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Research Article

Investigations in wear and friction behavior of blends of Laxmitaru-FAME with nanoparticles as additives

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Abstract

Blending of biofuels with petro-diesels has become indispensable for environmental conservation, offering considerably enhanced tribological qualities that contribute in power saving along with extension in the lifespan of compression-ignition (CI) engines. The objective of this work is to investigate the tribological features of nanoadditivated Laxmitaru- fatty acid methyl ester (FAME) blends in petro-diesel, by means of a 4-ball tribometer following American Society for Testing and Materials (ASTM) D 4172 standard. The experiments involved B-10 (10 percent biodiesel mixed with petro diesel), B-20 and B-30 variants along with neat petro-diesel. Nano Silicon dioxide (SiO_2) was added in varying concentrations of 0.20%, 0.50%, 0.75%, and 1% by weight with Laxmitaru-FAME. The results revealed 75 % decrease in coefficient of friction (COF) and 55% reduction in wear compared to neat diesel (B0). Wear patterns of the experimental spheres were analysed by means of scanning electron microscopy (SEM), which indicated the material insertion and consequential mending on interface by nanoparticles due to highly stable dispersions.

1. Introduction

The continued dependence on fossil fuels remains significant, despite their release of harmful gases into the atmosphere. These toxic emissions pose serious risks, particularly by damaging the ozone layer, which protects the Earth from harmful ultraviolet (UV) radiation. Human-induced air pollution has led to deteriorating air quality, especially in cities. Alarmingly, nine out of ten people globally struggle to access clean air. In regions where pollution levels exceed safe limits, there is a heightened risk of illness. The accumulation of these pollutants threatens the environment and human health, contributing to climate change, rising temperatures, melting glaciers, and escalating sea levels. This urgent situation calls for a global shift from conventional fuels to renewable energy sources, which offer a promising solution to reducing pollution and fostering a healthier environment [1]. Biofuels exhibit superior lubricating properties than petro-diesel. When biofuel is improved by nano additivation, it further enhances lubricity beyond that of neat biodiesel. This enhancement prolongs the lifespan of engine parts, specifically diesel injection system along with diesel pumps, that rely on diesel for lubrication. Maintaining adequate lubricity in engine fuel is essential for extending the durability of engine parts and safeguarding surfaces from wear during relative motion. Enhanced lubrication ability correspondingly lessens power loss via lessening motion resistance amid engine parts. In contrast, traditional diesel fuel exhibits poor lubricating characteristics compared to biofuels, highlighting the importance of exploring alternative fuels to meet increasing necessities [2, 3]. While numerous biofuels reveal favorable lubricity performance,

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some exhibit unacceptable abrasion attributes due to rust and interface damage, posing potential harm to engines and limiting their utility. This underscores the need for tribological investigations into various biodiesels and the utilization of novel nanoparticles for addressing the lacunas [3]. Additionally, few overlooked biofuels warrant investigation in this regard. Several researchers have utilized various nanoparticles to enhance the tribological properties of lubricant oils, yielding highly beneficial outcomes. Ensuring the proper dispersion and precise mass/volume ratios of nanoparticles are crucial when incorporating them. Ultrasonication is employed to verify effective dispersion [2,4-16]. The following Table 1 shows the summary.

Table 1. Use of different Nanoparticles by various researchers

Nanoparticle Type	Size (nm)	Weight% (wt.%)	Improvement/Characteristics Observed
La_2O_3 [2]	20–1000	1%	Exhibits optimal adhesive wear at high loads and abrasive wear at high speeds
Al_2O_3 [4,30]	20-30	3%	Thermal conductivity increased by 31%, Better combustion in engine
CeO_2 [5]	10-50	0.6%(1:3 ratio)	Demonstrates minimal wear and low friction
Copper oxide(CuO) [6,7,19,26,28]	20-50	0.5-1%	Enhanced tribological performance due to strength and shape retention
Magnesium-doped zinc oxide (ZMO)[8]	10-100	2.5	Small particle size provides superior tribological properties
Activated carbon nanoparticle from bamboo [9]	50	0.01-0.05%	Maximal enhancement in lubrication efficiency with respect to friction coefficient and wear reduction.
Silicon dioxide (SiO_2)[10,12,19,27,30]	10-100	0.5-3%	Improves tribological characteristics due to stability, large surface area, and effective dispersion
Carbon nanotubes (CNTs)[11]	10-50	0.1-5%	Reduces wear by 73% and increases load capacity by 20%
Unstructured carbon, graphite, graphene[13,14]	10-100, 20-100, 1-100	1.0%	Provides optimal friction and wear performance
Halloysite nanotubes (HNT)[15]	30-70	1.5%	Enhances friction and wear properties compared to non-additive oil
Titanium oxide-TiO_2 and Zinc oxide-ZnO[21]	20-50	30ppm	Enhancement in engine performance

