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Tribological Response of Watermelon Seed Oil on AISI52100 and AISI 1045 Friction Pair

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ABSTRACT

This study investigated the tribological responses of watermelon seed oil on steel contacting surfaces. Mineral oil as a major source of lubrication has, three major drawbacks: poor lubricity, non-biodegradability, and a high coefficient of friction. Hence, there is an urgent need for an environmentally friendly lubricant of which oils from plant sources such as vegetable seed oil can serve as an alternative source of lubrication. The choice of the watermelon seed oil is intended to address these drawbacks. Hence, this study presents a comprehensive way of not only determining the physicochemical characteristics of the vegetable oil but its tribological responses on steel contacting surfaces. Watermelon seed (Citrullus lanatus) oil was the vegetable oil investigated in this study. The friction and wear characteristics on both dry and lubricated conditions were examined using a tribometer (version 6.1.17). The coefficient of friction for the dry condition was observed to be in the range of 0.147 to 0.264, while for moderate (2 to 20) N lubricated condition was within 0.102 to 0.125, showing a drastic reduction in both friction and wear in the order: watermelon seed oil is greater than the mineral oil. Series of tests were performed to examine the physicochemical properties of the oils. The tests included viscosity test, density, pour point, etc. The reduction in friction and wear when lubricated with watermelon seed oil and its superior physicochemical properties suggests its potentials as a lubricant.

KEYWORDS: Friction, Lubrication, Surfaces, Tribometer, Wear, Watermelon seed oil.

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1. INTRODUCTION

Lubrication is a technique of using lubricants to mitigate friction and wear which are serious industrial challenges has application in the field of tribology. Lubricants in the field of tribology could be solid such as molybdenum disulfides (MoS_2), solid/liquid dispersions such as grease, liquids such as mineral and vegetable oils. Vegetable and mineral oils both have the potentials of a lubricant with mineral oil being widely used because of some of its established properties, but the risk it poses on the eco-system makes it very important to discontinue it, and possibly replace it with an environmental base-stock (Syahrullail *et al.*, 2013).

Statistics have it that about 5 to 10 million tons of petroleum products enter the environment every year, with 40% of that representing spills, industrial and municipal waste, urban runoff, refinery processes, and condensation from marine engine exhaust. Thus, strict specifications on biodegradability, toxicity, occupational health and safety, and emissions have become mandatory in certain applications. The enactment of these specifications, along with uncertainty in the petroleum supply for political and economic reasons, has stimulated the search for alternative energy sources (Anjana & Preeti, 2013).

Vegetable oil as a lubricant has remained an active area of research. An increase in environmental concerns has made it pertinent for researchers to develop eco-friendly lubricants, among which vegetable oils are of real interest because of their biodegradability, superior lubricity, low coefficient of friction (COF), and high viscosity index (Odi-Owei, 1989). Studies on the lubricant properties of some vegetable oils in comparison with the conventional mineral

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oil using some physicochemical apparatus such as viscometer, hydrometer, proved that vegetable oils have some properties that are comparable with those of the mineral oils with some exceptions. It was concluded that the bio-lube is more environmentally friendly (Sevim & Svajus, 2015).

The comparative analysis of tribological properties of commercial mineral oil and pure castor oil in boundary lubrication regime proved that castor oil has high biodegradability, superior lubricity and low coefficient of friction (COF) because of their high viscosity index (VI) (Bhaumik & Pathak, 2016). Also, the enhancement of the tribological properties of biodegradable oils by organic additives carried out by Chikezie and Ossia (2018) with the aid of a four-ball tribometer proved that vegetable oils performed better than mineral oil under extreme conditions. Hence, vegetable oils can serve as extreme pressure lubricants.

Studies carried out by Adedeji (2018) on the extraction and evaluation of oil from watermelon (citrullus lanatus) seed with the aid of a 5litres capacity soxhlet extractor and petroleum ether as solvent proved refractive index (1.50 at 27^{0}C), high level of acid value 85% (0.85), with the presence of oleic acid, stearic and palmitic acid and traces of linoleic acid and absence of arachidic, myristic and linolenic acids. The results indicated very low level of unsaturation, marked level of oiliness, and presence of high level of reasonable amount of free fatty acids. It was concluded that the watermelon seed oil can be used as a lubricant. Studies on the extraction and determination of physicochemical properties of watermelon seed oil with solvent extraction method using hexane solvent at 60^{0}C to 70 ^{0}C gave acid value to be 2.37, iodine value to be 121.51, density to be 0.85, and viscosity to be 2.48 cSt. It was concluded that watermelon seed oil could be used as a lubricant (Duduyemi *et.* al., 2018).

