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Research Article

Tribological behavior of choline chloride as additive to vegetable oil

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Abstract – The tribological properties of sunflower oil were improved by using choline chloride-based IL as sustainable bio-lubricant additive at various concentrations including 0.25 - 1 wt% IL. With a pin-on-disc tribometer, the lubricants were tested under realistic conditions of a 20 N load, 500 rpm rotational speed and ambient temperature, to measure their ability to reduce friction and protect the surface from wear. The oil blended with 1 wt% choline chloride IL showed a significant decrease of 60.43% in friction coefficient and 53.65% in wear scar volume, compared to the neat oil. Scanning electron microscopy (SEM) and stylus profilometry showed that a strong, protective tribofilm was formed which reduced surface roughness and lowered the amount of abrasive wear. The reason for the excellent tribological performance is that ILs are stable, have ionic structures and easily attach to metal surfaces which supports both extra load capacity and more even shear stress distribution at the contact point. The results suggest that choline chloride ILs are suitable eco-friendly additives for bio-lubricants and can replace the common use of mineral oils in industrial applications. Following the right experimental approach and detailed surface analysis, the study presents a good starting point for further improvements and wide use of IL-modified bio-lubricants in industries. This work adds valuable information to the field of ionic liquid-based additives and encourages the use of more environmentally friendly lubrication solutions.

Keywords – Choline Chloride, Ionic Liquids, Tribological Mechanism, Friction, Wear.

I. INTRODUCTION

The renewable, biodegradable and widely available characteristics of sunflower oil have made it a popular consideration for sustainable lubrication solutions [1]. Although pure vegetable oils offer many benefits, their lack of thermal stability, weak resistance to oxidation and decreased effectiveness in harsh conditions prevents them from being used widely as lubricants in machining operations [2,3]. These limitations prevent their effective use in harsh conditions where tribology is required. To solve these problems, adding functional additives, mainly ionic liquids (ILs), has been found to be effective in improving the properties of lubricants by decreasing friction and wear. Choline chloride-based ILs draw a lot of interest since they are non-flammable, chemically and thermally stable, hardly volatile and have high conductivity which makes them safe lubricant additives [4,5,6]. The main reason choline chloride ILs are beneficial in tribology is that they create protective films at the sliding interface, thereby protecting the surfaces from friction. Adding ILs to vegetable oils has been found to improve their properties. Researchers have found that including ILs in bio-lubricants increases tool life and decreases the forces used during stainless steel machining which demonstrates the potential of IL-enhanced bio-lubricants in manufacturing [7-12]. Yet, how well an IL works as a lubricant depends on its molecules, the amount used and how well it blends with the base oil. This means that thorough research is important to develop the best IL formulations for bio oils and similar bio-based lubricants [13]. The structure of the IL, the type of base oil and the work environment are very important factors in determining the friction and wear of lubricants[14]. The effectiveness and stability of the lubricating film are determined by how ILs behave and interact with base oil constituents [15,16]. As a result, it is essential to adjust IL additives at the molecular level to achieve the best lubrication performance in machining operations[17,18].

Recent researches have proved that adding ionic liquids (ILs) to base oils and cutting fluids can significantly improve their tribological properties by minimizing friction, wear and boosting their thermal stability in many lubrication solutions especially in machining operations. The findings show that ILs have strong ionic bonds, good wettability and can withstand heat which enables them to form tough boundary films that safeguard metal surfaces during sliding and cutting. Researchers have found that neem, canola and mineral oil blends, like those in the present study, also confirm the value of IL additives in bio-based lubricants which helps advance sustainable ways to make lubricants[19-26]. Based on these findings, we anticipate that choline chloride ILs in sunflower oil, as studied in this work, can provide both eco-friendly and excellent tribological properties for use in industrial lubricants.

Choline chloride ILs are unique because they are biodegradable and have low toxicity which helps them comply with new environmental regulations and the worldwide push for greener technologies[27]. SEM and stylus profilometry were used to examine wear scar features and surface roughness which helped to understand how IL additives protect the surface. The research finds that choline chloride ILs are effective and environmentally friendly additives for sunflower oil and offers the recommended concentration for lower friction and reduced wear. The results give useful advice for making better biodegradable lubricants that work well, supporting sustainability and lowering the impact on nature. In addition, studies show that IL additives play a key role in improving tribology in various base oils, with their performance being linked to their anion-cation structure, amount used and how they interact with oil components.

