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DEVELOPMENT OF BIODEGRADABLE LUBRICATING OIL FOR TURBINE BEARING FROM PALM KERNEL AND CASTOR OILS

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ABSTRACT

The search for sustainable and environmentally friendly alternatives to conventional mineral-based oil lubricants has led to increasing research into bio-based lubricants for industrial applications. This study develops biodegradable lubricating oil for turbine bearing from palm kernel and castor oils through chemical modification and additive blending. Using transesterification method, the oils were converted to their various methyl esters and blended with additives such as ethylene glycol, ascorbic acid, trimethylopropane, and graphene. Physiochemical evaluations of both palm kernel and castor developed lubricating oils showed improved viscosity, pour point, thermal stability, neutralization number, and flash point against their natural oils. While their tribological evaluation revealed that among the developed samples, Palm kernel oil-based turbine lubricant 1 (PKOTL1) exhibited the best tribological properties having the lowest friction coefficient (0.047), with less frictional force (2.617N), as against the mineral oil ISO VG6 conventionally used for lubricating turbine bearings with coefficient of friction (0.051) and frictional force (2.862N), this improved tribological properties were as a result of the additives blend in the development of the bio lubricating oil. Among the developed castor oil turbine lubricant, sample (COTL3) have the lowest coefficient of friction (0.058), less frictional force (3.242N) and low wear scar diameter (0.49mm). The study confirms that the modified vegetable oils are suitable, eco-friendly alternatives to mineral-based turbine lubricants with competitive performance with that of mineral oil ISO VG46.

Keywords: Biodegradable, Chemical modification, Mineral oil, Turbine bearing, Vegetable oil

INTRODUCTION

Over the years, maintenance of Power infrastructures and projects in developing countries particularly Nigeria has been worrisome. Despite huge amounts of capital worth billions of dollars invested in the sector in the last two decades by successive Nigerian Governments, sufficient power generation is still elusive (Claudius, 2014). This is due to some factors which include high cost of maintenance as most of the spare parts for replacement and lubricants used in oiling and servicing of its movable parts is often imported (Emodi and Yusuf, 2015).

Mineral base oils derived from petroleum are mostly used as turbine lubricants due to their tremendous properties such as high oxidation stability, corrosion protection and good extreme temperature quality (Aminu *et al,* 2024). Environmental challenges and disposal have been a major setback in the use of this mineral base oils as huge volume of oil making up about 16,000liters is required for use in a single turbine (Siemens manual, 2011). These therefore, call for researches into alternative oils that are less harmful to the environment when disposes off and also economically friendly.

The performance limitations of vegetable based lubricants stem from low thermal and oxidative stability, poor low-temperature fluidity, and hydrolytic instability (Brajendra *et al,* 2006; Lawal *et al,* 2011; Owuna *et al,* 2019; Bilal *et al,* 2013; Alhassan *et al*, 2024) which hinder their usage for industrial lubrication. Therefore, this study seeks to investigate the development of a lubricating oil for turbine bearing from Palm kernel oil and castor oil, chemically modified and optimized with additives to enhance their physicochemical and tribological properties.

Table 1 shows the physiochemical properties of chemically modified castor oil (CO) and Palm kernel oil (PKO) by various researchers under review alongside with the properties of the turbine bearing mineral oil (MO) ISO VG46 presently in use at Geregu power generation company limited, Ajaokuta. From the table, some physiochemical properties of the mineral oil were not carried out on the modified CO and PKO, therefore their suitability for use as turbine bearing lubricating oil cannot be ascertained. Also, available values of some of the properties of both modified PKO and CO such as viscosity, neutralization number, pour point etc, when compared with that of MO (ISO VG 46) are not within the standard limit recommended for turbine lubricating oil. These has created a research gap, hence there is need to study the chemical modification of CO and PKO and its proper characterization for turbine bearing lubricating purpose alongside with necessary property enhancing additives in order to make them suitable for use as turbine bearing lubricating oil.

Table 1: Physiochemical Properties of Turbine Mineral Oil/Modified CO/PKO

S/N	Properties	Kinematic viscosity at 40^0C ASTM D445 (mm^2/s)	Neutralization number ASTM D974 (mg KOH/g)	Demulsibility ASTM D1401 (min)	Density at 15^0C ASTM D1298 (kg/m^3)	Flash point ASTM D92 (^{0}C)	Pour point ASTM D97 (^{0}C)	Corrosion protection of steel
1	Siemens (2011) Mineral Oil, ISO VG46	41.4-50.6	≤0.20	≤20	≤900	>185	≤-6	≤0 - pass
2	Biniyam *et al*, (2015) Modified CO	30.4	-	-	0.888	-	-5	-
3	Keera *et al*, (2018) Modified CO	2.42	0.12	-	0.838	69	-6	-
4	Woma, (2021) Modified CO	90.2	1.8	-	0.931	222	-27.5	-
5	Ejeromedoghene (2021) Modified PKO	2.30	0.64	-	0.926	136	9	N0. 1A
6	Alamu *et al*, (2016)Modified PKO	8	-	-	0.851	270	17.7	-
7	Egbuna *et al*, (2021)Modified PKO	42.53	-	-	-	235	-11	-

MATERIALS AND METHODS

Materials

The materials used for this research are presented in Table 2 and the equipment presented in Table 3. The equipment listed in Table 3 is all sourced from Agric Engineering Laboratory, FUT, Minna. The various additives used and the functions they perform is shown in Table 4.

