Experimental studies on viscosity, thermal and tribological properties of vegetable oil (kapok oil) with boric acid as an additive

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Abstract
Non-renewability and damage caused to the environment while using mineral based and synthetic based lubricants become the greatest concern of this century. Disposal issues initiated a global trend to utilize vegetable based lubricants in industries. Vegetable oils are environmentally friendly, have low toxicity and highly biodegradable in nature. The main objective of this work is to improve the viscosity and reduce the friction and wear rate of Kapok oil using boric acid as an additive. The tribological properties of kapok oil with three different concentrations (1, 3 and 5 wt%) of boric acid is evaluated and compared with pure kapok oil using pin on disc tribometer. The worn out surface of the pin are analyzed using the optical microscope after the wear test. The viscosity and thermal properties of kapok oil with 5 wt% of boric acid possess the better performance compared to other samples. Boric acid particles suspension exhibits reduction in friction and wear when compared with pure kapok oil. Overall, the kapok oil combined with 5 wt% of boric acid acts as the better bio lubricant oil which would help to reduce the global demand of petroleum-based lubricant sustainability.

1 | INTRODUCTION

Generally, lubricant plays a vital role in industrial and as well as in the machine components which are used to reduce the friction between the two contacts surfaces and also used to minimize the heat between the two surfaces [1]. The viscosity of the lubricant has a great influence on the quality of the lubrication of the machine components [2]. The liquid lubricants are classified into three types that is, synthetic, mineral and vegetable oil. The synthetic oil is the chemical composition of the artificial made, is manufactured using the chemical reformation from the petroleum component rather than the complete crude oil. Mineral oils are mostly used in the motor and engine applications, which are also obtained from the petroleum-based crude oil. The mineral oil is harmful to the environment which causes more toxicity and non-biodegradable [3]. The mineral oil lubricants have hydrocarbons which cause those effects and the natural lubricants are obtained from esters [4]. Vegetable oil is mostly an environmental friendly lubricant, easily biodegradable and non-toxic [5, 6]. Vegetable oil has good lubricant properties but limited in thermal stability and oxidation stability properties [7, 8]. While comparing with the mineral oil, vegetable oil has a high pour point, enhanced better viscosity index, and low evaporation loss [9]. In this work, one such vegetable oil (kapok oil) is considered and its change in properties are studied using boric acid as an additive. The friction and wear rate characteristics of kapok oil possess minimum when compared with mineral oil (SAE 20W 40) and Palm oil [10].

Lot of works were carried out using Nanoparticles and Nanomaterials as an additive with lubricant oil [11, 12]. Depending upon the characteristics of nanoparticles such as size, shape and concentration, the friction and wear between the two contacting surfaces were reduced [13]. The lubricating properties of boric acid (H₃BO₃) were studied which was commercial available in the market and environmentally safe [14]. The environmental protection agency act established that boric acid does not cause any harm or pollution. In order to reduce friction and wear, various additives were added in the lubricating oil [15].

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The various additives like calcium borate nanoparticles [16], lanthanum borate [17], multiwalled carbon nanotube (MWCNT) [18], CeO2/CuO, graphite [19], ZDDP, CuO, TiO2, Silicon dioxide (SiO2) and molybdenum disulphide (MoS2) [20] were used to reduce friction and wear rate between two interfacing surfaces. Over a period of 30 years, boric acid was used as additives in solid lubricant to reduce the friction and wear during the sliding contact [21]. Special materials such as tungsten, graphite disulphate, zinc [22], ferrous, copper and boric acid [23, 24] were also used as an additive with the lubricant.