Lubrication as an engineering process is a necessary measure in the modification of friction and wear, liquid lubricants that may be applied are; mineral oil such as SAE 10W30 and vegetable oils such as watermelon seed oil. The watermelon seed regarded as waste in Nigeria is biodegradable; as such oil derived from it will be environmentally friendly. Hence, its oil can be used as a substitute for mineral oil. Watermelon seed oil was used in this study instead of edible vegetable oils to avoid unnecessary competition with food security.

In a way to achieve the aim of this study, some objectives were set: covered the physicochemical properties of watermelon oil (*Citrullus lanatus*) such as viscosity, pour point, flash point, iodine number, etc. The tribological properties of the watermelon seed oil on steel contacting surface in comparison with mineral oil (SAE10W30) was carried out with the aid of a tribometer with a ball-on-disc configuration (6.1.17 version, Austria). The steels used for this study were stainless steel grade AISI 52100 the ball and a mild steel grade AISI 1045 as the disc.

2. MATERIALS AND METHODS

2.1 Preparation of Disc Material

The disc used for the study was of grade AISI 1045 with tensile strength 565 MPa, Rockwell B hardness 84, poisons ratio 0.27, shear modulus 80 GPa was fabricated with the aid of a lathe machine, by applying cylindrical grinding mechanical operation. The disc specimens were machined to a desirable size of 12mm in diameter, and 10mm in thickness. The cylindrical grinder has a grinding (abrasive) wheel, two centers that hold the workpiece, and a chuck, grinding dog, or other mechanisms to drive the work. The cylindrical grinding machines have a swivel to allow the forming of tapered pieces. The wheel and workpiece move parallel to one another in both the radial and longitudinal directions. Tolerances for the fabrication of the discs were held within ±0.0005

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inches (13 µm) for diameter and ±0.0001 inches (2.5 µm) for roundness.

2.2 Physicochemical Property Test

Some physicochemical properties tested included viscosity, VI, flash point, pour point, relative atomic number, acid number, FFA, and density. Test materials such as glass capillary viscometer, flash point apparatus, pour point apparatus, and hydrometer were used for the measurement of the properties that are measurable (American Society for Testing and Materials [ASTM], 2017). While properties such as the VI, iodine number, FFA, and acid number were calculated and the molecular weight of the vegetable oils were obtained from literature.

$$VI = \frac{L-U}{L-H}100 \quad (1)$$

U is the oil viscosity @ 40^{0}C, L and H are the corresponding values at 100^{0}C.

$$\text{Acid Value (mgKOH/g)} = \frac{\text{Titre value x 5.61}}{\text{Weight of Sample used}} \quad (2)$$

where titre value is 0.1M of KOH

$$\text{Free Fatty Acid (mgKOH/g)} = \frac{\text{Acid Value}}{2} \quad (3)$$

$$\text{Iodine Number} = \frac{(b-a)\ X1.269}{Weight\ of\ Sample} \quad (4)$$

where b is titre value of blank and a titre value of the sample

2.3 Determination of Nature and Fatty Acid Composition of Watermelon Seed Oil

The Gas Chromatography-Mass Spectrometry (GC-MS) technique (Mass Hunter GC–MS 15977) was used to determine the free fatty acid in the watermelon seed oil. The sample solution was injected into the Gas Chromatography (GC) inlet where it was vaporized and swept onto a chromatographic column by the carrier gas (helium). The sample flows through the column and the compounds comprising the mixture were separated by their relative interaction with the coating of the column (stationary phase) and the carrier gas (mobile phase). The latter part of the column passes through a heated transfer line and ends at the entrance to the ion source where compounds eluting from the column are converted to ions.

