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Development of Vegetable Oil-Based Nano-Lubricants Using Ag, h-BN and MgO Nanoparticles as Lubricant Additives

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DEVELOPMENT OF VEGETABLE OIL-BASED NANO-LUBRICANTS USING AG, H-BN AND MGO NANOPARTICLES AS LUBRICANT ADDITIVES

A Thesis

by

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ABSTRACT

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Because of the harmful impact of petroleum-based lubricant on the environment and human body, vegetable oil-based lubricant with eco-friendly nanoparticles has a great potential to be an alternative lubricant if it possesses proper lubricating properties. In this study, thermal conductivity, viscosity and tribological properties (wear scar diameter and coefficient of friction) of vegetable oil-based nanolubricant, developed from soybean oil and sunflower oil, modified with Ag, h-BN and MgO nanoparticles as lubricant additives, were evaluated. For thermal conductivity evaluation, a line heat source method was used with KD2 Pro-Thermal Property Analyzer. For viscosity evaluation, Haake Mars 40-rheometer was used to evaluate viscosity as a function of share rate and temperature. And for tribological properties evaluation, a fourball tester, named FBT-3 was used to obtain coefficient of friction and a digital image acquisition system, IAS-3 was used to measure wear scar diameter. It is observed that for all the samples, thermal conductivity increased as a function of nanoparticle concentration with increased temperature. The viscosity of all the sample showed a consistent result as a function of nanoparticle concentration and dropped significantly in response to increased temperature. Also, it has been observed that coefficient of friction and wear scar diameter lowered down to a certain nanoparticle concentration and then

raised again as a result of increased nanoparticle concentration. These newly developed nanofluids can be promising alternatives to conventional petroleum-based lubricant.

DEDICATION

This thesis work is dedicated to Chandana Choudhury, my mother; Hillol Sarker Jogesh, my elder brother; Sarker Hirendra Chandra, my beloved father; and Dipasree Bhowmick, my loving wife. They completely inspired, motivated, and supported me in every way possible to complete this degree. Thank you for your kindness and understanding.

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CHAPTER I

INTRODUCTION

1.1 Problem Statement

Lubrication is an old concept, reaching back to the prehistoric time. The application of fluid to different surfaces that are moving to reduce wear as well as friction is known as lubrication(Chen et al. 2020). The primary purpose of lubricant is to lessen friction and wear in machinery (bearing, shaft), to transmit heat away from hot surfaces, and to prevent mechanical parts from failure. Mineral oil is produced from fractional dstillation of crude oil and it has long been used as a lubricant, although it has certain detrimental health and environmental implications. As a result, the top objective now in research area is to reduce pollution and develop something environmentally friendly. Researchers are actively seeking for alternatives, such as biodegradable vegetable oils, in response to this problem. Vegetable oils are derived from various types of seeds, nuts, cereal grains, and fruits(Savva and Kafatos 2016). Furthermore, the depletion of fossil resources, fluctuating petroleum prices, and rising environmental health concerns have raised interest in biodegradable lubricants. The substitution of vegetable oils for mineral and petroleum-based oils has been

proposed as a viable solution to these problems. Though vegetable oil could be a potential source of vaiable, it has some downsides as well. Researchers have been trying to address this issues.They have been applying different methods including adding different nanoparticles as an additive with these vegetable oilsto improve their properties; like thermal conductivity, viscosity, tribological properties etc. There are different types of nanoparticles which can have an impact on the properties of a fluid, such as carbon-based nanoparticles, metal nanoparticle, ciremic nanoparticle, polymer nanoperticle etc(Khan, Saeed, and Khan 2019). But not all of these nanoparticles are environmentaly friendy. Some can hamper the ecology of the environment while other can detoriate human or animal health(Khan, Saeed, and Khan 2019). So even if the fluid is environment friendly in nature, adding nanoparticles which is harmful for the environment with these fluid will sabbotage the mission to develop a proper environment friendly lubricant eventually. That's why choosing appropriate nanoparticle is a very important step while developing such eco-friendly lubricant. Now, it is important to understand wheather adding nanoparticle to vegetable oil is contributing to improving fluid properties or not. And to confirm that there are different tests which can be performed; such as evaluating thermal conductivity, viscosity, tribological properties etc. Thermal conductivity of a fluid is a physical property which indicates how fast it can conduct heat from one point to another point within the fluid. On the other hand, viscosity defines the resistance of the fluid to flow under shear stress. Tribological properties, like dimension of wear scars on the moving machine parts, coefficient of friction while using the lubricant within a machine help user to indentify how effectivly the lubricant is working against wearing.

To evaluate thermal conductivity, different thermal conductivity measuring techniques can be used. Among them, to measure thermal conductivity in a short period of time, transient hot wire technique could be a very reliable method(Palacios et al. 2019). To measure viscosity, rotational viscometry is a method which is widely used because of it's simplicity in use and accuracy of results. It provides viscosity in respose to a range of changing shear rate and can be used to evaluate viscosity of a fluid at elevated temperatures as well. For tribological test, among various test methods, four ball test method is well known for its applicability for different types of fluids and accuracy of results.

Ease of use is also a determining factor for choosing four ball test method to evaluate tribological properties.

Now, having all these test reults will finally help us understand which combination of fluid and nanoparticle is performing better under certain circumstances and validate the reasoning behind choosing a particular nanofluid for a certain type of application.

1.2 Proposal Statement

Petroleum-based lubricant is imposing several detrimental effect on the environment such as reducing oxygen level in the water(Aluyor and Ori-jesu 2009), low biodegrability(Specialties 2020), deteriorating soil quality(Abosede 2013)and many more. For example, oil droplets produced from open cutting machine can cover the soil, water surfaces as well as leaves of plants which might have a strong effect on the ecosystem(Nowak, Kucharska, and Kamiński 2019). Even 1ppm of oil in water is considered contaminated (Nowak, Kucharska, and Kamiński 2019). Oil spillage in an aqatic body may prevent sunlight enter the bottom area of a water body which eventually may cause starvation of oxygen and hinder developmnt of aqatic plants. Also, oil mist upon getting through the respiratory system can hamper several major human organs including kidney, heart, liver, lungs and many more (Nowak, Kucharska, and Kamiński 2019). So, to address these problems, a greater emphasis has been placed on biodegradable lubricants as opposed to mineral and petroleum-based lubricants. Because, these ecofriendly lubricants are readily biodegradable and has properties which is essential for a fluid to be used as a lubricant. On the other hand, because of their efficiency in improving lubricant properties, nanoparticles are being explored as lubricant additives to increase lubricant's overall thermal performance and minimize system wear and friction. This study investigates the effects of Ag, h-BN, and MgO nanoparticles as lubricant additives with soybean oil and sunflower oil.

1.3 Research Objectives

The fundamental goal of this research is to encourage and inspire future researchers to develop new low-cost, environmentally friendly nanomaterial-based lubricants. Various quantities of Ag, h-BN, and MgO nanoparticles will be used to test the lubricating ability of vegetable oils (soybean and sunflower), which includes the ability to remove heat from a heated area, having sufficient load carrying capacity and viscosity, and the capability to reduce friction between two rubbing surfaces. This research will examine thermal conductivity, tribological properties (wear scar diameter and coefficient of friction), and viscosity of lubricants to investigate how the inclusion of nanoparticles with soybean oil and sunflower oil at different concentrations impacts these parameters.

