ARID ZONE JOURNAL OF ENGINEERING, TECHNOLOGY & ENVIRONMENT
AZOJETE September 2025. Vol.21(3):682-692
Published by the Faculty of Engineering, University of Maiduguri, Maiduguri, Nigeria.
Print ISSN: 1596-2490, Electronic ISSN: 2545-5818
https://doi.org/10.63958/AZOJETE/2025/21/03/001
www.azojete.com.ng

ORIGINAL RESEARCH ARTICLE

THE EFFECT OF ZINC DIALKYL DITHIOPHOSPHATE (ZDDP) ADDITIVE ON THE TRIBOLOGICAL PROPERTIES OF MAHOGANY (*Khaya senegalensis*) SEED OIL

D. M. Ayuba[*1], **A. A. Hammajam**[2], **M. A. Abba-Aji**[3] **and C. Amos**[1]

[1]*National Centre for Technology Management (NACETEM), Yola, Nigeria*
[2]*Department of Mechanical Engineering Nigerian Army University Biu (NAUB), Biu, Nigeria*
[3]*Department of Mechanical Engineering University of Maiduguri, Maiduguri, Nigeria*
**Corresponding author's email: davidayubamshelia@yahoo.com*

ARTICLE INFORMATION

Received: 5th March 2024
Revised: 13th August 2025
Accepted: 15th August2025

Keywords:
Additives
Khaya senegalensis
Bio-lubricant
Tribology
ZDDP
Wear rate
Coefficient of friction

ABSTRACT

Mineral oil based lubricants are non-renewable, harmful to health and prone to price fluctuations. Thus, vegetable oils are considered as suitable alternatives to mineral oils for lubricant production. As such, new research into the use of non-edible vegetable oils for lubricant development is advocated to address these challenges. In this study, tribological evaluation of lubricant developed from non-edible vegetable mahogany (Khaya senegalensis) oil for industrial applications was conducted. Interestingly, the oil was characterized, modified for suitability and used to develop lubricants for industrial applications. Additionally, commercially available mineral oil based lubricant SAE 20/W50 was used as a control. The effect of ZDDP additive on the tribological performance of mahogany seed oil based biolubricant developed was also studied. The results show that the developed mahogany seed oil based biolubricant had alkaline pH of 7.56, high viscosity index of 147.12, appreciable viscosity, excellent cold flow of -9.2 °C. Similarly, the coefficient of friction of the biolubricant developed reduced from 0.095 to 0.090when 1% of ZDDP was added and form 0.095 to 0.087 when 3% of ZDDP was added but the coefficient of friction increased from 0.095 to 0.099 with the addition of 5% of ZDDP. Therefore, developed mahogany seed oil biolubricant was observed to be suitable and environmentally friendly substitutes to mineral oil base lubricant SAE 20/W50 for application in metal cutting and lubrication of gears in food processing industry.

1.0 Introduction

Lubrication is the process in which a layer or a film of oil is applied between two objects, which are in relative motion with each other, to reduce the friction between them (Nehal and Amal, 2013). Lubricating oil or lubricant is a substance which is required to decrease the friction and wear between surfaces having relative motion with each other (Nehal and Amal, 2013). Thus, lubricant must have certain objectives such as reducing wear and power loss in overcoming friction and reducing the oxidation to protect it from corrosion, and also to act as a shock absorber in automotive engine parts, acting as a cleansing agent in various applications, and reducing the heat from friction (Nehal and Amal, 2013). A good lubricant must have the characteristics of; high viscosity, and viscosity index, thermal stability, high oxidation resistance, and prevention against corrosion (Nehal and Amal, 2013). The conventional source of lubricant is petroleum or crude oil. It is a by-product of the refining process of petroleum. Though the uses of mineral oil are limited due to its less availability, the decay of oceanic as well as terrestrial environment is caused by the disposal of crude oil (Nehal and Amal, 2013). The application of petroleum-based oil in automotive engine result in the emission having metal traces such as magnesium, zinc, and iron is harmful to the environment (Singh *et al.,* 2015).

Research has recently targeted alternative bio-lubricants in resolving the challenges faced by the use of mineral-based lubricants (Ahmad, 2021). Bio-lubricants can biodegrade easily and fast (Noreen *et al.,* 2021). In addition, they are nontoxic to humans, aquatic life and land (Salih *et al.,* 2011). They could be based on oils extracted from plants, animals or esters manufactured from modified oils. Some typical examples of oil used for bio-lubricant production include jatropha seed oil, castor seed oil, soybean oil, sunflower oil, amongst others (Cavalcanti *et al.,*2018; Odetoye *et al.,*2016; and Kumar *et al.,*2021).

However, the non-edible plant oil–based lubricant is very suitable for lubrication processes, together with physicochemical characteristics that make it preferable than fossil oil–based lubricants (Joshi, *et al*., 2023). These consist of having an elevated lubricity property, viscosity index, and lower evaporative expeditions during operation (Joshi, *et al*., 2023). There are several research works performed to enhance the physical and chemical characteristics of inedible crop-based oil lubricants. The investigations showed that inedible plant-based oil lubricants could be effective as well as economical alternatives to the petroleum-based lubricants (Joshi, *et al*., 2023). In the study by Mahipal and Krishnanunni (2014), they analyzed the lubricant properties of zinc dialkyldithiophosphate (ZDDP) additive on Karanja oil. In this study, they used experimental method to determine the Coefficient of friction (COF), wear scar diameter (WSD) and viscosity. Zainal (2015) investigated the physical property of canola oil when blended with ZDDP as an additive.The meta-analysis of the research papers done by different investigators is presented in Table 1(Singh *et al.,* 2019).