Table 2: List of materials used for the research

S/N	Materials	Specifications	Source	Function
1	Palm kernel oil	Cold pressed	Joemad Oil processing factory, Kogi State	Based oil
2	Castor oil	Cold pressed	Hajabd Organic raw materials, Abuja	Based oil
3	Mineral oil	ISO VG46	Geregu generation company, Ajaokuta	Conventional oil used for turbine bearing, serves as control
3	Methyl alcohol	99.5 % purity	JHD Chemical Reagents Co. Ltd, Guangzhou	Reagent for chemical modification
4	Trimethyloloropene (TMP)	98.0 %	Lobachemie Private Limited	Additive
5	Potassium hydroxide	98.0%	Qualikems	Base for chemical modification
6	Distilled water	99.9 %	WAFT Lab, Minna	Used in washing methyl esters after transesterification
7	Sulphuric acid	99.0%	JHD Chemical Reagents Co. Ltd, Guangzhou	Used as catalyst to reduce free fatty acid content in oils before transesterification.
8	Isopropyl alcohol	99.0 %	JHD Chemical Reagents Co. Ltd, Guangzhou	Used for solvent in neutralization and titration tests for free fatty acid (FFA) and acid value determination.
9	Phenolphthalein indicator	Analar	JHD Chemical Reagents Co. Ltd, Guangzhou	Used as pH indicator to determine the neutralization number of oil samples
10	Potassium methoxide (30% in methanol)	99.0 %	WAFT Lab	Catalyst for chemical modification
11	Ethylen glycol	98.0%	Agric. Engineering Laboratory	Additive
12	Ascorbic acid	99.0%	JHD Chemical Reagents Co. Ltd, Guangzhou	Additive
13	Graphene		Agric Engineering Lab	Additive

Table 3: List of laboratory instruments/equipment used for the research

S/N	Instrument/Equipment	Manufacturer	Functions
1	Digital weighing balance	OHAUS Corporation (USA)	Used to accurately measure the mass of oil samples, catalysts, additives etc
2	Stirrer (magnetic)	Thermo Fisher Scientific (USA)	For mixing of the oil, alcohol, and catalyst uniformly during
3	Evaporator (rotary)	Yamato Scientific (Japan)	For solvent recovery and purification of methyl esters
4	Stand (retort)	Thermo Fisher Scientific (USA)	Supports glassware such as flasks, condensers, and funnels during chemical reactions and separations.
5	Conical flask	Corning Inc. (USA)	Holds reaction mixtures during esterification and transesterification
6	Pipette	Thermo Fisher Scientific (USA)	Measures and transfers precise volumes of reactants
7	Oven	Yamato Scientific (Japan)	Used for drying oil samples, catalysts, washed oil and remove residual moisture
8	Separating funnel	Thermo Fisher Scientific (USA)	Used for Separating the glycerol layer from the methyl ester, washing and purification of modified oils
9	Beakers	Corning Inc. (USA)	Used for mixing, heating, and storing liquid samples, preparing reactant solutions
10	Three necked bottom flask	Chemglass Life Sciences (USA)	Used as a reaction vessel for transesterification, provides ports for thermometer insertion, catalyst addition, and reflux setup
11	Leibig condenser	Welch (USA)	For cooling and condensation of vapors
13	Thermometer (500˚C)	Omega Engineering (USA)	Monitors temperature during chemical reactions
14	Water bath And stirrer	Thermo Fisher Scientific (USA)	Used for uniform heating of reactions and temperatures control
19	Digital pH meter	Omega Engineering (USA)	Used to measure the acidity or alkalinity of the oil before and after modification
20	Viscometer	Anton Paar GmbH (Austria)	Determines the kinematic viscosity of oil samples

Table 4: Additives used for the research

S/N	Additive Composition	Function	Sample
1	Ethylen glycol	Anti-freezing, used improves pour point	A
2	Ascorbic Acid	Antioxidant to prevent oxidative degradation of the biolubricant during operation	B
3	Trimethylopropane	To improve viscosity index, enhances lubricity and increase thermal and oxidative stability	C
4	Graphene (GN)	To enhance anti-wear and anti-friction properties (due to its excellent mechanical and tribological properties)	D

Methods

Palm kernel oil (PKO) and castor oil (CO) were firstly characterized and compared with that of mineral oil (MO) ISO VG46. The oils were later modified into palm kernel oil methyl esther (PKOME) and Castor oil methyl esther (COME). The PKOME and COME were developed into turbine bearing lubricating oil by blending with additives. Details of the methods are presented in the following sub sections.