Subsequent research reviewed FAME production using numerous kernels, identifying Algae, Castor, Laxmitaru (*Simarouba glauca*) and many more promising sources. The cultivation of Laxmitaru was originated at the National Bureau of Plant Genetic Resources in Orissa, India. Unattended Laxmitaru-FAME (Simarouba glauca Methyl Ester) was tested in a CI engine. Laxmitaru-FAME exhibited lower brake thermal efficiency compared to diesel. Emission analysis revealed significant reductions in HC and smoke emissions (22% and 33% for B50 blend; 40% and 27% for B100) but increased NOx emissions (8% for B100; 5% for B50). Laxmitaru-FAME blends' brake thermal efficiencies were marginally inferior compared to petro-diesel. Assessments showed comparable performance between Laxmitaru-FAME-diesel blends and standard diesel [17]. Research was carried out to explore the potential use of Laxmitaru crude oil in biodiesel production. Simarouba glauca seed oil was identified as a viable feedstock for biodiesel synthesis. When tested, its performance and emission characteristics were found to be favorable compared to conventional diesel, meeting the requirements of ASTM D6751, BIS, and European standards. [18]. Literature reveals that a B-20 Laxmitaru-FAME blend narrowly matches petro-diesel. While the mechanical efficiency of diesel slightly surpasses Laxmitaru-FAME blends, B0 and B20 perform similarly. Laxmitaru-FAME at 20% exhibited slightly superior brake thermal efficiency to petro-diesel. Exhaust emission temperatures for all FAMEs were higher than petro-diesel, with B20 showing lower average variations in CO and HC but higher NOx emissions. Despite this, B20 is deemed the most suitable biodiesel blend, with potential for reducing NOx emissions through advanced technologies. Combustion characteristics of Laxmitaru-FAME B20 blends closely resembled diesel, positioning Laxmitaru-FAME as a viable alternative to conventional diesel. Neat biodiesel, known as B100, is rarely used due to its tendency to clog injectors. More commonly available biodiesel blends include B20 (20% biodiesel, 80% petroleum diesel) and B5 (5% biodiesel, 95% petroleum diesel). B20 is approved for use in heavy-duty diesel trucks, and modern diesel engines like Ford Power Stroke, GM Duramax, and Dodge Cummins can run B20 without voiding warranties. Since 2011, Ford Super Duty trucks even feature a "B20" badge on the Power Stroke fender. B20 has been found to offer optimal engine performance, requiring no engine modifications and showing Brake Thermal Efficiency (BTE) and Brake Specific Fuel Consumption (BSFC) similar to neat diesel (B0)[1,19,20]. Another study investigated the combustion, efficiency, and emissions of a single-cylinder diesel engine using three fuel blends: biodiesel-diesel (B20), biodiesel with chemically and biologically synthesized nanoparticles (B20A30C30), and biodiesel with conventional particles (B100). A homogeneous fuel mixture was created using titanium oxide (TiO_2) and zinc oxide (ZnO) nanoparticles, enhancing combustion due to their high surface area. The engine with nanoparticles (B20A30C30) showed 16% higher brake thermal efficiency, with significant reductions in nitrogen oxides (32%), carbon monoxide (62%), hydrocarbons (48%), and smoke emissions (40%) [21]. Further study used Zinc oxide nanoparticles mixed with Tungsten phosphoric acid (TPA) as a catalyst for biodiesel production from waste cooking oil. An optimal methanol-to-oil ratio of 1:6, at 60-65°C with 4 wt.% catalyst, resulted in a 94% ester conversion. The biodiesel properties largely met ASTM standards, and blends (B10, B20, B100) showed better engine performance and lower carbon emissions compared to diesel [22]. Hence it is evident that B20 is the most suitable blend. Another research investigates friction and wear issues related to Simarouba glauca biodiesel (SGB) in automotive engines using a pin-on-disc tribotester. Different fuels were tested, including SGB100 biodiesel and various blends (SGB15, SGB30, SGB50) under controlled conditions. The results revealed that SGB had the lower coefficient of friction and wear scar, indicating better performance than diesel, along with reduced metal loss. This suggests that Simarouba glauca biodiesel blends can enhance tribological properties compared to conventional diesel fuels. [23]

Rising oil prices, dwindling crude oil reserves, and environmental concerns regarding lubricating oil pollution have underscored the need for alternative lubricants. Biolubricant oils offer eco-friendly alternatives to mineral oils, boasting inherent characteristics such as increased lubricity, higher viscosity index, eminent flash points, along with reduced evaporation. These natural oils can be utilized in both lubrication regimes due to their long fatty acid chains and the presence of polar groups in vegetable oil compositions [16,24]. Thus, wear and friction studies of Laxmitaru-FAME are imperative to assess its suitability in practice. Present study involves investigational study of the friction and wear of petro-diesel, Laxmitaru-FAME and petro-diesel mixtures with nanoparticle additives using a 4-ball tribotester utilizing Silicon dioxide (SiO_2) nanoparticles. From literature survey it is found that SiO_2 nanoparticles are very meagrely employed. Its non-poisonous nature, blandness, pollution-freeness, elemental strength, suspension, large surface area, small dimension, efficient dispersion, low cost, fluidity with good load-viscosity characteristics are the factors of its qualification in this research. Consequently, advances in the nano-additives in order to enhance the utilization array of the lube-oils are required. The intension is also to check the capability of nano SiO_2 to maintain its sole properties at elevated loads as numerous nanomaterials fail to do so. This will broaden the application scope of lubricants using SiO_2 additives [19, 25,27].

2. Materials

The biofuel was extracted from Simarouba glauca oil through transesterification method. In transesterification the chemical reaction with Laxmitaru oil is carried out utilizing alcohol and alcohol-esters as well as glycerol gets generated. The triglyceride gets transformed by sequential removing the alkyl forming a diglyceride, a monoglyceride and in conclusion a glycerol. This intends to enhance flowability of biofuel. In addition, triglycerides gums and waxes are segregated. FAMEs are popular amid the fatty acid esters. Figure 1 demonstrates chemical balance and Figures 3 and 4 reveal the blend variants. The fatty acid contents of Laxmitaru biofuel from gas chromatography reveals that the percentage of Oleic acid is highest.

While ethanol is favored for transesterification because of its environment-friendly characteristics and lower toxicity, methanol is frequently chosen owing to cost-effectiveness with respect to other options. Consequently, FAMEs are more prevalent than Fatty acid alkyl esters (FAAE). Tables 2-4 reveal the important attributes of Laxmitaru-FAME along with mixture details. The diesel fuel was taken from Bharat Petroleum Corporation Ltd Kolhapur Petrol Pump. It had following major attributes: Acidity Inorganic-Nil, Acidity total mg of KOH/g- 0.20, Ash percent by mass -0.01, Carbon residue (Ramsbottom) on 10 percent residue, % mass - 0.30, Cetane Number - 46, Cetane Index - 48, Flash Point-a. Abel, °C 35, b. Pensky Martens, °C- 66 (1), Kinematic Viscosity, cSt at 40° C- 4.9 mm^2/s, Total Contamination, mg / kg-24, Density at 15°C kg/cu.m-822, Total Sulphur, mg/kg, 336, Water Content, mg/kg, 169, Total Sediment, mg per 100 ml- 1.5, Oxygen content,% vol. - 0.5.