Table 1: Meta-analysis of non-edible oil-based lubricants(Singh *et al.,* 2019)

Reference lubricant	Bio-lubricant	Testing method	Results obtained	References
2T oil	Castor oil	Gasoline engine two stroke air cooled engine	Flash point higher, enriched lubricity, less emissions	(Singh 2011)
SAE20/W40	Jatropha oil	Pin on disc machine	Frictional losses low, less wear	(Bhale *et al.,* 2008)
SAE40	Cotton seed oil	Pin on disc machine	Less wear at high speed, high lubricity, lower coefficient of friction, eco-friendly, biodegradable	(Agarwal *et al.,* 2014)
SAE20/W40	Jatropha oil	Pin on disc machine	Minimum specific wear rate at high velocity	(Singh 2015)
SAE20/W40	Mongongo oil	Four-ball wear tester	Less coefficient of friction, high viscosity index, less deposit forming tendencies	(Singh *et al.,* 2017a, b)
SAE20/W40	Pongamia oil	Pin on disc machine	Surface wear less, minimum degradation of lubricant at all applied loads	(Singh *et al.,* 2017a, b)

For the purpose of improving the physical and chemical properties of non-edible oils, certain additives are introduced, as they enhance specific characteristics of the base oil so that the resultant formulation can meet increasing performance demands and conform to required specifications (Puhan, 2021).

An Anti-wear (AW) additive is a tribochemical active substance. In essence, tribochemical refers to the chemical action that takes place in a rubbing/abrasive contact which could affect and be affected by the rubbing/abrasive action (Ioan *et al.,* 2013). The AW additive develops a reaction layer on the work piece surface during the machining process. The reaction products are easily deformed and removed, reducing the loading of the abrasive tool. The fundamental mechanism of ZDDP as anti-wear is the reaction of ZDDP with the metal surface to form a solid protective film and the reaction layer (Zhang and Spikes, 2016). When metal is immersed in ZDDP solution in a lubricant or other non-polar solvent, a thermal film rapidly forms at the metal surface (Zhang and Spikes, 2016). Apparently, these films are not simply zinc phosphate, zinc phosphide or iron phosphate (Galvin, 1976). Figure 1 below showed the layered structure of surface film formed from ZDDP.

Therefore, the objective of this study is to systematically investigate the effect of zinc dialkyldithiophosphate (ZDDP) as an additive on the tribological properties of mahogany seed oil. In particular, the study seeks to analyse the impact of varying concentrations of ZDDP on the coefficient of friction, wear resistance, and load-carrying capacity of the oil under boundary lubrication. In so doing, the study aims to determine the prospects

Corresponding author's email address: davidayubamshelia@yahoo.com of ZDDP-modified mahogany seed oil as an eco-friendly biolubricant substitute for traditional mineral-based lubricants, hence advancing the cause for environmentally friendly and high-performance lubrication systems.

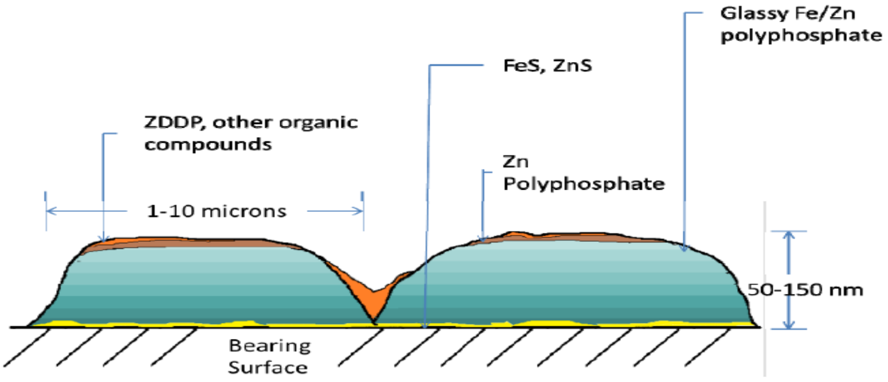

Figure 1:Layered structure of surface film formed from ZDDP(Johnson and Hills, 2013).

2. Materials and Method

The study utilized locally sourced mahogany seed oil from shaffa in Hawul local government area Borno State, as well as a commercially available lubricant (SAE 20/W50) obtained from Ammasco International Limited in Yola, for comparison. Distilled water and Potassium methoxide were prepared in the Petroleum Chemistry laboratory at the American University of Nigeria (AUN) in Yola using direct reaction method. Various chemical reagents and lubricant additives were also used.

2.1 Lubricant additive

Zinc dialkyl dithiophosphate (ZDDP) was used as lubricant additive in this study.

2.2 Tribo-meter

The Anton Paar standard tribo-meter TRN version 6.1.19 was used for the tribological evaluation of the oil and lubricant. The TRN model standard tribo-meter is an Austrian design which can be used as a pin-on disc or ball-on-disc tribo-meter. It has an electronic microscope fitted for wear measurements and has several sensors connected to a computer for data acquisition and processing.

In this study, different concentrations of anti-wear additives, sliding speeds and normal loads were used. The full factorial method was used to determine the influence of control parameters on the coefficient of friction and wear rate. The Minitab 18 computer program was used to statistically analyse the data. The experimental factors and levels used in experimental design are listed in Table 2. Three factor full factorial experimental design method was used so as to determine the effect of more than one independent variable on a dependent variable and to determine the possible interaction of the multiple independent variables. The design (3^3) refers to the 27 runs experimental design to examine three factors. Each was used on three levels in the study.