Chemical Modification

The oils were subjected to acid-catalyzed esterification, followed by base-catalyzed transesterification to produce their respective methyl esters (PKOME and COME). The transesterification reaction used a methanol-to-oil molar ratio of 10:1, with 1% w/w KOH as a catalyst, heated at 60°C for 90 minutes as adopted by Woma *et al* (2019). Plate 1 (a) and (b) shows the experimental set up

(a)

(b)

Plate 1: Esterification of Palm kernel oil and castor oil (a) Palm kernel oil (b) Castor oil

Development of Bio Turbine Lubricant Oil

The modified oils were blended with four additives which are ethelyn glycol, Ascorbic acid, Trimetylopropane and graphene using a D-Optimal Design under Response Surface Methodology (RSM) to determine optimal formulation. The factors were constrained with upper and lower limit for each additives based on the specific roles they played. These gave a result of 20 experimental runs. Table 5 shows various factors with their upper and lower limits. The experimental analysis was done using the Design-Expert software version 13 to optimize the developed oils based on key physical property responses, including density viscosity index, pour point, and flash point. The three most desirable blends were picked for further tribological analysis.

Table 5: Factors with upper and lower limits taking into consideration

S/N	Factors	Lower limit	Upper limit
1	Ethylen glycol (A)	8.980	15.000
2	Ascorbic Acid (B)	0.050	1.000
3	Trimethylopropane (C)	3.900	10.000
4	Graphene (D)	0.020	0.100

Tribological Evaluation of the developed PKO and CO Turbine Bearing Lubricant

The tribological evaluation of the developed PKO and CO Turbine lubricant was carried out using a Tribometer. The experiment was conducted at the Defense Industries Cooperation of Nigeria (DICON), Kaduna. The evaluation was done with a computer controlled four ball tribometer, model; MRS-10W, serial number; E21111501. The machine was turned on and the test software on the monitor was launched. The test balls made up of AISI 52100 chrome steel were inserted, and oil sample of 2ml was poured into the machine and the rotating motor was tested. The tribological test parameters as shown in Table 6 were imputed into the system and turned on for data acquisition at each experimental interval and the acquired data was processed and results saved. The experimental set up is shown in Plate 2

Table 6: Tribotester parameter for tribological evaluation

S/N	Parameter	Unit	Value
1	Speed	rpm	1200
2	Temperature	^0C	100
3	Average diameter of ball	mm	0.43
4	Run time	s	3600
5	Force	N	392

Plate 2: Experimental set up for tribological analysis

RESULTS AND DISCUSSION

Characterization of Palm kernel oil (PKO) and Castor oil (CO)

The results of the physical and chemical characteristics of Palm kernel oil, castor oil and mineral oil (ISO VG46) are presented in Table 7 and are been discussed in the following sub sections.

Table 7: Physical and chemical analysis of palm kernel oil, Castor oil and Mineral oil ISO VG46

S/N	Properties	PKO	CO	MO	Units
1	Kinematic viscosity	39.28	227.36	46.93	(mm^2/s) ASTM D445
2	Neutralization no	10.64	46.98	0.17	(mgKOH/g) ASTM D974
3	Demulsibility	14min, 13sec	18min,45sec	9min,52sec	(min) ASTM D1401
4	Density @15^0C	0.988	0.950	0.856	(kg/m^3) ASTM D1298
5	Pour point	24	12	-12	(^{0}C) ASTM D97
6	Flash point	215	246	195	(^{0}C) ASTM D92
7	Corrosion Protection of steel	0	0	0	ASTM D665
8	Thermal stability	5.46	7.89	0.94	(meq/kg) AOCS C8-53

Kinematic viscosity

The kinematic viscosity of the Palm kernel oil and castor oil at 40^0C are 39.28mm^2/s and 227.36mm^2/s respectively while that of the mineral oil that was locally carried out was 46.93mm^2/s. The kinematic viscosity of the palm kernel oil is higher than the value (30.4 mm^2/s) reported by Biniyam *et al*, (2015). Similarly, that of castor oil is higher than the value (90.2 mm^2/s) reported by Woma (2021). The kinematic viscosity of the Castor oil is about 6 times that of Palm kernel oil, this means palm kernel oil has a better flow capability than the castor oil. The recommended range of viscosity of the mineral oil is 41.4-50.6mm^2/s which is of ISOVG46 grade, both vegetable oil falls short of the desired viscosity range. The viscosity of both oils could be improved on by chemical modification or use of viscosity modifier.

