Bulgarian Chemical Communications, Volume 53, Issue D (pp. 18-24) 2021 *DOI: 10.34049/bcc.53.D.08*

Comparative study of castor oil and dehydrated castor oil as lubricants

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Received: October 13, 2021; Revised: January 01, 2022

Lubricants play a prime role not only in automobiles but also in mechanical systems used in various industries. Castor oil, one of the promising non-edible vegetable oils, can serve as base lubricating oil. It is abundantly available, non-edible oil. The viscosity, density, thermal conductivity, and pour point of castor oil are at par with conventional lubricants, however, the viscosity of castor oil is very high at 25° C that affects the efficiency of mechanical systems. Dehydrated castor oil, obtained after dehydration of castor oil, has much lower viscosity values than castor oil. It has been observed that dehydrated castor oil shows viscosity reduction up to 39-40% and a 17.5% increase in thermal conductivity as compared to castor oil. Under similar flow conditions, if the flow of dehydrated castor oil is in a turbulent region, castor oil flow is in the laminar region. Similarly, the value of the Prandtl number is higher in the case of dehydrated oil. The antiwear and antifriction performance of castor oil and dehydrated castor oil has also been studied and 14.5 % more reduction in coefficient of friction has been achieved with dehydrated castor oil, while wear reduction of 23 % more has been achieved with castor oil. In the present paper, the physicochemical, thermal, heat transfer and tribological properties of both castor oil (CO) and dehydrated castor oil (DCO) have been compared and discussed. Their advantages, disadvantages and performances as lubricants have also been explored.

Keywords: Castor oil; Vegetable oil; Dehydrated castor oil; Lubricant

INTRODUCTION

Lubricants are essentially required for mechanical parts of the systems. Conventionally, mineral oils have been used as lubricants for automotive, industrial and transport applications because of their good technical properties. These are petroleum-based hydrocarbons and their exposure to the environment generates pollution. In addition, several issues like depletion of petroleum reserves and increasing demand for lubricants due to industrialization promoted new alternatives of mineral oils. Vegetable oils are perceived to be a substitute to mineral oils due to certain inherent technical properties and their ability to be biodegradable. Vegetable oils have been used as lubricating oils from ancient days [1], till 19th century they have been used as an integral part of lubricating oil. Vegetable oils are triglycerides of fatty acids. Increasing crude oil prices and emphasis on the development of renewable, environmentally friendly industrial fluids have brought vegetable oils to a place of priority. As compared to mineral oil, vegetable oil has a high pour point, better viscosity index, low evaporation loss and works as a green lubricant [2]. The polar groups and long-chain fatty acids present in vegetable oil make it amphiphilic and provide a better film/force interconnection [3-5] that helps in minimizing friction and wear. Plant oils biodegrade more easily than mineral oils because of their glyceride fatty acids. Vegetable oil-based lubricants are efficient in both boundary and hydrodynamic regimes [4,6,7]. The biggest benefit with these oils is the vegetable base origin and their abundant nature, while conventional lubricants depend upon petroleum resources. The usage of edible oils like soybean, sunflower, coconut, etc., as a lubricant is difficult as these have to fulfil the domestic requirements of a big population. Nonedible oils like castor oil can serve the purpose due to their abundance and excellent physical and chemical properties. Another advantage of castor is that its growing period is much shorter than that of Jatropha and Pongamia oilseeds. Being an annual crop it gives farmers the ability to shift away easily depending on market conditions. It is extracted from castor beans containing about 44-48 % of oil. Fig. 1. shows the castor tree, seeds and oil. Earlier, castor oil has not only been used in engines but also as gear and transmission oil, its application as a base stock for environmentally friendly lubricants in grinding [8], high-speed turning [9] and precision turning [10] has also been reported.

Fig. 1. Castor tree, seeds and oil

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Suhane *et al.* [11] investigated castor oil-based lubricant for automotive applications in comparison to available commercial servo gear oil.

Chemical composition of castor oil

Castor oil has 90% ricinoleic acid which is monounsaturated, 18-carbons fatty acid. Fig. 2 depicts the structure of this unique acid. In its structure, there is an acid group at the first carbon, a double bond between the ninth and tenth carbon followed by a hydroxyl functional group at the twelfth carbon [12].