Boric acid has low friction and shear strength values, another often overlooked lamellar solid materials which were strongly bonding with each other [4]. The coefficient of friction and shear strength of the boric acid was measured under the ambient condition which was less than 0.02 and 23 MPa respectively. The physical characteristic of boric acid was commonly termed as orthoboric (or boracic) acid. In atmospheric pressure, the boric acid is softened around 400°C and dehydrate above 170°C [25]. The wear performance of the mineral oil (15W40), pure canola oil, and addition of canola oil with 5% of boric acid were evaluated using a pin on disc at a constant speed under various weights of 60, 120 and 180 N and it was found that the layer structure of 5% of boric acid particles can slide over each other and it also reduces the friction and wear [4]. The boric acid had a strong tendency to form chemical bonding films on the oxidized surface aluminium [26]. The nanoboric acid [27] were added with engine oil (5W40) and its tribological properties were investigated using the ball on disc reciprocating tribometer and the results indicate nBA can considerably improve the tribological properties. The boric acid had better tribological property [24, 28], the wear resistance was increased as the temperature increased, and the friction coefficient decreased [29]. Based on the available literature, it can be concluded that the suspension of boric acid as an additive with vegetable oil and mineral oils provides a better result to reduce the friction and wear between the two sliding contacts.

Till now, no authors studied the effect of friction, wear, viscosity and thermal properties of kapok oil with a combination of boric acid as an additive. In the present study, the kapok oil is mixed with varying weight proportions of 1%, 3% and 5% of boric acid and its properties are tested using a pin on disc tribometer. The objective of the research is to study the effectiveness of additives added in the bio lubricant oil which is compared with pure kapok oil (without additives) under the 50 and 150 N. In addition to the tribological studies, viscosity and thermal properties were also evaluated.

2 EXPERIMENTAL METHOD
2.1 Preparation of nanolubricant

In the present study, the boric acid (BA) was mixed with the kapok oil through a weight proportion of 1%, 3% and 5%. The boric acid (>99 % purity) was commercially purchased from the scientific lubricants private limited, India. Figures 1(a,b) shows the typical SEM image of boric acid. Figure 1(a) shows that the morphological image of boric acid in low magnification. From the magnified SEM image (Figure 2(b)), it is found that the size of boric acid ranges from 50 to 150 nm. The boric acid is very stable at room temperature and soluble in boiling water. When the boric acid is heated above 170 °C, the solid loses water and slowly converted into metaboric acid and on further heating, it was converted into boric oxide [30]. Eco-friendly lubricant from the class of vegetable oil (kapok oil) was premixed with 1, 3 and 5 wt% of boric acid separately mixed using a magnetic stirrer for 2 h at ambient temperature (34 °C) until the nanoparticles was evenly spread throughout the lubricant and without any solvent/surfactants. The boric acid is not completely dissolved in the kapok oil, but it is observed that boric acid particles have suspended in oil. Hence, by increasing more wt% of boric acid in kapok oil that is without any solvent or surfactants, it might have a chance of deposited at the bottom of the vessel/container. The density of pure kapok oil is 0.89 g/cc at ambient temperature (34 °C).
2.2 Viscosity measurement and thermal properties

The viscosity of the lubricants were one of the most important characteristics of the lubricant for industrial purposes. The viscosity of the base oil and nanolubricant were evaluated using the Redwood viscometer as per ASTM D445 Standard. The time required for emptying 50 mL of oil was measured and the viscosity of the oil was calculated using redwood formula. The variations of kinematic viscosity were obtained over a temperature range of 34–100 °C. The flash point is the oil temperature which indicates the volatility and safe operating temperature of the lubricant oil. Fire point temperature indicates at which temperature lubricant oil gets fired with the source of external spark. The flash point and fire point were estimated using Cleveland open cup equipment as per the ASTM D92 standard.

2.3 Tribological properties by using a pin on disc tribometer

The tribological study of the base oil (Kapok Oil) and nanolubricants (Kapok Oil added with Boric Acid) were carried out using a pin on disc tribometer supplied by M/s Magnum Engineers, Bangalore, India. As per the ASTM standard (ASTM G99), computerized tribometer was used to compute the coefficient of friction and wear rate as shown in Figure 2. The cylindrical flat pin was used in the present study. The pin was made up of Steel (EN 24) of having a diameter of 8 mm and a length of 25 mm and rotating disc is made up of EN31 of 180 mm diameter having 60 HRC and constant sliding distance of 70 mm was set for all cases. The perfect sliding contact was ensured between the base of the pin and disc, which was placed parallel to each other to get the maximum contact. The experiments were performed under a room temperature of 33 °C. In the current study, the experiments were conducted at 50 and 150 N loads and at various operating speeds, such as 300, 450, 600, 750 and 900 rpm respectively.