2.4 Friction and Wear test

The tribometer with a ball-on-disc configuration (6.1.17 version), Anton Paar Strasse 208054 Graz-Austria was applied to investigate the friction and wear responses of the friction pair, both on dry and lubricated conditions. A hard steel ball of 6.0mm diameter reciprocates the normal load and a 1 mm stroke length at a frequency of 10 Hz for 506s. The lubricant temperature was kept at 29^0 C; the friction coefficient was measured by a piezoelectric force transducer.

$$U \frac{u\eta}{E'R'^2} \quad (5)$$

where U is the linear velocity (m/s), η is dynamic viscosity (Pas), E' is the reduced Young's modulus (Pa), R' is the reduced radius of curvature (m)

$$U = \alpha E' \quad (6)$$

where α is the pressure-viscosity coefficient (Pa-1) $\alpha = (0.6 + 0.965 log_{10}\eta)x10^{-8}$ (7)

$$W = \frac{w}{E'R'^2} \quad (8)$$

$$E' = \frac{E}{1-v^2} \quad (9)$$

(For same material).

3. RESULTS AND DISCUSSION

3.1 Physicochemical Properties of the Oils

Table 1 presents the physicochemical properties of the oils examined in this study which included: viscosity (ν), viscosity index (VI), density (ρ), pour point (PP), flash point (FP), molecular weight (MW), acid number (AN), free fatty acid (FFA) and Iodine number (IN). Table

1 shows watermelon seed oil as having the highest viscosity of 7.90 cSt at 100°C as compared to that 7.20 cSt of the mineral oil (SAE10W30). The watermelon seed oil also has the highest VI of 146 with the mineral oil having the least VI of 129.

Table 1: Physicochemical Properties of the Oils

Properties	Watermelon Seed Oil	SAE10W30
ν at 40^{0}C	38.60±0.1	67.50±0.1
ν at 100^{0}C	7.90±0.1	7.20±0.1
VI	146	129
PP(^{0}C)	12±0.1	205±0.1
FP(^{0}C)	162±0.1	205±0.1
MW (g/mol)	282	-
AN	3.10±0.1	-
IN	115±0.1	-
FFA	1.55	0.88±0.1
ρ (g/cm^3)	0.89±0.1	

The superiority of the watermelon seed oil in terms of viscosity index (VI) over the mineral oil SAE10W30 is an indication that the vegetable oil shows serious resistance to decline in viscosity with temperature than the mineral oil (Bhaumik & Pathak, 2016). The viscosity index (VI) 129 obtained for the mineral is the same as the one reported in an earlier study by Syahir *et al*. (2017). The flash point, pour point, viscosity and viscosity index (VI) of 205^{0}C, -34.6^{0}C, 7.20cS and 129 respectively obtained in the study for SAE10W30 mineral oil are slightly different from the 214^{0}C, -12^{0}C, 5.07cS and 101 respectively obtained in another study carried out by Odi-Owei and Roylance (1976). Environmental factors could be responsible for the slight difference in the physicochemical properties of the mineral oil.

The low-temperature performance (high pour point) of the watermelon seed oil as compared to that of the mineral oil as can be observed in Table 1 shows the oxidative instability nature of the watermelon seed oil which is a result of the triacylglycerol molecules in the oil (Constantin *et al*., 2016). However, this drawback can be corrected by the addition of pour depressants (Emmanuel & Mudiakeoghene, 2015; Garcés *et al*., 2019).

3.2 Nature and Fatty Acid Composition of Watermelon Seed Oil

Table 2 presents the fatty acid composition of watermelon seed oil. The fatty acids identified in watermelon seed oil using a gas chromatograph-mass spectrometry (GC-MS) technique included lauric (saturated), myristic (saturated), palmitic (saturated), stearic (saturated), oleic (unsaturated), and linoleic (unsaturated). It was observed that linoleic (unsaturated) has the largest percentage composition of more than half the fatty acid compositions followed by oleic (unsaturated). It can be summarized that 81 percent of the fatty acid composition of watermelon seed oil was unsaturated while the remaining 19 percent was saturated.