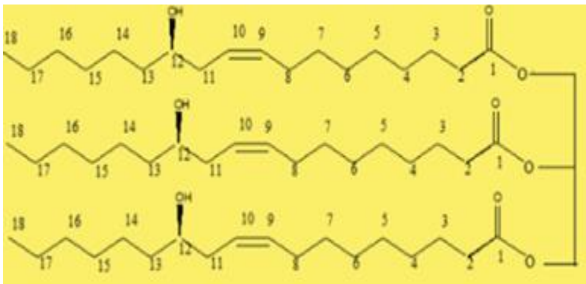

Fig. 2. Ricinoleic acid, the main fatty acid of castor oil

As a result, this unique functionality allows castor oil and its derivatives to find applications like lubricants, paints, inks & additives, textile and agricultural chemicals, rubber, plastic, food, cosmetics, paper, pharmaceutical and electronics & telecommunications sector. The ricinoleic acid comprises almost 90% of the total fatty acid composition. Other fatty acids are linoleic acid (4.0%), stearic acid (1.0%), palmitic acid (1.0%), dihydrostearic acid (0.6%), oleic acid (3.0%), linolenic (0.2%) and eicosanoic (0.2). Fig. 3. shows the pie chart distribution of castor oil constituents.

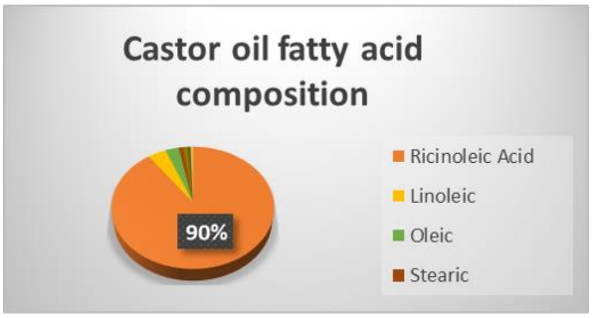

Fig. 3. Fatty acid composition of castor oil

It has been found that the viscosity of oil increases with increasing ricinoleic acid content of the oil, Viscosity performs a crucial part in mechanical system performance and reducing power losses. If the lubricant has a too high viscosity, it may make some part of the lubricant area deficient and increase drag that may lead to reduced efficiency. The viscosity and other properties of castor oil are highly changed once it is dehydrated.

Dehydration of castor oil

When castor oil is heated in presence of certain catalysts, water is removed from the ricinoleic acid chain and dehydrated castor oil is formed, as shown in Fig. 4. Numerous catalysts have been notified for dehydration of castor oil like sulfuric acid, phosphoric acid, sodium bisulfate, and acid-activated clays [13,14]. The elimination of the hydroxyl group and an adjacent hydrogen atom leads to the generation of a new double bond in the fatty acid chain [15]. In this procedure, ricinoleic acid is reacted with an acid, takes away a hydroxyl group and a vinyl group is formed. The dehydrated castor oil is often used as a lubricant [16]. Dehydrated castor oil is now recognized with independent identity having its characteristics and benefits.

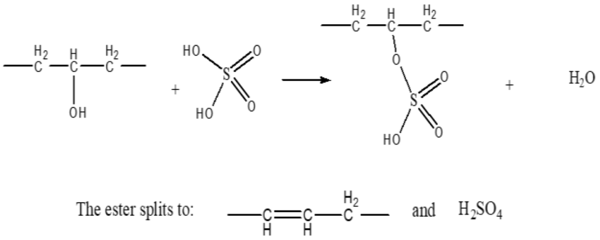

Fig. 4. Formation mechanism of dehydrated castor oil

MATERIALS AND METHOD

Castor oil and dehydrated castor oil have been obtained from Jayant Agro Organics limited (Mumbai, Maharashtra, India). FTIR spectra of both oils have been recorded by Perkin Elmer FTIR model Spectrum-2 in the mid higher range (4000-400 cm^{-1}). The thermal behavior of castor and dehydrated castor oil has been evaluated using a SDT Q600 thermal analyzer by TA Instruments. Thermal analyser measures the heat flow as a function of temperature under a controlled nitrogen atmosphere. The density of both oils has been measured in a pycnometer according to ASTM D287 method. Viscosity as an important property of lubricant can be evaluated using ASTM D-445 using Ostwald viscometer. Hydroxyl value is a measure of the content of hydroxyl groups in the oil that has been calculated for both oils by the ASTM D-1957 method. The thermal conductivity was evaluated by a thermal conductivity meter, Decagon Devices Inc., KD2Pro instrument. Flashpoint of castor and dehydrated castor oil was determined by ASTM D-92 using Cleveland open cup tester while pour point of castor and dehydrated castor oil was determined according to ASTM D-92 using pour point instrument model NEWLAB 1300-SA supplied by Linetronic Technologies. Specific heat of both oils has been measured by the Nanofluid heat capacity apparatus supplied by Mittal enterprises New Delhi. Ducom four-ball tester model TR-30L-PNU-IAS has been used to evaluate the tribological properties of both oils. Evaluation of lubricant properties was conducted with speed of 1200 rpm, and load of 294 N at 75 ^{0}C. The test was conducted according to ASTM D4172. The frictional torque and coefficient of friction (COF) have been calculated using the following formula:

$$\mu = T\sqrt{6}/3Wr$$

where μ= coefficient of friction, T= frictional force Kg.mm, W= applied force in Kg and r= 3.67. Wear scar diameter was calculated by the image acquisition system. Morphology of worn surfaces was examined by FESEM, TESCAN, and MIRA-3.

RESULTS AND DISCUSSION

FTIR characterization of castor oil

For the identification of expected functional groups and bands, especially hydroxyl groups, FTIR of both castor and dehydrated castor oil has been recorded. Fig. 5 shows the FTIR scan of both oils. The ester carbonyl (C=O) functional group shows the characteristic stretching band of triglyceride at 1743.25 cm^{-1} of both oils. It has been observed that the broad peak at 3435.48 cm^{-1} signifies the hydroxyl group (O-H) of the ricinoleic fatty acid present in castor oil but in the case of dehydrated castor oil the peak intensity becomes smaller because of the splitting of ricinoleic acid.

Physiochemical properties evaluation of castor oil and dehydrated castor oil

The important physicochemical characteristics of castor oil and dehydrated castor oil are shown in Table 1. Density plays a major role in lubricant functioning and performance in mechanical systems. It is also useful in calculating several physical factors of a fluid. From Table 1 it is evident that the castor oil has a density range that is advantageous in high bearing load and highly stable in severe conditions although pumpability is better with dehydrated castor oil due to lower density.

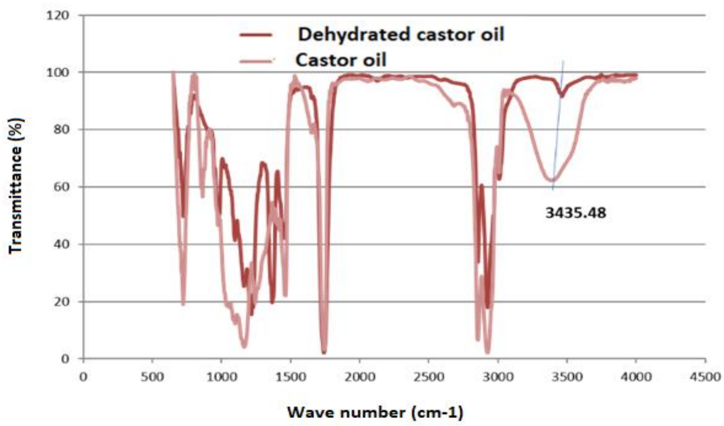

Fig. 5. FTIR comparison of castor oil and dehydrated castor oil

Table 1. Physicochemical characteristics of castor oil and dehydrated castor oil

Properties (Units)	Castor oil (CO)	Dehydrated Castor oil (DCO)
Density (Kg/m3)	0.964-0.969	0.926-0.937
Kinematic viscosity (cst)		
@ 25 °C (cSt)	662.67-667.79	135.43-139.05
@100 °C (cSt)	19.72-20.32	18.29-19.32
Hydroxyl value (mg KOH g^{-1})	150-160	7.0-8.0
Thermal conductivity (W/m°K) at 25ºC	0.148±0.001	0.174±0.001
Flashpoint (°C)	245	211
Pour point (°C)	-27	-34

It has been observed that the viscosity of the castor is much higher as compared to dehydrated castor oil because of the increasing ricinoleic content of the oil. A higher value of viscosity can cause churning losses to generate excessive heat generation due to molecular friction. In such cases, dehydrated castor oil can serve as a potential lubricant in mechanical systems. Thermal conductivity is a necessary parameter in upgrading the heat transfer of base fluid. It is therefore beneficial for the fluid to own high thermal conductivity. Dehydrated castor oil shows an almost 17.5% increase in thermal conductivity as compared to castor oil. The hydroxyl value of dehydrated castor oil is less as compared with castor oil because during dehydration of castor oil, the hydroxy group-containing ricinoleic acid gets converted into 9,11 and 9,12 linoleic acid. Castor oil has a higher value of flash point. It means that the oil is less flammable, safer to handle or transport, beneficial in the high-temperature application as compared with dehydrated castor oil. It will be useful in the vehicle engine and as gearbox lubricant. Pour point of dehydrated castor oil is better than that of castor oil. Low pour point characteristics help easier handling and usage of lubricant in cold weather conditions.