Table 2: Treatments for the 3^3 Full factorial Design of Experiment

		Factor A		
Factor B	**Factor C**	**0**	**1**	**2**
0	0	000	100	200
0	1	001	101	201
0	2	002	102	202
1	0	010	110	210
1	1	011	111	211
1	2	012	112	212
2	0	020	120	220
2	1	021	121	221
2	2	022	122	222

Corresponding author's email address: davidayubamshelia@yahoo.com

2.3 Determination of the contributions of additive and other factors

The empirical data collected were analyzed using analysis of variance (ANOVA) to determine the contributions of the additive and other factors on the tribo-performance of the developed bio-lubricant.

3. Results and Discussion

Table 3 showed the experimental design matrix (3^3) consisting of 27 runs with different combinations of the levels of each of the factors and responses as specified by the full factorial design.

Table 3: Experimental Process Parameters and Reponses for Mahogany Seed Oil Bio-lubricant blended with ZDDP

Run Order	Sliding speed (m/s)	% of ZDDP	Normal load (N)	Coefficient of friction	Wear rate (10^{-3}mm^3/N/m)
1	0.2	3	20	0.082	4.48
2	0.1	3	20	0.077	4.39
3	0.3	1	10	0.088	5.55
4	0.2	3	30	0.091	4.63
5	0.3	5	30	0.118	6.97
6	0.2	1	30	0.094	5.72
7	0.3	5	10	0.099	6.88
8	0.2	5	20	0.097	6.76
9	0.1	5	30	0.102	6.74
10	0.2	1	20	0.089	5.69
11	0.1	1	10	0.078	5.40
12	0.2	1	10	0.083	5.51
13	0.1	1	20	0.085	5.61
14	0.3	1	30	0.100	5.83
15	0.1	3	10	0.072	4.20
16	0.1	1	30	0.090	5.66
17	0.1	3	30	0.085	4.51
18	0.3	3	10	0.080	4.51
19	0.3	3	30	0.096	4.68
20	0.2	3	10	0.078	4.33
21	0.2	5	30	0.109	6.79
22	0.2	5	10	0.091	6.71
23	0.3	5	20	0.106	6.91
24	0.3	1	20	0.093	5.74
25	0.3	3	20	0.087	4.60
26	0.1	5	10	0.085	6.65
27	0.1	5	20	0.090	6.69

The tribological performance of mahogany seed oil with ZDDP additive at different loads and sliding speeds is summarized in Table 1. The results indicate that ZDDP concentration has the most overriding effect on both the coefficient of friction (COF) and wear rate. Frictional performance is reasonably improved at low additive concentration (1%), with COF ranging from 0.078 to 0.094 and wear rates between 5.40×10^{-3} and 5.83×10^{-3} mm^3/N/m. The performance is significantly better at 3% ZDDP, where the minimum COF (0.072) and lowest wear (4.20×10^{-3} mm^3/N/m) are obtained under 10 N load at 0.1 m/s sliding speed (Run 15). This suggests that at moderate concentration, ZDDP induces the formation of a uniform anti-wear tribofilm, which suppresses asperity contact and minimizes friction as well as material loss. These observations are consistent with the results of Zhang *et al.*, (2020), who demonstrated that ZDDP improves boundary lubrication by forming protective phosphate films on steel surfaces.

But when concentration is raised to 5%, performance is drastically worse, with COF values of 0.118 and wear rates of up to 6.97×10^{-3} mm^3/N/m under high-speed, high-load conditions (Run 5). This effect has already been reported by Spikes and Tysoe (2015), who observed that too much ZDDP can lead to the generation of thick and unstable tribofilms that collapse under shear, forming abrasive debris that promotes wear. So, while

ZDDP plays a critical role in friction reduction, its performance is concentration-dependent, with an optimum of about 3% for this study.

Sliding speed also exhibits a steady influence on performance. At low speed (0.1 m/s), the system shows better tribological behavior, especially at 3% ZDDP, validating that lower shear rates facilitate more stable tribofilm formation. As the speed increases (0.2–0.3 m/s), COF and wear gradually rise, with the most adverse condition at 0.3 m/s, 5% ZDDP, and 30 N load. This trend aligns with previous research (Martin *et al.,* 2013; Zhang *et al.,* 2019), where higher sliding speeds were found to increase surface temperatures, compromise additive film integrity, and hasten wear particle formation.

The influence of normal load further highlights the contribution of contact stress to film stability. At 10 N, wear is still low, especially with 3% ZDDP, corroborating that mild contact enables the additive-derived film to resist shear. At intermediate (20 N) and high (30 N) loads, however, wear rises dramatically, with rates $>6.7 \times 10^{-3}$ mm^3/N/m under severe conditions. This is consistent with observations by Gosvami *et al.,* (2017), where high contact stresses were seen to enhance tribofilm rupture, resulting in adhesive and abrasive wear. Nevertheless, even under these extreme conditions, 3% ZDDP concentration still outperforms 1% or 5%, implicating that moderate concentrations achieve the optimal compromise between film growth and mechanical stability. Collectively, the findings show that the tribological behavior of ZDDP-blended mahogany seed oil is controlled by a subtle interplay among additive concentration, sliding speed, and load. The best performance is achieved at 3% ZDDP, 0.1 m/s, and 10 N, wherein a stable phosphate-based tribofilm minimizes friction and wear. At the other extreme of high load, high speed, and excess additive, film breakdown and abrasive wear are promoted. These observations support the well-documented "inverted-U" response of ZDDP in lubricant systems (Zhang *et al.,* 2020), wherein the performance increases up to an optimum concentration before being undermined by film instability.

3.1 Tribological properties of the developed mahogany seed oil bio-lubricant

The coefficient of friction of the developed mahogany seed oil bio-lubricants as compared to the mineral oil base lubricant is shown in Figure 2. It was observed that the mahogany oil bio-lubricant had lower friction coefficient (0.095) compared to mineral base lubricant of 0.115. Mahogany seed oil bio-lubricant friction coefficient is higher than the friction coefficient of the unmodified mahogany seed oil. The vegetable (mahogany) oil-based lubricant had a better friction reduction property than the commercial mineral oil-based lubricant (SAE 20/W50).