Table 2: Nature and Fatty Acid Composition of Watermelon Seed oil

Fatty Acid	% Composition	Nature
Lauric	1	Saturated
Myristic	3	Saturated
Palmitic	5	Saturated
Stearic	10	Saturated
Oleic	17	Unsaturated
Linoleic	64	Unsaturated
Summary		
Total	19	Saturated
Total	81	Unsaturated

These values as obtained with the gas chromatograph-mass spectrometry (GC-MS) technique are slightly in agreement with the results of an earlier study by Zahra and Ali (2015) where it was reported that the total unsaturated content of watermelon oil is 81.6%, with linoleic acid 68.3% percentage composition being the dominant fatty acid. The high unsaturated nature of watermelon oil could be

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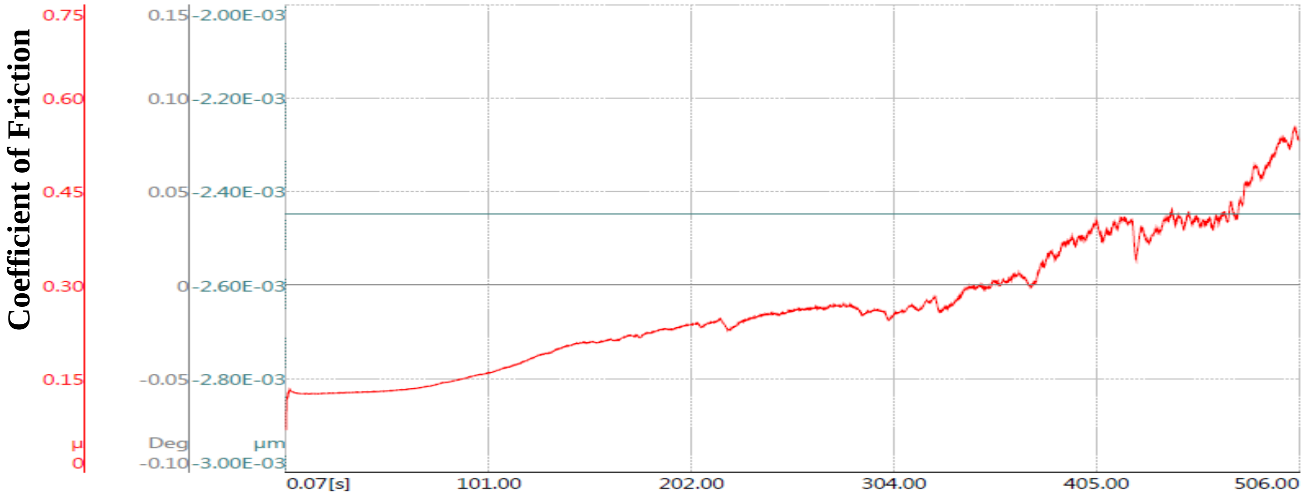
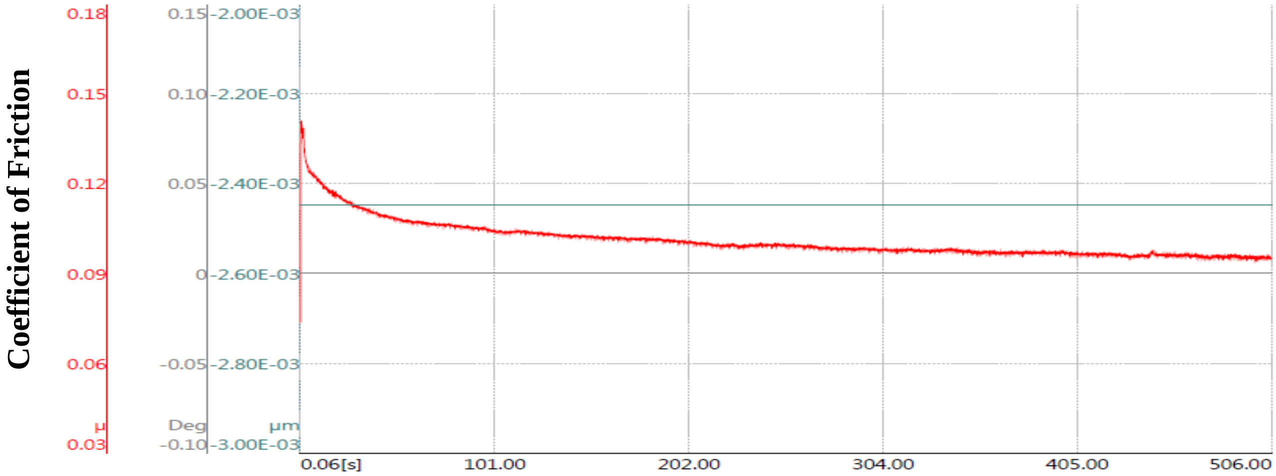
responsible for its physical characteristics (superior viscosity, viscosity index, molecular weight and very poor pour point) and chemical behaviour; high acid and iodine values (Chia *et al.*, 2018).