Heat transfer evaluation in castor oil and dehydrated castor oil

Dimensionless numbers determine the fluid flow behavior in many aspects. Reynolds and Prandtl numbers help in assessing the flow behavior of both castor and dehydrated castor oil.

Reynolds number: The Reynolds number is the main dimensionless number in fluid mechanics anticipating the flow arrangements in different fluid flow conditions. It forms a basis to segregate the laminar and turbulent regimes. It can be evaluated using Equation 1:

$$N_{Re} = DV\rho/\mu \qquad (1)$$

where D = diameter of the tube (m), V and ρ = velocity (m/s), density of liquid (Kg/m^3), μ= dynamic viscosity (Pa-s) of liquid. The value of the Reynolds number for a laminar flow is always below 2100, whereas for turbulent flow its value is above 5000 [17].

In the case of dehydrated castor oil for a well-developed turbulent flow N_{Re}= 5000,

$$DV = 135.43\times5000\times10^{-6} = 0.67.$$

Putting this value of DV and kinematic viscosity in the case of castor oil in Equation 1, the Reynolds number becomes:

$$N_{Re} = 0.67/662.67\times10^{-6} = 1011.$$

For similar conditions of tube diameter and velocity, if the flow of dehydrated castor oil is in a turbulent region the flow of castor oil is in the laminar region. Thus, the heat transfer properties of dehydrated castor oil are better than those of castor oil and it acts as a good lubricant.

Prandtl number: This dimensionless number expresses the relation between the viscosity of a fluid and the thermal conductivity. It, therefore, evaluates the relation between momentum and thermal transport competency of a fluid. It is defined as:

$$Pr = \text{Momentum Diffusivity}/\text{Heat Diffusivity} = (\mu/\rho)/(k/\rho C_p) = C_p\,\mu/k \qquad (2)$$

where μ = dynamic viscosity (Pa-s), ρ = density (Kg/m^3), k = thermal conductivity (in W.m^{-1}.K^{-1}) and Cp = specific heat of liquid (J.kg^{-1}.K^{-1}).

In the case of dehydrated castor oil (DCO):

dynamic viscosity = $135.43\times0.926\times10^{-3}$ =125.40×10^{-3}, Cp = 2.88, k = 0.174. Putting all values in equation (2):

$$Pr(DCO) = 125.40\times10^{-3}\times2.88\times10^{3}/0.174 = 2075.72$$

In the case of castor oil (CO):

dynamic viscosity = $662.67\times0.964\times10^{-3}$ = 638.81×10^{-3}, Cp = 1.8, k = 0.148. Putting all values in equation (2):

$$Pr(CO) = 638.81\times10^{-3}\times1.8\times10^{3}/0.148 = 7769.$$

If the Prandtl number is less, thermal diffusion is predominant as compared to momentum diffusion. If the flow situations go on the same, for a higher heat transfer rate we have to choose a fluid with a lower Prandtl number, in this way dehydrated castor oil is much better than castor oil because of the lower value of Prandtl number. Oils with small values of Prandtl number are free-flowing liquids having a larger value of thermal conductivity.

Thermal properties evaluation of castor oil and dehydrated castor oil

The differential scanning calorimetry (DSC) thermal curves give a way of distinguishing between both oils. Fig. 6(a) depicts the DSC curve for castor oil, which shows sudden exothermic decomposition at elevated temperature. The decomposition initiates at 343.95°C with a peak value of 379.79°C. The value of enthalpy of decomposition is 157.4J/g. Fig. 6(b) shows the decomposition behavior of dehydrated castor oil which initiates at 347.61°C with a peak value at 389.69°C, the enthalpy value of decomposition is 340.3J/g. From both curves we may conclude that onset decomposition temperature of dehydrated castor oil is higher than that of castor oil so that it can be used up to higher temperatures.