1.4 Thesis Organization

There are five chapters in this dissertation. The first chapter contains background information on the subject at hand, as well as a summary of the research questions, assumptions, and objectives. The second chapter is a literature review, focusing on the history of lubricants, lubricant additives, and why we chose these particular base oils and additives. The third chapter outlines the whole experimental setup, including material preparation and testing techniques. All of the experimental findings are described and discussed in the fourth chapter. Finally, chapter five brings the research endeavor to a close.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

Today in industrial metal-mechanic field, manufacturing involves stamping, machining, sheet forming etc. wearing and damage of tooling can happen while the process generates a high amount of friction. Therefore, it is crucial to reduce friction and remove the heat generated from the process as well. For these purposes, lubricants are used extensively. Lubricant generates a thin film between two contact surfaces that mitigate friction between them, hence, reduce the damage(Belluco and De Chiffre 2002). On the other hand, there are different mechanisms through which the generated heat is dissipated. If the lubricant is not able to draw out heat from the system efficiently, the generated heat can deteriorate the machine parts which is in contact with the lubricant and quality of final product can also be compromised. It can also cause a costly damage in some instances. Petroleum based lubricants have been serving all the purposes efficiently for a long time. But a recent concern of compatibility of petroleum lubricant with the environment is arising to save the environment from being contaminated. To tackle the challenge, different approaches have already been taken by many researchers. In the next sections, we will discuss what are the downsides of petroleum lubricants and how researchers are coming up with different ideas to confront the challenges.

2.2 Issues With Current Petroleum-Based Lubricants

Petroleum based lubricants are being used for many years (Vowles 1932). But it has different issues which come into play while choosing it. Biodegradability is one of them (Nowak, Kucharska, and Kamiński 2019). When we refer something as biodegradable lubricant, we consider the lubricant is readily biodegradable, which is not applicable in case of petroleum-based lubricant. According to ISO 9439 or OECD 301B standards(Specialties 2020), biodegradable lubricant degrades more than 60% within 28 days. Petroleum lubricants are not readily biodegradable as it doesn't satisfy this standards. They only degrade naturally 25% to 35% in 28 days, while the required rate is 60%.

In the purest form, petroleum oil contains a little toxicity, but the scenario is different in case of petroleum oil-based lubricant. Pure oil cannot be used as an effective lubricant as it lacks some required properties. Additives are mixed with the pure oil to improve the lubricity and the resulted oil posseses more negative impact overall on the environment(Nowak, Kucharska, and Kamiński 2019). A lubrucating oil may contain multiple additives which may ranges from ppm scale to few percentage(Tang and Li 2014). Now, as the lubricant market is growing every year, an excessive use of petroleum lubricant is expected in coming years which is now a major concern both for environmentalist and also for public health personals.

2.2.1 Environmental Issues

Lubricating oil is released into the atmosphere in the form of oil mist and microdroplets, and it is responsible for a significant amount of environmental damage. The composition, emission volume, and frequency in a given area are closely related to the intensity and consequences of interactions caused by oil derivatives. And this emission of oil into the environment can happen in different ways. Used lubricant disposed in open environment can contaminate both soil and air.

For an aquatic ecosystem, this lubricating oil is largely threatening. Any leakage while transporting lubricant by water path can result in a disastrous event for the aquatic life. If the water contains 1ppm of oil, it is considered contaminated(Nowak, Kucharska, and Kamiński 2019). The thin film of oil on water surface, resulted from the spillage or discard of used lubricant oil can hinder exchange of oxygen and gas between water and the air. On top of that it can also prevent sunlight from being penetrated to deep water. This phenomenon can lead to a disturbance of functioning and metabolism of aquatic environment, and consequently, a lack of oxygen can occur in the water body which eventually can lead to a disorder in the ecology disorder. The process of photosynthesis will eventually slow down as a consequence of this. It is possible for eutrophication of the reservoir to occur as a result of an increase in water temperature caused by the absorption of solar radiation. This can prevent the healthy development of aquatic vegetation(Aluyor and Ori-jesu 2009).

When the life cycle of motor oil, i.e., lubricating oil used in combustion engine, comes to an end, it is stored separately to be recycled. If at any stage of storage, the oil gets leaked, it can seep into the soil and damages it through multistep physiochemical process. This process changes the shapes and forms of carbon, phosphorus, nitrogen based organic matter. [11]. Besides, as verity of microorganism and higher living organisms have an ecosystem around soil, spoiling it can lead to a disastrous effect on biological life system on soil and the ecosystem may not be able to work as it should. On top of that the oil can clog the pore spaces of soil which can prevent air and water enter soil. As a result, the amount of oxygen compound may be reduced in the ground and the permeability of soil might get limited. And also, degradation of soil can happen due to lack of oxygen [11].

2.2.2 Health Issues

Concerning the long-term health impacts of oil application and emission, the carcinogenicity of base oils that are obtained from crude oil is a topic of public controversy(Włodarczyk-Makuła 2016). While operating a machine with open cutting system generates oil mist which goes into the respiratory system, it affects the lungs and also causes damaging major human organs (Aluyor and Ori-jesu 2009). It can be irritating to the skin as well as trigger allergic reactions. People who are subjected to the oil mist that results from the operation of cutting devices for extended periods of time have an increased risk of developing cancer, most commonly skin cancer(Aluyor and Ori-jesu 2009).

A saw operator, for instance, because of the nature of their activity, such as logging, stays in an environment that has a high degree of contamination with harmful substances. This is the case because of their exposure to these substances. This oil mist may contain a variety of hazardous compounds, including aromatic hydrocarbons and polycyclic aromatic hydrocarbons, among others (PAHs). Additionally, it may contain toluene, benzene, or methylbenzene, all of which have the potential to have a detrimental effect on the respiratory system of the operator. According to research, typical complaints from operators include irritation of the eye, problems with the upper respiratory tract, headaches, and weariness (Gawęda, Bednarek, and Szydło 2005; Neri et al. 2016). Mineral oils are also known as carcinogens, and we can see from medical records that it can cause eczema and oil acne On the other hand, long term exposure to oil-based oil mist may cause irritation to the respiratory tract if it is not properly ventilated(Järvholm et al. 1982).

Benzene, butane, n-hexane, isopentane, pentane, and stoddard Solvent are all present in crude oil(Barker 1985). Benzene is a proven human carcinogen that has been classified as a Group

1 carcinogen by the National Toxicology Program, OSHA, and the International Agency for Research on Cancer. Leukemia and other malignancies are caused by chronic inhalation of minute amounts of benzene(D'Andrea and Reddy 2018). Butane inhalation can induce brain irreversible damage owing to suffocation. Butane is also cardiotoxic, meaning that it has the potential to bring about both ventricular fibrillation and cardiac arrest(Tahir, Pokorny, and Malek 2021). In a study, Takeuchi *et al*.(Takeuchi et al. 1980) found n-hexane is responsible for the motor nerve disturb. However, n-pentane is found to be non-toxic(Takeuchi et al. 1980).

In addition, the majority of petroleum products deteriorate over time. In fact, it is occasionally vulnerable to unavoidable interactions with ambient components. The products undergo change as a result of sunshine and interaction with oxygen and soil components. Generally, secondary compounds may be more poisonous and hazardous to human health than their primary counterparts. It is anticipated that derivatives resulting from the bioconversion of chemicals released into the environment may be more hazardous than their original antecedent (Rogoś and Urbański 2010).