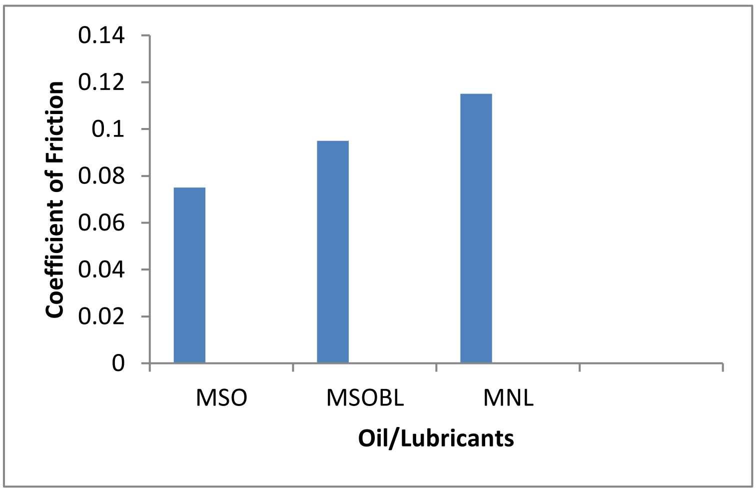

Figure 2: Coefficient of friction of developed mahogany seed oil bio-lubricant and mineral based lubricant

Figure 3 showed the wear rate of the developed mahogany oil bio-lubricant. The results revealed that the wear rate of the developed mahogany seed oil bio-lubricant was 0.00660 mm ^{3}N^{-1}m^{-1} which is lower than the wear rate of the mineral base oil (0.00670 mm^{3}N $^{-1}$ m $^{-1}$). The developed mahogany seed oil bio-lubricant performed better in friction and in wear protection than the commercial mineral oil base lubricant (SAE 20/W50).

Corresponding author's email address: davidayubamshelia@yahoo.com

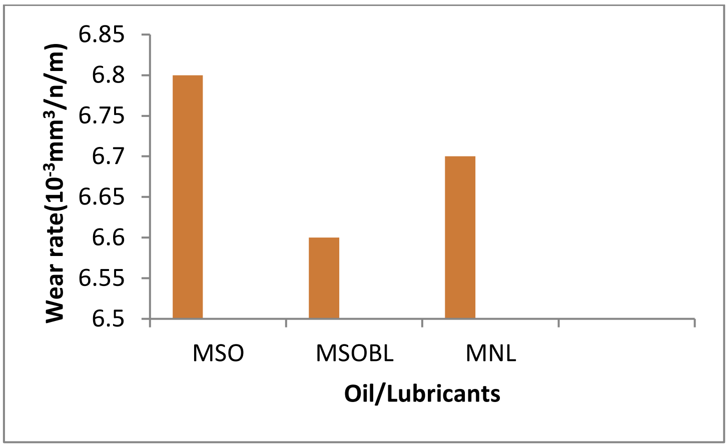

Figure 3: Wear rate of developed mahogany seed oil bio-lubricant and mineral based lubricant

It can be deduced here that the transesterification of the mahogany seed oil with TMP polyol slightly improved its tribological properties in terms of wear property, but the friction coefficient was increased. The transesterification with TMP polyol improved wear resistance by forming a stronger, more stable boundary film, but increased the friction coefficient because this film has higher shear strength and resists sliding more than the natural oil layer.

3.2 Effect of additives on the coefficient of friction of oil and bio-lubricants developed

The main effects plot displaying the impact of the additive and the other factors on the friction coefficient for the mahogany seed oil bio-lubricant is shown in Figure 4. It is clear that the concentration of ZDDP (%) additive, the normal load and the sliding speed have significant effect on the coefficient of friction of the mahogany seed oil bio-lubricant. The tribological performance of mahogany seed oil bio-lubricant is strongly influenced by ZDDP concentration, load, and sliding speed. ZDDP improves friction behavior by forming protective boundary films, but its effect depends on operating conditions. Optimal load and sliding speed enhance film stability and reduce friction, while extremes of these parameters can cause film failure, oil degradation, or increased friction.

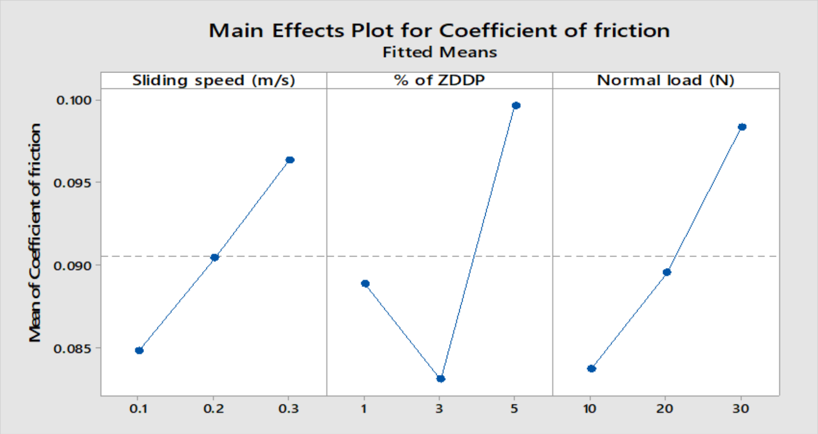

Figure 4: Main Effects Plot for coefficient of friction of mahogany seed oil based bio-lubricant