Five lubricant samples were prepared for this study: pure sunflower oil and sunflower oil with 0.25, 0.5, 0.75 and 1 wt% choline chloride IL. The friction and wear properties of sunflower oil were examined in a tribological test at room temperature using 20 N load and 500 rpm.

II. MATERIALS AND METHOD

Table 1 presents the Specifications of Choline Chloride

Table 1. Choline Chloride Specifications

IUPAC Name	(2 hydroxyethyl trimethyl ammonium chloride)
Molecular Formula	$C5H_{14}CINO$
Color	Colorless to white
Molecular Weight	139.6 g/mol
PH(20˚C)	6-8
Purity (%)	98

A. MATERIALS AND SAMPLE PREPARATION

The tribology test applied five lubricant mixtures containing pure sunflower oil and sunflower oil mixed with choline chloride ionic liquid (IL) at different compositions of 0.25%, 0.5%, 0.7% and 1 wt%. Choline chloride IL which is both environmentally friendly and works well for tribology, was supplied by a certified chemical source Sigma-Alrdrich and was not further purified. To prepare IL–base oil mixtures, IL and sunflower oil were carefully weighed and blended for 30 minutes using ultrasonication at room temperature. We confirmed that the mixtures were stable and mixed well before testing, good dispersion of the oil is important because past research shows it helps the lubricant function better.

Fig 1. Choline Chloride

Fig 2. Lubricants Sample

Table 2 presents composition of lubricants which consists of variable concentration of ionic liquid and base oil.

Table 2. Composition of different samples

Sample Number	Composition
1	Base Oil Only
2	0.25 wt% IL + Base Oil
3	0.5 wt% IL + Base Oil
4	0.75 wt% IL + Base Oil
5	1 wt% IL + Base Oil

B. SURFACE CHARACTERIZATION

To study how the IL-enhanced lubricants affect wear and their protection of surfaces, SEM was used to check the appearance of wear scars on the pins. The aim of this analysis was to look for pits, furrows and tribofilms, showing that the ionic liquid additive provided protection against wear. SEM imaging helps reveal the tiny ways in which additives in lubricants interact with contacting parts in a tribological testing. In addition, the roughness of the pins after wear was measured with a stylus profilometer to find the average roughness (Ra) of each surface. When Ra values are low, the surface is smoother, proving that the film forms well and reduces wear, viewing results seen for IL-based lubricants. The data was checked for reliability by repeating each measurement three times on the same sample.

Fig 3. TESCAN SEM VEGA3 Microscope

Fig 4. Stylus Surface Roughness Apparatus

C. Tribological Tests

The tribological tests were carried out using a pin-on-disc machine, with a fixed mild steel pin facing a rotating GCr15 steel disc. To resemble real-world situations, the test involved a 20 N load on the pin and a rotation of the disc at 500 rpm for 10 minutes. All the tests were performed at room temperature which matches the usual conditions for checking the performance of bio-based lubricants.

The COF was checked throughout each test to discover how the lubricant films behaved under load and speed. The amount of wear can also be calculated by weighing the pin before and after testing, using an analytical balance with a ±0.01 mg precision.

During the experimentation, the level of load, speed, temperature and sample preparation was managed to ensure only the IL concentration affected the lubrication performance, as recommended in tribological testing. A thorough assessment made it possible to compare the tribological improvements brought by choline chloride IL at several concentrations within a sunflower oil matrix.

