Project title: Enhancing Lubrication Characteristics of Soybean-Based Oils as a Multifunctional Bio-based Lubricant

Principal and Co-Investigators: Sougata Roy (PI), Clement Tang (co-I), Brajendra K. Sharma (co-I), Majher Sarker (co-I)

Background Information: Extensive global research is currently focused on the development of bio-based lubricants due to the environmental concerns associated with mineral oil, which is also rapidly depleting. As a result, there is a growing search for alternative lubricants. Among the most popular base oils are vegetable oil, algae oil, and animal fat oil. Vegetable oils such as soybean oil, sunflower oil, and canola oil are particularly prominent as base oils. Various modification processes, including hydrogenation, esterification, chemical modification, and thermal modification, have been conducted on these oils. While some processes have shown promising results, others have not been as successful. One process of interest is isopropylation, which involves implementing isopropyl group onto the double bonds of unsaturated fatty acids. This process has been carried out on animal fat, such as chicken and beef, with promising outcomes. However, it has not yet been explored on vegetable oils. In this research, isopropylation process was implemented on high oleic soybean oil and observed the resulting changes.

Research Objectives: This proposed research sought to address these challenges by focusing on the primary objective of establishing soybean-based oil as a next-generation multifunctional bio-lubricant and a significant substitute for mineral-based lubricants. The research laid the foundation by investigating the effects of a novel chemical modification process, aiming to formulate high-performance lubricants using high oleic soybean oil. By leveraging the renewable and eco-friendly nature of soybean oil, this research aimed to develop lubricants that not only surpassed the environmental compatibility of mineral oil but also delivered exceptional performance characteristics.

Materials: Regular soybean oil (RSOY), high oleic soybean oil (HOSOY), and modified high oleic soybean oil (BHOSOY) were used for the tests. BHOSOY was produced by replacing the double bonds in saturated fatty acids with isopropyl groups. AISI 52100 steel was used as the flat surface, which slid against silicon nitride balls for friction and wear testing under controlled conditions. Additionally, four distinct types of lubricant additives (MoS2, CuO, ZDDC, ZDDP) were obtained to enhance the performance of the soybean-based lubricant in future applications.

Tribological process parameter design: Process parameters for the friction and wear testing was finalized to simulate gear or bearing contacts for automotive components. The parameters are: applied load-75N, resulting Hertzian contact pressure 1.9 GPA, sliding velocity 0.1 m/s with stroke length 10 mm for a total sliding distance of 500m. Tests were conducted in room and 100°C temperature.

Design and development of small-scale sample holder: When conducting research with limited funding, it's important to be able to run tests using smaller amounts of lubricants. To address this, a sample holder was designed that required only 10 ml of lubricant per test, compared to the usual 35 ml in a standard holder. Initially, a Generation 01 of the holder was developed, but it encountered design issues and yielded inconsistent results during testing. Subsequently, the drawing board was revisited, and modifications were made to create Generation 02, which proved to be highly successful. For the initial prototypes, aluminum was used for its ease of shaping, but the final version utilized A36 Alloy steel for superior quality.

Results: The physico-chemical properties of three types of soybean oils were measured: HOSOY, BHOSOY, and RSOY. From table 1, It was observed that BHOSOY had a significant increase in viscosity compared to both HOSOY and RSOY. However, there were positive improvements in other properties. The oxidative peak temperature of BHOSOY increased from 211.1°C to 213.7°C, indicating enhanced resistance to oxidation, which was higher than both HOSOY and RSOY. Furthermore, BHOSOY exhibited improved pour point, going from -10.5°C to -14°C, indicating a lower temperature at which solidification begins, compared to HOSOY and RSOY. Similarly, the cloud point of BHOSOY decreased from 12.4°C to 5.9°C, indicating a lower temperature at which cloudiness or haze appears, also outperforming RSOY.

Table 1: Physico-chemical properties of three different soybean oils

	Temp, °C	RSOY	HOSOY	BHOSOY
Density (g/cm3)	40	0.9066	0.8993	0.8965
	100	0.8668	0.8596	0.8573
Dynamic viscosity (mPa/s	40	27.83	35.02	127.42
	100	6.53	7.30	16.62
Oxidative Peak Temp, PT (°C)	-	189.8	211.5	213.7
Pour Point (PP ºC)	-	-8.1	-10.5	-14.5
Cloud Point (CP ºC)	-	17.4	12.4	5.9

Two friction and wear tests were performed using soybean oils RSOY and HOSOY, showing similar results. Due to the higher stability of HOSOY, it was chosen for further tests. Three experiments were conducted to compare the performance of two soybean oil types: HOSOY and BHOSOY. The aim was to see how they behave under friction and wear conditions. From Fig 1, it was found that BHOSOY had higher friction than HOSOY at both normal and high temperatures. This was because BHOSOY was thicker and more viscous. However, BHOSOY showed more stable friction behavior than HOSOY in all conditions. When it came to wear, BHOSOY performed better than HOSOY by being 10.6% more resistant to wear. This means that BHOSOY lost less material or got damaged less compared to HOSOY under the same conditions. To reduce the friction of BHOSOY and improve its wear resistance, future studies will look into using different additives.