Table 4 showed an overall summary of results derived from the analysis of variance (ANOVA) of the coefficient of friction of the bio-lubricant based on mahogany seed oil. Concentration of ZDDP was found to be the main determinant, accounting for 43.63% of the total variability of the frictional behavior. Normal load and sliding speed contributed 33.20% and 20.24% of the variation, respectively. The error term was very low at 2.93%, reflecting the reliability and robustness of the experimental design utilized. The results clearly indicate that the concentration of ZDDP has a dominant effect on the coefficient of friction, overriding the effects due to both load and speed. Such dominance is likely due to the capacity of ZDDP to form a protective tribofilm on the sliding interface, thus changing the lubrication regime. These findings are in agreement with the results obtained by Azhari (2014), who also underscored the considerable contribution of additive concentration on tribological behavior. As such, the optimization of the concentration of ZDDP constitutes a promising approach to improving the frictional performance and overall effectiveness of mahogany seed oil as an eco-

Corresponding author's email address: davidayubamshelia@yahoo.com

friendly bio-lubricant. It also suggests that variations in sliding speed can also affect the coefficient of friction of the bio-lubricant.

3.2 ANOVA for the coefficient friction mahogany seed oil-based bio-lubricant

Table 4: ANOVA for Coefficient of Friction of Mahogany seed oil based bio-lubricant

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Sliding speed (m/s)	2	0.000590	20.24%	0.000590	0.000295	69.09	0.000
% of ZDDP	2	0.001271	43.63%	0.001271	0.000635	148.93	`0.000
Normal load (N)	2	0.000967	33.20%	0.000967	0.000483	113.31	0.000
Error	20	0.000085	2.93%	0.000085	0.000004		
Total	26	0.002913	100.00%				

3.3 Effects of additives on the rate of wear of mahogany seed oil-based lubricant

The main effect plot displaying the effects of the additives, sliding speed and normal load on the mean wear rate of mahogany seed oil-based bio-lubricant is shown in Figure 5. It is notable that the (%) of ZDDP additive has a significant effect on the wear rate of the mahogany seed oil bio-lubricant while the sliding speed and the normal load have no significant effect as seen .This implies that the wear rate of the mahogany seed oil bio-lubricant is primarily influenced by the concentration of ZDDP additive, while the sliding speed and normal load have minimal impact on the wear rate.

Therefore, changes in the concentration of ZDDP additive will lead to changes in the wear rate of the bio-lubricant. On the other hand, variations in sliding speed and normal load may not have a substantial effect on the wear rate of the bio-lubricant. Thus, understanding these relationships can help in optimizing the formulation of the bio-lubricant to minimize wear and improve its performance in practical applications.

3.4 ANOVA for the wear rate of the mahogany seed oil-based bio-lubricant

The ANOVA for the wear rate of the mahogany seed oil bio-lubricant is shown in Table 5. It was observed that the concentration of ZDDP with 98.28% contribution had the dominant influence on the wear rate. Similarly, the sliding speed with 0.76% contribution had the second dominant influence on the wear rate of the mahogany seed oil-based bio-lubricant. Furthermore, the normal load contributed 0.75% while the error accounted for 0.22% of the wear rate. This indicates that changes in the concentration of ZDDP additive will have the most substantial impact on reducing or increasing wear in the bio-lubricant. The concentration of ZDDP is critical because it dictates the formation and resilience of the protective tribofilm. In contrast, sliding speed and load primarily influence the lubrication regime by modifying shear rate and contact stress. Thus, it is the additive concentration that determines whether the system maintains a stable film or degrades into abrasive conditions, making it the dominant factor affecting wear performance.

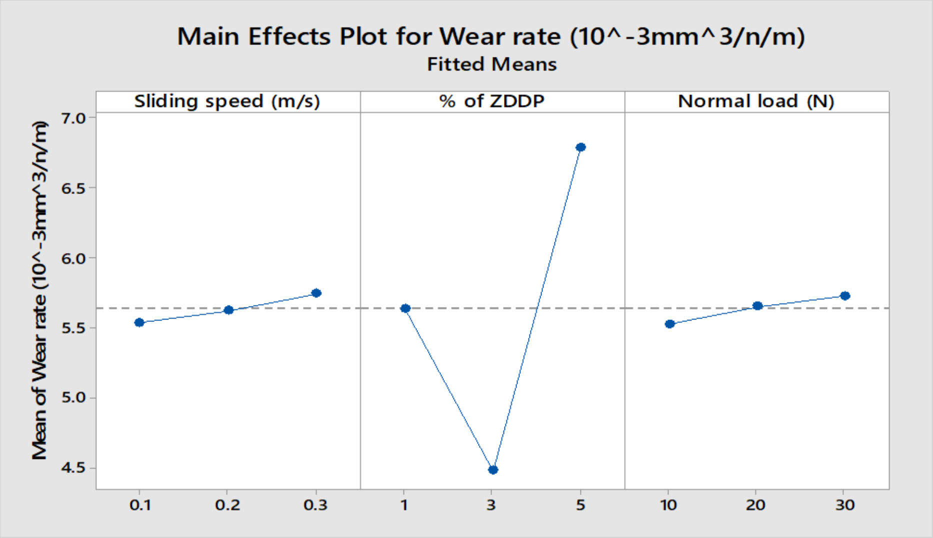

Figure 5: Main Effects Plot for wear rate of mahogany seed oil-based bio-lubricant

Corresponding author's email address: davidayubamshelia@yahoo.com

Table 5: ANOVA for Wear rate of Mahogany seed oil-based bio-lubricant

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Sliding speed (m/s)	2	0.1855	0.76%	0.1855	0.0927	34.98	0.000
% of ZDDP	2	23.9663	98.28%	23.9663	11.9831	4519.41	0.000
Normal load (N)	2	0.1821	0.75%	0.1821	0.0910	34.34	0.000
Error	20	0.0530	0.22%	0.0530	0.0027		
Total	26	24.3869	100.00%				