Fig. 5 Sample of Mild Steel Pin

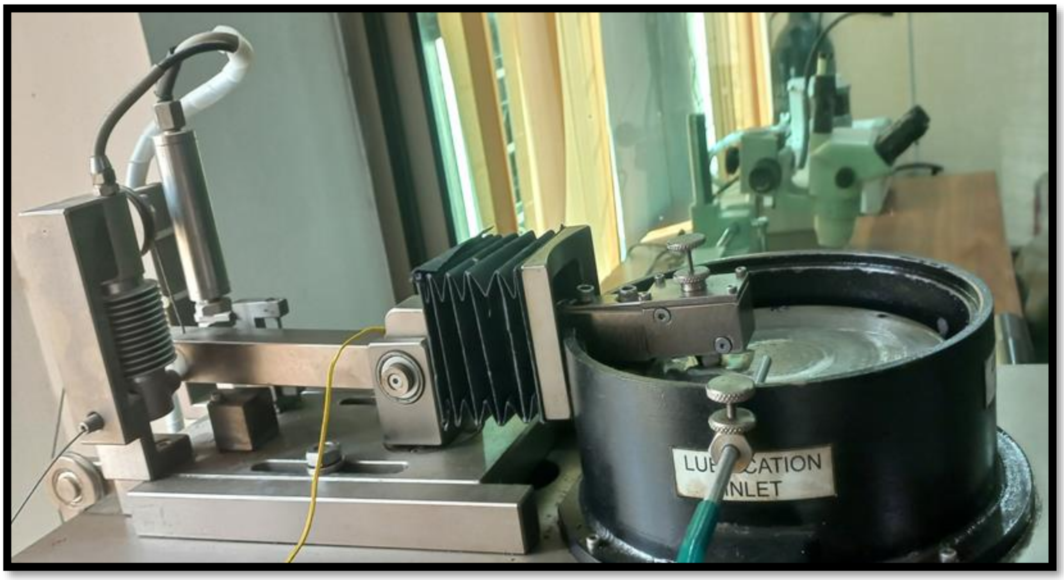


Fig 6. Pin on Disc Apparatus

III. RESULTS AND DISCUSSIONS

A. The Characteristics of ILs and Base Oils

The use of choline chloride-based ILs in lubricants has become popular due to their special properties such as low volatility, great thermal stability and strong interactions between the ions. The presence of ILs in biodegradable sunflower oil improves tribological performance and generates tribofilms that decrease friction and wear. Sunflower oil which is both environmentally friendly and mixes well with additives, makes an excellent base oil. Its good viscosity and clean combustion make sunflower oil suitable for use in industries for machining operations. When choline chloride ILs are added to it, it becomes more reliable under stress and can distribute shear forces more effectively.

B. Friction Test

To check the lubricating ability of IL-enhanced sunflower oil, pin-on-disc tests were performed with 20 N load, a sliding speed of 500 rpm and ambient temperature. The COF was determined for IL concentrations of 0.25 wt%, 0.5 wt%, 0.75 wt% and 1 wt%, as well as for pure sunflower oil.

The formulation with 1 weight percent IL showed the strongest effect on friction, as it reduced COF by 60.43% compared to the base oil. The improved performance is due to the strong adsorption of IL molecules onto the metal which helps to establish a protective and slippery film that stops direct contact between the asperities.

