Fathimunnisa Begum ✉
N. Ravi Kumar
V. Ramachandra Raju

https://doi.org/10.21278/TOF.463024920
ISSN 1333-1124
eISSN 1849-1391

TRIBOLOGICAL EXPERIMENTATION WITH JATROPHA BIOFLUID AND NANOPARTICLES AS LUBRICANT ADDITIVES

Summary

The use of vegetable oils as lubricants in automobiles is rapidly increasing due to the prevailing environmental aspects. Vegetable oils are also suitable for other applications because they come from renewable and sustainable natural sources and have high biodegradability and low toxicity. Nanoparticles have been extensively investigated for a long time as potential performance improvers of traditional antifriction and antiwear additives because of their inherent properties such as size and shape. The primary aim of the study is to investigate the use of jatropha oil mixed with graphite, molybdenum disulfide (MoS_2), and titanium dioxide (TiO_2) nanoparticles as a nanoparticle biolubricant. The nanoparticles of graphite, molybdenum disulfide, and titanium dioxide are added in varying weight percentages to jatropha oil and a tribological analysis is carried out using a pin-on-disc tribometer. The analysis is focused on tribological quantities, such as coefficient of friction, wear volume, and frictional force. The experiment was carried out for 5 minutes under varying loads at different disc speeds. At an optimum concentration of nanoparticles, the coefficient of friction, frictional force, and the wear rate were found to have the lowest values, but when the level of nanoparticles increases above the optimum level, the friction coefficient and wear rate seem to be increased. The pin-on-disc experiments revealed that nanographite powder mixed in jatropha oil gives better tribological performance than the other two tested nanopowders. Subsequently, multiple regression models are developed using input and output variables. A non-linear fit between the response and the corresponding significant parameters is considered.

Key words: *Lubrication, Jatropha oil, Graphite nanoparticles, Molybdenum disulfide (MoS_2) nanoparticles, Titanium dioxide (TiO_2) nanoparticles, Wear, Frictional force, Coefficient of friction.*

1. Introduction

Recent years have seen the use of various types of lubricating oils including mineral oils, synthetic oils, refined oils, and vegetable oils. Most lubricants are based on mineral oils, extracted from petroleum, which are not eco-friendly due to their inherent properties of toxicity and non-biodegradability [1]. The increasing oil prices, the depletion of crude oil reserves in the world, and the demand to protect the environment against pollution caused by lubricating oils and their uncontrolled deposition have renewed interest in developing and using alternative lubricants. Bio-based lubricating oils are perceived as alternatives to mineral oils because they possess certain natural mechanical properties and they are biodegradable. When compared with mineral oils, vegetable oil-based lubricants exhibit higher lubricity, higher viscosity index (VI), higher flash point, and lower evaporative losses [2–7]. Both the boundary and the hydrodynamic lubrication can be obtained from bio-based lubricants due to their long fatty acid chains and inherent presence of polar groups in the structure of vegetable oils [8–11]. Vegetable oils can be obtained from oil-containing seeds that are available throughout the world. According to some reports, 350 oil-bearing crops are available worldwide. Examples include jatropha [12], karanja, neem, rice bran, rapeseed, castor, linseed, mahua [13], palm [14], sun flower, coconut, soybean, olive, and canola [15]. Vegetable oils can be edible and nonedible. Many researchers have reported using vegetable oils as engine fuel, but only a few have reported using vegetable oil-based lubricants for automotive applications. In the last few decades, numerous research papers have discussed the use of biolubricants as alternatives in automotive applications. However, only a few of these papers have analysed and reviewed biolubricants. Numerous researches have been investigating the effect of nanoparticles added to the lubricant. Researchers have investigated the antiwear and antifriction properties of nanolubricants, and have observed specific fuel consumption and fuel economy while using nanolubricants for automotive engines. Their observations reveal lower specific fuel consumption when nanolubricants are used. The use of nanolubricants also leads to improved fuel economy and lower energy consumption, which in turn reduces the greenhouse gas emissions. [16-20]