Neutralization number

From Table 7, the neutralization number or acid number for Palm kernel oil, castor oil and that of the mineral oil that was locally carried out are 10.64mgKOH/g, 46.98mgKOH/g and 0.17mgKOH/g respectively and their free fatty acid are 5.32mgKOH/g, 27.49mgKOH/g and 0.085mgKOH/g respectively. The values for the neutralization number of the vegetable oils fall short of the allowed range which is ≤0.20mgKOH/g. This indicates that there is high level of acidic content in the vegetable oils. These can be taking care of by chemical modification.

Demulsibility

The demuslsibility of the vegetable oils are 14min, 13sec; 18min, 45sec and 9min 52sec for Palm kernel oil, Castor oil and the mineral lube oil respectively. The allowed range of demulsibility for mineral turbine oil is ≤20mins as shown in Table 7. Therefore, both vegetable oils fall within the accepted range of demulsibility for turbine lubricating oil.

Density

From the result of Table 8, the Palm kernel oil and castor oil has density of 0.988kg/m3 and 0.950kg/m3 respectively. This is above the recommended density of the mineral base oil of ≤0.900 kg/m3.

Pour point

From Table 7, the pour point of the Palm kernel oil is 24^0C while that of the castor oil is 12^0C and that of the mineral oil that was locally carried out is -12^0C. Both vegetable oil have bad flow properties at low temperature and fall far short of the recommended value range of turbine mineral oil which from Table 7 is ≤-6. Chemical modification of both vegetable oil will result in the significant reduction of their pour point.

Flash point

The flash point of the Castor oil is 246^0C, that of the African palm kerenel oil is 215^0C. the mineral oil is 195^0C. Both vegetable oil shows good flash point as the required flash point is ≤185^0C as shown in Table 8.

Corrosion protection of steel

No rust spot was found on all filter papers containing cast iron soaked with castor oil (CO), Palm kernel oil (PKO) and Mineral Oil (MO). Thus CO and PKO exhibit excellent corrosion inhabitation characteristics and are both of corrosion grade 0 as reported by Woma (2021). The corrosion protection of steel for both vegetable oils also fall within the acceptable range when compared with MO ISO VG46

Thermal Stability

The peroxide value of the PKO, CO and MO is 5.46 meq/kg, 7.89 meq/kg and 0.94 meq/kg respectively. The peroxide value of PKO is lower than that of castor oil, thus PKO oil has a better thermal stability compared to CO. Both PKO and MO have poor thermal stability when compared to the MO (0.94 meq/kg). Thermal stability is a major challenge that is often faced by vegetable oil when use as industrial lubricant as they are capable of breaking down at elevated temperature.

Chemical Modification of Palm kernel and Castor Oils

The chemical modification of palm kernel oil (PKO) yielded 94.8% Palm Kernel Oil Methyl Ester (PKOME), while castor oil (CO) yielded 92% Castor Oil Methyl Ester (COME). These values are consistent with the findings of Woma (2021), who reported a yield of around 95% for PKOME. The slightly lower yield of COME compared to PKOME can be attributed to the higher impurity content in castor oil, which affects transesterification efficiency.

Table 8: Physical and chemical analysis of palm kernel oil, Castor oil and Mineral oil ISO VG46

S/N	Properties	PKO	CO	MO	Units
1	Kinematic viscosity	38.94	56.69	46.93	(mm^2/s) ASTM D445
2	Neutralization no	0.14	0.18	0.17	(mgKOH/g) ASTM D974
3	Demulsibility	12min 10sec	15min,27sec	9min,52sec	(min) ASTM D1401
4	Density @15^{0}C	0.854	0.878	0.856	(kg/m^3) ASTM D1298
5	Pour point	-11	-9	-12	(^{0}C) ASTM D97
6	Flash point	230	254	195	(^{0}C) ASTM D92
7	Corrosion Protection of steel	0	0	0	ASTM D665
8	Thermal stability	2.26	4.43	0.94	(meq/kg) AOCS C8-53

Kinematic viscosity at 40^{0}C for PKOME and COME

From Table 8, the kinematic viscosity of PKOME (38.94 mm²/s) and COME (56.69 mm²/s) decreased after modification compared to unmodified oils due to de-acidification and removal of impurities. However, the PKOME viscosity fell below the recommended range of turbine bearing oil (ISO VG46), while COME exceeded it. Jain and Sharma (2010) indicated that methyl esters derived from palm oil typically have viscosities ranging from 35 to 40 mm²/s at 40°C, while castor oil methyl esters range from 50 to 60 mm²/s. This supports the observation that the high viscosity of COME is characteristic of castor oil derivatives, primarily due to the presence of ricinoleic acid, which has a hydroxyl group that increases viscosity.