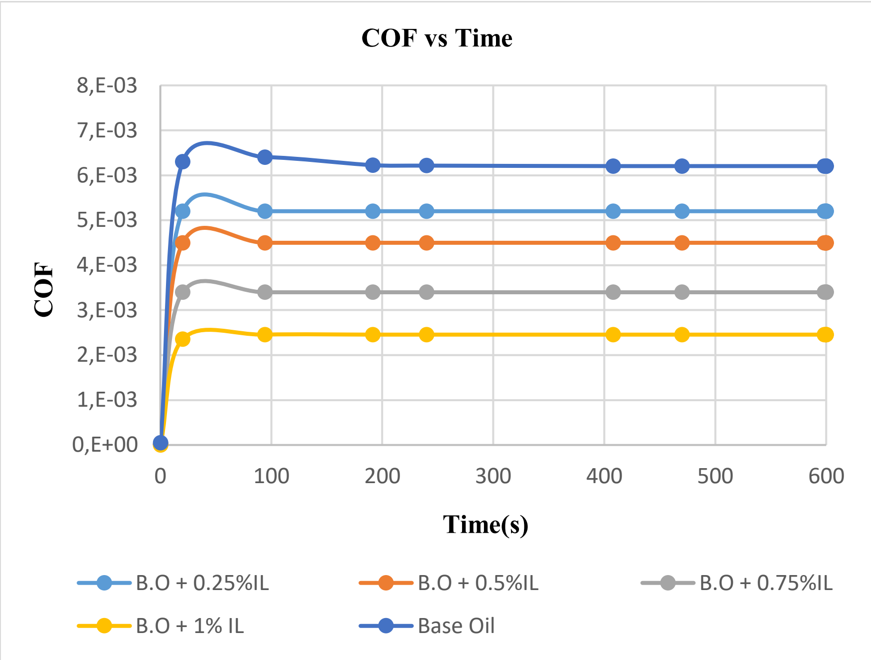


Fig 7. COF vs. Time graph

It is clear from the graph that IL-based lubricants perform much better than the base oil in reducing COF.

Table 3. Percentage Reduction in Coefficient of Friction (COF) Relative to Pure Sunflower Oil

Sample No	Oil + IL	COF	% reduction of COF as compared to the pure sunflower oil (COF=0.006205)
1	0.25 wt% IL + Base Oil	0.005201	16.18%
2	0.5 wt% IL + Base Oil	0.00449896	27.49%
3	0.75 wt% IL + Base Oil	0.00339763	45.24%
4	1 wt% IL + Base Oil	0.00245531	60.43%

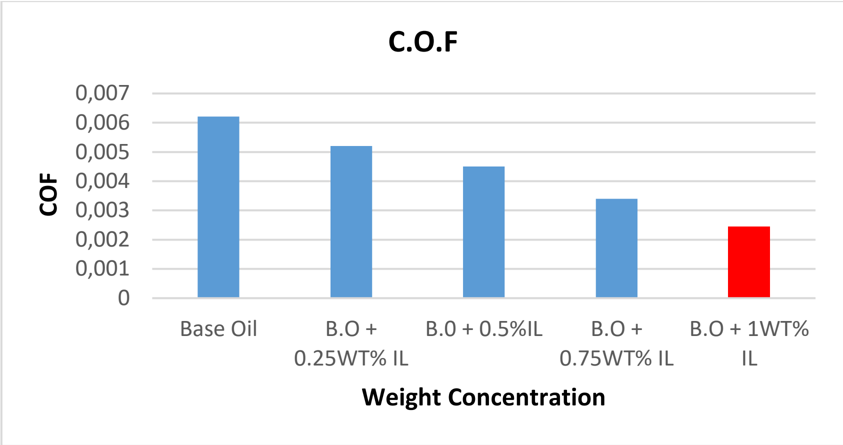


Fig 8. Impact of IL Concentration on the COF of Lubricants

Figure 8 demonstrates the change in the coefficient of friction (COF) as the weight percentage (WT%) of an ionic liquid (IL) additive varies in the base oil. The bars reveal that raising IL concentration causes the COF to drop, meaning the lubrication gets better and the lowest COF (1 WT% IL) is seen at the highest IL concentration.

C. Wear Test

The same pin-on-disc test was used to see how much wear each lubricant caused and the rate of wear was calculated for each formulation. There was a strong link observed between IL concentration and how much wear is prevented.

The 1 wt% IL sample reduced 53.65 % wear, when compared to pure sunflower oil which indicates that a protective boundary film was formed to prevent material loss during sliding.