The SiO_2 nanoparticles were purchased from Sigma-Aldrich dealer in Kolhapur. According to specifications by supplier, SiO_2 nanoparticles are almost sphere-shaped, normal dimension 20 nm, mass 2.2-2.6 g/cm^3 and 99.5 % pure. The SEM image of SiO_2 nanoparticles is shown in Figure 2. The important physicochemical attributes of FAME of test oil are Density [ASTM D1448]- 0.876 gm/ cm^3; HCV [ASTM D6751]- 37.5 MJ/Kg; Kinematic Viscosity [D445]- 5.38 mm^2/s at 40°C; Flash point [ASTM D93]- 138°C [19].

Table 2. The important attributes of mixtures

Mixture	Higher Calorific Value J/Kg	Viscosity mm^2/s	Density gm/cm^3
B-10	39.8×10^6	5.1	0.827
B-20	38.9×10^6	5.23	0.830
B-30	38.5×10^6	5.33	0.838
B-100	37.5×10^6	5.38	0.876
Diesel	45.6×10^6	4.9	0.822

Table 3. The important attributes of mixtures

Sr. No.	Details	Quantity
1.	Neat Petro- diesel:-(B-0)	50 ml
2.	Petro-diesel and 10% biodiesel:(B-10)	
3.	Petro-diesel and 20% biodiesel:(B-20)	
4.	Petro-diesel and 30% biodiesel:(B-30)	

Table 4. The important attributes of mixtures

Sr. No.	Mixture Particulars	Quantity
1.	Neat petro-diesel-(B-0)	01
2.	Neat-petro-diesel + Neat Simarouba glauca Methyl Ester (B-10, B-20 and B-30) variants.	03
3.	Neat petro-diesel + Modified Simarouba glauca Methyl Ester with nano-SiO2 (0.2, 0.5, 0.75 and 1 % Weight) and B-10, B-20 and B-30 variants.	12

3. Methods

3.1 Generation of Additivated Simarouba Glauca Methyl Ester

The dispersion of nano-SiO_2 additives was carried out in Simarouba glauca Methyl Ester with amount of 0.2, 0.5, 0.75 and 1% on weight basis. Ultrasonication was done for 15 minutes by Model-LMUC-3, Make- LABMAN. The dispersion steadiness was ascertained for 7 days. Overall, sixteen variants are made in order for test [19]. Literature suggests that many researchers have used concentrations in the range of 0.2 to 1% with uniform increments. The optimal concentrations are also found within the same range. Hence the similar range of 0.2, 0.25, 0.75 and 1 wt.% is chosen for present study [4-15, 26].

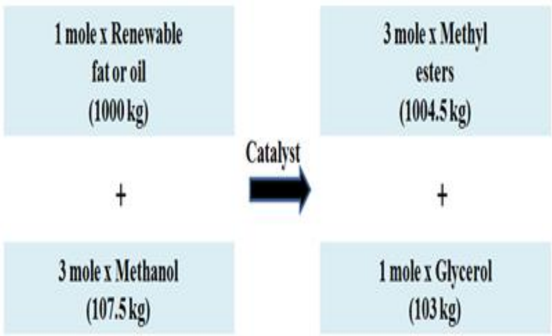

Fig. 1. Chemical reaction for biodiesel production [19]

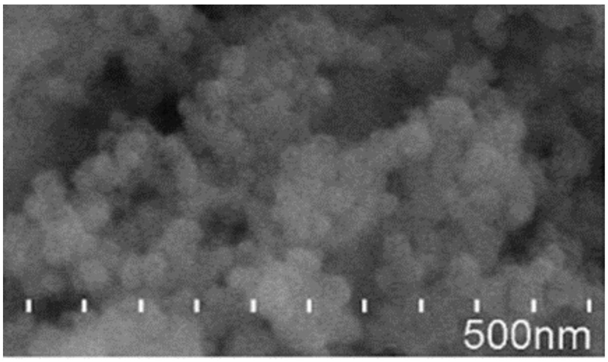

Fig. 2. The SEM image of SiO_2 nanoparticles

3.2 Making of Blends of Laxmitaru-FAME and Additivated Laxmitaru-FAME with Petro-Diesel

Mixtures of Simarouba glauca Methyl Ester and nano additivated Simarouba glauca Methyl Ester in petro-diesel were made taking 10%, 20% and 30% amounts (B10, B20 and B30) by volume. It is known that B20 has manifested better performance characteristics, yet, B30 blend is also investigated in this research [1,18,19]. This is because of the fact that the Simarouba glauca biodiesel is quite novel and literature survey also depicts that very less tribological research has been carried out on the same. Hence its tribological behaviour is still not completely known.

Consequently, it was decided to work on B30 blends also as it is possible that Simarouba glauca might give better performance for B30 blend also. In order to ascertain this likelihood experimentation has been carried out on B30 blends also. The higher blends more than 30% have following issues so maximum B30 blends were chosen. They face lack of legal encouragement and pricing. Higher blend has a solvent effect which can dissolve engine deposits. The discharge of these deposits may block filters and necessitate recurrent filter replacement. Also, they contain less energy than petroleum diesel. It also decreases engine life. It thickens at cold temperatures and also has high viscosity in general. Consequently, these exhibit distinctive storage issues, increase nitrogen oxide emissions, although it greatly reduces other toxic emissions.

