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. Some of the major 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. Additionally, the study explored the incorporation of select additives to enhance the oil's surface protection behavior. 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 in 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 (MoS_2, 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 utilized during testing were: 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 (figure 1) that required only 10 ml of lubricant per test, compared to the usual 35 ml in a standard holder. Initially, a Generation 01 holder was developed, but it encountered design issues and yielded inconsistent results during testing. Subsequently, the drawing

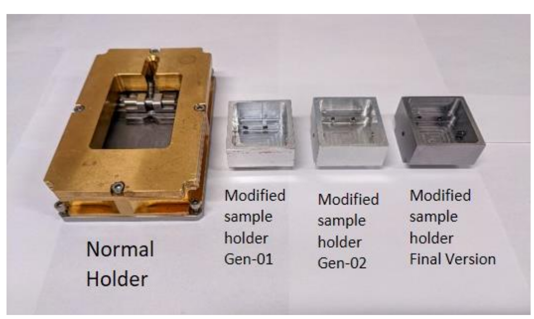

Figure 1: Sample holder development for tribo-tests

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 and discussions: Overall findings can be broadly divided into two parts-(a) physio-chemical properties of raw and chemically modified soybean oil and (b) tribological behavior of lubricants before and after chemical modification.

Enhancement of physio-chemical properties due to chemical modification: During the tests, 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 HOSOY and RSOY. These findings suggest that BHOSOY demonstrates favorable improvements in oxidative stability, pour point, and cloud point compared to both HOSOY and RSOY. In particular, for colder regions like North Dakota or Minnesota, the chemically modified lubricant can outperform regular and high oleic soybean oil-based lubricants.

Table 1: Physicochemical 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 °C)	-	-8.1	-10.5	-14.5
Cloud Point (CP °C)	-	17.4	12.4	5.9

Comparative analysis of tribological behavior of soybean oil-based lubricants: Preliminary tribological tests were conducted using RSOY and HOSOY lubricants as presented in Figure 2. Test results revealed similar friction behavior but slightly enhanced wear resistance under HOSOY lubricated condition was observed. Consequently, the additional tribological tests using chemically modified HOSO an raw HOSO were performed. Three experiments were conducted to compare the performance of two soybean oil types: HOSOY and BHOSOY. As showed in Figure 3, BHOSOY presented higher coefficient of friction than HOSOY in both room and high temperatures. The increase in the coefficient of friction in BHOSOY was likely due to its higher viscosity, meaning it was thicker. However, BHOSOY showed more stable friction behavior than HOSOY in all conditions. In terms of wear volume, which represents the amount of material worn away or removed due to friction or abrasion, BHOSOY outperformed HOSOY by exhibiting 10.6% greater wear resistance. This means that BHOSOY experienced less material loss or damage compared to HOSOY when subjected to the same friction and wear conditions. In order to address the higher friction value of BHOSOY compared to RSOY and enhance its wear resistance, future studies will explore the use of different additives. The aim will be to minimize the friction value and improve the overall wear performance of BHOSOY.