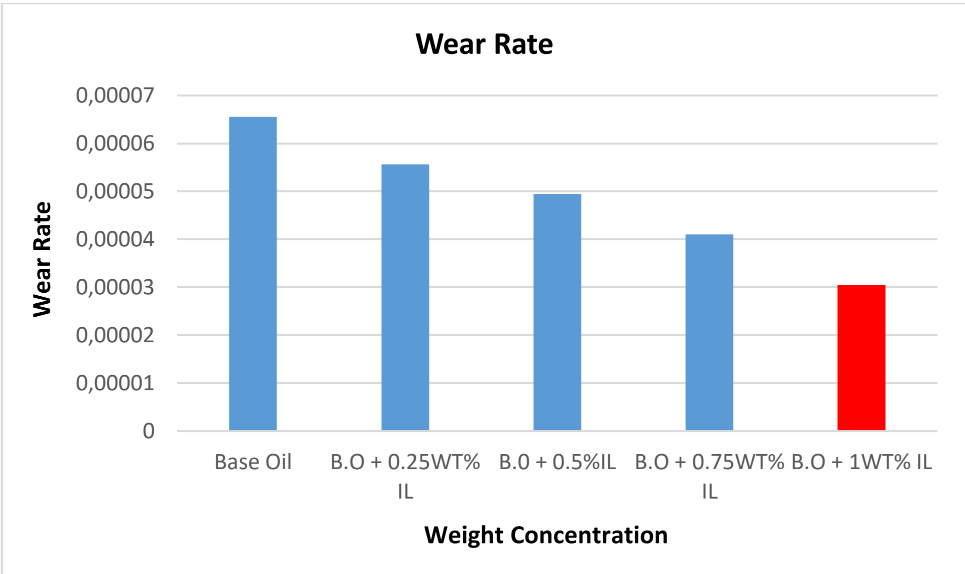


Fig 9. Impact of IL concentration on wear rate

Figure 8 shows how the wear rate of base oil changes depending on the weight concentration of IL additives used. It is clear from the data that the rate at which the parts wear out decreases as the IL concentration rises, indicating a better level of wear protection. The sample with the lowest wear rate (1 WT% IL) was the one with the best anti-wear performance among them all.

Table 4. Percentage Reduction in Wear Rate Relative to Pure Sunflower Oil

Sample No	Oil + IL	Wear Rate	% Reduction of wear rate than pure sunflower oil (wear rate=0.0000656)
1	0.25 wt% IL + Base Oil	0.0000556	15%
2	0.5 wt% IL + Base Oil	0.0000495	24.54%
3	0.75 wt% IL + Base Oil	0.000041	37.5%
4	1 wt% IL + Base Oil	0.0000304	53.65%

Table 4 demonstrates that adding IL to base oil decreases the wear rate much more than using sunflower oil alone. Adding IL additives at 1 wt% instead of 0.25 wt% can significantly reduce wear by up to 53.65%.

D. Study of the Surface and Structure of Worn Tracks

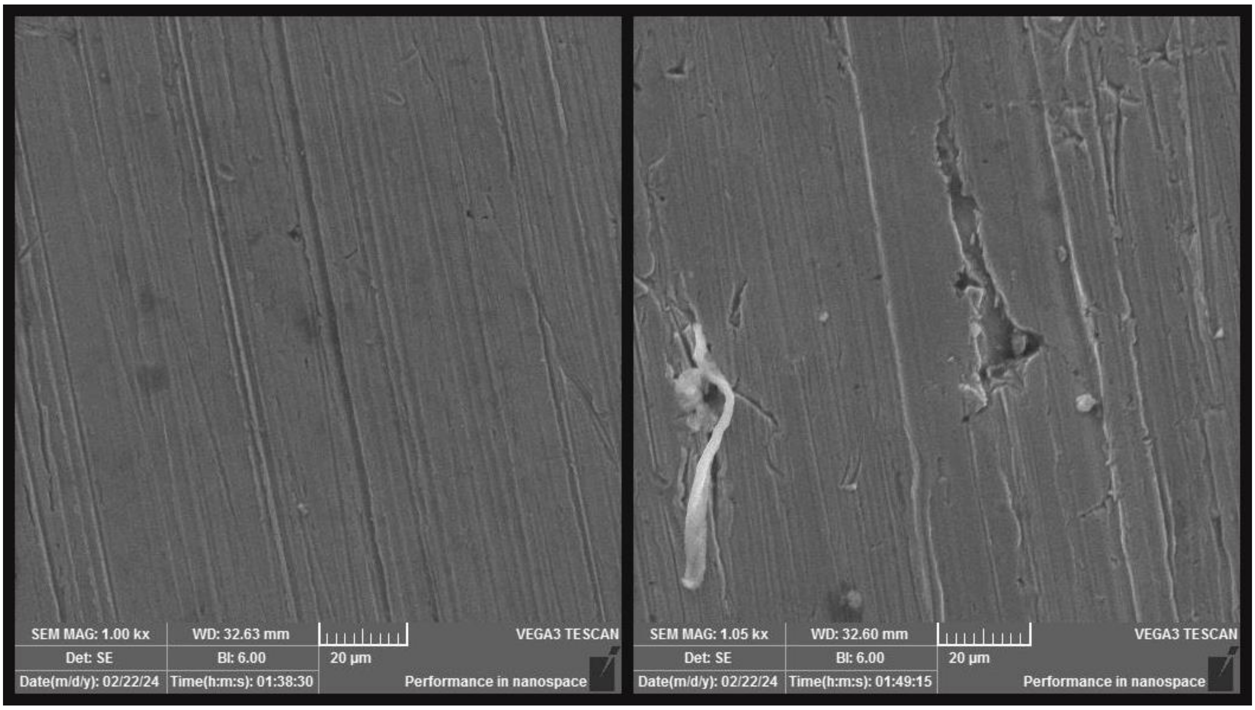
To check the wear condition of the pins after lubrication, a profilometer and SEM were used.