3.5 ZDDP additives at different percentage concentrations

Figure 5 illustrates the variation in the coefficient of friction of mahogany seed oil bio-lubricant with and without ZDDP additives under different loads and sliding speeds. For the base oil without ZDDP, the coefficient of friction at 10 N and 0.1 m/s was 0.090, which increased slightly to 0.096 at 0.2 m/s and 0.100 at 0.3 m/s. At 20 N, the values were 0.095, 0.099, and 0.103, while at 30 N they rose from 0.098 at 0.1 m/s to 0.102 at 0.2 m/s and 0.108 at 0.3 m/s. With the addition of 1% ZDDP, the coefficient of friction reduced to 0.078 at 10 N and 0.1 m/s, increasing gradually to 0.085 and 0.090 as the sliding speed rose to 0.2 and 0.3 m/s, respectively. At 20 N, the values were 0.083, 0.089, and 0.094, and at 30 N they increased from 0.088 to 0.093 and 0.100 with increasing speed. At 3% ZDDP concentration, the coefficient of friction further decreased, recording 0.072, 0.077, and 0.085 at 10 N across the speed range, 0.078, 0.082, and 0.091 at 20 N, and 0.080, 0.087, and 0.091 at 30 N. At the higher concentration of 5% ZDDP, the coefficient of friction increased relative to 3%, with values of 0.085, 0.090, and 0.102 at 10 N; 0.091, 0.097, and 0.109 at 20 N; and 0.099, 0.106, and 0.118 at 30 N for sliding speeds of 0.1, 0.2, and 0.3 m/s, respectively.

Figure 6 illustrates the variation in wear rate of mahogany seed oil bio-lubricant with and without ZDDP additives under different loads and sliding speeds. For the base oil without ZDDP, the wear rate at 10 N and 0.1 m/s was 6.45 × 10^{-3} mm^{3}/N/m, which increased slightly to 6.56 × 10^{-3} at 0.2 m/s and 6.61 × 10^{-3} mm^{3}/N/m at 0.3 m/s. At 20 N, the wear rate rose from 6.68 × 10^{-3} at 0.1 m/s to 6.73 × 10^{-3} and 6.80 × 10^{-3} mm^{3}/N/m with increasing speed, while at 30 N the values increased from 6.71 × 10^{-3} to 6.76 × 10^{-3} and 6.87 × 10^{-3} mm^{3}/N/m across the same speed range. With the addition of 1% ZDDP, the wear rate decreased, recording 5.40 × 10^{-3}, 5.51 × 10^{-3}, and 5.55 × 10^{-3} mm^{3}/N/m at 10 N, followed by 5.61 × 10^{-3}, 5.69 × 10^{-3}, and 5.74 × 10^{-3} mm^{3}/N/m at 20 N, and 5.66 × 10^{-3}, 5.72 × 10^{-3}, and 5.83 × 10^{-3} mm^{3}/N/m at 30 N for increasing sliding speeds. At 3% ZDDP concentration, the wear rate was further reduced, with values of 4.20 × 10^{-3}, 4.33 × 10^{-3}, and 4.51 × 10^{-3} mm^{3}/N/m at 10 N; 4.39 × 10^{-3}, 4.48 × 10^{-3}, and 4.60 × 10^{-3} mm^{3}/N/m at 20 N; and 4.51 × 10^{-3}, 4.63 × 10^{-3}, and 4.68 × 10^{-3} mm^{3}/N/m at 30 N. At the higher additive concentration of 5% ZDDP, the wear rate increased again, recording 6.65 × 10^{-3}, 6.71 × 10^{-3}, and 6.88 × 10^{-3} mm^{3}/N/m at 10 N; 6.69 × 10^{-3}, 6.76 × 10^{-3}, and 6.91 × 10^{-3} mm^{3}/N/m at 20 N; and 6.74 × 10^{-3}, 6.79 × 10^{-3}, and 6.97 × 10^{-3} mm^{3}/N/m at 30 N as the speed increased from 0.1 to 0.3 m/s.