2.3 Use of Vegetable Oils

In search of a solution, researchers have been looking for alternatives that are sustainable, free of harmful substances, dependable, and affordable. One of the most important breakthroughs occurred in the transportation industry, with the development of biodiesel as a more environmentally friendly and renewable fuel alternative to diesel fuel (Kasolang et al. 2012). As a result, vegetable oil has been put through various tests, and it looks to have the ability to replace fluids that are based on mineral oil. They don't contain toluene, xylene, benzine or other toxic compound which can detriment human health. Vegetable oil, unlike petroleum oil, is sustainable in nature. Only 1.42 trillion barrels of petroleum oil are left in the proven reserve, which is equivalent to 47 years of anticipated demand(World Oil Statistics - Worldometer n.d.). Vegetable oils, on the other hand, may be cultivated in the field without the depletion that petroleum oil does. Furthermore, whereas petroleum oil has a biodegradability of 30%(M. Rafiq et al. 2015), vegetable oil has a biodegradability of over 95% and is renewable in nature(Oommen 2002; Tenbohlen and Koch 2010).

These oils include essential lubricant characteristics including low volatility, high lubricity, a high viscosity index and advanced attributes comparable to mineral oil, such as low toxicity and high biodegradability(Syahrullail et al. 2011). Comparable to mineral oils, vegetable oils include advanced qualities, including low volatility. Usually, vegetable oils are comprised of triglycerides which are molecules of glycerol with three molecules of long-chain fatty acids attached to the hydroxyl group by ester bonds (Samion, Nakanishi, and Kamitani 2005). Triglycerides make up the majority of vegetable oils. The chain lengths and numbers of double bonds of the fatty acids that can be found in natural vegetable oils are each unique. The ratio of carbon-carbon double bonds and their positions in the molecule are what determine the fatty acid makeup. In the majority of instances, the carbon in the long chain is held together by either one, two, or three double bonds, which correspond to the oleic, linoleic, and linolenic fatty acid components, in that order. In other words, the number of double bonds that hold the carbon together depends on the number of fatty acid components. The vast majority of oils obtained from plants contain at least four and frequently as many as twelve different kinds of fatty acids. This is true for almost all of the oils. Triglycerides, according to their structure, possess favorable qualities that contribute to the lubricating of borders. They are capable of producing lubricant coatings that have a high strength and strongly interact with metallic surfaces because of the long and polar fatty acid chains that make up their structure. Because the robust connection among molecules are resistant to changes in temperature, the viscosity, also known as the high viscosity coefficient, is maintained with greater consistency. Because of these powerful interactions between molecules, a long-lasting lubricating coating is produced. The fluid does not lose its ability to biodegrade and maintains a low level of toxicity during its whole existence.

Lubricant formulations are currently being designed with careful consideration being paid to the benefits and downsides associated with the use of vegetable oils. In comparisons of anti-wear and friction efficiency, scuffing load capacity, and fatigue resistance, mineral-based oils performed more poorly than vegetable oils without additives (Samion, Nakanishi, and Kamitani 2005; Tiong et al. 2012). Because of this, vegetable oil has a lower friction coefficient, a comparable load carrying capacity, and superior pitting resistance than other oils.

2.3.1 Issues with Vegetable Oil-Based Lubricant

Although vegetable oil is promising to substitute petroleum based lubricant, it also has some drawbacks that petroleum-based lubricants didn’t have. Vegetable oil-based lubricant has low oxidation stability. Oxidation stability can be defined as the resistance of a lubricant’s molecular structure to rearrange or disintegrate in presence of oxygen at higher temperature (Pullen and Saeed 2012). Vegetable oils which possess poly-unsaturated fat mostly have low oxidation stability (Madhujith and Sivakanthan 2018). It is believed that the structural "double bond" elements in the fatty acid part of vegetable oils and the " β -CH group" of the alcoholic (glycerin) components are to blame for the oxidative instability of these oils. In most cases, the presence of many double bonds is problematic for technical application (Maszewska et al. 2018). In alkalyn chains there is bis-allylic protons which has multiple bonds and those are highly likely to radical attack and afterward they go oxidative degradation and form polar oxy compound (Salimon, Salih, and Yousif 2011). By this, it generates in-soluble deposits and increase in viscosity and oil acidity which in turn caused higher corrosion in the machine part which are being lubricated. On the other hand, sedimentation and sludge can clog the valves and circuits and they also cause equipment's to malfunction. So, when its properties degrade, lubricant needs to be changed. On top of that, the replacement cost causes a higher operating cost. Now, different methods have already been applied to challenge the problems. Before looking into those in detail, first, we will see how petroleum-based lubricants properties have been improved using nanoparticles. It will provide the contex how the same approaches have made vegetable oil worth competiting enough with petroleum based lubricant.

2.4 Properties of Lubricant

2.4.1 Thermal conductivity

Thermal conductivity of a substance can be defined as how fast heat can travel from one point of a substance to another point(Dayana et al. 2020). It depends on the chemical structure of the material, temperature and pressure they contain and their phase as well. A lubricant does provide a barrier layer between two moving surfaces, however, it also takes heat out of the hot surfaces as thenmoving parts move against each other(Dayana et al. 2020). Otherwise, the contact points will melt and deteriorate the materials of the moving surfaces and also can impact the final product if the fluid is used as cutting fluid. Steady state method is one of the standard methods for measuring thermal conductivity. To measure it, heat has to be applied on the substance and wait for until there is no temperature changes on it. In this method we measure heat flux and temperature gradient to measure thermal conductivity. But a drwback of thos method is sometime we have to wait a long time to get the temperature at steady state and sometime this situation can never be achieved. To tackle the chalange, there is another method, called transient line heat source method, which is being used widely. In this procedure, a short pulse of heat is applied on a needle. And temperature adjacent to needle is measured and amount of heat applied is used to measure themal conductivity accurately.

The thermal conductivity might be determined by applying Equation 1 to the problem.
$$\Delta T = \frac{q}{4\pi k} \ln\left(t + t_0 \right) + C$$

Equation 1

Here,

Δ T = Temperature drift in probe

q = Heat applied in the probe (W/m)

k = Thermal conductivity of fluid(W/m.k)

t = time(s)

t_0 = Time of offset (s)

2.4.2 Viscosity

Viscosity of a material can be defined as the resistance of a fluid to move in response to shear stress. For a lubricant, viscosity plays a vital role for proper functioning of the moving parts. If viscosity of the lubricant is too high, i.e. the fluid is too thick, the machine will require more power to circulate the fluid within the system; as a result, it will generate more hear, wear and tear. On the contrary, if viscosity is too thin the protective layer which prevents the moving surfaces from wearign and tearing may not able to. So it is important to have viscosity under a certain limit for a specific operation. To measur viscosity, the following equation can be followed:

$$\mu = \frac{\tau}{\gamma}$$

Equation 2(M. 2018)

Here,

m = viscosity of the fluid (cP)

g = Shear rate of the fluid (s-1)

t = Shear stress on the fluid (Pa)

2.4.3 Coefficient of Friction and Wear Scar Diameter

Coefficient of friction (COF) is a key property to evaluate how a lubricant may perform under certain conditions. COF can be defined as the frictional force that acts against the applied force to the normal force(Bird and Chivers 1993). A lubricant is said to be of more COF if upon applying it on rubbing surfaces require more force and vice-versa. COF can be determined by using following equation:

$$COF = \frac{Frictional\ Force, (F)}{Norman\ Force, (N)}$$

Equation 3

It is a key parameter to analyze the trbological properties of a lubricant. COF of a system using nanolubricant is dependent on the shape, size and concentration of nanoparticles dispersed in it, and the temperature of the system as well(Bhanvase and Barai 2021). Usually, as the concentration of nanoparticles goes up, rolling mechanism dominates the load bearing of two rubbing surfaces against each other and exhibits an lowest COF upto a certain nanoparticle concentration. Beyond that, sliding mechanism takes over rolling mechanism and COF starts to rise up again. There is also an effect of nanofluid syntering which onto the cracks and pore spaces of the surfaces, hence, smoothens the surfaces and reduce COF as a result. However, this phenomenon is not the same as floculation or aggregation of nanoparticles within the base fluid(Bhanvase and Barai 2021).