Neutralization number for PKOME and COME

The high neutralization number of vegetable oils is one of the major challenges that hinder their use as industrial lubricant. This is because the higher the neutralization number of oil, the higher the tendency of the oil to corrode the machine parts under lubrication. The chemical modification of both PKO and CO saw to the drastic reduction of their neutralization number. The neutralization number of the PKOME of 0.14mgKOH/g is lower than that of COME of 0.18mgKOH/g this is because the CO contains more acidic content than the PKO. Generally, the neutralization number of both PKOME and COME falls within the recommended range of turbine bearing MO ISO VG46 ($\leq$ 0.20). Similar results were obtained by Bamgboye and Hansen (2008), who reported that palm kernel-based esters generally have lower acid numbers compared to castor oil-based esters. This is attributed to the lower free fatty acid content of PKO.

Demulsibility for PKOME and COME

According to Pathmasiri and Perera. (2019), demulsibility is crucial for lubricating oils, as poor water separation can lead to emulsification and corrosion. The demulsibility of PKOME (12 min 10 sec) and COME (15 min 27 sec) falls within the acceptable range ($\leq$20 mins) for turbine lubricating oils (ISO VG46). PKOME showed better water separation compared to COME, likely due to its lower polar functional groups.

Density for PKOME and COME at 15^{0}C

The densities of PKOME (0.854 kg/m³) and COME (0.878 kg/m³) fall below the densities of PKO (0.988 kg/m³) and CO (0.950 kg/m³), apparently due to the reduction in their acidic content and impurities. However, both densities of PKOME and COME fall within the recommended value of turbine lubricating oil, ISO VG46 of $\leq$900 kg/m^3. Similar findings by Kamhoua *et al*. (2023) reported densities of palm kernel and castor methyl esters as 0.85 kg/m³ and 0.88 kg/m³, respectively, attributing the density reduction to the removal of heavier compounds during transesterification.

Pour point for PKOME and COME

The pour point of the PKOME is -11^{0}C while that of the COME is -9^{0}C. The chemical modification of both oil resulted to a significant reduction of their pour point, this signifies an improvement in their flow properties at low temperature after modification. Both PKOME and COME pour points fall within the recommended range of turbine lubricating oil ISO VG46 which is $\leq$-6. Demirbas (2017), reported improved pour points after esterification and transesterification processes which indicate that reducing pour points improves the usability of biolubricants in cold climates.

Flash point for PKOME and COME

The flash point of the PKOME and COME is 230^{0}C and 254^{0}C respectively. Both vegetable oil have their flash point increased after modification as compared to that of PKO and CO. this is as a result of the various chemical reaction processes they went through during transesterification. The flash points reported here are consistent with those of Woma *et al*. (2019), who documented flash points above 200°C for both PKOME and COME, highlighting enhanced safety profiles for lubricant applications. Both PKOME and COME flash points falls within the required range for turbine lubricating oil of ISO VG46 which is >185^{0}C.

Corrosion protection of steel for PKOME and COME

No rust spot was also found on all filter papers containing cast iron soaked with PKOME and COME. They both exhibited excellent corrosion inhabitation characteristics and are both of corrosion grade 0 which is within the acceptable range of corrosion protection of steel for Turbine lubricating oil of ISO VG46 which is $\leq$ 0=pass. Woma *et al*. (2019) also demonstrated that biolubricants from vegetable oils offer superior corrosion protection when modified to reduce acidic content.

Thermal Stability for PKOME and COME

According to Woma, *et al* (2019), the lower the peroxide value, the higher or better the thermal stability of oil. The peroxide value of the PKOME, COME and MO was 2.26meq/kg, 4.43 meq/kg and 0.94meq/kg respectively. From the results, the peroxide value of PKO and CO was found to be improved upon after modification. Therefore, the PKOME with lower peroxide value tends to be more thermal stable than the COME. Both oil when compared to that of MO still shows lower thermal stability after modification.

Development of Bio Turbine Lubricant Oil

The results from the statistical design of experiment gave the mixture blend of the modified oils and additives. The best three blends is show in Table 9 and Table 10 for Palm kernel oil turbine lubricant and castor oil turbine lubricant respectively.

Table 9: Developed Palm kernel oil turbine lubricant (PKOTL)

Samples	A	B	C	D
PKOTL1	9.989	0.743	9.168	0.100
PKOTL2	10.132	0.758	9.009	0.100
PKOTL3	10.446	0.794	8.660	0.100

Table 10: Developed Castor oil turbine lubricant

Samples	A	B	C	D
COTL1	15	1.0	3.98	0.02
COTL2	15	0.062	4.918	0.02
COTL3	10.190	0.721	8.989	0.100

The developed PKOTL and COTL exhibit improved physical and chemical properties compared to their respective modified oils, Palm kernel methyl esters (PKOME) and Castor oil methyl esters (COME), primarily due to the incorporation of additive blends. Their physical and chemical characteristics are presented in Table 11 and are discussed in the following subsections.