3.3 Tribological Experiments

Tribological assessments were conducted using a 4-ball-tribometer, with Figure 5 illustrating the specifics about the experimental configuration. The machine and all its important parts are indicated. Prior to each test, all testing equipment underwent thorough cleaning. Neat petro-diesel besides other 15 variants, enumerated in Table 3 and Table 4, got evaluated in the 4-ball-tribometer. Testing procedures adhered to ASTM-D-4172 guidelines. Test balls made of chrome alloy steel AISI standard E52100, with a diameter of 12.7 mm, Grade 25 EP (Extra Polish-0.02-micron Ra), and hardness ranging from 64-66 HRC, were employed. Comparative analysis of test results was conducted. Acetone was employed for washing the steel balls after every experimental iteration. Wear rates were determined based on the mean Wear Scar Diameter measured on the 3 fixed balls. The Figure 6 shows the macro image of the wear scar obtained on one of the sample lower balls. The the SEMs are taken in the same order for all the balls and they all show similar wear. Also Figure 7 shows the three balls fixed inside the cup. Four ball tester kinematic details are depicted in Figure 8. Friction coefficients were continuously monitored throughout every experiment. Assessment parameters for all samples aligned with ASTM-D-4172 specifications, detailed as follows:

- Load during Testing: 392±2N
- Duration of Testing: 3600 seconds
- Rotational Speed: 1200 +/- 60 revolutions per minute
- Temperature-: 75°C +/- 2°C

Fig. 3. Samples of Diesel blends with Simarouba glauca Methyl Ester (B10, B20, B30) [19]

Fig. 4. Simarouba glauca Methyl Ester with SiO_2 nanoparticles samples prepared for experimentation [19]

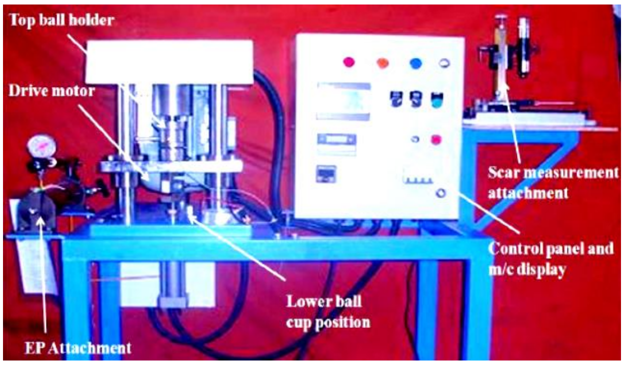

Fig. 5. Experimental Set up: Four Ball Tester (ASTM D4172)

Fig. 6. Macro Image of Wear Scar

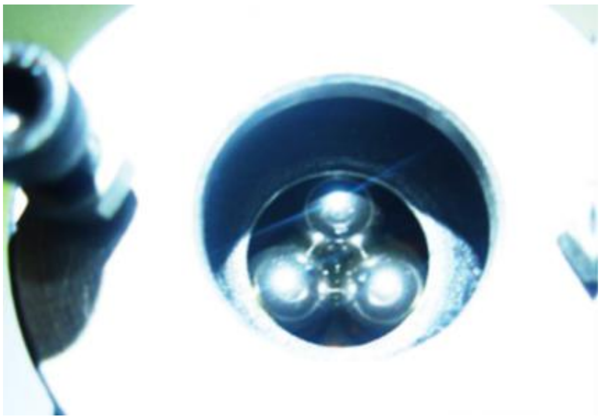

Fig. 7. Balls fixed inside the cup

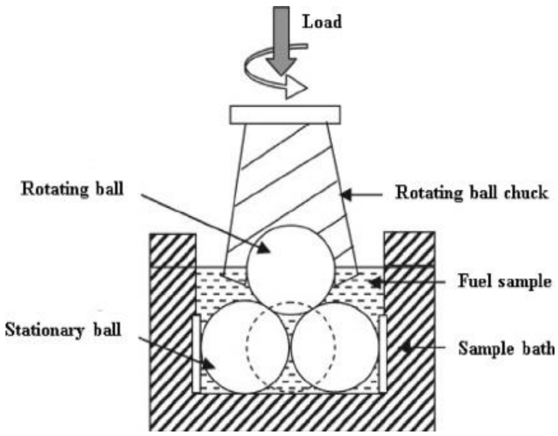

Fig. 8. Four ball tester kinematic details [3]

The Average COF is estimated using a torque meter by the machine. The torque meter measures this resistance to rotation, which is directly related to the frictional force between the balls. Throughout the test, the torque values are recorded at regular intervals. The data acquisition system linked to the 4 Ball Tester processes this data and calculates the instantaneous COF. The average COF is determined by calculating the mean of these recorded COF values over the test duration.

The ball's worn surface is assessed by SEM for particular maximum and minimum wear of balls. This is used further for deciding the mode of wear prevalent then. [19,27,28]. Every experimental test was repeated for three times to minimize possible error in data recorded. The uncertainties in values of different quantities were estimated. The overall uncertainty level was found to be within ±2%. Similar trends were found in each iteration.

4. Results and Discussion

4.1 Friction Analysis

Following results were observed after experimentation on different sixteen combinations of diesel, Simarouba glauca Methyl Ester and nanoparticles. Figures 9-13 indicate the outcome of the diverse percentage permutation of Diesel, Simarouba glauca Methyl Ester and SiO_2 Nanoparticles with Wt. % of 0.2, 0.5, 0.75, and 1% respectively on COF. The reduction in COF in the presence SiO_2 nanoparticles can be credited towards their ball-bearing effect at interface. There is a combination of polishing and rolling phenomena. Due to asperity polishing bulk COF drops as a result of good surface finish. The sudden changes in the friction graph are observed in Figure 9 (diesel +30% SGME) and Figure 12 (diesel +20% SGME). In Figure 9 this is due to the fact that four ball test has transition between lubrication regimes, such as boundary lubrication to mixed/hydrodynamic lubrication. Changes in these regimes and polishing effect of nanoparticles results in low friction levels. Also, the rise in the friction in Figure 12 may be due to Local surface damage resulting in temperature rise during the test affecting lubricant viscosity and wear rate. As temperature increases, lubricant viscosity decreases, reducing its ability to form a stable film. And transition to boundary lubrication takes place which has led to sudden higher friction [29]