With the addition of IL, the surface roughness was greatly reduced, as seen by stylus profilometry. Compared to lower concentrations and the base oil, the 1 wt% IL sample had a very low surface roughness of 1.37 µm.

Table 5. Surface roughness values.

Sample No.	Sample Composition	Surface Roughness Values (µm)
1	Pure Sunflower Oil	2.97
2	Sunflower oil + 0.25 % IL	2.29
3	Sunflower oil + 0.5 % IL	1.98
4	Sunflower oil + 0.75 % IL	1.72
5	Sunflower oil + 1 % IL	1.37

Results from SEM micrographs supported these findings. Adding 1 wt% IL to the worn surface made it smoother and showed fewer grooves, showing that adhesive and abrasive wear were reduced. Meanwhile, the base oil sample had major wear scars and lost a lot of material which is typical of higher friction and wear.



(a) (b)

Fig 10. SEM Micrographs of the samples

As from the SEM image of the 1 wt% IL + sunflower Oil sample (a) and Pure sunflower oil sample (b) it is evident that 1 wt % IL + sunflower oil proved to be effective in reducing wear and forming effective tribofilm on the pin surface. The enhanced surface and wear performance can be explained by ILs being attracted to metal which helps to form tribochemical films that remain stable and resistant to shear.

III. DISCUSSION

The significant decrease in friction and wear when adding 1 wt% choline chloride IL to sunflower oil indicates that the tribofilm produced by IL greatly reduces metal contact by using strong adsorption forces and distributing the load evenly. This research construes with past studies on IL additives in mineral and synthetic oils and shows that sunflower oil mixed with choline chloride ILs can give similar or better results than others. It has been found through surface analysis that the tribofilm prevents abrasive and adhesive wear which makes the worn surfaces smoother and the components last longer. The fact that choline chloride ILs are stable and sunflower oil is biodegradable and burns cleanly makes this lubricant a good choice for light industrial uses. However, more research should be done to check how IL-based oils behave at different temperatures, how long they last and if combining them with other base oils is possible. Overall, this study takes a step towards greener lubrication by using ILs and bio-based oils together for high-performance results.

IV. CONCLUSION

In this study, sunflower oil was mixed with choline chloride ionic liquid (IL) at several concentrations and tested as an eco-friendly anti-wear additive at normal temperature and typical load conditions. The study showed that adding just 1 wt% IL to sunflower oil improved tribological properties the most, resulting in a 60.43% lower coefficient of friction and a 53.65% reduced wear rate compared to pure sunflower oil. The analysis of surface roughness and SEM images confirmed that the formulation led to the smoothest worn surfaces and fewer defects which means tribofilm formed and protected the surface better than others. The protective film is made by choline chloride IL molecules sticking to the metal surface, so the metals do not come into direct contact and friction is reduced. When ILs were present in smaller amounts, the performance improved slightly, but insufficient coverage on the surface made them less effective than the optimal 1 wt% concentration. The results suggest that choline chloride IL is an effective and sustainable additive for bio-based lubricants. The research supports the development of improved, eco-friendly lubricant formulas that can make vegetable oil-based lubricants more durable and efficient for use in machining operations. Improving the concentration of ILs and studying their interactions with base oils in future research will help create better formulations for various operational conditions.

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