Table 11: Physical and Chemical Characteristization of PKOTL1, PKOTL2, PKOTL3 and COTL1, COTL2, COTL3

S/N	Properties	PKOTL1	PKOTL2	PKOTL3	COTL1	COTL2	COTL3
1	Kinematic viscosity	39.28	227.36	46.93	66.47	68.32	69.20
2	Neutralization no	10.64	46.98	0.17	0.18	0.19	0.18
3	Demulsibility	14min, 13sec	18min,45sec	9min,52sec	16min,32sec	18min,56sec	17min,44sec
4	Density @15^{0}C	0.988	0.950	0.856	0.885	0.889	0.882
5	Pour point	24	12	-12	-10.2	-10.5	-11.8
6	Flash point	215	246	195	249.641	250.652	271.321
7	Corrosion Protection of steel	0	0	0	0	0	0
8	Thermal stability	5.46	7.89	0.94	1.94	1.60	1.51

Kinematic Viscosity at 40^{0}C

From Table 11, the kinematic viscosities for PKOTL1, PKOTL2, and PKOTL3 are 45.89 mm²/s, 45.20 mm²/s, and 44.62 mm²/s, respectively. There is a significant improvement in the kinematic viscosity of the developed PKOTL1–PKOTL3 compared to Palm kernel Methyl Ester (PKOME), which has a kinematic viscosity of 38.94 mm²/s. This improvement is attributed to the additive blends incorporated into the developed Palm kernel Oil. Similarly, the kinematic viscosities of COTL1, COTL2, and COTL3 are 66.47 mm²/s, 68.32 mm²/s, and 69.20 mm²/s, respectively, which are higher than that of the modified Castor Oil Methyl Ester (COME) at 56.69 mm²/s. The kinematic viscosities of PKOTL1–PKOTL3 fall within the recommended range for MO ISO VG46 (41.4–50.6 mm²/s). However, the kinematic viscosities of COTL1–COTL3 exceed this range.

Neutralization number

The neutralization numbers for PKOTL1, PKOTL2, and PKOTL3 are 0.15mgKOH/g, 0.17 mgKOH/g, and 0.16 mgKOH/g, respectively, while those for COTL1, COTL2, and COTL3 are 0.18 mgKOH/g, 0.19 mgKOH/g, and 0.18 mgKOH/g, respectively. These values show a slight increase compared to their respective modified oils, likely due to the presence of ascorbic acid (B) in the additive blends. Nevertheless, all values fall within the acceptable range for MO ISO VG46 (≤ 0.20 mgKOH/g), indicating that the developed lubricants are suitable for use without the risk of bearing corrosion during application.

Demulsibility

From Table 11, the demulsibility values for PKOTL1, PKOTL2, and PKOTL3 are 14 minutes 2 seconds, 16 minutes 5 seconds, and 16 minutes 40 seconds, respectively. For COTL1, COTL2, and COTL3, the values are 16 minutes 32 seconds, 18 minutes 56 seconds, and 17 minutes 44 seconds, respectively. There is a slight increase in demulsibility compared to their respective modified PKOME and COME. However, all values fall within the recommended range for MO ISO VG46 (≤ 20 minutes)

Density at 15^{0}C

The densities of PKOTL1, PKOTL2, and PKOTL3 are 0.873 kg/m³, 0.879 kg/m³, and 0.881 kg/m³, respectively, while those of COTL1, COTL2, and COTL3 are 0.885 kg/m³, 0.889 kg/m³, and 0.882 kg/m³, respectively. These values show a slight increase compared to their respective PKOME and COME, likely due to the effect of the additive blends. However, all PKOTL and COTL samples exhibit desirable densities within the recommended range for MO ISO VG46 (≤ 0.900 kg/m³).

Pour point

The pour points of PKOTL1, PKOTL2, and PKOTL3 are -16.6°C, -15.7°C, and -11.8°C, respectively, while those of COTL1, COTL2, and COTL3 are -10.2°C, -10.8°C, and -11.6°C, respectively. There is a significant improvement in the pour points of both PKOTL and COTL compared to their respective modified oils. These is attributed to the presence of ethylen glycol as pour point improver in the additive blends. All developed lubricants fall within the recommended pour point range for MO ISO VG46 (≤ -6°C)

Flash point for PKOME and COME

The flash points of PKOTL1, PKOTL2, and PKOTL3 are 248°C, 244°C, and 239°C, respectively, while those of

COTL1, COTL2, and COTL3 are 259°C, 264°C, and 271°C, respectively. Both PKOTL and COTL show an increase in flash points compared to their respective PKOME (230°C) and COME (254°C), likely due to the effect of additive C (TMP) in the additive blends. All developed lubricants fall within the acceptable range for MO ISO VG46 (> 185°C).