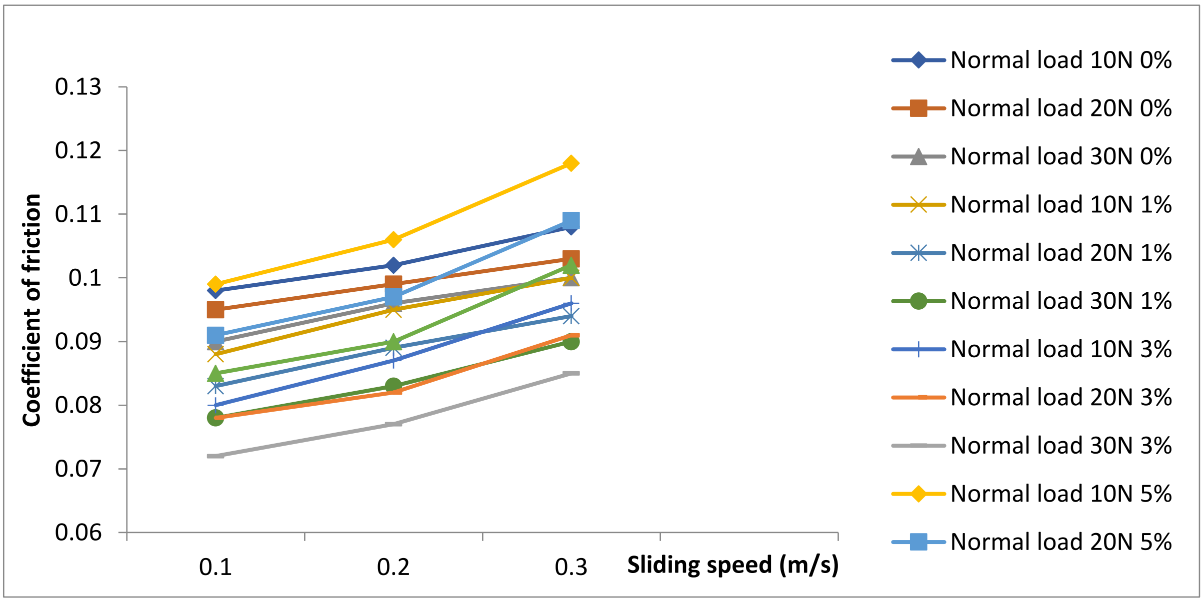

Figure 5: Charts showing the coefficient of friction of mahogany bio-lubricant with ZDDP additives at different percentage concentrations

Corresponding author's email address: davidayubamshelia@yahoo.com

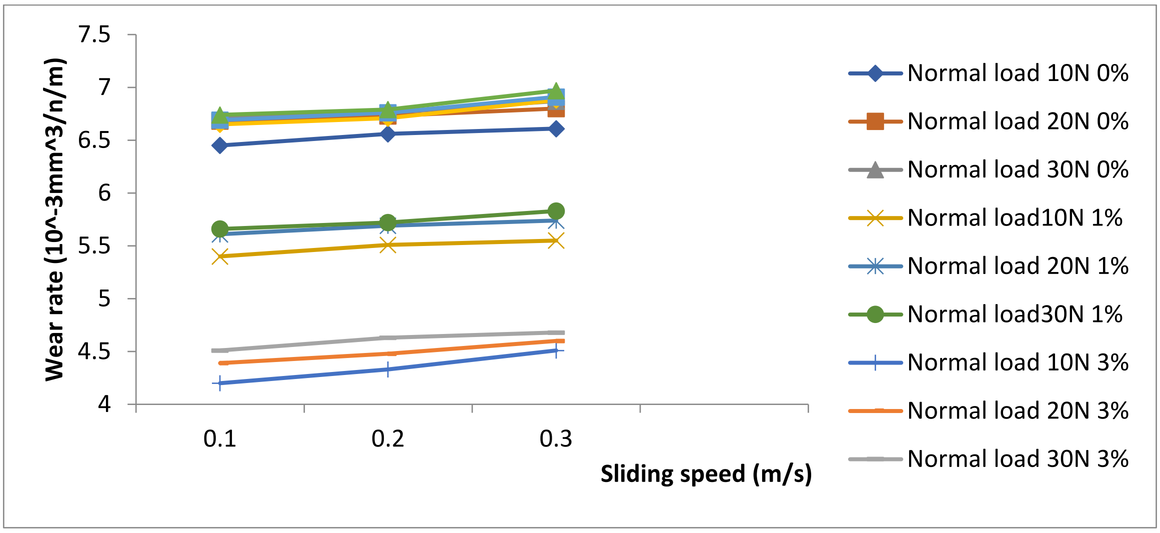

Figure 6: Charts showing wear rate of mahogany bio-lubricant with ZDDP additives at different percentage concentrations

4. Conclusions

The tribological evaluation of a lubricant developed from mahogany seed oil for industrial applications was successfully carried out in this study. The study concluded that the developed mahogany seed oil-based lubricant is a suitable replacement of the synthetic lubricants in medium-load gear systems used in manufacturing machinery, offering comparable performance with reduced ecological impact.

In the tribological evaluation of the mahogany seed oil-based lubricant, it was found that the oil performed better than SAE 20W/50 in reducing friction, while SAE 20W/50 was better in preventing wear. The modification of mahogany seed oil through acid-catalysed esterification reduced its friction performance but improved its wear performance. The developed mahogany seed oil bio-lubricant at 3% of ZDDP was found to have better frictional performance than SAE 20W50 and similar wear performance to SAE 20W/50.

The concentration of the ZDDP (%) additive was found to have a significant effect on the wear property and the coefficient of friction of the developed mahogany seed oil-based bio-lubricant. The sliding speed was found to have a significant effect on the wear rate of the developed mahogany seed oil-based bio-lubricant while on the friction response, there was no significant impact. The normal load has significant effect on the friction response but its effect on the wear property of the mahogany seed oil-based bio-lubricant developed is not significant.

Acknowledgement

The first author wishes to acknowledge the assistance of the Petroleum Technology Development Fund (PTDF) for sponsorship in terms of study scholarship with award number: MISS20210000000041.

References

Ahmad, R. 2021. RSM and Artificial Neural Networking based production optimization of sustainable Cotton bio-lubricant and evaluation of its lubricity and tribological properties. Energy Report, 7: 830–839.

Anand M., Hadfield M., Thomas B. and Cantrill R. 2017. The depletion of ZDDP additives within marine lubricants and associated cylinder liner wear in RNLI lifeboat engines. Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications. 231(1-2):162-170.

Cavalcanti, EDC., Aguieiras, ÉCG., Priscila, R., Duarte, JG., Cipolatti, EP., Fernandez-lafuente, R., André, J., Silva, C. and Freire, D. 2018. Improved production of bio-lubricants from soybean oil and different polyols via esterification reaction catalyzed by immobilized lipase from *Candida rugosa*. Fuel, 215: 705–713.

Cecilia, JA., Plata, DB., Saboya, RMA., de Luna, FMT., Cavalcante, CL. and Rodríguez-Castellón, E. 2020b. An overview of the bio-lubricant production process: Challenges and future perspectives. In Processes, 8(3): 257-272.