In general, majority of studies agree that nanoparticles improve the tribological properties of a lubricant deposited on a contact area. A quantity of nanoparticles added to lubricants enhance their tribological properties. The nanoparticles that are present in the lubricants may enter the gap between the interacting surfaces of the tribopair in action, thereby causing reduction in wear. Nanolubricants possess enhanced thermophysical properties (thermal conductivity, in particular) which aid in carrying away the heat generated due to excessive friction [16, 21–24]. The main classes of nanoparticles are carbon-based nanoparticles, metal nanoparticles, metallic alloy nanoparticles, ceramic nanoparticles, semiconducting material-based nanoparticles, polymeric nanoparticles, composite nanoparticles, and lipid-based nanoparticles. The general types of nanoparticles used for dispersion into fluids are molybdenum disulphide (MoS_2), hexagonal boron nitride (h-BN), aluminium oxide (Al_2O_3), copper oxide (CuO), diamond, tungsten disulphide (WS_2), zinc oxide (ZnO), silver (Ag), and titanium dioxide (TiO_2) [25–28]. However, carbon-based nanoparticles are widely used due to their inherent properties. The combination of their physical and mechanical properties results from the hexagonal arrays of SP^2 hybridized carbon atoms. Specifically, the carbon-based nanoparticles comprise single and multi-walled carbon nanotubes, fullerenes, nanodiamonds, and graphene [29, 30]. Various factors to be considered in the use of nanoparticles as additives in lubricants are the size, shape, hardness, and the weight percentage of nanoparticles. The size of nanoparticles ranges mostly between 0 and 100 nm.

Thus, in this paper, the tribological characteristics and compatibility of nonedible jatropha oil-based biolubricant in automotive applications. The reason for selecting the jatropha oil as a feedstock is that it is a nonedible oil and the plant has the advantage of growing even on marginal land.

2. Preparation of nanoparticle biolubricant using ultrasonication

Preparation of nanoparticle biolubricants involves a number of steps. The major challenge is the agglomeration of nanoparticles. This effect is dealt with by the process of sonication which reduces the agglomeration. The present study involves the use of jatropha oil as a biolubricant instead of conventional lubricants which are hazardous. The properties of jatropha oil are given in Table 1.

Table 1 Properties of jatropha oil

Parameters	Jatropha oil
Density at 40˚C	0.936 g/cm^3
Viscosity at 40˚C	16.5 cSt
Flash point	225±4˚C
Fire point	240±4˚C

Jatropha oil was mixed with nanoparticles in a size of 15-30 nm in a given weight ratio calculated by Eq. 1. The size of nanoparticles was analysed using a scanning electron microscope. The nanoparticles in weight percentages of 0.25 and 0.50 % were added to the oil. The mixture was subjected to ultrasonication for a period of 4 hours in order to mix the combination properly and prevent agglomeration.

$$\text{Weight Percentage} = \left[\frac{(\text{Wtofgraphitenanoparticles})}{(\text{Wtofgraphitenanoparticles} + \text{Wtofthebaselubricant})}\right] \times 100 \qquad (1)$$

Fig. 1 Ultrasonicator for mixing nanoparticles with the base oil

Fig. 2 Jatropha oil with nanopowder after sonication

3. Experimental methodology

The experimentation involved the measurement of frictional force, wear, and coefficient of friction. Various input parameters are considered for the purpose of experimentation. A pin-on-disc tribometer, with a load carrying capacity of approximately 100 N and a speed range of 200 to 2000 rpm, is used in this study (Fig. 3). This wear testing machine facilitates the study of friction and wear characteristics in sliding contacts; in this machine, sliding occurs between the stationary pin and the rotating disc, while the normal load, rotational speed, and wear track diameter are the variables to meet the test conditions. The frictional force and wear are obtained by the use of inbuilt electronic sensors.

Specifications of the machine are shown in Table 2.

Table 2 Specifications of pin-on-disc tribometer

No.	Parameter	Working Range
1	Wear track diameter	Min: 40 mm; Max :140 mm in steps of 2mm
2	Disc speed	Min: 200 rpm; Max: 2000 rpm in steps of 1rpm
3	Normal load	Min:0.5 kg; Max: 20 kg in steps of 0.5 kg by weights
4	Frictional force	Min: 0.1 N; Max: 200 N; least count 0.1N
5	Wear	Min: 0 μm; Max: 2000 μm; least count 1μm

Experiments were carried out for 5 minutes with loads of 5 kg and 10 kg. The rotational speeds considered for the experimentation using a pin-on-disc tribometer are 1000 and 1500 rpm. Wear, frictional force and coefficient of friction of the tested nanoparticle biolubricant were analysed. The additional parameter considered for the analysis is the particle size of the nanopowder mixed with the oil. The particle size considered is 15-30 nm.

Fig. 3 Pin-on-disc tribometer

4. Results and discussion

The results of experiments are discussed with respect to wear, frictional force, and coefficient of friction. The nanopowders mixed with jatropha oil are graphite, molybdenum disulphide (MoS_2), and titanium dioxide (TiO_2). The following weight percentages of the nanopowders are added to jatropha oil in the experiments conducted here:

(i) Jatropha oil
(ii) Jatropha + 0.25% graphite,
(iii) Jatropha + 0.25% MoS_2,
(iv) Jatropha + 0.25% TiO_2,
(v) Jatropha + 0.5% graphite,
(vi) Jatropha + 0.5% MoS_2,
(vii) Jatropha + 0.5% TiO_2

The experimental values are evaluated with respect to time.