Wear scar diameter is another parameter to analyze lubricating property of a nanolubricant. Usually after a four ball tribological test, diameter of scars that happen in the outer surfaces of the balls is observed under microsope and analysed to evaluate the average value of it. It has been seen that usuallu as the nanoparticle concentration goes up to a certain point, we obserbe the lowest wear scar on the test balls. And following that as the concentration goes up further, wear scar diameter starts to increase as well, as like in case of coefficinet of friction.

Before proceeding further, we'll take a look at the basic parameters of a commercial petroleum-based lubricant, soybean oil and sunflower oil. By this, we'll understand where we stand now. In table 1 below we can see different properties of different lubricating oils.

Table 1 : Viscosity, thermal conductivity and coefficient of friction(COF) of different lubricating oils.

Oil	**Viscosity (mPa.s) at 23C**	**Thermal Conductivity (W/m.k)**	**Coefficient of Friction- Test condition ASTM D5183-05**
Soybean Oil	55(Nwoguh, Okafor, and Onyishi 2021)	0.157(Janke et al. 2013), at 40°C	0.112(Nair, Nair, and Rajendrakumar 2017)
Sunflower Oil	72(Cortes et al. 2020)	0.162(E. Rojas, Coimbra, and telis-Romero 2013), at 40°C	0.0742(Nair, Nair, and Rajendrakumar 2017)
Canola Oil	93.99(E. E. G. Rojas, Coimbra, and Telis-Romero 2013)	0.166(E. E. G. Rojas, Coimbra, and Telis-Romero 2013) , at 40°C	0.065(Biresaw, Bantchev, and Cermak 2011)
Corn Oil	69.903(E. E. G. Rojas, Coimbra, and Telis-Romero 2013)	0.162(E. E. G. Rojas, Coimbra, and Telis-Romero 2013) , at 40°C	0.054(Biresaw, Bantchev, and Cermak 2011)
SAE20W40	280	0.135(Dev Choudhury et al. 2021; Thermal conductivity of Fresh and Used Engine Oil n.d.), at 40°C	0.107(Nair, Nair, and Rajendrakumar 2017)

Form the table above, we see that soybean oil and sunflower oil show thermal conductivity of 0.157 W/m.K and 0.167W/m.K at 40C, whereas, SAE20W40 shows thermal conductivity of 0.135 W/m.K at the same temperature which is less than soybean oil and sunflower oil. In terms of viscosity, SAW20W40 shows a value way larger than soybean oil and sunflower oil. While soybean oil and sunflower oil exhibited viscosity of 55 cP and 72 cP respectively, SAE20W40 showed a value of 280 cP. Besides that, the coefficient of friction (COF) of soybean oil was 0.112 and COF of sunflower oil was found 0.0741; wheareas, COF of SAE20W40 was found to be 0.107. Although canola oil and sunflower oil showed slightly better thermal and tribological properties, but soybean and sunflower oils are comparatively more available in the market(Jaime Taha-Tijerina, Shaji, et al. 2020a; Woma et al. 2019).

2.5 Improvement of Mineral-Based and Natural Lubricant Properties with Nanoparticles

2.5.1 Improvement of Thermal Conductivity

Mineral oil has a thermal conductivity in the range of 0. W/m.K. But in different applications we might need more thermal efficient lubricating oil. For example, a great effort is being given to develop more thermally efficient coolant for car radiator (Ahmed et al. 2018; Desai, Nagaraj, and Sabnis 2021). Or, an improved life expentency of electrical transformer can come out with a improved thermally efficient coolant, which can also deter irrevocable impairment of insulation of the transformer (Muhammad Rafiq et al. 2021). In cutting tools, which are being used to cut metal and the other hard materials, we need to use efficient lubricating oil which will cool down the tool and at the same time provide lubrication to it. Otherwise, the excessive heat may deteriorate the cutting tools and the product as well.

However, until 19th century, there were no well-established technique to increase thermal conductivity of a liquid. But later, people learned to disperse different particles of higher thermal conductivity to improve its thermal performance. But then it was not as effective as now because nanoparticle was not yet there. After nanoparticle invention, this method is being used more successfully. Same way, researchers have been using nanoparticles in petroleum-based lubricant to improve its thermal conductivity. There are many different models which have been proposed to explain the way nanoparticles increase thermal conductivity of a fluid. But none of them is able to explain the mechanism perfectly. However, researchers are not sitting idle to apply the method in real applications while searching for the heat transfer mechanism at the same time. And they have got some real improvements on heat transfer. Here, some research carried out in this area is outlined below in table 2.

Table 2: Thermal conductivity of nanolubricants from different researches.

S.no	**Type of Nanoparticles**	**Size**	**Concentration**	**Base Oil**	**Findings (room temperature)**	**Reference**

1	SWCNTs and MWCNTs	10–50 nm	1 vol%	Rotella 15W-40	Thermal conductivity increases by 45%	(Marquis and Chibante 2005)
2	Silica	15 nm	5 vol%	Synthetic oil (Therminol66)	The thermal conductivity increased by 15%	(E. V. Timofeeva et al. 2011)
3	Al_2O_3 and CuO	28 nm, 23 nm	8 vol%	Ethylene glycol	Thermal conductivity increases by 40%	(Full Text n.d.)
4	CuO	100 nm	0.1 vol%	SAE20W40	Thermal conductivity increases by 3%	(Ettefaghi et al. 2013)
5	CuO	Thickness 78nm(nanorods)	6 wt.%	SAE20W50	Thermal conductivity increases by 8.3%	(Farbod, Kouhpeymani asl, and Noghreh abadi 2015)

So, it's evident that adding nanoparticles on petroleum lubricant does improve its thermal conductivity.

When researchers considered vegetable oil as an alternative of petroleum lubricant, they eventually tried to meet the same properties the petroleum lubricant has. As they got some wonderful results after implying nanoparticles on petroleum lubricant, they considered the same to improve vegetable oil properties. To improve thermal conductivity, different researchers have tried different nanoparticles. Farade *et al.*, while investigating the dielectric and thermal properties of cottonseed oil by adding h-BN Nanoparticles, achieved an increase of thermal conductivity of around 33% of that of base fluid at 0.1 wt%. (Farade et al. 2020). Yao *et al.* went through a research where they prepared a nanofluid with a base fluid of FR3 oil, which is a natural oil and used hexagonal Boron Nitride (h-BN) nanoparticle. They conducted the experiment at different temperature to understand the impact of temperature on thermal conductivity. And they came up with an improvement in thermal conductivity of 11.9% at 25°C and 14% at 90°C (Yao et al. 2018a).