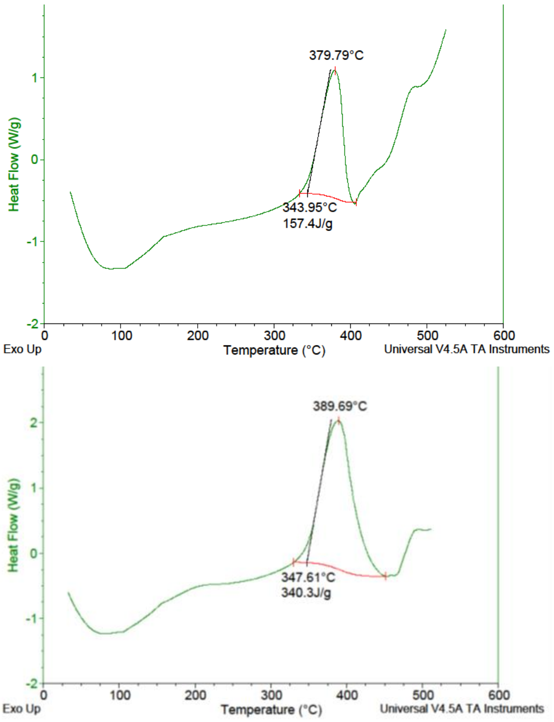

Fig. 6 (a, b). Differential scanning calorimetry of castor oil and dehydrated castor oil

Tribological properties evaluation of castor oil and dehydrated castor oil

Tribological tests were carried out according to the standard test methods for measurement of frictional and wear-preventive properties of castor oil and dehydrated castor oil in a Ducom four-ball tester, model TR-30L-PNU-IAS. The tests were carried out at atmospheric pressure of both castor oil and dehydrated castor oil at a load of 294N and 75°C temperature with a constant speed of 1200 rpm. After 30 minutes of run, the three bottom balls have been taken off, cleaned with acetone. The scars marked on the bottom of the three balls were observed under an optical microscope to access the wear characteristics of the lubricants. The wear characteristics were analysed by observing the pattern of wear created over the balls called wear scar diameter. The wear scar diameter was measured along the minor and major axis and was found the same on both axes. The frictional behaviour, i.e. frictional torque, coefficient of friction (COF) of castor oil and dehydrated castor oil is shown in Fig. 7 (a). The value of COF of dehydrated castor oil and castor oil were 0.0482 and 0.0552, respectively. The reduction in friction characteristics was found to be 12.6%. The thin lubricating film formation ability on the surfaces of contacting mechanical components, determines the friction reduction efficiency which is better with dehydrated castor oil. Due to the better film-forming ability and lubricity of dehydrated castor oil compared to castor oil the frictional force got reduced rendering a reduction in the coefficient of friction. The frictional force and the wear scar images of castor and dehydrated castor oil are shown in Figs. 7 (b) and 7 (c), respectively. In the case of castor oil, a smaller wear scar diameter was present as compared with dehydrated castor oil. The worn surface analysis of bottom balls in both oils has been examined using FESEM at a magnification of 250×. Figs. 7 (d, e) show the morphology of scars present in both oils. The worn surface of castor oil shows a circular, smoother and flatter scar, with 445 µm diameter in balls while dehydrated castor oil shows a rough surface with scratches and grooves having a scar of 550 µm diameter in balls. The viscosity of lubricants plays a very important role in the lubricating and tribological properties of the lubricants. In the case of dehydrated castor oil the viscosity is much lower. Due to the lower viscosity of the dehydrated castor oil its wear-preventive property is comparatively lower than that of the castor oil. Owing to lower viscosity, there is more wear in the case of dehydrated castor oil. Due to higher wear there is more formation of wear particles. The broken particles present on the scar image as shown in Fig.7(e) will act like abrasive particles and will cause abrasive and erosive wear when the oil is used as a lubricant in an engine or any other mechanical system. The anti-wear property of castor oil is better compared to dehydrated castor oil. The reduction in wear characteristic accessed through measuring wear scar diameter of castor oil compared to dehydrated castor oil was found to be 23%.