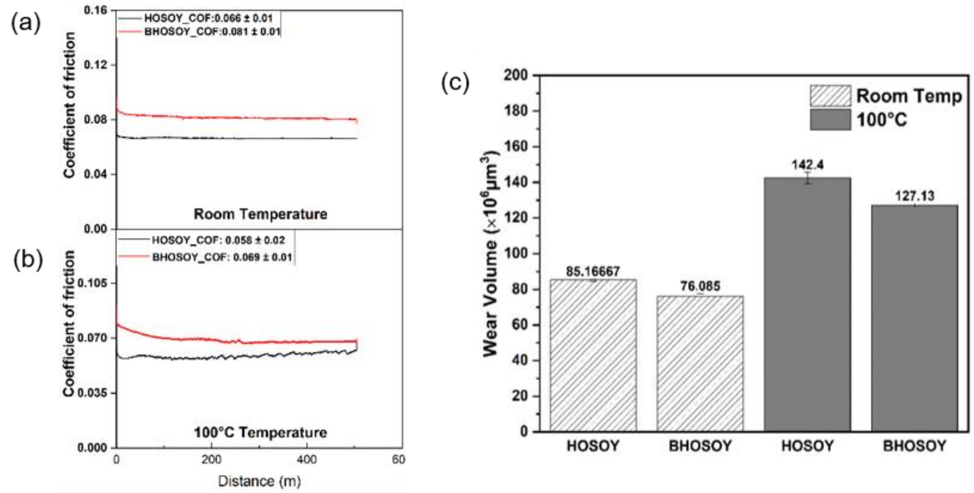

Fig 1: Coefficient of friction result (a) room temperature (b) high temperature (c) wear volume loss

Profilm images in (Fig 2) show that wear marks are similar for both HOSOY and BHOSOY when viewed from the top, but there is a noticeable difference in depth (Fig 2b) when viewed from the cross section.

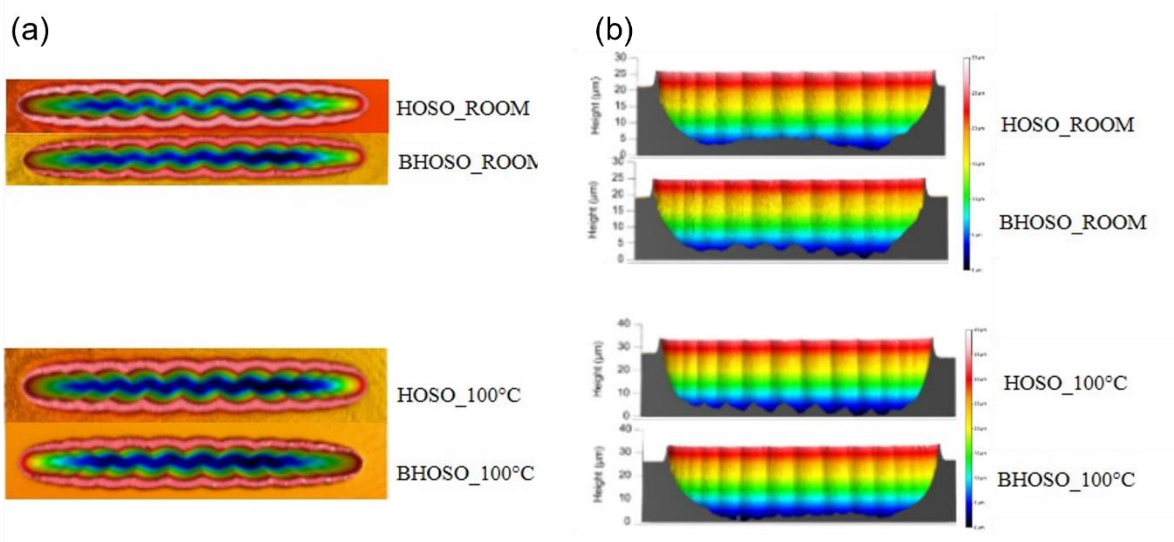

Fig 2: White light interferometry images of wear tracks (a) top view (b) cross-sectional view

SEM and EDS analysis of wear tracks (Fig 3) showed that only abrasive wear occurred in all samples, with no material transfer from the ball to the flat samples. Material removal was observed, except for BHOSOY at room temperature. HOSOY had the highest material removal compared to BHOSOY. Additionally, when looking at the width of wear, BHOSOY had the smallest values in both temperature conditions compared to HOSOY.