2.5.2 Improvement of Viscosity

On the other hand, the effectiveness of a lubricant is determined greatly by its viscosity. If the oil is too thick and has more resistance to flow, it is said to have more viscosity. As a result, for example, the oil will not flow to all the required part of the engine during the cold start (Khalafvandi, Pazokian, and Fathollahi 2022). And if the oil is too thin, the oil is of low viscosity, and it cannot generate an effective film between two moving parts of a machine which are needed to be protected from wearing (Khalafvandi, Pazokian, and Fathollahi 2022). When nanoparticle is added to the oil, researchers mostly don't have any control over viscosity. Usually it goes up just as a result of increased thermal conductivity. Viscosity can vary within a wide range. It can range from 32 cP for SAE grade 10W, to 220 cP for SAE grade 50, at 40°C. Whearese, at 100°C, viscosity ranges from 5.4 cP to 19.4 cP for SAE grade 10W and 50, respectively(ISO Grade Oils - Viscosities and Densities 2008).

When nanoparticle is added to a fluid, Brownian motion brings these particles closer to each other resulting in an increase in viscosity. Besides, due to Van-der-Walls attraction, nanoparticles come closer to each other and forms a cluster. When the concentration goes up, the cluster gets bigger, which imposes a greater shear stress on the fluid. And that causes fluid viscosity to increase.

In a study, Sepyani et al. (Sepyani, Afrand, and Hemmat Esfe 2017) conducted research where the mixed nano-ZnO with SAE 50 – an engine oil. They varied the shear rate from 1333 to 13,333 1/s and the temperature variation was from 25-50°C. They realized that at 1.5 wt.% concentration, viscosity was the highest with 12% increase than the base oil. Esfe at al. (Hemmat Esfe et al. 2017) on a whole different study mixed ZnO nanoparticles with SAE 10W40 engine oil. And they varied the concentration from 0.25 to 2wt.% and temperature from 5 to 55°C to study viscosity. They got the highest viscosity at 2 wt.%.

Table 3: Research on viscosity of different nanolubricant.

S.no	**Type of nanoparticles**	**Size**	**Base Oil**	**Concentration**	**Findings (at room temperature)**	**Reference**
1	ZrO_2	30-60 nm	dimethoxy-end-capped poly (propylene glycol)-PAG2	2 wt.%	Viscosity increased from 143 mPa.s to 148.4 mPa.s	(Guimarey et al. 2018)
2	CNHs	80 nm	Poly-alkylene glycol	1 wt.%	Viscosity increased from 7.13 mPa.s at 0% to 82.82 mPa.s	(Zin et al. 2016)
3	CNTs	10–40 nm	N,Ndimethylformamide (DMF) (10 wt%)	2 wt.%	Viscosity increased from 13.05 mPa.s to 88.74 mPa.s	(Khalil et al. 2018)
4	CuO	50 nm	Water	2 wt.%	Viscosity increased from 0.9 mPa.s to 1.0 mPa.s	(Duangthongsuk and Wongwises 2009)

Unlike thermal conductivity, vegetable oil has much less viscosity than that of petroleum oil. Kinematic viscosity of SAE 20W40(an engine oil) is 120 mPa.s, and palm oil is 40.24 mPa.s at 40°C (Reddy et al. 2014). At 100°C temperature, kinematic viscosity of SAE 20W40 is 14-16 mPa.s, and palm oil is 7.89 mPa.s (Reddy et al. 2014). To improve viscosity, incorporating nanoparticle can play a vital role, just like in mineral oil. Many researchers have been working on this. In 2017, Mechiri et al. got the highest increase in viscosity while they were using Cu:Zn in 50:50 proportion along with vegetable oil as base fluid (Mechiri, Vasu, and Venu Gopal 2017). Kumar *et al.(Kumar Gajrani and Ravi Sankar 2017)* on a different set up found even higher, a 61% increase of viscosity with Cu:Zn composite nanofluid. Sadiq *et al.* in 2018 was able to improve viscosity of coconut oil form 35 mPa.s to 53 mPa.s at 40°C, using 1.05wt.% SiC (Sadiq et al. 2018). Though the improved viscosity is not close to motor oil viscosity, but they are very similar to commercial cutting fluids. For example, Jokisch Monosh Atos N3S(S-91), a widely used cutting oil has viscosity of 30 mPa.s at 40°C which is very close to viscosity achieved by Nwoguh *et al.* in 2021, where they were able to improve viscosity of soybean oil from 28.5 mPa.s to 34.5 mPa.s using 4 wt.% Al_2O_3(Nwoguh, Okafor, and Onyishi 2021).

2.5.3 Improvement of Tribological Properties

One more important parameter to evaluate a lubricant's performance is it's tribological properties. When two surfaces rub against each other it generates scars, as a result, form debris within the system. A lubricant's function is to minimize the scar as low as possible, creating a thin layer between two rubbing surfaces. The lower the scar diameter, better the lubricant. On the other hand, the layer which protects two surfaces from wearing has a peak point until which it can bear the load applied upon it. Beyond this loading point, the protecting layer breaks down and no longer serve protecting these two surfaces. The ease of moving two surfaces opposing each other is evaluated by a termed called “coefficient of friction(COF)”. It is the ratio of the frictional force, which is the force that prevents motion between two surfaces that are in contact with one another, to the normal force, which is the force that presses the two surfaces together. The usual value of COF for mineral based oil is around 0.1 (Nair, Nair, and Rajendrakumar 2017). The lower the COF number, the better the lubricant, because it allows the surfaces to move more readily without much resistance. Wear scar diameter (WSD) is another parameter used to assess lubricant efficacy. Because less material is weared, the lower the WSD, the better the lubrication.

To improve tribological properties many researchers have tried different nanoparticles added with the lubricant. There are different mechanisms which facilitate reduced wearing and friction; nanosized bearing, mending, polishing and creating tribofilms between two surfaces are some of the most prominent effects.

To explain the lubricating process of nanoparticles, a variety of different mechanisms have been proposed; one of these mechanisms is the rolling effect (Lee et al. 2009), protective film (Liu et al. 2004), mending effect (Tao, Jiazheng, and Kang 1996), and polishing effect (Calabi-Floody, Theng, and Mora 2009) are all examples of recognized nanoparticle lubrication mechanisms. Figure 1 (Cortes and Ortega 2019) depicts all of these. These mechanisms can be categorized into two distinct types.(Lee et al. 2009). The first is nanoparticle direct lubrication enhancement (ball bearing effect/protective film creation), and the second is nanoparticle surface enhancement (polishing/mending).

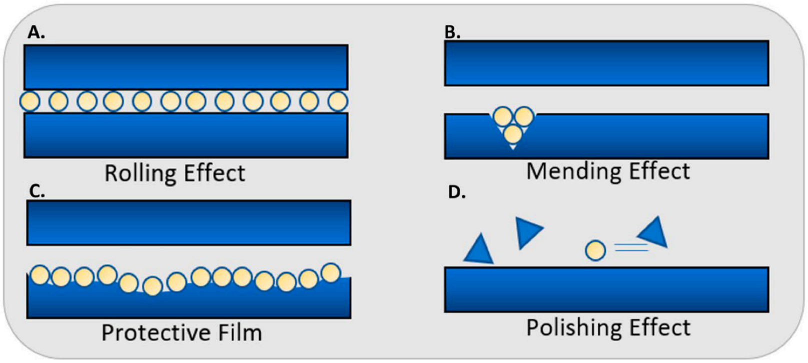

Figure 1 : Lubrication mechanism of nanoparticles (Cortes and Ortega 2019).

Within the rolling effect mechanism, nanoparticles that are typically spherical or quasi-spherical and are suspended in lubricating oil perform the role of ball bearings between the friction surfaces. Nanoparticles are caused to roll between two surfaces as a result of the rolling effect, which transforms sliding friction into a combination of rolling friction and sliding friction. In addition, they improve surface protection by coating the rough friction surfaces, which results in the creation of a protective film or an amorphous layer. This protective layer minimizes the actual area of contact, which significantly cuts down on the amount of friction that occurs.