4.1 Wear characteristics

Wear characteristics of different nanoparticle biolubricant samples were tested under different load and speed conditions. Figures 4 (A) and 4 (B) show the wear characteristics with respect to the increase in speed of the disc from 1000 rpm to 1500 rpm at a constant load of 5 kg. Figures 4 (C) and 4 (D) show the wear characteristics with respect to the same increase in speed at a constant load of 10 kg.

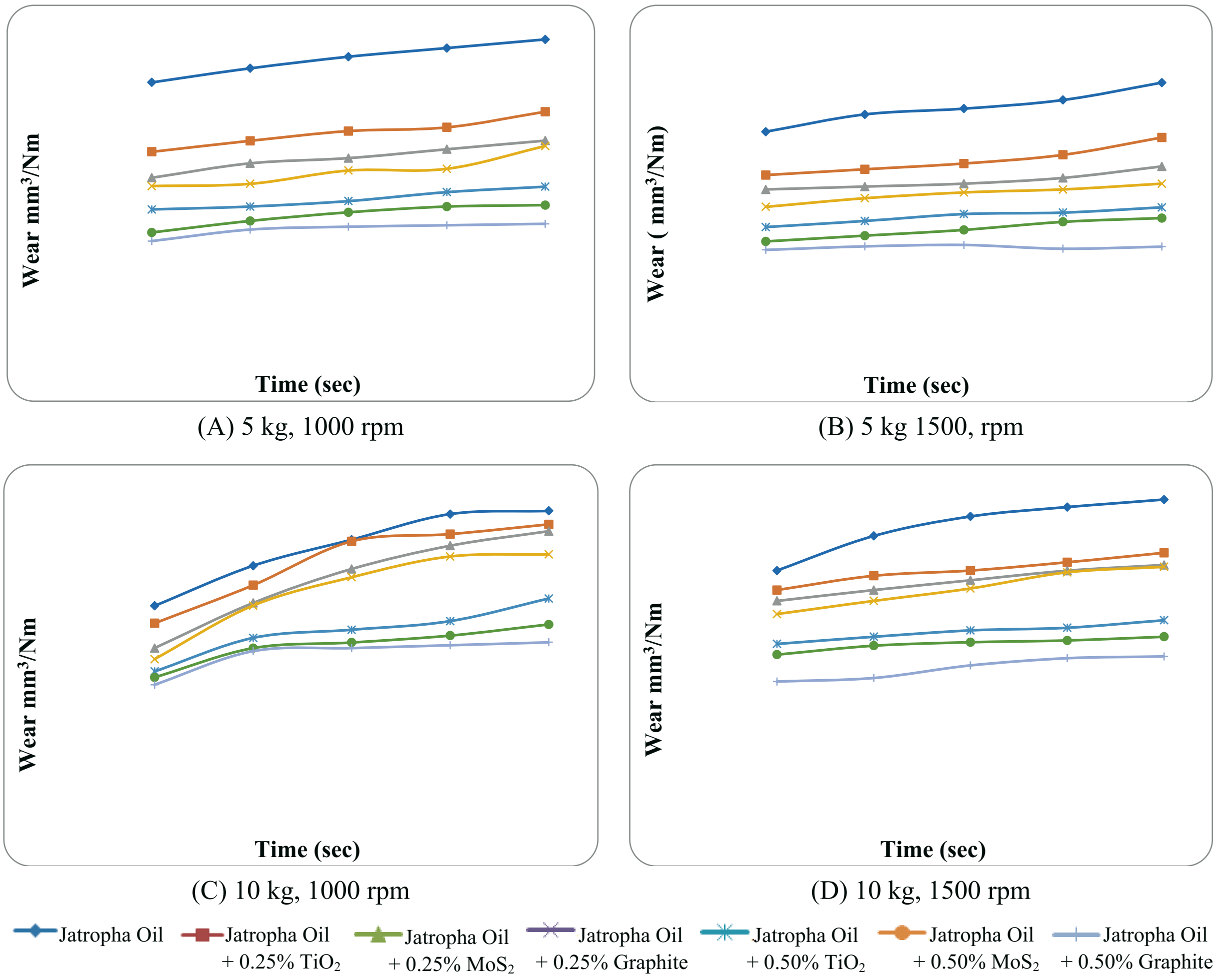

Fig. 4 Effect of lubricants on wear rate

It can be observed that with the use of nanocrystalline graphite as an additive to the jatropha biolubricant, there is a decrease in the wear rate irrespective of the load conditions and the speed of the disc. Figure 4(A) shows that the average wear rate for pure jatropha oil is 8.82 mm^3/Nm and for the jatropha oil with 0.50% graphite it is 2.91 mm^3/Nm. This shows that there is a decrease of 67% in the wear rate when 50 % of graphite is added to jatropha oil. A similar decrease in wear rate of 69.7 % is noted at a load of 5 kg and a disc speed of 1500 rpm. It is observed that in all the cases of applied load and disc speed, pure biolubricant exhibits higher wear rates than the biolubricant with added nanopowders. It is observed that the mixture of nanographite powder and the biolubricant exhibits lower wear values than the mixtures of the biolubricant and molybdenum disulphide (MoS_2) or titanium dioxide (TiO_2) nanopowders; the wear rate decreases with an increase in the percentage of added nanopowder. The other parameter to be observed is the increase in the wear rate when the load applied is lower and the speed of the disc is kept low.