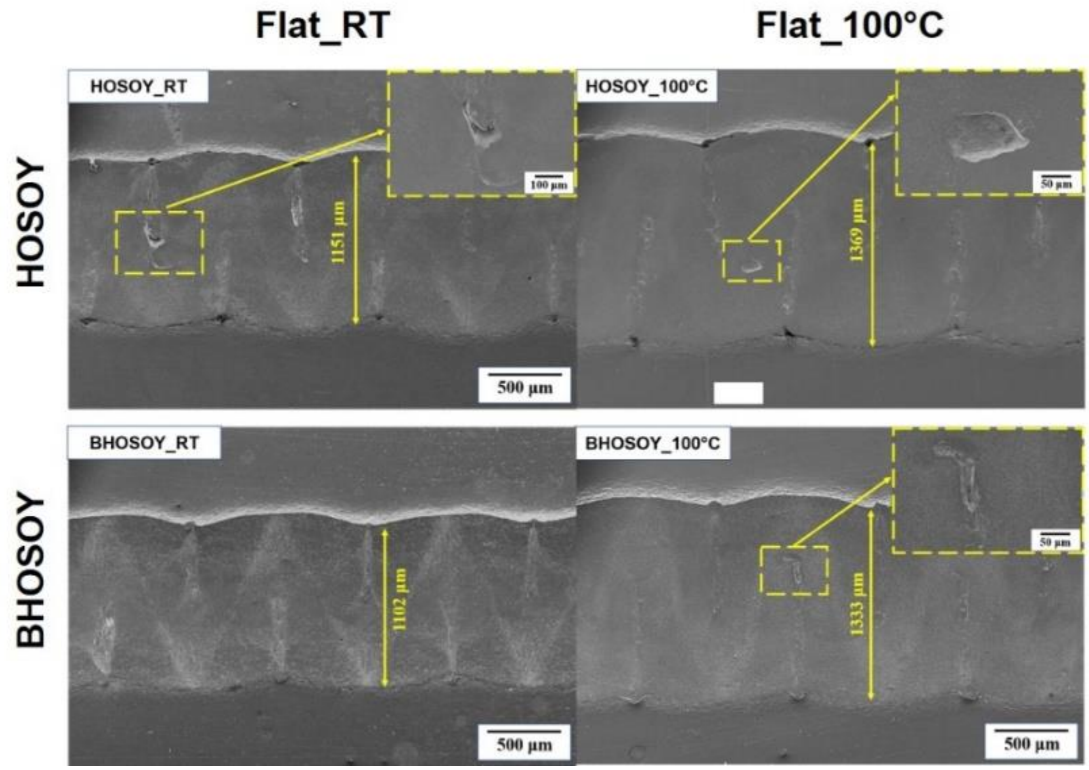

Fig 3: Scanning Electron Microscopy images of wear tracks experimented under different lubrication conditions. (Note- RT-Room temperature, Flat-AISI 52100 test sample)

Benefits to ND soybean farmers and Industry: The research on bio-based lubricants using soybean oil holds significant potential to benefit farmers in North Dakota. With soybean production in the state increasing over 50 times from 1980 to 2022, North Dakota demonstrates a remarkable capacity for soybean growth. In 2015, the production of soybeans in North Dakota reached almost 250 million bushels, indicating a strong foundation for further expansion. By focusing on soybean cultivation, farmers can tap into a market that offers increased profitability. Currently used primarily in food products, cooking oil, and animal feed, the utilization of soybean oil for lubricating oil production opens up new opportunities. If soybean oil becomes a prominent ingredient in lubricants, there is a strong possibility of a surge in soybean market prices, which would greatly benefit North Dakota farmers. Additionally, this research contributes to sustainable agricultural practices, aligning with the growing demand for eco-friendly products. By diversifying their income streams and embracing this research, farmers can stimulate economic growth, create employment opportunities, and enhance their overall resilience in North Dakota's agricultural sector.

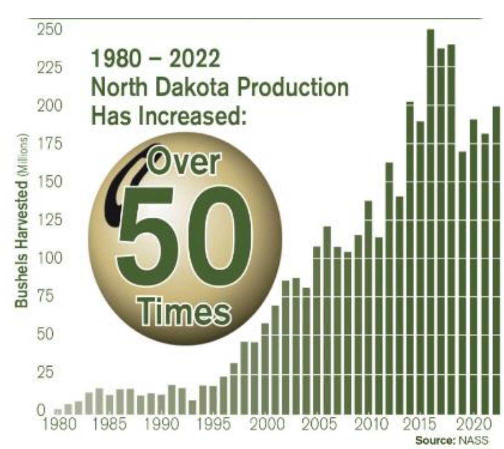

Figure 4. Harvested Soybean Yield in North Dakota (1980-2020)