improved wear rate general performance, with the exception of under load of 5 N, when values were quite similar to those of the pure jatropha lubricant. Unmodified lubricant produced 1.33 * (10^{-9} $mm^3/N/m$) at 5 N, 1.68 * (10^{-9} $mm^3/N/m$) at 10 N, and 1.73 * (10^{-9} $mm^3/N/m$) at 20 N. Compared to unmodified lubricant, the performance of nanolubricants improves with increasing load. The wear rate enhancement from the additives were due to their nanosized structure, thus easily diffuses into the sliding region during lubrication. This mechanism causes seperation between the sliding bodies leading to wear rate reduction[23,24)]. The percentage reduction on inclusion of additives on base jatropha oil are listed in Table 4.

Using 25 N for 15 minutes, an extensive analysis of the operating wave trend was performed to obtain the various COF as shown in Fig. 8. It is obvious that increase in load resulted in better tribological performance of the nano-lubricant. The operations from the graph revealed that unmodified lubricant wave peak was very high at the beginning, begins to drop, again increases at about 180 s, until about 720s, yielding COF of 0.0631 as illustrated in Fig. 8.

Table 4: COF percentage increament/reduction of the various lubricants used.

Lubricants and working condition (load)	COF (%) increment/reduction			Wear rate (%)increment/reduction		
	5 N	10 N	20 N	5 N	10 N	20 N
0.5 wt.% poly. + 0.5 wt.% h-BN	-2.13%*	-3.64%*	4.69%	-0.75%*	7.14%	8.67%
0.5 wt.% poly. + 0.6 wt.% h-BN	-2.59%*	0.91%	6.25%	0.75%	7.74%	10.98%
0.5 wt.% poly. + 0.7 wt.% h-BN	-3.70%*	-2.73%*	3.91%	0.01%	5.36%	7.34%
0.5 wt.% poly. + 0.8wt.% h-BN	-6.48%*	-4.55%*	3.13%	-0.76%*	4.70%	7.34%

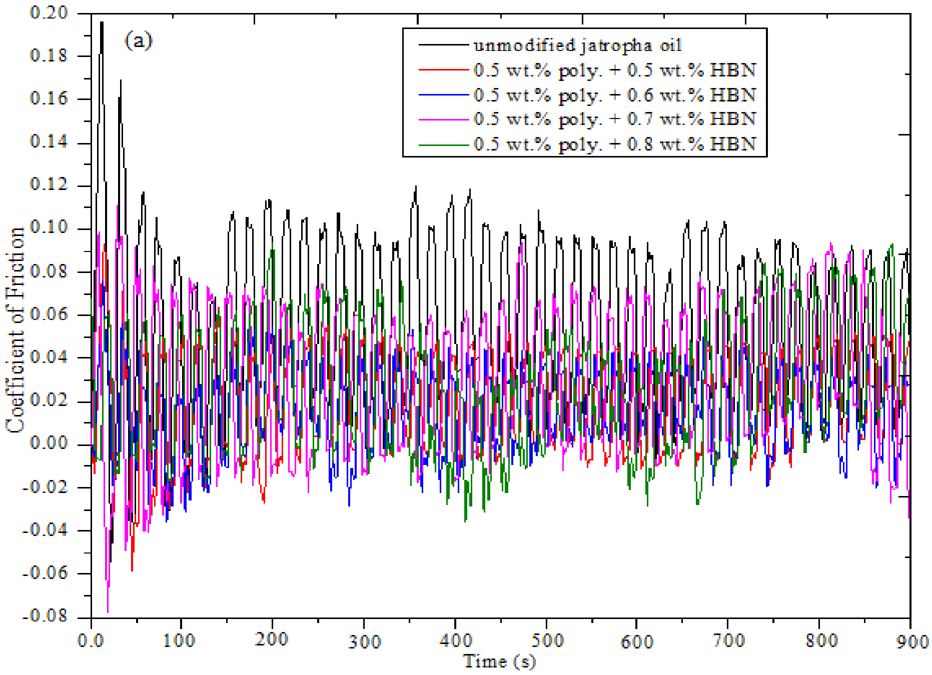


Fig. 8: Results of COF of the various lubricants under 25 N and stroke of 5 mm.