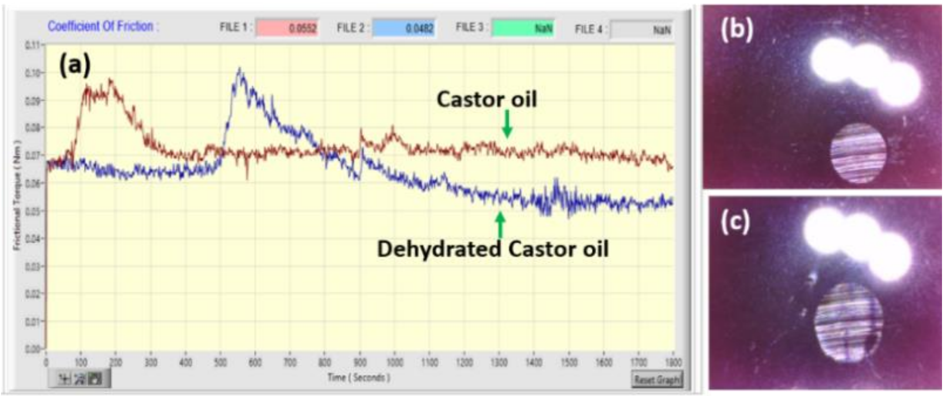

Fig. 7 (a) COF of castor oil and dehydrated castor oil (b, c) Wear scar image

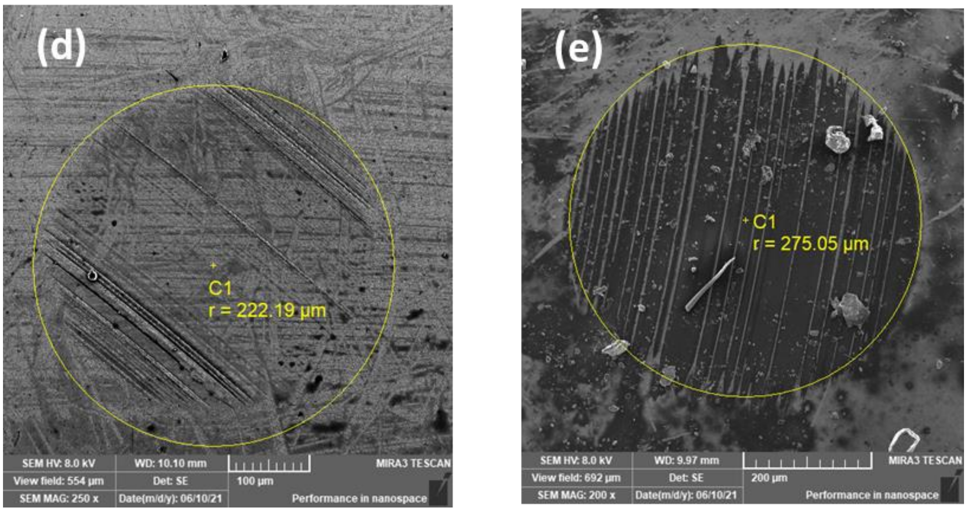

Fig. 7 (d, e). FESEM of castor oil and dehydrated castor oil

CONCLUSIONS

- Castor oil itself is a good alternative for lubrication, because of its good physiochemical, heat transfer and tribological properties necessary for lubricants.
- Dehydrated castor oil shows viscosity reduction up to 39-40% as compared with castor oil.
- The thermal conductivity of dehydrated castor oil is by 17.5 % higher than of castor oil.
- Under similar conditions of tube diameter and velocity, if the flow of dehydrated castor oil is in a turbulent region, castor oil flows in the laminar region. Thus, the heat transfer properties of dehydrated castor oil are better than of castor oil and it acts as a good lubricant.
- The value of Prandtl number for dehydrated castor oil is 2075.72 while that for castor oil is 7769. Therefore, dehydrated castor oil is a good option for heat-conducting liquids.
- It was observed that dehydrated castor oil yields a response to friction test by 14.5% more reduction in COF as compared with castor oil.
- The anti-wear behaviour of castor oil was better and 23 % more reduction in wear scar diameter has been obtained as compared to dehydrated castor oil.
- The dehydrated castor oil can serve as a potential alternative as a lubricant. Its viscosity at 25^{O}C is much lower than that of base castor oil. Lower viscosity-oils can reduce frictional losses between moving mechanical parts of the engine and lower pumping and cranking losses, thus improving fuel economy and efficiency of engines.

Acknowledgement: *J. S. would like to express his special thanks to Dr. N. Eswara Prasad, OS & Director, DMSRDE, for his constant motivation and encouragement to conduct this work.*

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