From the results shown in Fig. 4, one can see that the degree of wear shown on the disc using a nanoparticle lubricant is much smaller than that of the wear shown on the disc using pure biolubricant. The use of biolubricant with nanoparticles resulted in a greater wear reduction than that of pure biolubricant. Better antiwear effects in the case of nanolubricants are closely related to the formation of tribofilm on the contact area of the pin and the disc.

4.2 Frictional force characteristics

The frictional force measured during the experiment is shown graphically in Fig. 5. The x-axis indicates the time considered in the experiment and the y-axis shows the frictional force in N.

The experiment was carried out are at two different loads and two different disc speeds. Figure 5 (A - D) shows the experimental values of the frictional force under the stated input conditions. At a constant load of 5 kg and a speed of 1000 rpm, it is found that there is a decrease of 18.3 % in the frictional force when jatropha oil mixed with 0.5 % nanographite powder is used, compared to the use of pure jatropha oil. Similarly, there is decrease in the frictional force when the load and speed conditions specified in section 3 are applied and experimentations are carried out. As the disc speed increases, it is observed that the frictional force decreases.

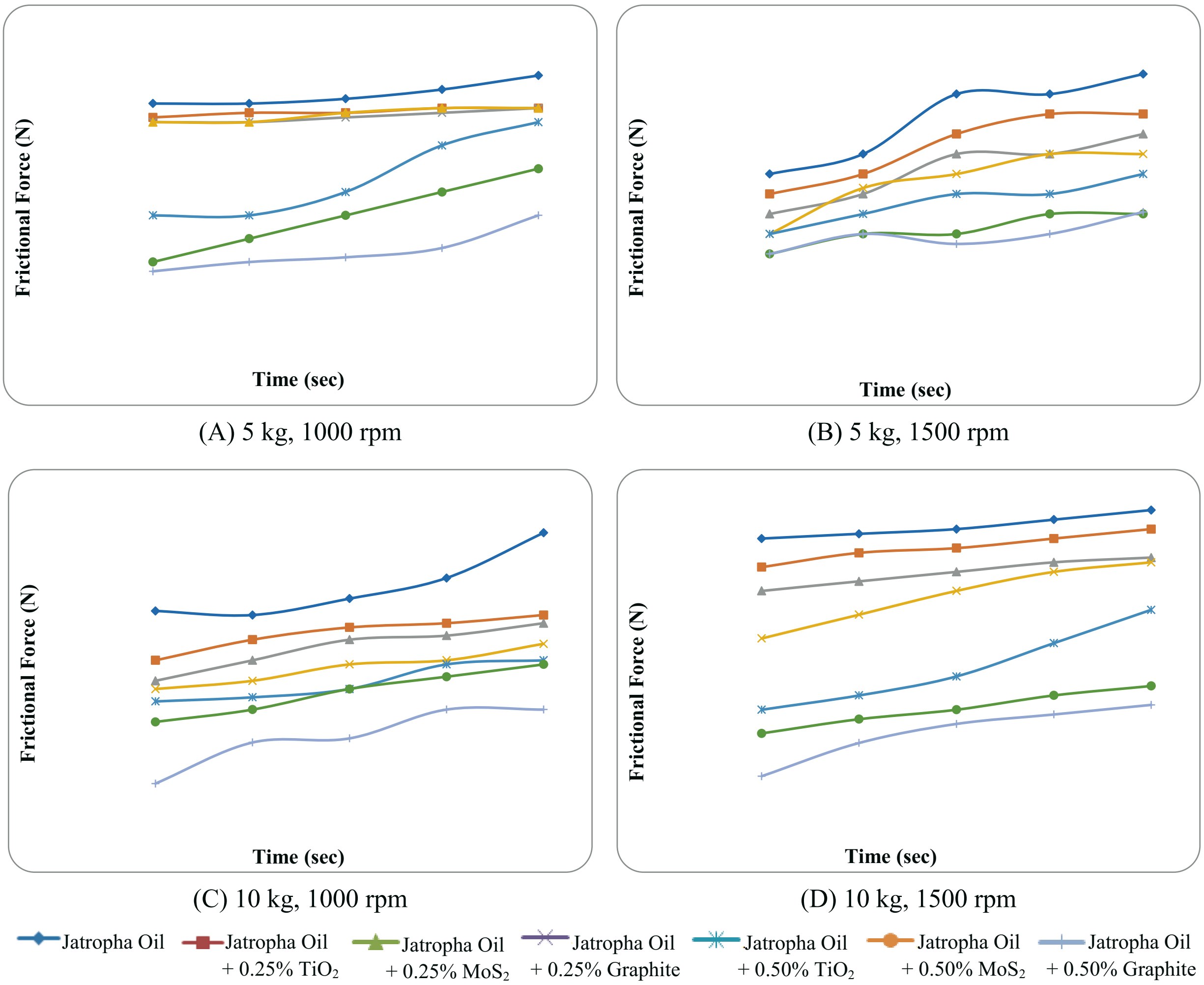

Fig. 5 Effect of lubricants on frictional force

4.3 Coefficient of friction characteristics

Coefficient of friction experimental values are presented in the form of graphs taking into account different input variables. Experiments were conducted using three different types of nanopowders mixed in the jatropha biolubricant. Figure 6 shows the experimental values obtained under loads of 5 kg and 10 kg, at speeds of 1000 and 1500 rpm. It is observed that graphite mixed in jatropha oil at a concentration of 0.5% gives the best output.

At a speed of 1000 rpm and a load of 5 kg, it is observed that the the coefficient of friction decreases by 32.8 % when compared to the use of pure jatropha and 0.5% of nanographite mixed in jatropha. However, when the speed increases to 1500 rpm, the coefficient of friction decreases by 45.3 %. It is evident that the coefficient of friction decreases with the increase in the disc speed. The use of nanographite particles at a weight percentage of 0.5% exhibits a lower value of coefficient of friction than that of other nanopowders mixed in jatropha.