On the side of nano-lubricant, the wave revealed a significant COF drop especially under 0.5 wt.% poly. + 0.6 wt.% h-BN (0.0315) given the best result, followed by 0.5 wt.% poly. + 0.5 wt.% h-BN (0.0347), while 0.5 wt.% poly. + 0.7 wt.% h-BN (0.0401) which appears similar to 0.5 wt.% poly. + 0.8 wt.% h-BN (0.0402). The research observed that at higher concentrations of additives, poor tribological performance was recorded, owing to inability form good tribo-chemistry on the substrate surface. Also, starvation of lubricant at the contact region was noted, thus reported similar by Opia et al.,[21].

4. Wear morphology and nano lubricants mechanism

As demonstrated in Fig. 9, the effect on reducing wear scar diameter was pronounced with modified jatropha lubricants compared to unmodified jatropha lubricant. Analyzing the surfaces, grooves were seen, however detected more under unmodified jatropha lubricant. Under nano-lubricant application, the lubricants demonstrated reduction on wear scar diameter through healing operation by the formulated films. Lubricant with 0.5 wt.% poly. 0.6 wt.% h-BN revealed least WSD (461.027 µm), followed by 0.5 wt.% poly. 0.5 wt.% h-BN0.5 wt.% poly. 0.7 wt.% h-BN (499.049 µm), before 0.5 wt.% poly. 0.8 wt.% h-BN (532.060 µm), while 0.5 wt.% poly. 0.5 wt.% h-BN gave the highest WSD (552.015 µm) as presented in Fig. 9. The lubricating film formation was via nanoparticles tribo-reactions on the tribo-pair surfaces and by deposition of nanoparticles on the worn areas leading to mending mechanism, thus similar with the findings observed by Ali et al.,[25].