The nanoparticles deposit and aggregate on the rubbing surface, compensating for mass loss, a phenomenon known as the mending effect (Liu et al. 2004). It enables nanoparticles to fill in any pores or scars on the surface of the specimens being evaluated. Furthermore, nanoparticle-assisted abrasion reduces the roughness of the lubricating surface. That is also known as a polishing effect (Tao, Jiazheng, and Kang 1996). The nanoparticles polish the rubbing surface in this way. The polishing action serves to remove any asperities on the surface, reducing friction and smoothing out the material's surface. This is also known as the smoothing effect.

To leverage the aforementioned effect of nanoparticles on lubrication, Ali et al.(Ali et al. 2016) conducted a research where they used Al_2O_3 and TiO_2 to develop two different nanofluids using 5W30, a commercial lubricant, and evaluated their coefficient of friction(COF). They had been able to reduce COF from 0.13 to 0.08 and 0.06 respectively using Al_2O_3 and TiO_2 nanofluids. In another study, Ag/graphene nanocomposite had been used along with paraffin oil which reduced COF 40% at 0.1% weight concentration(Wang et al. 2020). In 2018, Meng et al.(Meng, Su, and Chen 2018) were able to witnessed 36.4% reduction in COF while they were using 0.18% Nano-Ag/MWCNTs with 10W40 engine oil. In a separate study, Wan et al.(Wan et al. 2015)were able to reduce COF from 0.07 to 0.02 using 0.1wt% BN with SE 10W-40, a commercial lubricant. Del Rio et al. (Liñeira del Río et al. 2019) found an 25% reduction in COF with 0.75wt% h-BN and TMTO - a synthetic oil nanolubricant. Celik et al. (Çelik, Ay, and Göncü 2013) used h-BN nanoparticles to investigate the friction and wear parameters of SAE 10W. For the tribological testing, a CSM ball on disc tribometer is utilized, and the nanoparticles' diameters range from 50 to 190 nm. These nanoparticles are also introduced in varying volume percentages, which can range anywhere from 0 to 10%. It has been discovered that h-BN nano additives can reduce the amount of friction and wear by 14.4% and 65%, respectively. Because of the mending mechanism contained inside the nanoparticles, the frictional and wear properties have been significantly improved. By combining h-BN nanoparticles with SAE20W50, Charoo and Wani were able to investigate the anti-wear and frictional properties of oil. The frictional tests are carried out with the assistance of a universal tribometer, while the wear tests are carried out with the assistance of both a universal tribometer and a four-ball tester. When compared to the SAE20W50, the concentration of h-BN that produces the smallest WSD is one weight percent, and the reduction in WSD that is measured by the four-ball tester is around twenty percent. The universal tribometer records a reduction in wear of between 30 and 70 percent depending on the circumstances of the loading. The concentration of h-BN at 100 N with the lowest COF being 0.0401 is low when compared to the COF of base oil. The concentration of h-BN is 3 weight percent (0.0621). The improvement in tribological qualities is due to the formation of a thin protective layer on the tribopair that is made up of the piston and the cylinder ring(Charoo and Wani 2017).

Adding nanoparticles into vegetable oils imparts similar results as that in case of COF and wearing with mineral based oil. Tijerina et al.(Jaime Taha-Tijerina, Shaji, et al. 2020a) were able to reduce COF from 0.0385 to 0.0345 while using Ag nanoparticle with soybean oil. In case of sunflower oil, COF was reduced to 0.0372 from 0.437 with Ag nanoparticle. Sing *et al.* in 2021, developed a nanofluid using neem oil-MgO nanoparticles with different MgO concentration from 0.2wt% to 1.2wt% (Singh et al. 2021). It was found that the lowest COF was found while using 0.6wt% MgO while COF went down from 0.09 to 0.035.

2.6 Disadvantages of Using Nanoparticles as An Additive with Lubricant

The most significant elements affecting a nanomaterial's toxicity to humans are its size and chemical structure. The basic reason for the majority of the characteristics that emerge in nanomaterials is the nanoscale size of the particles, which exponentially increases the surface area of the particles relative to their volume and has an effect on the chemical and physical properties of the particles. Despite the existence of additional elements such as composition and structure, these alterations can make NMs more reactive and hazardous. Cells can be easily penetrated by NMs smaller than 100 nm, nuclei can be entered by NMs smaller than 40 nm, and the blood-brain barrier can be penetrated by NMs smaller than 35 nm(Ganguly, Breen, and Pillai 2018; Malakar et al. 2020). Additionally, smaller NMs can have higher catalytic activity, adsorption rates, and binding capacities, which may affect how long they stay inside the body(Sajid et al. 2015). Numerous cells, including RAW 264.7 macrophages, bronchiolar epithelial cells and 3T3 fibroblasts, are susceptible to cytotoxicity when exposed to TiO2 and SiO2 NMs(Baranowska-

Wójcik et al. 2020). Because there are currently no defined toxicity protocols among scientists to compare various data, it is much more difficult to generalize the size ranges of various NMs to increase toxicity. Scientists concur that the main cause of toxicity is that it will typically rise with smaller size NMs.

The effects of nanoparticles on human body may also depend on the geometry of the NMs. Gold nanospheres (61.46 nm) were more hazardous to fibroblast cells than nanostars of lower diameter (33.69 nm)(Favi et al. 2015). Additionally, nanostars at 400 g ml-1 and smaller nanospheres at 40 g ml-1 concentrations both killed the test subjects(Favi et al. 2015).

Vegetable oil has been tried in place of petroleum-based lubricants so far in an effort to improve the properties by fortifying them with nanoparticles. We also learned how used NPs end up polluting the environment and harming human health.

2.7 Research Plan

As far here, we know that different vegetable oils have the prospect to be the replacement of mineral oils if they are reinforced properly and can achieve desired properties. And again, there are several options to choose from while it is the case of choosing nanoparticles. But as our first concern is to produce an eco-friendly lubricant, we will use soybean oil and sunflower oil as these two oils are readily available in the market and many researchers have already experienced their potential to be an alternative lubricant(Jaime Taha-Tijerina, Shaji, et al. 2020a; Woma et al. 2019). They are readily biodegradable, and their thermal properties are very competitive with petroleum-based lubricant. While petroleum based lubricant has thermal conductivity of 0.135 W/m.k[42] [43] at 40°C, soybean oil has thermal conductivity of 0.157 W/m.k(Janke et al. 2013), at the same temperature. It's also the most widely available vegetable oil on the market, second only to palm oil(Global vegetable oil consumption, 2019/20 n.d.). We could use palm oil, however, palm oil has a high pour point of 19.7°C, which can induce lubricant solidification during everyday operations in cooler environments(Verma, Sharma, and Dwivedi 2016). Whereas, soybean oil has a pour point of -16°C which is a safe number while using it in a machinery in an operating condition(Sanni et al. 2017). Rapeseed oil is the third most widely accessible vegetable oil after soybean oil(Global vegetable oil consumption, 2019/20 n.d.). However, we chose sunflower oil as our second selection due to the lack of scientific research on rapeseed oil as a viable lubricant. Sunflower oil also shows a wonderful thermal conductivity. Woma et al. got thermal conductivity of sunflower oil at 0.161 W/m.K at 40°C and viscosity of 29 mPa.s (Woma et al. 2019). For nanoparticles we will choose, Ag, h-BN and MgO because of their biocompatibility. And, we will prepare our nanofluids with 0.01 wt.%, 0.05 wt.%, 0.10 wt.% and 0.25 wt.% nanoparticle concentration as higher concentration may cause sedimentation which may compromise physical and tribological properties of the nanofluids(Cortes and Ortega 2019; Nallusamy and Logeshwaran 2017; Shajahan and Breugem 2020). Here, the primary goal of our research is to develop lubricant which will have higher thermal conductivity, lower wear scar diameter and coefficient of friction than their respective base oils (soybean oil and sunflower oil). Usually, while developing a nanofluid, we don't have any control over viscosity; sometimes it increases and sometimes it decreases as a function of increased nanoparticle concentration. However, the lower the viscosity the better the lubricant is considered, as it aids favorable flow characteristics and demads less lubricant pump efficiency.