Corrosion protection of steel

No rust spots were observed on the filter papers containing cast iron soaked with the developed PKOTL and COTL. All samples exhibited excellent corrosion inhibition characteristics, with a corrosion grade of 0, which is within the acceptable range for MO ISO VG46 (≤ 0 = pass)

Thermal Stability for PKOME and COME

The peroxide values of PKOTL1, PKOTL2, and PKOTL3 are 1.16 meq/kg, 1.28 meq/kg, and 1.32 meq/kg, respectively, while those of COTL1, COTL2, and COTL3 are 1.94 meq/kg, 1.60 meq/kg, and 1.51 meq/kg, respectively. There is a significant improvement in the thermal stability of both PKOTL and COTL compared to their respective PKOME (2.26 meq/kg) and COME (4.43 meq/kg), indicating the positive effect of the additive blends. However, the thermal stability of the developed lubricants is still poor to that of MO ISO VG46 (0.94 meq/kg).

Tribological Evaluation

The tribological evaluation was carried out on the three developed Palm kernel Oil Turbine Lubricants (PKOTL1, PKOTL2, and PKOTL3) and Castor Oil Turbine Lubricants (COTL1, COTL2, and COTL3), along with Mineral Oil (MO). The details of their results are discussed in the following subsections.

Frictional Force

Frictional force is a measure of the resistance between surfaces in relative motion. A lower friction force indicates better lubrication and reduced energy loss. The results of the frictional forces are presented in Figure 1. PKOTL1 had the lowest friction force (2.617 N), outperforming all COTL and MO (2.862 N). This suggests superior lubrication and reduced metal-to-metal contact. COTL samples exhibited higher friction forces (3.926 – 3.242 N), suggesting they have lower lubricity compared to PKOTL and MO. Among COTL samples, COTL3 (3.242 N) performed best, while COTL1 (3.926 N) had the highest friction force, indicating poorer lubrication. The low friction force can be attributed to the high presence of additive C (TMP) in the additive mixture blend of PKOTL1 as shown in Table 9.

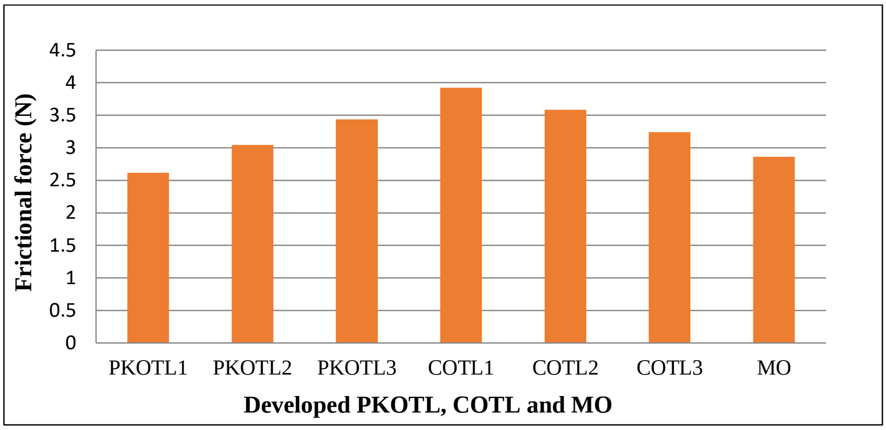

Figure 1: Frictional forces for PKOTL, COTL and MO

Friction Coefficient

The coefficient of friction (COF) is a dimensionless value indicating how easily two surfaces slide over each other. Lower values indicate better lubrication and reduced wear. The friction coefficient for PKOTL, COTL and MO is presented in Figure 2. From Figure 2, PKOTL1 (0.047) had the lowest friction coefficient, meaning it provides the best lubrication with higher potential to reduce energy loss, even better than MO (0.051) and all the samples of COTL. COTL1 had the highest friction coefficient (0.070), indicating higher resistance and poorer lubrication. Among the COTL samples, COTL3 performed best (0.058), while COTL1 performed worst (0.070). All PKOTL samples had better lubrication than COTL samples. The low friction coefficient can be attributed to the high presence of additive C (TMP) in the additive mixture blend of PKOTL1 as shown in Table 9.