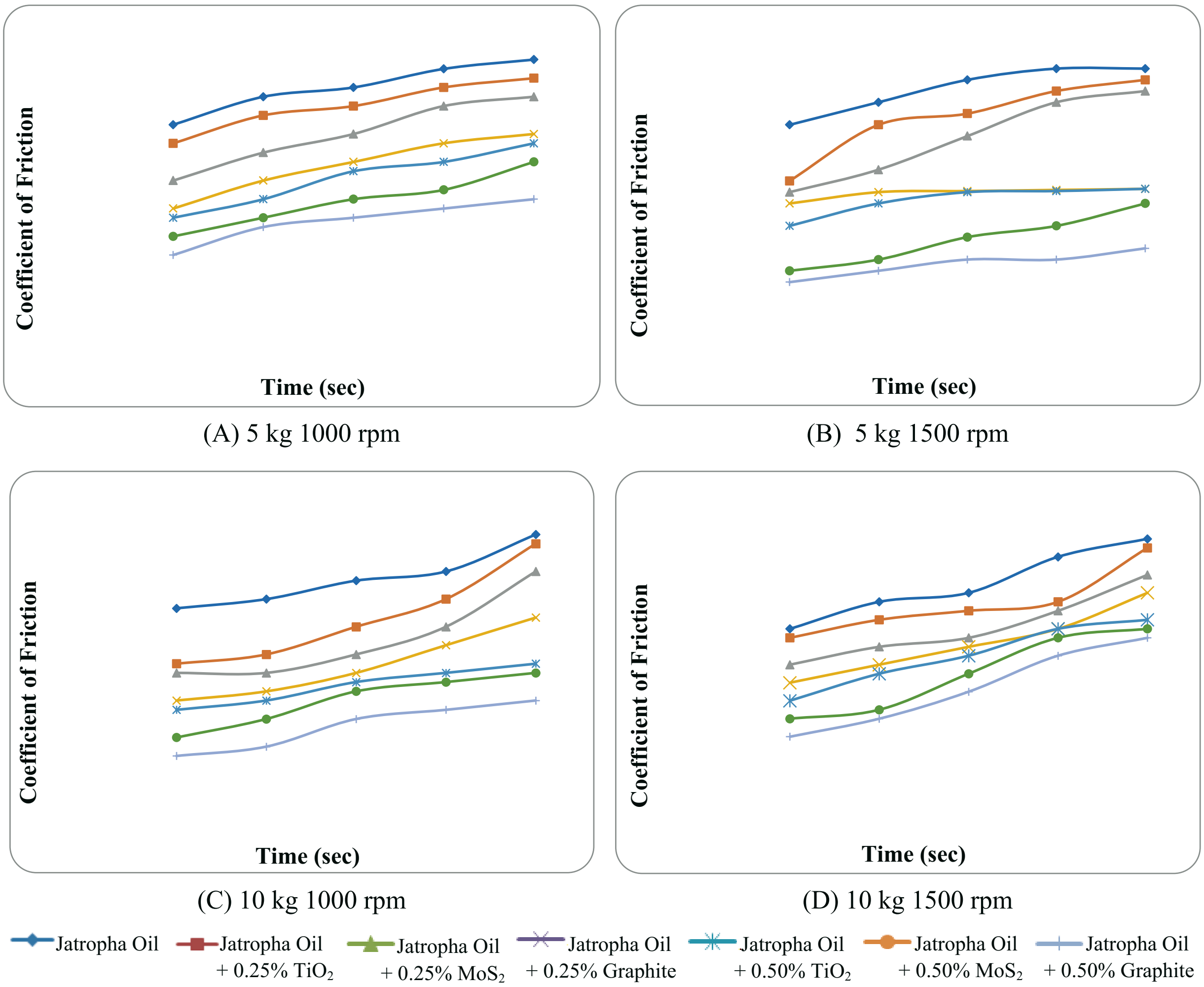

Fig. 6 Effect of lubricants on the coefficient of friction

5. Mathematical Correlation of Experimental Parameters

In order to obtain a quantitative relationship between the inputs and the output, modelling is carried out for the tribological process. Experimental results obtained during the tribological experimentation are used to model the various responses using multiple regression analysis. A nonlinear fit between the response and the corresponding significant parameters is considered. A commercially available mathematical software package, SPSS Statistics, was used for the computation of regression constants and parameters. The responses measured were wear rate, frictional force, and coefficient of friction.

Multiple regression analysis is a practical, economical and relatively easy to use method that is widely used for modelling and analysing experimental results. The mathematical models created for the tribological experimentations, with the parameters under consideration, are represented by:

$$Y = f(L, S, T, W) \tag{2}$$

where Y is the tribological response, f is the response function, and L,S,T,W are the input parameters (L - load applied, S - speed in rpm, T - time, and W - weight percentage). Equation (2) is expressed in nonlinear form as

$$Y = A + (L \times B) + (S \times C) + (T \times D) + (W \times E) \tag{3}$$

The following mathematical models are formulated in the present study:

$$\text{Wear} = A_1 + (L \times B_1) + (S \times C_1) + (T \times D_1) + (W \times E_1) \quad (4)$$

$$\text{Frictional force} = A_2+(L \times B_2)+(S \times C_2)+(T \times D_2)+(W \times E_2) \quad (5)$$

$$\text{Coefficient of friction}=A_3+(L \times B_3)+(S \times C_3)+(T \times D_3)+(W \times E_3) \quad (6)$$