The nanolubricant oil was supplied at the interface in a drop-wise manner in order to maintain the boundary/thin-film lubricating condition. The flow rate was adjusted with the help of a flow control valve as 10 mL/min. Three trials were conducted for each speed and concentration, the average values were taken for the calculation. Before conducting the experiment, the pin was cleaned using acetone and methanol. For each test, the initial and final weight of a pin was measured using a 0.0001 mg sensitive scale for the calculation of wear using a weight-loss method.

3 RESULT AND DISCUSSION

3.1 Analysis of kinematic viscosity and thermal properties

Figure 3 shows the variation of kinematic viscosity of nanolubricant with the increase in temperature. The kinematic viscosity of pure kapok oil was minimum when compared to the three different nanolubricants at various temperature (34–100 °C). From the graph, it was observed that, if the weight proportion of boric acid is increased and correspondingly the kinematic viscosity is also increased at various temperature. The kinematic viscosity of kapok oil with 5% BA possess the maximum value throughout while comparing with other samples. Hence, the boric acid added with kapok oil will act as a good viscosity modifier. As expected, the viscosity of lubricants generally decreases with an increase in the temperature.

The addition of nanoparticles suppresses the amount of decrease in viscosity with an increase in temperature, making the oil more suitable for high-temperature applications [31]. The flash and fire point of nanolubricant are illustrated in Figure 4. As the temperature of oil increased, flash point denotes to the condition when the fumes produced from the oil are just enough to produce the flame. For the fire point, uninterrupted vapour form is necessary for continuous burning. The pure kapok oil shows the minimum flash and fire point when compared to the nanolubricants. The graph clearly shows that while the addition of nanoparticles in kapok oil, the flash point and fire point were marginally increased for all the nanolubricant. Boric acid nanoparticles are not flammable. The weight proportion of the boric acid is increased, a higher temperature is necessary for the continuous burning of the oil. This could be the reason for the increase in flash point and fire point with
an increase in the weight proportion of the boric acid. The thermal conductivity of the pure kapok oil is $(0.2 \text{ W m} < \text{sp} > -1 < \text{sp} > \text{K})$ which is constant throughout the various temperature [32].

### 3.2 Friction characteristics

The coefficient of friction (COF) of pure kapok oil was compared with three different weight proportions (1%, 3% and 5%) of boric acid under two different loads that is, 50 and 150 N as shown in Figures 5(a) and 5(b) respectively. Six sliding speeds were considered such as 1.1, 2.2, 3.3, 4.4, 5.5, and 6.6 m/s for the duration of 60 min. From Figure 5(a) initially the coefficient of friction seems to be high between the two contact surfaces and the lubricant film was not yet formed at low speeds. If the sliding speed further increased, the coefficient of friction was marginally decreased due to the presence of lubrication; a thin film was generated between the two contacting surfaces. The coefficient of friction was gradually decreased for pure kapok oil and as well as kapok oil with additives up to 3.3 m/s and further increasing the sliding speed, the COF value was gradually increased from 4.4 to 6.6 m/s. While the temperature increases, the viscosity of the lubricant oil gets increased and due to that, the lubricant layer of the film gets thinner. In addition to that, the flow rate of oil was also high. The COF for three different weight proportions (1%, 3% and 5%) significantly represent that the coefficient of friction was decreased when compared with pure kapok oil. Boric acid particles attached in between the two contact surface of the pin and disk which resulted in a decrease in the coefficient of friction. For 150 N load, the coefficient of friction was slightly decreased initially and further gradually increased for the pure kapok oil and also for kapok oil with additives. Figure 5(b) represents when the applied load increased, the coefficient of friction was also slightly increased. Among all the cases, kapok oil with 5% of Boric acid as additives possess the minimum coefficient of friction for both 50 and 150 N load. When the boric acid powder interacts with kapok oil, the coefficient of friction was less between the two contact surfaces.
3.3 Effect of wear