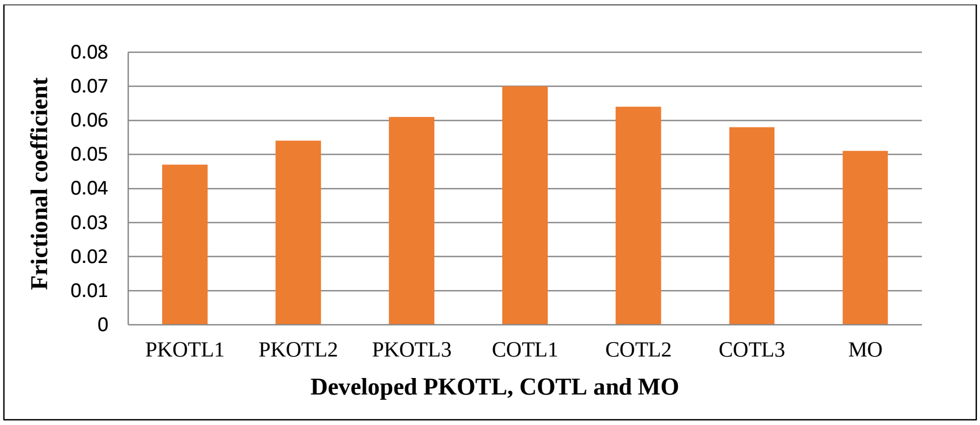

Figure 2: Friction coefficient for PKOTL, COTL and MO

Wear Scar Diameter

The wear scar diameter measures how much material wears away during lubrication tests. A smaller wear scar means better anti-wear performance and longer turbine bearing life. The wear scar diameter for PKOTL, COTL and MO is presented in Figure 3. MO had the smallest wear scar diameter (0.38 mm), showing superior wear resistance. PKOTL1 (0.40 mm) was the best among bio-based lubricants, indicating strong anti-wear performance. COTL1 had the largest wear scar diameter (0.51 mm), meaning it performed the worst in wear resistance. Among COTL samples, COTL2 (0.44 mm) performed best, but still worse than PKOTL samples. The lowest wear scar diameter observed in MO could be as a result of presence anti-wear additive in the formation of MO

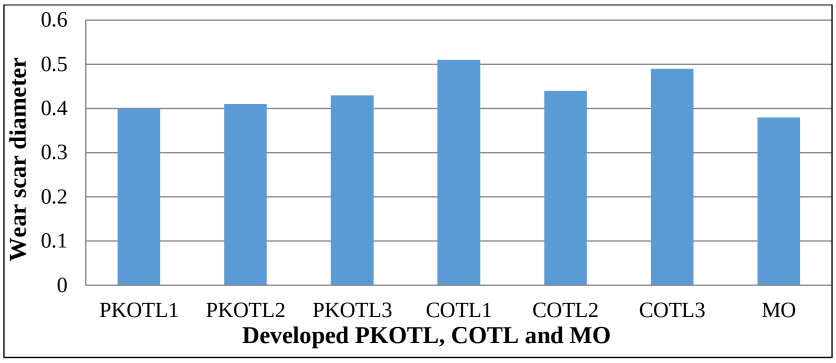

Figure 3: Wear Scar Diameter

CONCLUSION

The development of bio degradable lubricating oil for turbine bearing from Palm kernel oil and castor oil has successfully been carried out. The study revealed that chemical modification by transesterification method significantly improve their physiochemical properties. Both modified oils had better cold flow properties, reduced neutralization number and improved thermal stability. The modified oils were also of corrosion grade 0. However, the modified PKO is of less kinematic viscosity when compared to that of mineral base oil, while the kinematic viscosity for the modified Castor oil exceeded the required range for MO ISO VG46. The physical and chemical characterization of the developed Palm kernel Oil Turbine Lubricants (PKOTL1, PKOTL2, and PKOTL3) and Castor Oil Turbine Lubricants (COTL1, COTL2, and COTL3) demonstrates significant improvements over their respective modified oils, Palm kernel Methyl Ester (PKOME) and Castor Oil Methyl Ester (COME). These enhancements are primarily attributed to the incorporation of additive blends, which positively influenced key physiochemical and tribological properties such as kinematic viscosity, neutralization number, demulsibility, density, pour point, flash point, thermal stability, frictional force and friction coefficient. The trbological evaluation of the developed vegetable oils revealed that the Palm kernel oil turbine lubricants (PKOTL) performed better than Castor Oil-based lubricants (COTL). PKOTL1 showed the best tribological performance, with the lowest friction force, lowest friction coefficient, and strong wear protection when compared with all the developed vegetable oil samples. COTL1 had the worst performance in all aspects of the tribological test. The use of additives (Ethylene glycol (A), Ascorbic acid (B), TMP (C) and grapheme (D)) significantly improved lubrication properties, which is responsible for the low friction force and friction coefficient as observed in the PKOTL1 with the highest composition of additive (C) which function as viscosity index improver, enhances lubricity, and increases thermal stability. While PKOTL1 had a better friction force and friction coefficient as compared with MO, MO exhibited the best wear resistance having the lowest wear scar diameter. For practical applications, PKOTL1 is the best candidate for turbine bearings lubrication. It meets ISO VG46 viscosity requirements, has excellent oxidation stability, and provides the lowest friction force and coefficient. While the results of their physiochemical properties of the developed biodegradable oils are promising and their tribological evaluations validates its uses as turbine lubricating oil, further study is recommended to be carried out on thermal stability, anti-wear additive combinations and optimization in other to improve on the thermal stability and anti-wear resistance of the developed Palm kernel oil and Castor oil. Also, the study was carried out using laboratory equipment that are of small sizes and the developed oils were produced in small scale for analysis. Future research should focus on scaling up production of the developed bio lubricants in other to assess their performance in real-world turbine applications. This will help to further validate the performance of the developed bio lubricants under real operating conditions, providing valuable data on their long-term durability and effectiveness, and also help identify any practical challenges.

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