The constants and parameters are found using multiple regression analysis with the help of experimental results. The equations for the output variables in terms of the input parameters are shown in the equations below:

$$\text{Wear} =5.162+(L \times 1.148)-(S \times 0.003)+(T \times 0.008)-(W \times 13.216) \quad (7)$$

$$\text{Frictional force}=2.039+(L \times 0.057)+(S)+(T)-(W \times 0.772) \quad (8)$$

$$\text{Coefficient of friction}=0.036+(L \times 0.002)-(S \times 1.14E\text{-}005)+(T \times 2.83E\text{-}005)-(W \times 0.024) \quad (9)$$

The coefficient of determination which provides a measure of how well the observed outcomes are replicated by the mathematical model is shown in Table 3.

Table 3 Coefficient of determination (R^2)

Dependent parameter	R^2 value obtained	Adjusted R^2 value, calculated
Wear	0.901	0.889
Frictional force	0.912	0.902
Coefficient of friction	0.840	0.821

6. Conclusion:

Pin-on-disc experiments were carried out to determine the tribological performance in terms of friction and wear behaviour of various nanoparticles mixed with the biolubricant jatropha. Some important conclusion can be drawn in accordance with the wear tests conducted with a pin-on-disc configuration. An experiment for different conditions based on variations of different parameters was studied. Three types of nanopowders were investigated; it has been observed that nanographite powder added to jatropha oil is best suited as lubricant additive. The regression analysis has given the empirical relation between the input variables and the output variables.

Acknowledgements

The authors acknowledge the support of the MVGR College of Engineering, Vizianagaram, India, for allowing us to use their experimental facilities. This is a self-funded study conforming to the ethical standards of experimentation.