Conversely high amount of nanoparticles caused increase in COF due to local surface damage, which may be due to ill distributed tribo sintering. The Figures 14-17 show the effect of different percentage combination of Diesel, Simarouba glauca Methyl Ester and SiO_2 Nanoparticles with Wt. % of 0.2, 0.5, 0.75, and 1% respectively on average COF. From these the lowest COF is observed for 30% Simarouba glauca Methyl Ester and 0.2 wt.% SiO_2 nanoparticles i.e., 0.0198. This is the combined effect of less agglomeration of nanoparticles and the 30 % of Simarouba glauca Methyl Ester having high viscosity [7,10,13,16,19]. As observed in the Figure 23 for average COF, Blend variants and the nanoparticles % for SiO_2 nanoparticles there is a consistent decrease in the COF as the biodiesel % goes on increasing in the blends. But there is no such characteristic seen for increase in the nanoparticle percentage. 0.2% combination-B30 shows the lowest COF in the family of biodiesel blends. This is attributed to polishing effect of hard SiO_2 nanoparticles. For neat biodiesel B100 – 0.2% combination shows the lowest COF. For B20 blend increase in nanoparticle % shows adverse effect on COF, by increasing its value. It is possibly due to elevated hardness of SiO_2 nanoparticles and their agglomeration tendency leading to the abrasive wear. Also, the similar trend is seen for B100 variant i.e., increase in COF. Increase in COF is observed for 1% SiO_2 nanoparticles with the growing Simarouba glauca Methyl Ester %. i.e., B:30 blend. From the friction plots it is evident that the lubrication regime typically falls within the boundary lubrication and mixed lubrication regions.

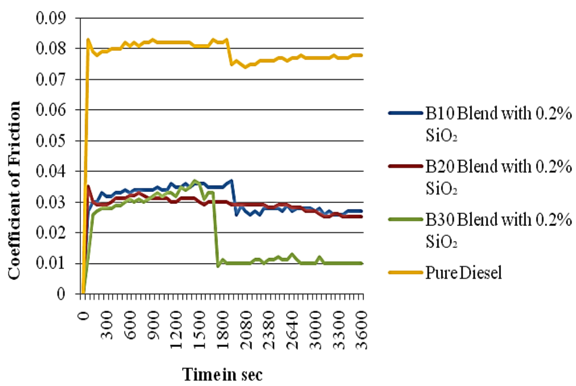

Fig. 9. Influence of 0.2% of SiO_2 nanoparticles in Laxmitaru-FAME in petro-diesel blend on COF

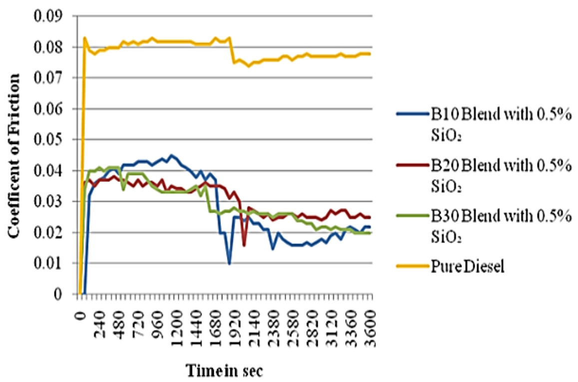

Fig. 10. Influence of 0.5% of SiO_2 nanoparticles in in Laxmitaru-FAME in petro-diesel blend on COF

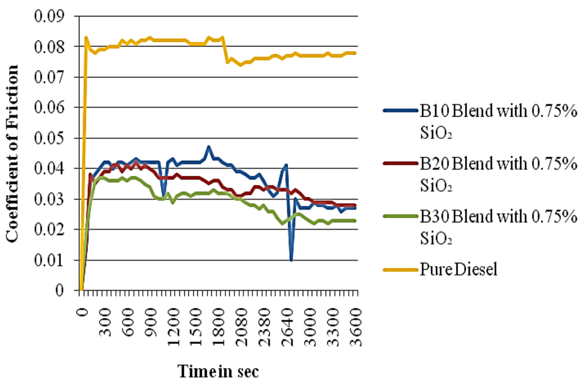

Fig. 11. Influence of 0.75% of SiO_2 nanoparticles in in Laxmitaru-FAME in petro-diesel blends on COF

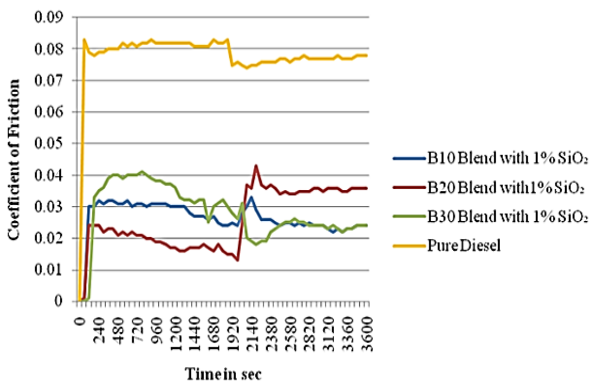

Fig. 12. Influence of 1% of SiO_2 nanoparticles in in Laxmitaru-FAME in petro-diesel blends on COF

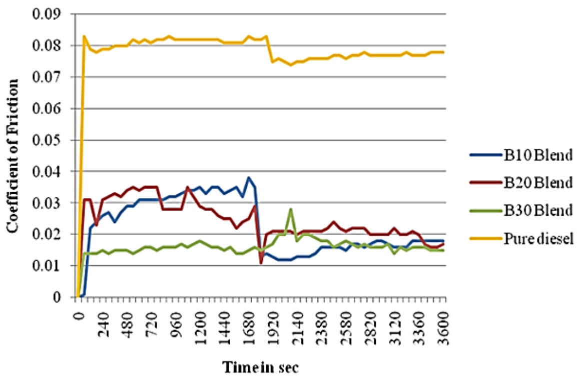

Fig. 13. Influence of % of Simarouba glauca Methyl Ester in blends on friction

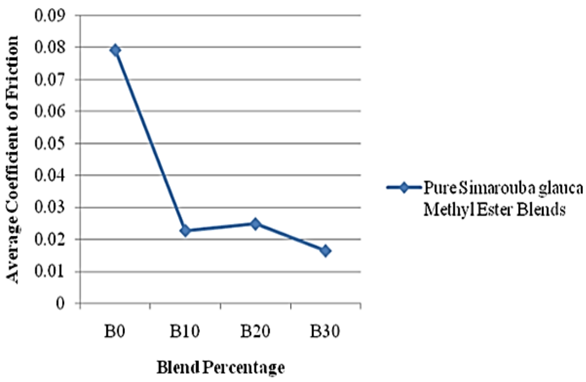

Fig. 14. Influence of % of Simarouba glauca Methyl Ester in blends on average friction