Figures 6(a) and 6(b) shows the variation of wear rate of kapok oil with a different weight proportion of boric acid with pure kapok oil at various sliding speeds under 50 and 150 N respectively. Figure 6(a) represents that the wear rate was higher at a sliding speed of 1.1 m/s and then suddenly reduced at 2.2 m/s. Due to the increase in the speed of the rotating disc, a rise in temperature of the pin, the oxide layer is formed which leads to reduce the wear rate. The wear rate was suddenly decreased when it reaches the sliding speed of 2.2 m/s for both 50 and 150 N load. It was also observed that when sliding speed increases it decreases the wear rate [33] because the time required to dissipate the heat was increased. The sliding speed was also one of the major factor in the wear rate. Ravikiran et al [34] found that the oxidation layer was formed in the pin surface at high temperatures that protect it from the high wear during sliding operation. During the lowest sliding speeds, the wear debris were present in the track, due to this effect the abrasive wear was formed that leads to an increase in wear rate at the beginning. When sliding speed increased, due to the centrifugal force of the disk and also the presence of lubricating oil, wear debris moves out from the track along with the lubrication oil that contributes to the reduction in wear rate. From the graph, it was evident that when the load increased further, the amount of wear between the two sliding surfaces was also increased.

When the applied load increased, the contact between the two surfaces was also increased due to this effect the temperature of lubricating oil was increased rapidly. This will contribute a thin-film of lubricant, in addition, if additives were added in the lubricant, that has the tendency to form a small layer and that protect the surface which reduces the wear rate of the material. When the percentage of boric acid increased with the kapok oil, the wear rate was decreased when compared with pure kapok oil. For 150 N, pure kapok and 5% of boric acid powder with kapok oil had the wear rate of 3.12E-04 mm$^3$ m < sp > -1 / s p > and 1.14E-04 mm$^3$ m < sp > -1 / s p >
respectively at the sliding speed of 1.1 m/s. It was found that when increasing the amount of composition of boric acid powder which reduces the amount of wear between the two contacting surfaces. In addition, it was noticed that 5% weight of boric acid powder with kapok oil indicate that the wear rate was minimum throughout all cases compared with pure kapok oil.

### 3.4 Effect of temperature

The variation of temperature around pin surface with and without additives under 50 and 150 N loads were illustrated in Figures 7(a) and 7(b). The thermocouple was attached in the pin on disk apparatus to measure the temperature effect of the pin surface. The temperature of the pin was gradually increased while increasing the sliding time, velocity and distance. The experimental tests were conducted for a period of 60 min. Our previous work concluded that pure kapok oil possesses a lower temperature when compared with the mineral oil and palm oil at various sliding speeds under the applied load of 50 and 150 N [10]. In addition, the boric acid powder was added as additive in kapok oil with three different weight proportions, it was found that when increasing the composition in kapok oil, the effect of temperature on the pin surface was marginally decreased. The amount of heat dissipation gets increased in the surface of the pin. It was perceived that when increasing applied load, the temperature of the pin surface was also rapidly increased. Due to the applied load, the lubricant film becomes thinner in between the contact surfaces. While the temperature of the oil increased proportionally, the viscosity of the oil was also increased. Overall, in this case, 5% of boric acid with kapok oil holds better temperature control in the pin surface in all the cases under the 50 and 150 N.
3.5 | Effect of surface roughness