REFERENCES

[1] Adhvaryu, A.; Z. Liu; Erhan, S.Z. Synthesis of novel alkoxylated triacylglycerols and their lubricant base oil properties. Industrial Crops and Products, 2005,21(1), 113-119. https://doi.org/10.1016/j.indcrop.2004.02.001

[2] Erhan, S.Z.; Asadauskas, S.Lubricant base stocks from vegetable oils. Industrial Crops and Products, 2000, 11,277-82. https://doi.org/10.1016/S0926-6690(99)00061-8

[3] Jayadas, N.H.; Nair, K.P.; Ajith kumar, G. Tribological evaluation of coconut oil as an environment friendly lubricant. Tribology International, 2007, 40, 350-4. https://doi.org/10.1016/j.triboint.2005.09.021

[4] Lathi, P.S.; Mattiasson, B. Green approach for the preparation of biodegradable lubricant base stock from epoxidized vegetable oil. Applied Catalysis B: Environmental, 2007, 69,207-12. https://doi.org/10.1016/j.apcatb.2006.06.016

[5] Jayadas, N.H.; Nair, K.P.; Ajith kumar, G. Tribological evaluation of coconut oil as an environment friendly lubricant. Tribology International, 2007, 40,350-4. https://doi.org/10.1016/j.triboint.2005.09.021

[6] Alves, S.M.; Barros, B. S.; Trajano, M. F.; Ribeiro, K. S. B.; Moura, E. Tribological behavior of vegetable oil-based lubricants with nanoparticles of oxides in boundary lubrication conditions. Tribology International, 2013, 65, 28-36. https://doi.org/10.1016/j.triboint.2013.03.027

[7] Atabani, A.E.; Silitonga, A.S.; Ong, H.C.; Mahlia, T.M.I.; Masjuki, H.H.; Anjum, B.I. Non-edible vegetable oils: a critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production. Renewable & sustainable energy reviews, 2013, 18, 211-45. https://doi.org/10.1016/j.rser.2012.10.013

[8] Shahabuddin, M.; Masjuki, H.H.; Kalam, M.A.; Bhuiya, M.M.K.; Mehat, H. Comparative tribological investigation of bio-lubricant formulated from a non-edible oil source (Jatropha oil). Industrial Crops and Products, 2013, 47, 323-30. https://doi.org/10.1016/j.indcrop.2013.03.026

[9] Nagendramma, P.; Savita, K. Development of eco-friendly / biodegradable lubricants: an overview. Renewable and Sustainable Energy Reviews, 2012, 16,764-74. https://doi.org/10.1016/j.rser.2011.09.002

[10] Li, W.; Shi, W.; Jiang, X.; Hu, J.; Ye, X.; Tian, H. Research on the liquid film force of water lubricated bearing in desalination multistage pumps and its coupled dynamics with rotor. Journal of Coastal Research, 2015, 73, 453-458. https://doi.org/10.2112/SI73-080.1

[11] Pavani, P. N. L.; Pola Rao, R.; Prasad, C. L. V. R. S. V.; Srikiran, S. Performance Assessment and Study of Tribological Properties of Self-lubricating Materials for Dry Lubrication. Journal of Mechanical Engineering Research and Developments, 2016, 39 (3), 670-680.

[12] Kabir, M.A.; Higgs, C.F.; Lovell, M.R. A pin-on-disk experimental study on a green particulate-fluid lubricant. Journal of Tribology, 2008, 130, 1131- 1137. https://doi.org/10.1115/1.2908913

[13] Srikiran, S.; Ramji, K.; Satyanarayana, B.; Ramana, S.V. Investigation on turning of AISI 1040 steel with the application of nano-crystalline graphite powder as lubricant. Proceedings of IMechE Part C: Journal of Mechanical Engineering Science, 2014, 228 (9), 1570-1580. https://doi.org/10.1177/0954406213509612

[14] Biresaw, G. Elasto hydrodynamic properties of seed oils. Journal of the American oil Chemists' Society , 2006, 83,559-66. https://doi.org/10.1007/s11746-006-1240-9

[15] Adhvaryu, A.; Erhan, S.Z.; Perez, J.M. Tribological studies of thermally and chemically modified vegetable oils for use as environmentally friendly lubricants. Wear, 2004, 257,359-67. https://doi.org/10.1016/j.wear.2004.01.005

[16] Ali, M. K. A.; Xianjun, H.; Abdelkareem, M. A. A.; Gulzar, M.; Elsheikh, A. H. Novel approach of the graphene nanolubricant for energy saving via anti-friction/wear in automobile engines. Tribology International, 2018, 124, 209-229. https://doi.org/10.1016/j.triboint.2018.04.004

[17] Ali, M. K. A.; Xianjun, H.; Mai, L.; Qingping, C.; Turkson, R. F.;Bicheng, C. Improving the tribological characteristics of piston ring assembly in automotive engines using Al2O3 and TiO2 nanomaterials as nano-lubricant additives. Tribology International, 2016, 103, 540-554. https://doi.org/10.1016/j.triboint.2016.08.011