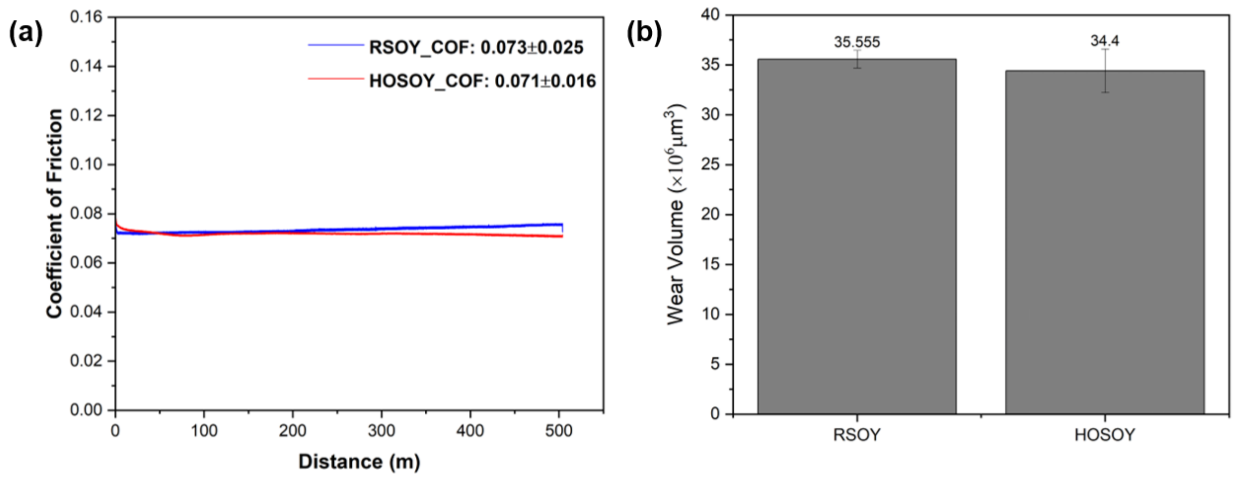

Figure 2: Comparison of Coefficient of Friction (a) and Wear Volume (b) in regular and high oleic soybean oil

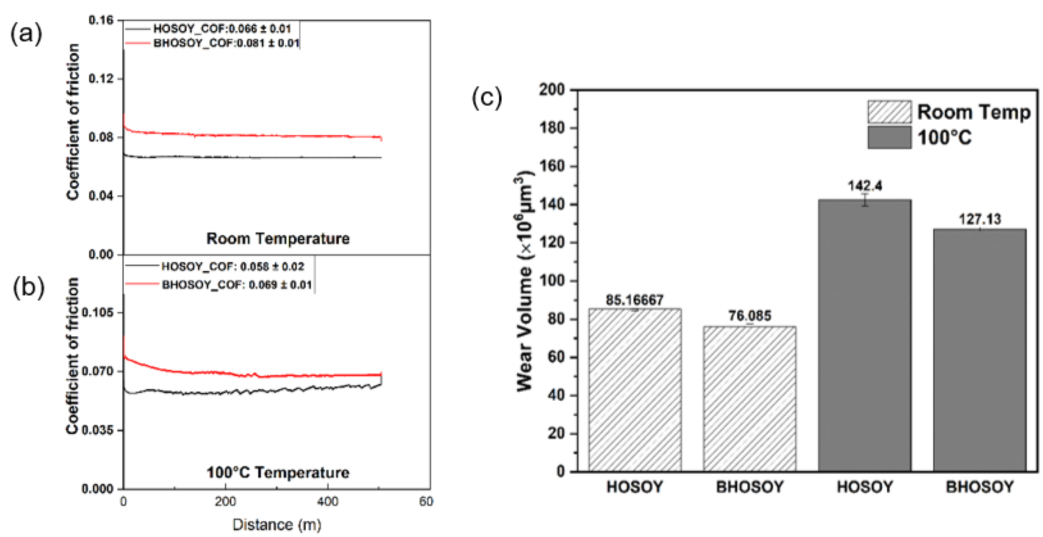

Figure 3: Coefficient of friction result (a) room temperature (b) high temperature and (c) wear volume loss

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 turn-over with various value-added products. Currently it is used primarily in food products, cooking oil, and animal feed, but the utilization of soybean oil for lubricating oil production will open 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.

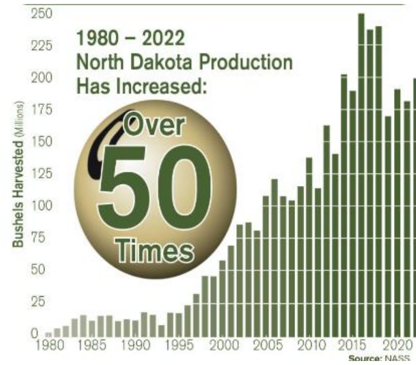

Figure 4. Harvested Soybean Yield in North Dakota (1980-2020)