High roughness value indicates corresponding to high friction and wear. Here the surface roughness (Ra) was measured using the surface profilometer (µm). Figure 8(a,b) compares the surface roughness of kapok oil and three different ratios of boric acid blended with kapok oil. Figure 8(a) represents, For 50 N load, the surface roughness value was slightly higher at the beginning and then gradually decreased from the sliding speed of 1.1–5.5 m/s. Further, the value gets increased when the sliding speed increases from 5.5 to 6.6 m/s that is due to the change in the viscosity with respect to the temperature of the lubricant. Due to this effect, a thin lubricant film was formed between the two mating surfaces. It is observed that the COF was increased while increasing the sliding speed. It was most likely due to the progression of abrasive wear which was formed on the surface, thus increasing the surface roughness at the contact region. The evidence shows that based on the wt% of the boric acid powder which leads to a decrease in surface roughness for 50 N load. In addition, it was noticed that kapok oil combinations with 5 wt% of boric acid possess minimum surface roughness at various sliding speeds. Figure 8(b) represents for 150 N load, the roughness value was marginally increased as sliding speed increases, due to the area of contact becomes more as compared with 50 N load. Normally the kapok oil have free fatty acid due to that tendency which makes to form an oxide layer in pin surface and protects the wear in the surface as well as reduces the friction coefficient [35].

The molecular structure of the boric acid allows it to act as an effective solid lubricant film. When crystallized, boric acid forms weak van der Waals bonds between individual layers and strong hydrogen (covalent) bonds within a layer [7]. Hence the combination of boric acid mixed with kapok oil forms a hybrid tribofilm. From Figure 8, it was noticed that kapok oil mixed with 5 wt% of boric acid will act as better hybrid tribofilm and it possess minimum surface roughness value throughout all the cases at different sliding speeds for both load conditions 50 and 150 N.

3.6 | Effect of surface texture

The surface texture is one of the most important phenomena used to improve the tribological properties of the two contacting surfaces [36]. It controls the friction and transformation layer to move from one place to another during sliding operation.

Most of the wears are abrasive and adhesive in nature. The texture clearly shows that the grooves were formed in straight because of sliding direction. This is because of the relationship with the thickness of the lubricant layer, properties of the hard surface passes over the soft surface [37]. The optical image of tested EN24 surface of kapok oil with/without additives under 50 and 150 N loads were represented in Figure 9(a–f). Menezes et al [38] also concluded based on the surface texture; the amplitude of oscillation was fluctuating during stick-slip motion. The lubricating film thickness plays a crucial role in reducing the abrasive and adhesive wear.

4 | CONCLUSION

In this study, viscosity, thermal and tribological properties of nanolubricant (boric acid is added as an additive in kapok oil) are carried out and compared with pure kapok oil. Viscosity and thermal properties were increased for kapok oil with 5%wt proportion of boric acid compared to pure kapok oil, kapok oil with 1 wt% and kapok oil with 3 wt%. The coefficient of friction and the amount of wear were higher for 150 N when compared with 50 N load under different sliding speeds. Boric acid particles
FIGURE 9  Optical micrographs of pin worn surface.  
(a) 0 wt% of boric acid under 50 N; (b) 0 wt% of boric acid under 150 N; (c) 1 wt% of boric acid under 50 N; (d) 1% wt of boric acid under 150 N; (e) 3 wt% of boric acid under 50 N; (f) 3 wt% of boric acid under 150 N; (g) 5 wt% of boric acid under 150 N; (h) 5 wt% of boric acid under 150 N

suspension exhibits a reduction in friction and wear when compared with pure bio lubricant oil (kapok oil). The surface roughness for the 150 N load was higher compared with the 50 N load because of the effect of a rise in temperature forms a thin lubricant film between two sliding surfaces. From the surface texture analyses, the straight grooves were formed in the pin surface. It was noticed that wear was more abrasive in nature for all the cases. Overall, Kapok oil with a combination of 5 wt% of boric acid had the best tribological, viscosity and thermal behaviour that reveals a reduction in the friction and wear between the two sliding surfaces. In the future work, nanolubricant will be used in engine oil in the four-stroke engine and their performance will be evaluated and compared with pure kapok oil and mineral oil.

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