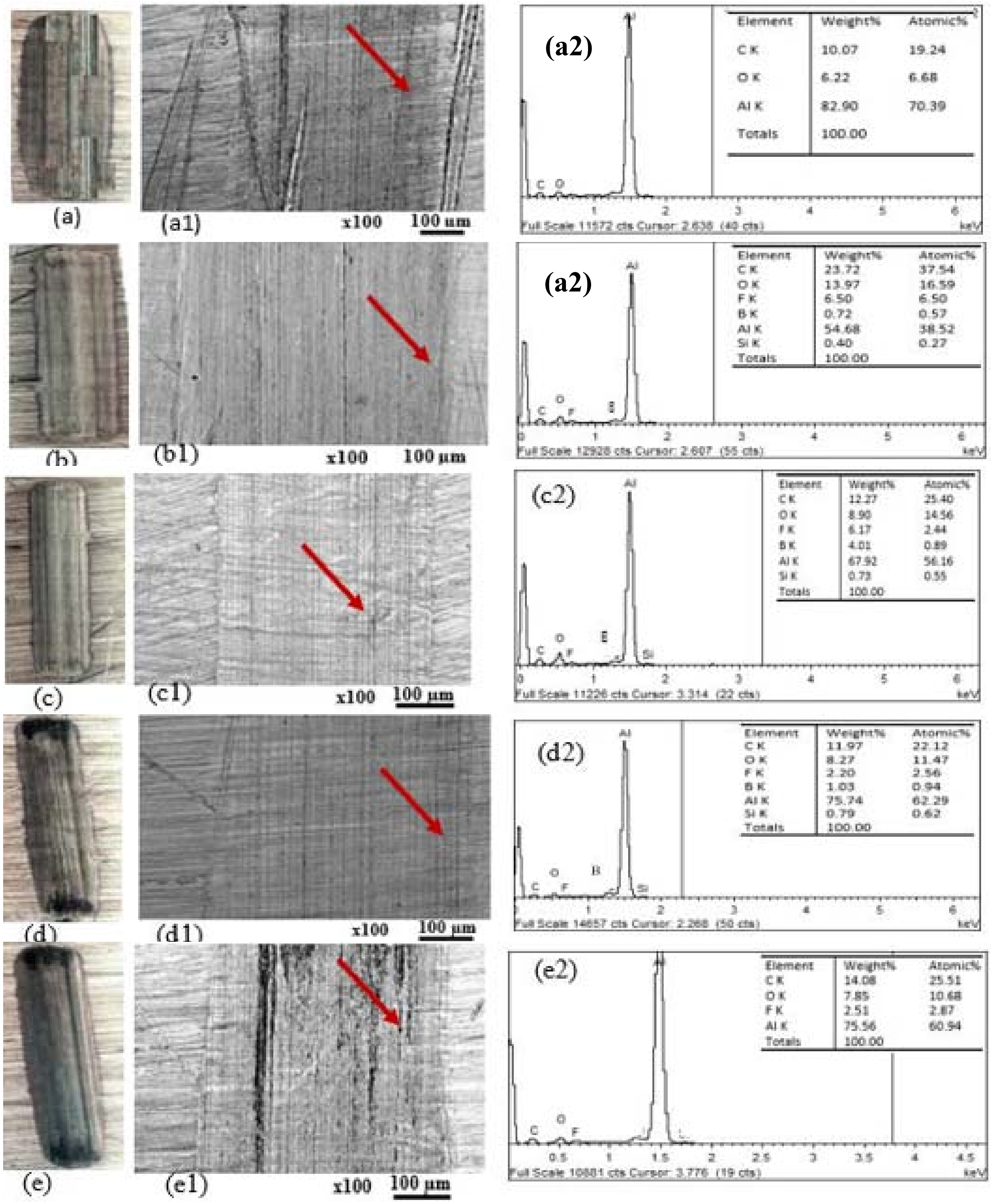


Fig. 9: Images of full wear track (a-e) extracted SEM (a1-e1) and EDX (a2-e2) of surfaces lubricated with different lubricants (unmodified jatropha (a-a2); 0.5 wt.% poly. 0.5 wt.% h-BN (b-b2); 0.5 wt.% poly. 0.6 wt.% h-BN (c-c2); 0.5 wt.% poly. 0.7 wt.% h-BN (d-d2); 0.5 wt.% poly. 0.8 wt.% h-BN (e-e2)) under speed of 100 rpm and 25 N.

As detected by the EDX from the pointed red arrows, elements found on the lubricated worn surfaces are presented. Apart from the Al, C, and O that were identified on surfaces lubricated with unmodified jatropha, it was observed via EDX analysis that extra elements were detected on surfaces lubricated by modified jatropha, indicating the existence of additives used. Although, element of F and B found were small in percentage, discovered to be from insufficient tribo-reaction of the lubricant during lubrication owing to lack of frictional energy, thus reported similar observations in literature [26]. Black spots were noticed at both ends of slide grooves, as shown in Fig. 9 (d and e), which suggests a higher concentration of the nano additives used.

Again, information on the effectiveness of additives in lowering surface roughness (Ra) and worn surface depth (Rz) is provided by the surface morphology. The optimal nano lubricant (0.5 wt.% polymer + 0.6 wt.% h-BN) and unmodified jatropha oil are shown in 3D images in Fig. 10. The investigation took into account six different positions on the worn surfaces, resulting in the determination of the average Ra and Rz. Unmodified jatropha lubricant produced 1.366 um (Ra) and 7.933 um (Rz), as shown in Fig. 10, while the best modified candidate (0.5 wt.% poly. + 0.6 wt.% h-BN) yielded 0.663 um (Ra) and 3.133 um (Rz). Research showed that the nano lubricant utilized in this work, when subjected to a 25 N load, effectively reduced Ra.