Corresponding author's email address: davidayubamshelia@yahoo.com

Johnson DW. and Hills JE. 2013. Phosphate esters, thiophosphate esters and metal thiophosphotes as lubricant additives. ISSN 2075-4442, 4: 132–148.

Epelle, E., Otaru, A., Zubair, Y. and Okolie, J. 2017. Improving the Viscosity Index of Used Lubricating Oil by Solvent Extraction. Journal of Engineering and Technology Management,4(12): 1581-1585

Galvin, GD. and Robert JB. 1976. The application of photoelectron spectroscopy to the study of EP films on lubricated surfaces". Wear, 37: 143–167.

Gosvami, N. N., Bares, J. A., Mangolini, F., Konicek, A. R., Yablon, D. G., & Carpick, R. W. (2017). Mechanisms of antiwear tribofilm growth revealed in situ by single-asperity sliding contacts. Science, *348*(6230), 102–106.

Ioan DM. Brain. R., Boris D. and Hitoshi, O. 2013. Tribology of Abrasive Machining Processes (2nd ed.). Elsevier, Ohio: 204-213

Jeimin R.J., Khodidas K.B. and Jigar V.P. 2023. A review on bio-lubricants from non-edible oils-recent advances, chemical modifications and applications. Journal of the Indian Chemical Society, 100(1): 49-65.

Khan, T., Koide, S., Tamura, Y., Yamamoto, H. and Neville, A. 2018. Effects of Using Alternative Extreme Pressure (EP) and Anti-Wear (AW) Additives with Oxy-Nitrided Samples. Tribology Letters, 66.

Kraipat C. 2013. A study of wear properties of different soyabean oil. Energy Procedia,42: 633–639.

Kumar, A., Tirkey, JV. and Shukla, S. 2021. Comparative energy and economic analysis of different vegetable oil plants for biodiesel production in India. Renewable Energy, 169: 266–282.

Mahipal, D., Krishnanunni, P., Rafeekh, PM. and Jayadas, NH. 2014. Analysis of Lubrication Properties Of Zinc-Dialkyl-Dithio-Phosphate (ZDDP) Additive On Karanja Oil (*Pongamia pinnatta*) As A Green Lubricant. International Journal of Engineering Research, 3: 494–496.

Martin, J. M., Onodera, T., & Minfray, C. 2013. Mechanisms of ZDDP tribofilm formation: A chemical and mechanical perspective. Tribology Letters, 50(1): 95–104.

Muhammad, A.A., Nadia, S. and Nur, RM. 2014. The effect of zinc dialkyldithiophosphate addition to corn oil in suppression of oxidation as enhancement for bio lubricants: a review. ARPN Journal of Engineering and Applied Science, 9(9): 1447–1449.

Nehal, S. and Amal, M. 2013. Lubrication and Lubricants. Tribology - Fundamentals and Advancements.Jürgen Gegner, Intechopen, London, 48-63.

Noreen, S., Khalid, K., Iqbal, M., Baghdadi, HB., Nisar, N., Siddiqua, UH., Nisar, J., Slimani, Y., Khan, MI. and Nazir, A. 2021. Eco-benign approach to produce biodiesel from neem oil using heterogeneous nano-catalysts and process optimization. Environmental Technology and Innovation, 22: Article 101430

Odetoye, T.E., Afolabi, T.J. and Onifade, K. 2016. Effects of Extraction Process Parameters on the Quality Characteristics of *Parinari polyandra B.* Seed Oil. Nigerian Journal of Technological Development,13(2): 40–49.

Puhan, D. 2021. Lubricant and Lubricant Additives. IntechOpen.

Reeves, C., Menezes, P., Jen, TC. and Lovell, MR. 2012. Evaluating the tribological performance of green liquid lubricants and powder additives based green liquid lubricants. Society of Tribologists and Lubrication Engineers Annual Meeting and Exhibition 2012: 62–64.

Salih, N., Salimon, J. and Yousif, E. 2011. The physicochemical and tribological properties of oleic acid-based trimester bio-lubricant. Industrial Crops Production, 34: 1089–1096.

Singh, Y., Garg, R. and Kumar, S. 2015. Aspects of Non-edible Vegetable Oil-Based Bio-lubricants in the Automotive Sector. Green, 5(1-6): 59-72.

Singh, Y., Sharma, A., and Singla, A. 2019. Non-edible vegetable oil–based feedstocks capable of bio-lubricant production for automotive sector applications—a review. Environmental Science and Pollution Research, 26(15): 14867–14882.

Corresponding author's email address: davidayubamshelia@yahoo.com

Spikes, H. and Tysoe, W. T. 2015. On the commonality of mechanochemical and thermochemical reaction mechanisms. Tribology Letters, 59(1): 21.

Woma, YT. 2021. Tribological Evaluation of Lubricants Developed from Selected Vegetable based oils for Industrial Applications. (Doctoral Thesis Federal University of Technology, Minna). http://repository.futminna.edu.ng:8080/jspui/handle/123456789/14530.

Zainal, SH. 2015. Effect of ZDDP Addition in Canola Oil as Antioxiding Agent for Lubrication Application.Univesiti Teknikal Malaysia Melaka FYP, Report: 20-43.

Zhang, J. and Spikes, H. 2016. On the Mechanism of ZDDP Antiwear Film Formation. Tribology Letters, 63(24): 1-15.

Zhang, J., Spikes, H. and Nevshupa, R. 2019. Shear and thermal effects in boundary film breakdown of ZDDP. Tribology International, 134: 1–10.

Zhang, S., Jiang, X. and Zhao, G. 2020. Influence of ZDDP concentration on tribofilm growth and friction behavior under boundary lubrication. Lubricants, *8*(7): 61.

Corresponding author's email address: davidayubamshelia@yahoo.com