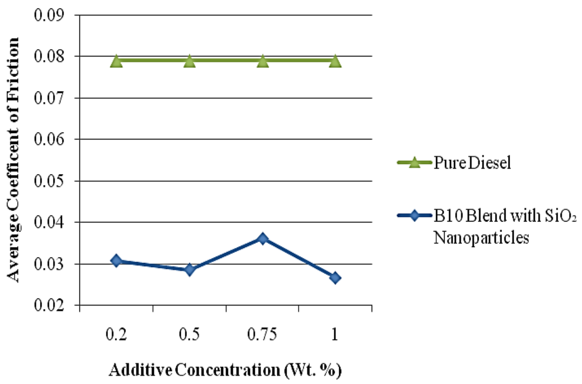

Fig. 15. Influence of % of SiO_2 nanoparticles in Simarouba glauca Methyl Ester for B10 blends on average friction

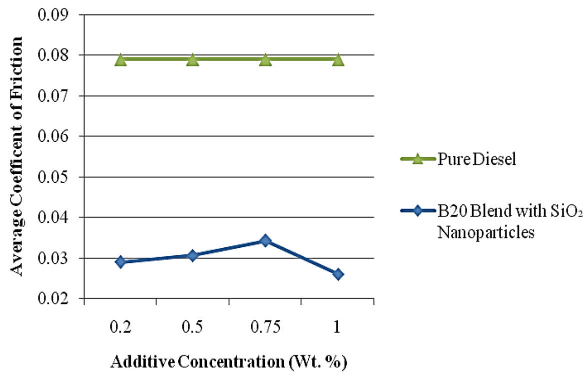

Fig. 16. Influence of % of SiO_2 nanoparticles in Simarouba glauca Methyl Ester for B20 blends on average friction

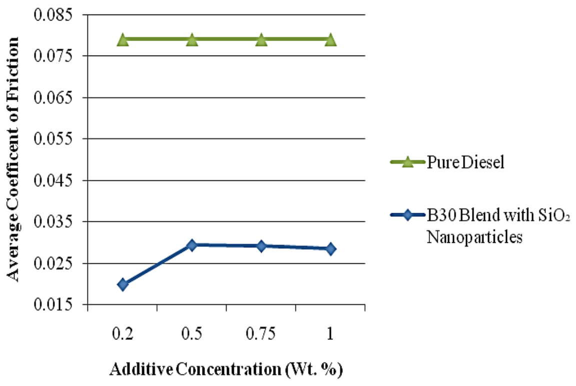

Fig. 17. Influence of % of SiO_2 nanoparticles in Simarouba glauca Methyl Ester for B30 blends on average friction

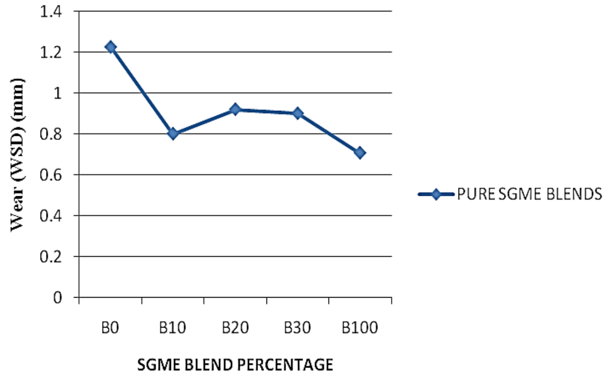

Fig. 18. Influence of % of Simarouba glauca Methyl Ester in blends on wear

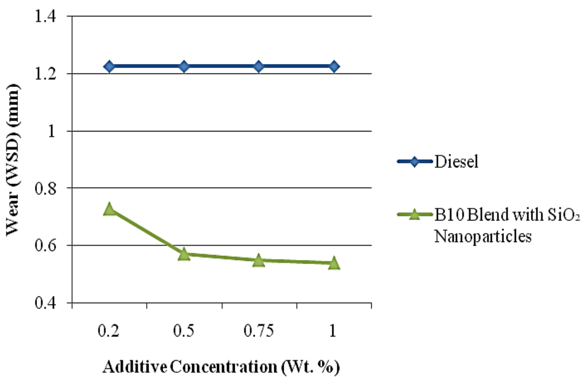

Fig. 19. Influence of % of SiO_2 nanoparticles in Simarouba glauca Methyl Ester for B10 blends on WSD

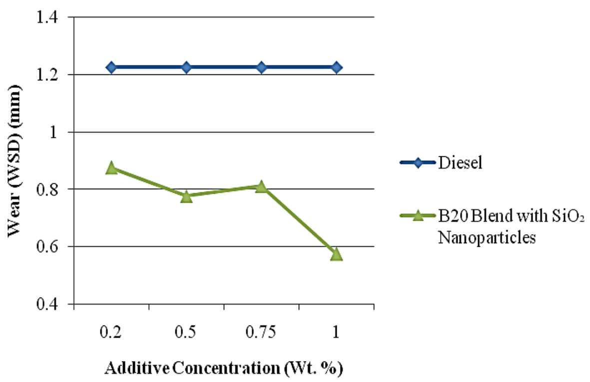

Fig. 20. Influence of % of SiO_2 nanoparticles in Simarouba glauca Methyl Ester for B20 blends on WSD