2.7.1 Properties of soybean oil and sunflower oil

Production of soybean oil involves cracking the soybeans, determining the amount of moisture they contain, heating them to temperatures ranging from 140 to 190 degrees Fahrenheit, rolling them into flakes, and then extracting the oil with hexanes. After that, the oil is refined, afterwards mixed for various uses, and occasionally hydrogenated. Both liquid and partially hydrogenated forms of soybean oil can be purchased as ‘vegetable oil’, and both forms can also be found as an ingredient in a broad variety of processed goods. The majority of the residue that is left over (soybean meal) is utilized as food for animals(Proctor 1997).

Fatty carboxylic acids can be found in soybean oil, although only in extremely minute quantities (about 0.3% by mass in the crude oil and 0.03% in the refined oil)(Rukunudin et al. 1998). However, it comprises of esters. The terms "fatty acids" and "acid" here, in the following section, relate to esters rather than carboxylic acids. There are 16 grams of saturated fat in every one hundred grams of soybean oil, along with 23 grams of monounsaturated fat and 58 grams of polyunsaturated fat (Poth 2001). The majority of the soybean oil (7 to 10%) triglycerides are composed of the polyunsaturated fatty acids alfa- linoleic acid (C-18:2) and linolenic acid (C-18:3), which together account for 51% of the total, as well as the monounsaturated fatty acid oleic acid (C-18:1), which accounts for 23% of the total. In addition, it has a 4% concentration of the saturated fatty acid stearic acid (C-18:0), and a 10% concentration of palmitic acid (C-16:0)(Poth 2001).

Table 4: Properties of soybean oil(FoodData Central 2018).

Type		**Composition (%)**
Saturated fatty acids		15.6
Monosaturated fatty acid	Total	22.8
	Oleic acid	22.6
Polysaturated fatty acid	Total	57.7
	Alfa-linolenic acid	7
	Linolenic acid	51

On the other hand, crude sunflower oil can be made from seeds that have only had part of their hulls removed by mechanical pressing, followed by extraction with hexane and degumming with water. The presence of relatively insignificant elements, such as phosphatides (Carelli, Brevedan, and Crapiste 1997) and waxes, can have a significant impact on the consistency and quality of sunflower oils(Carelli et al. 2002). The processing of oils results in changes to their chemical composition, which in turn affects both the quality of the oils and their resistance to oxidation (Brevedan, Crapiste, and Carelli Albarracin 2000). Before it reaches consumer market, it usually goes through degumming, neutralization, bleaching and dewaxing(Pal et al. 2015)

Table 5: Properties of sunflower oil(FoodData Central 2018).

Type		Composition(%)
Saturated fatty acids		8.99
Monosaturated fatty acid	Total	63.4
	Oleic acid	62.9
Polysaturated fatty acid	Total	20.7
	Alfa-linolenic acid	0.16
	Linolenic acid	20.5

Other than that, for nanoparticle, we need to choose something which would be compatible with human body, environment, and doesn’t cause any damage to it.

2.7.2 Properties of Silver (Ag) Nanoparticle

Silver(Ag) demonstrates low toxicity, and minimal risk is expected while clinical exposure by eating, inhalation, topical application, or the urological or hematogenous route(Lansdown 2006). Silver nanoparticle is also being used as an antimicrobial agent for many years(Dos Santos et al. 2014). As the impact of silver on human health is minimal compared to other conventional metal nanoparticles, we can use this for our purpose effectively. Taha-Tijerina et al. (Jaime Taha-Tijerina, Shaji, et al. 2020a) used silver nanoparticle to reinforce soybean, sunflower and corn oil. They were able achieve maximum 24% improvement in thermal conductivity at 50°C temperature and they also got a wonderful load carrying capacity.

Silver nanoparticle can be of different size and shape. It can have a spherical, highly branched or a flower like shape. It also has high thermal conductivity, 429 W/m.K(Iyahraja and Rajadurai 2015) which makes it a good choice for choosing as a lubricant reinforcing material.

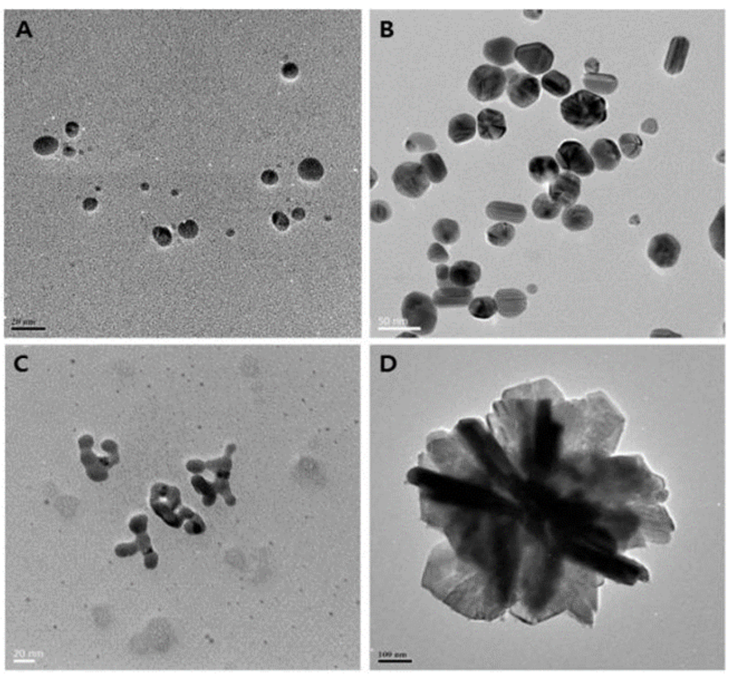

Figure 2: Various shapes of Ag nanoparticles. A) spherical; B) mixed shape; C) highly branched; D) shape like flower(Zhang et al. 2016).

2.7.3 Properties of hexagonal boron nitride (h-BN) nanoparticle

H-BN is also a good option considering it as a bio-compatible nanoparticle. Ramteke & Chelladurai in 2020 (Ramteke and Chelladurai 2020) published an article where they prepared a nanofluid using h-BN with 20W40(an petroleum based engine oil) as a base oil. They got a magnificent tribological performance and they were better than their base oil in terms of load carrying capacity.