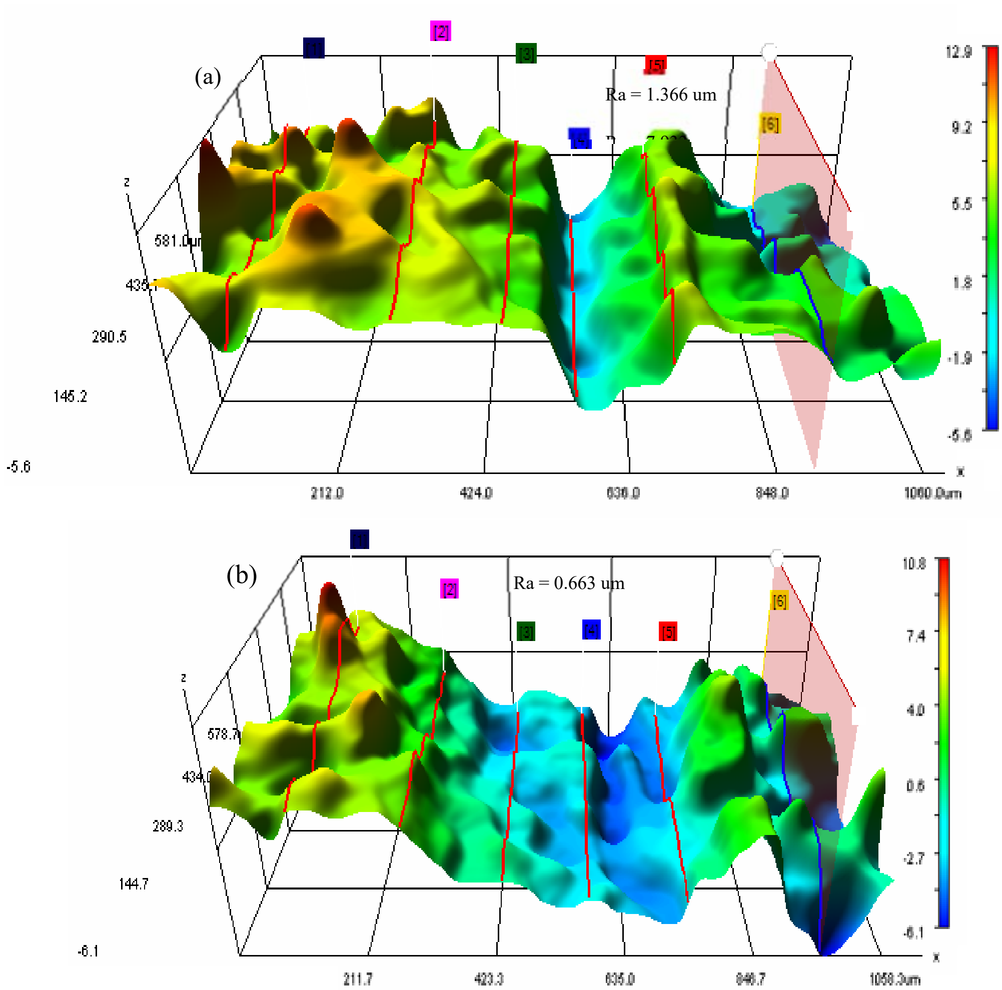


Fig. 10: 3D Surface roughness Morphology of the lubricated surfaces (unmodified jatropha (a) and 0.5 wt.% poly. + 0.6 wt.% h-BN) (b)