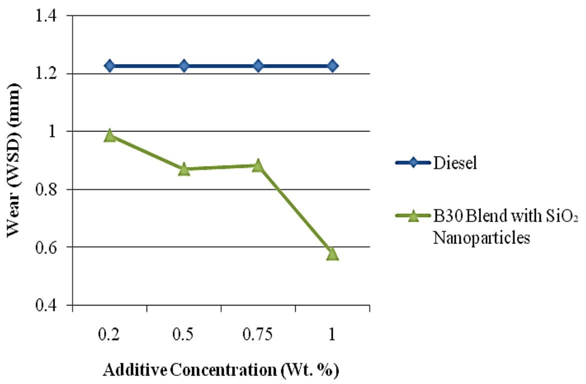

Fig. 21. Influence of % of SiO_2 nanoparticles in Simarouba glauca Methyl Ester for B30 blends on WSD

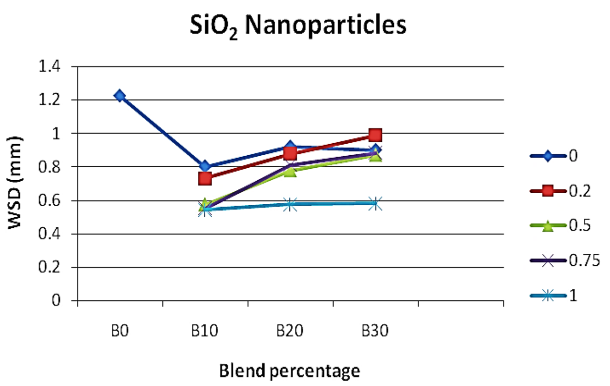

Fig. 22. Influence of % of Simarouba glauca Methyl Ester and SiO_2 nanoparticles in blends on WSD

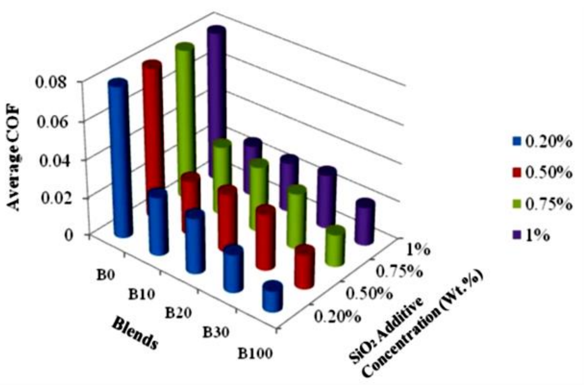

Fig. 23. General summing up of Change in Average COF for all permutations of SiO_2 nanoparticles

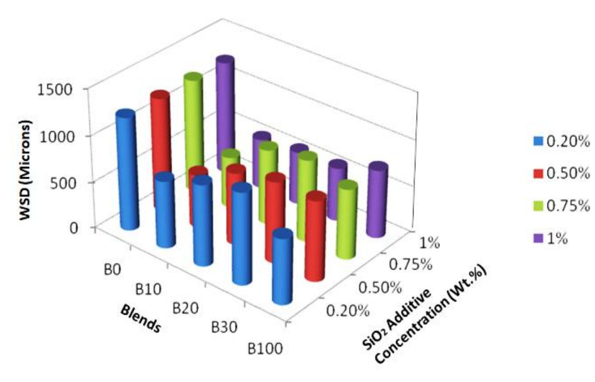

Fig. 24. General summing up of Change in WSD for all permutations of SiO_2 nanoparticles

4.2 Wear Analysis

The change of WSD (Wear Scar Diameter) as per various permutations of SG (Simarouba glauca) oil and nanoparticles as shown in Figures 18-22 and 24 indicate that the rise in the amount of Simarouba glauca Methyl Ester leads to improvement in the results. Also, these charts show that if additive concentration is increased the WSD of blended oil also improves. Additivated samples show combination of abrasive and adhesive wears and mending. As seen in the Figure 22 and 24 for WSD, blend variants and the nanoparticles % for SiO_2 nanoparticles there is a consistent decrease in the WSD as the nanoparticles % goes on increasing in the blends for B10,B20,B30. For neat biodiesel B100-0.20% combination shows the lowest WSD. For B100 increase in nanoparticle % shows adverse effect on WSD, by increasing its value in case of 0.5% of nanoparticles. This may be due to hardness and surface deterioration by SiO_2 nanoparticles. Also, the similar trend is seen for B20and B30 variants i.e., increase in WSD for 0.75% nanoparticle amount. Increment in WSD is seen in entire % of SiO_2 nanoparticles through the increment in biodiesel percentage.

Hard SiO_2 nanoparticles at the interface abrade the surface due to uneven tribo sintering as seen in Figure 25. The surface is rougher. This leads to high wear and results in maximum WSD. Conversely for same SiO_2 wear of steel ball for B10 and 1% wt. SiO_2 nanoparticles blend was observed to be lowest and 55% lower than that for neat diesel (B0) proving its advantage for this percentage. This can be attributed to more even dispersion of nanoparticles at B10 biodiesel giving highly uniform wear [7,13,16,19].

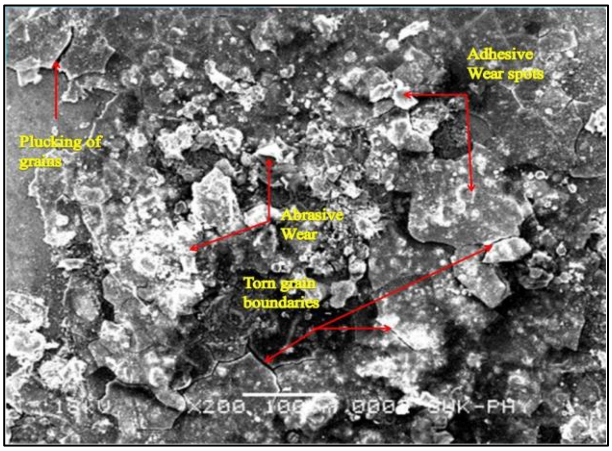

Fig. 25. SEM image showing the wear scar resulting from the use of neat diesel fuel without blending and nanoparticles (Maximum Wear Scar Diameter - 1.226 mm)