3.3 Tribological Response of Dry and Lubricated Disc Sample

Figure 1(a) presents the tribological response of the dry steel sample AISI 1045 under 8N load as acquired from a ball on disc tribometer using a sliding speed of 10cm/s, contact frequency of 10 Hz for 506 seconds duration. It can be observed that in the first stage of running-in, the sliding surfaces become adjusted to each other; this resulted in a lower coefficient of friction yet in greater wear.



(a) Duration of rubbing (s)



(b) Duration of rubbing (s)

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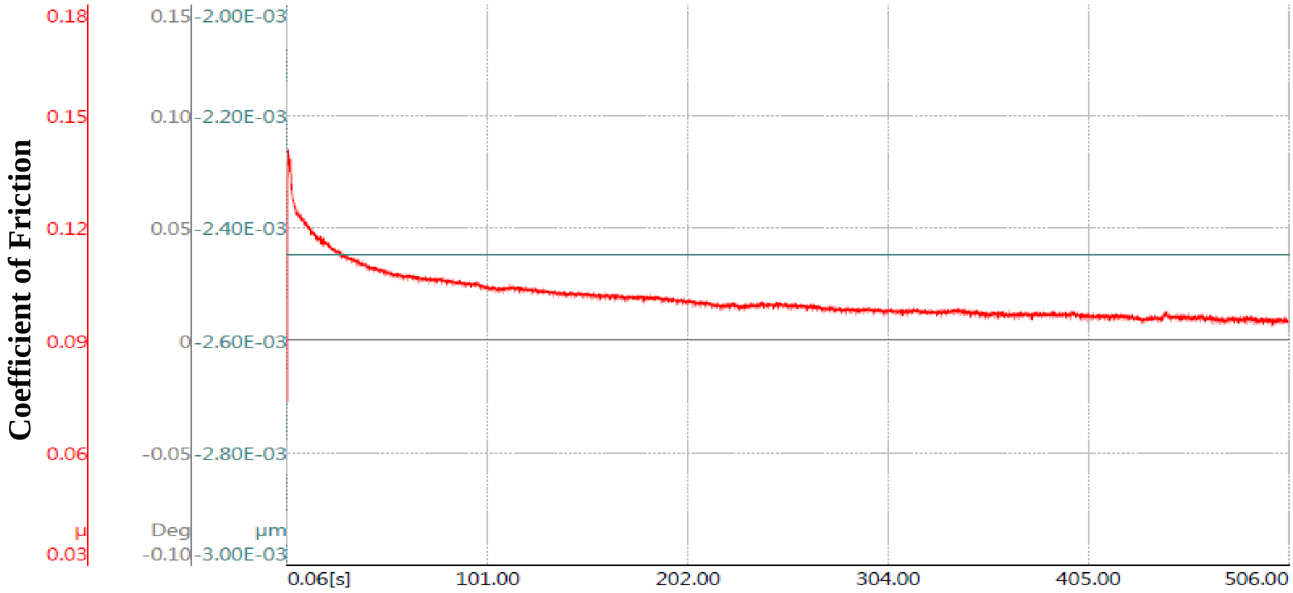

(c) **Duration of rubbing (s)**

Figure 1: Friction coefficients of dry and lubricated conditions of the steel at 8N load as a function of time: (a) Dry Steel Sample with 8N (b) Steel Sample with Mineral Oil (c) Steel Sample with Mineral Oil.

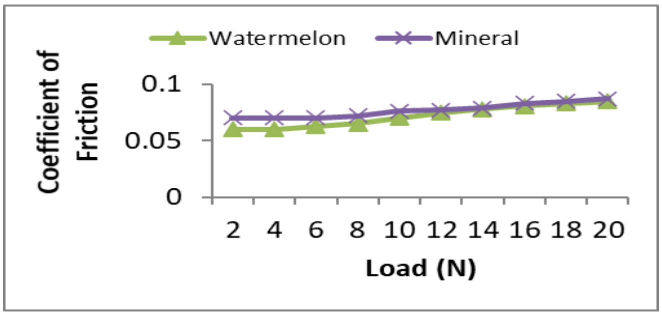

Figure 2: Mean Coefficient of Friction of the oils under moderate Loading Conditions