Fig. 11 provides an illustration of the formulation's friction-reducing mechanism. Under lower loads, it was found that the procedures lacked the frictional energy to produce a sacrificial constituent for contact separation but exhibited to some extent at higher loads. The evidence was the decrease in COF and wear under 25 N than 5 N, as shown in Fig. 8. The investigation showed that, while the ball was operating under reduced load, the front and rear of the ball were starved of lubricants, which made it challenging for the particles to diffuse in between the rubbing region, as illustrated in Fig. 11(a). This observation was not noticed under higher load (25 N) as presented in Fig. 10 (b). As operation attains frictional energy, molecules from tribo-film begins to be absorbed (fluorine, carbon, and boron) on the substrate surfaces thus, mending or healing effect occurs as indicated in Fig. 9 under EDX test, thus similar to previous study[27]

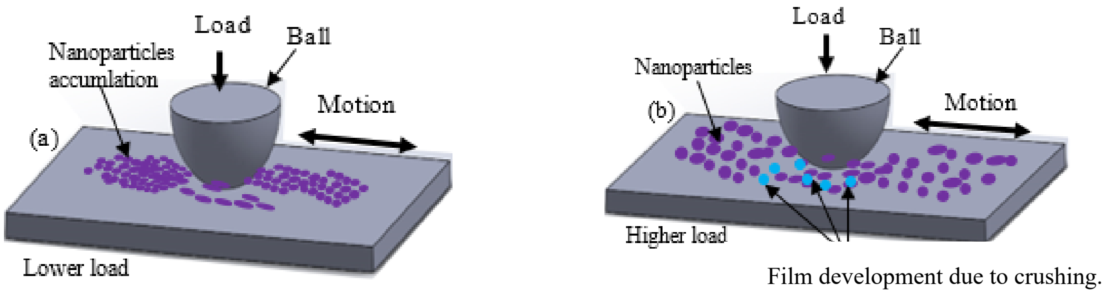


Fig. 11 Tribological mechanism of 0.5 wt.% poly. + 0.6 wt.% h-BN during lubrication

5. Conclusion

The need for bio-lubricants to replace petroleum basis in lubricant formulations for EVs has been investigated (due to quantity depletion and environmental impact). This is guided by global sustainability initiatives that encourage using affordable/available materials to meet human needs. For the tribological improvement of base jatropha oil, polytetrafluoroethylene and h-BN were used, formulated, characterized, and tribologically evaluated. Comparing the tribological enhancement of modified jatropha oil in terms of coefficient of friction, wear rate, and wear scar diameter. From the results of the work, the following conclusions were made.

1 The tested corrosion behavior of the mixture, when combined with the chosen additives, shows good performance, demonstrating the capacity to address related corrosion-related problems. It was demonstrated under flash point that the addition of additives increased the flash point value, which is necessary for applications involving electric vehicles.

2 When compared Polytetrafluoroethylene and h-BN to base jatropha lubricant, the COF performance was better with Polytetrafluoroethylene while h-BN yielded more wear rate reduction under higher loads. However, Polytetrafluoroethylene and h-BN demonstrated increment on COF but shows reduction on wear rate under lower load (5N).

3 Blending Polytetrafluoroethylene and h-BN on different concentrations demonstrated COF and wear rate reduction under 25 N, due to synergetic response from the two additives. The study revealed that 0.5 wt.% poly. + 0.6 wt.% h-BN demonstrated optimal performance with COF and wear rate percentage reduction of 6.25% and 10.98%, respectively. Therefore, it is advised to apply the formulation under test conditions at higher load than at lower load.

4 The study further revealed that at 25 N application, good wear scar diameter reduction was observed under modified jatropha lubricants compared to unmodified sample, thus recommended on electric vehicle at higher working conditions. The reduction on the COF and wear scar reduction was the ability of the nano lubricant developing tribo-film on the substrate surfaces. The reduction on the COF, WSD and surface roughness

were recorded from the mending mechanisms demonstrated by the nano lubricants. observed under modified jatropha lubricants compared to unmodified sample, thus recommended on electric vehicle at higher working conditions. The reduction on the COF and wear scar reduction was the ability of the nano lubricant developing tribo-film on the substrate surfaces. The reduction on the COF, WSD and surface roughness were recorded from the mending mechanisms demonstrated by the nano lubricants.

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