[18] Ali, M. K. A.; Fuming, P.; Younus, H. A.; Abdelkareem, M. A. A.; Essa, F. A.; Elagouz, A.; Xianjun, H. Fuel economy in gasoline engines using Al2O3/TiO2 nanomaterials as nanolubricant additives. Applied Energy, 2018, 211, 461-478. https://doi.org/10.1016/j.apenergy.2017.11.013

[19] Ali, M. K. A.; Xianjun, H.; Mai, L.; Bicheng, C.; Turkson, R. F.; Qingping, C. Reducing frictional power losses and improving the scuffing resistance in automotive engines using hybrid nanomaterials as nano-lubricant additives. Wear, 2016, 364-365, 270-281. https://doi.org/10.1016/j.wear.2016.08.005

[20] Sgroi, M. F.; Asti, M.; Gili, F.; Deorsola, F. A.; Bensaid, S.; Fino, D.; Kraft, G.; Garcia, I.; Dassenoy, F. Engine bench and road testing of an engine oil containing MoS2 particles as nano-additive for friction reduction. Tribology International, 2017,105, 317-325 https://doi.org/10.1016/j.triboint.2016.10.013

[21] Rasheed, A. K.; Khalid, M.; Rashmi, W.; Gupta, T. C. S. M.; Chan, A. Graphene based nanofluids and nanolubricants – Review of recent developments. Renewable Sustainable Energy Review. 2016, 63, 346-362. https://doi.org/10.1016/j.rser.2016.04.072

[22] Rasheed, A. K.; Khalid, M.; Javeed, A.; Rashmi, W.; Gupta, T. C. S. M.; Chan, A. Heat transfer and tribological performance of graphene nanolubricant in an internal combustion engine. Tribology International, 2016, 103, 504-515. https://doi.org/10.1016/j.triboint.2016.08.007

[23] Zin, V.; Barison, S.; Agresti, F.; Colla, L.; Pagura, C.; Fabrizio, M. Improved tribological and thermal properties of lubricants by graphene based nano-additives. RSC Advances. 2016, 6, 59477-59486. https://doi.org/10.1039/C6RA12029F

[24] Chandrabhan, S. R. ; Jayan, V. ; Parihar, S. S. ; Ramaprabhu, S. Development of a nitrogen-doped 2D material for tribological applications in the boundary-lubrication regime. Beilstein Journal of Nanotechnology, 2017, 8, 1476- 1483. https://doi.org/10.3762/bjnano.8.147

[25] Hernández Battez, A.; Viesca, J. L.; González, R.; Blanco, D.; Asedegbega, E.; Osorio, A. Friction reduction properties of a CuO nanolubricant used as lubricant for a NiCrBSi coating. Wear 2010, 268, 325-328. https://doi.org/10.1016/j.wear.2009.08.018

[26] Ben Difallah, B.; Kharrat, M.; Dammak, M.; Monteil, G. Improvement in the Tribological Performance of Polycarbonate via the Incorporation of Molybdenum Disulfide Particles. Tribology Transactions 2014, 57, 806-813. https://doi.org/10.1080/10402004.2014.913751

[27] Gara, L.; Zou, Q. Friction and Wear Characteristics of Water-Based ZnO and Al2O3 Nanofluids. Tribology Transactions. 2012, 55, 345-350. https://doi.org/10.1080/10402004.2012.656879

[28] Ghaednia, H.; Hossain, M. S.; Jackson, R. L. Tribological performance of silver nanoparticle-enhanced polyethylene glycol lubricants. Tribology Transactions. 2016, 59, 585-592. https://doi.org/10.1080/10402004.2015.1092623

[29] Khan, I.;Saeed, K.; Khan, I. Nanoparticles: Properties, applications and toxicities. Arabian Journal of Chemistry.2019, 12(7), 908-931. https://doi.org/10.1016/j.arabjc.2017.05.011

[30] Cha, C.; Shin, S. R.; Annabi, N.; Dokmeci, M. R.; Khademhosseini, A. Carbon-Based Nanomaterials: Multifunctional Materials for Biomedical Engineering. ACS Nano. 2013, 7, 2891-2897. https://doi.org/10.1021/nn401196a

Submitted: 29.11.2020

Accepted: 10.01.2022

Fathimunnisa Begum, Research Scholar*
Dept. of Mechanical Engineering,
Baba Institute of Technology & Sciences,
Visakhapatnam, INDIA, 530041

N. Ravi Kumar, Professor
Dept. of Mechanical Engineering,
MVGR College of Engineering,
Vizianagaram, INDIA, 535005
nravikumar.mvgr@gmail.com

V. Ramachandra Raju, Professor
Dept. of Mechanical Engineering,
JNTUK,
Kakinada, INDIA, 533003
drvrrjntuk@gmail.com

*Corresponding author:
mech.fathimunnisa@gmail.com