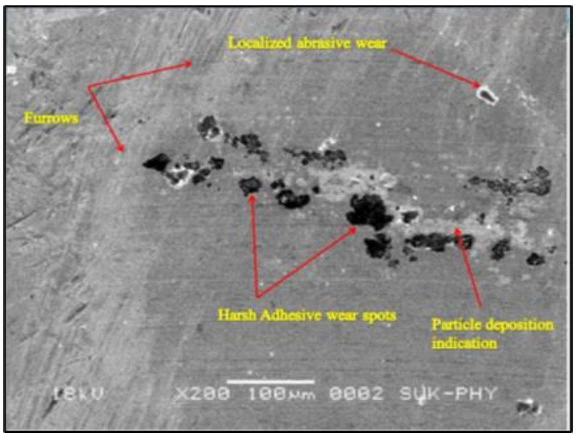

Fig. 26. SEM images displaying the wear scar from a diesel blend containing 30% Simarouba glauca Methyl Ester and 0.2 wt. % SiO_2 nanoparticles (Maximum Wear Scar Diameter - 0.988mm)

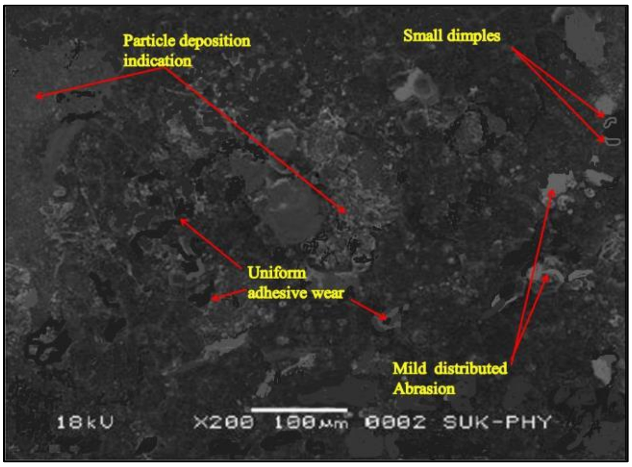

Fig. 27. SEM image depicting the wear scar resulting from a diesel blend containing 10% Simarouba glauca Methyl Ester and 1% by weight of SiO_2 nanoparticles (Minimum Wear Scar Diameter - 0.541 mm)

4.3 Worn Surface Micrographic Analysis

Worn-out surfaces of the balls were characterized using SEM. Figures 25, 26 and 27 show the SEM images of worn-out surface of balls for different bio diesel blends. The micrographs show material fiber fracture. Material fiber typically refers to the alignment or orientation of the material's grain structure or fibers within a material. Minimum WSD is observed for B10 blend having 1 % wt. of SiO_2 nanoparticles. It shows that the SiO_2 nanoparticles have more dispersiveness and load carrying capacity. Micrograph showed by Figure 27 indicates Ra improvement by mending. Figure 25 shows grain boundary crack initiation and propagation. This type of fracture takes place due to creep phenomena in which grains are stronger and grain boundaries are weaker. In such cases crack initiation is delayed but once initiated it propagates faster. This may be due to local temperature rise leading to adhesive and abrasive wear permutation. Very rough surface with grain separations is seen. This may be attributed to local overheating and interface fatigue. The Figure 26 displays micrograph for 30% Simarouba glauca Methyl Ester and 0.2 wt. % SiO_2 nanoparticles. Maximum Wear Scar Diameter of 0.988mm is obtained for this case which is very much unfavorable. Highly heterogeneous wear combination is observed like localized abrasive wear, furrows and harsh adhesive wear. This may be due to instantaneous localized crests due to SiO_2 promoting the localized adhesion. The Figure 27 for nano-SiO_2 additive makes uniformly spread wear all through the grains and grain boundaries in contrast with Figures 25 and 26. This may be credited to the material insertion by nanoparticles. This mending and polishing are seen in Figure 27. This noteworthy enhancement in the anti-wear property of SiO_2 additives is due to highly stable dispersions maintaining nonstop nanoparticles flow for mending on interface.

5. Conclusions

- There is a consistent decrease in the COF as the biodiesel percentage goes on increasing in the blends. But there is no such characteristic seen for increase in the nanoparticle percentage. B30-0.2% combination shows the lowest COF in the family of biodiesel blends. This is attributed to polishing effect of hard SiO_2 nanoparticles. This also enhances surface finish at the interface.
- For neat biodiesel B100 – 0.2% combination shows the lowest COF. For B20 blend increase in nanoparticle % shows adverse effect on COF, by increasing its value. It is possibly due to elevated hardness of SiO_2 nanoparticles and their agglomeration tendency leading to the abrasive wear. This can be overcome by using additional surfactant. Also, appropriate vegetable excerpt will be smart substitute which may perform as a basic agent in addition to coating agent. Also, the similar trend is seen for B100 variant i.e., increase in COF. Increase in COF is observed for 1% SiO_2 nanoparticles with the growing Laxmitaru-FAME %. i.e., B:30 blend.

- There is a consistent decrease in the WSD, as the nanoparticles % goes on increasing in the blends for B10, B20 and B30. For neat biodiesel B100-0.20% combination shows the lowest WSD. For B100 increase in nanoparticle percentage shows adverse effect on WSD, by increasing its value in case of 0.5% of nanoparticles. This may be due to hardness and surface deterioration by SiO_2 nanoparticles. Also, the similar trend is seen for B20and B30 variants i.e., increase in WSD for 0.75% nanoparticle amount. Increment in WSD is seen in entire % of SiO_2 nanoparticles through the increment in biodiesel percentage.
- The results revealed 75 % decrease in COF and 55% reduction in WSD compared to neat diesel (B0).
- Overall, it is perceived that SiO_2 performs meritoriously from friction and wear point of view. It justifies as a low-cost option to mitigate engine friction and wear.

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