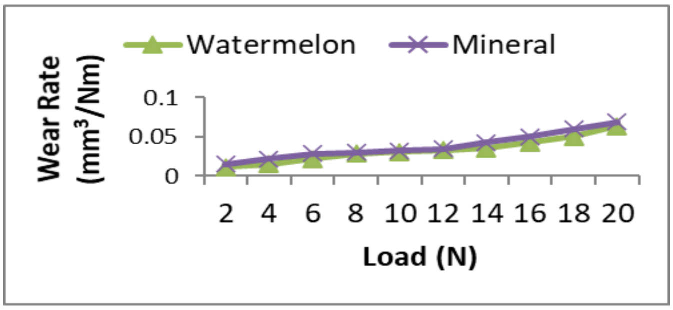

Figure 3: Wear Rate of the Oils under Moderate Loading Conditions

The dry friction necessitated large noise in the friction pair which was as a result of lack of fluid film to discourage direct contact between high points (asperities) of the opposite surfaces and the resultant effect was a high coefficient of friction, and this was responsible for the high surface roughness as can be observed from Figure 1(a) (Raina & Anand, 2017). Immediately the lubricants were applied, the noise suddenly reduced and steady friction was observed (see Figure 1(b-c)). All materials under study have shown a sharp decline in the value of the coefficient of friction at the beginning, and after some time of operation, its slight increase took place.

Figures 2 and 3 are the summaries of the friction coefficient and wear rate of the lubricating oils at moderate loading conditions respectively. Expectedly; all the lubricants showed a slight positive gradient signifying a linear relationship between the responses and load. The watermelon seed oil exhibited the best lubricity throughout. It was observed that the lubrication regime of all lubricated contacts was the boundary lubrication regime.

3.4 Analysis of Variance (ANOVA) for Wear Rate

Tables 3a and 3b present the analysis of variance (ANOVA) of wear rate of all the lubricants as performed with the aid of Minitab 16 software at 95 confidence level, the reason is to find out which amongst the predictors (load and speed) is having more impact on the wear rate. It is observed that the load is making the highest impact as compared to speed in all the analysis, p-values for the predictors is less than 0.05 this signifies that the test results of the dependent variables (wear rate) are statistically significant, that is the predictors all affect the dependent variable.

93% contribution to the wear rate was observed to be coming from load with R-Sq = 99.19%, R-Sq(adj) = 98.5. Watermelon seed oil has load to be 95% with R-Sq = 98.99% and R-Sq(adj) = 98.16%. R-Sq values for all the analysis signify that the test results fitted in very well with the empirical values. The higher R^2 value indicates that the selected model fits the data in determining the wear rate of the two mating bodies in all the lubricants. The ANOVA results obtained in this study which has load being the significant input parameter is contrary to the one reported by Bhaumik and Pathaka (2016) which reported speed been more significant, this disparity could be as a result of variation in the input parameters.

Table 3a: Analysis of Variance of Wear Rate for Mineral Oil

Source	Load(N)	Speed	Error	Total
DF	3	2	6	11
SS	0.03045	0.00211	0.00027	0.03283
MS	0.01015	0.00105	0.00006	
F	228.57	23.72		252.29
P	0.001	0.003		

Table 3b: Analysis of Variance of Wear Rate for Watermelon Seed Oil

Source	Load(N)	Speed	Error	Total
DF	3	2	6	11
SS	0.03132	0.00231	0.00034	0.03398
MS	0.01044	0.00116	0.00001	
F	183.32	20.33		203.65
P	0.001	0.003		

4. CONCLUSION

Studies were performed to evaluate the tribological response of watermelon seed oil on steel friction pair. Investigations carried out as the following conclusions:

(i) The major fatty acid composition of the watermelon seed oil was linoleic acid which was about 64% unsaturated, which makes it highly unsaturated.

(ii) Watermelon seed oil is superior to mineral oil under moderate loading conditions of (2 – 20) N

The analysis of variance (ANOVA) for wear rate as obtained in this study has load as the most significant input parameter.

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NOMENCLATURE

Abbreviation	Description
ASTM	American Society for Testing and Materials
ANOVA	Analysis of Variance
COF	Coefficient of Friction
DF	Degree of Freedom
FFA	Free Fatty Acid
GC-MS	Gas chromatograph-mass spectrometry
F	Load (N)
FP	Flash Point
MW	Molecular Weight
P	Predictor
PP	Pour Point