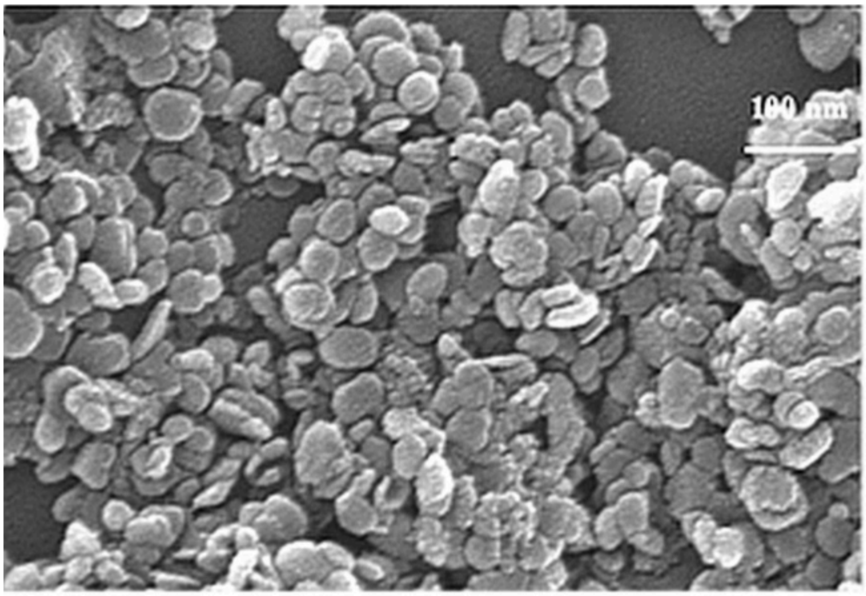

Figure 3: Morphology of h-BN*(Emanet Ciofani, Şen, and Çulha 2020)*.

Lu et al. in a study showed that water soluble h-BN can serve as an excellent biomedical platform for nanoparticle–biomolecular interactions(Lu et al. 2016). It has a low toxicity level and degrades slowly in aqueous conditions while having a high surface area. It has a platelet like structure and Ciofani *et al.*(Emanet Ciofani, Şen, and Çulha 2020) found average size of the particle 50 nm. In addition, the thermal conductivity of h-BN has been measured to be in between 220-420 W/m.K, which positions it as a leading contender for use in thermal management(Yuan et al. 2019). So, considering all these research results, h-BN will be a good choice for our research.

2.7.4 Properties of Magnesium Oxide (MgO) Nanoparticle

Nanoparticles made of magnesium oxide have no odor and non-toxic. They are typically found in the form of a white powder. They have a high melting point, along with high levels of both hardness and purity(Magnesium Oxide (MgO) Nanoparticles - Properties, Applications 2013)**.** It also shows a good antibacterial activity(Bindhu et al. 2016). Besides these physical properties, MgO also showed an excellent performance in a study conducted by Xie *et al.*(Xie, Yu, and Chen 2010), while being used as a reinforcing material with ethylene glycol as a base fluid. It demonstrated a 40% improvement in thermal conductivity at 30C and outperformed TiO_2, ZnO, Al_2O_3, SiO_2 nanofluids where the oxides were coupled with ethylene glycol in the same experiment.

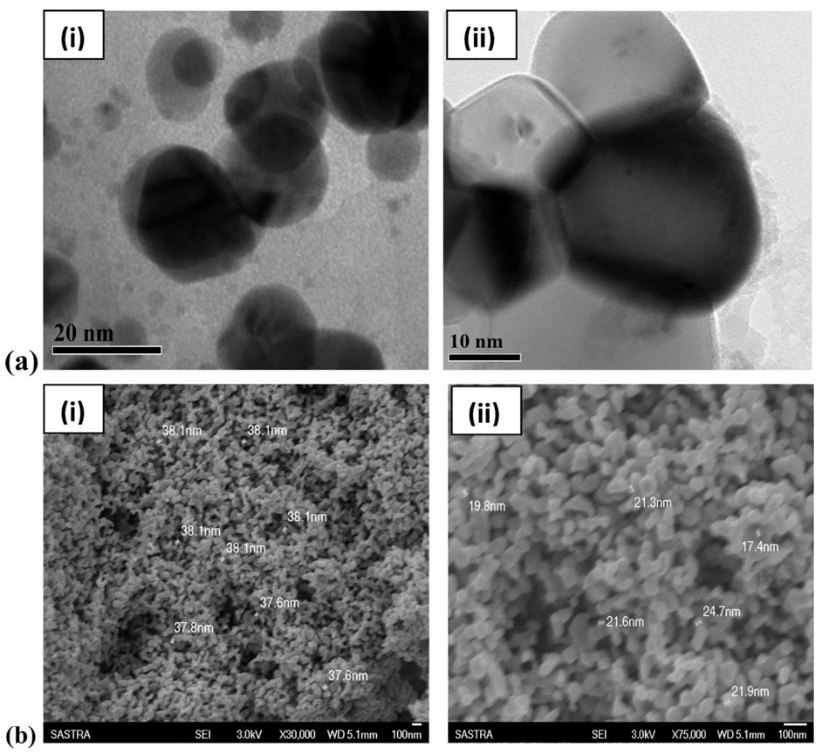

Figure 4: MgO nanoparticles at different magnification[98].

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CHAPTER III

METHODOLOGY

3.1 Nanofluid Sample Preparation

To prepare the sample for tribological test, 120 ml of base oil (soybean oil and sunflower oil separately) will be taken in a vial, with the capacity of around 150 ml, at room temperature. Then, required weight of the nanoparticles for different samples with different nanoparticle concentration will be measured in a weight balance machine, named Metler Toledo – ME204E. The accuracy of this device is 0.01 mg.

3.1.1 Apparatus

- Ultrasonic bath (Bransonic-CPX5800, Emerson)
- Weight balance machine (Metler Toledo – ME204E)
- Vials
- Spatula

3.1.2 Test Condition

- Room temperature
- Ultrasonicator water level – upto neck of the vials
- Sonication: 6 repeated cycles, each of 60 minutes with 10 minutes break in between

3.1.3 Work Procedure

The overall working procedure is described below:

- At first, the electronic balance needs to be turned on and the weight should be set on 0.

- Then, the weight of a paper sheet where nanoparticles were be placed was measured and calibrated as zero.

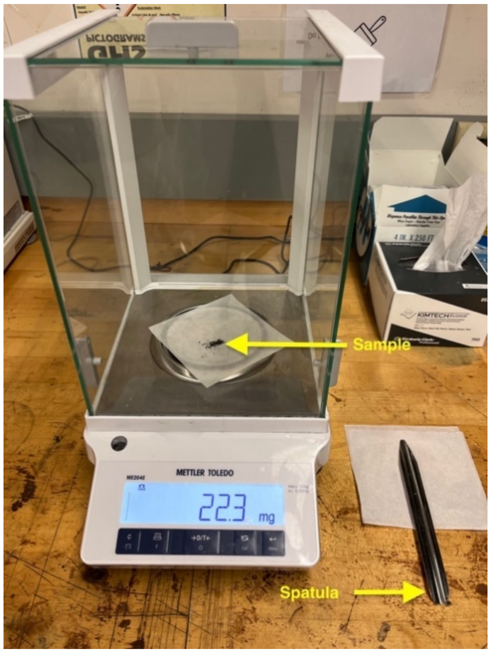


Figure 5: Measuring nanoparticle weight in weight balance machine

- After that, using a spatula, cleaned properly with acetone, nanoparticles were placed into the vial according to the required concentration.
- Finally, nanoparticles were poured into the oil. Following that, the samples were manually shaken by hand for 10 minutes so that the particles get completely mixed with the oil. Then the oil sample filled with nanoparticle was taken into a sonicator. In this case, Bransonic CPX5800 sonicator which can handle 6 vials once at a time will be used.

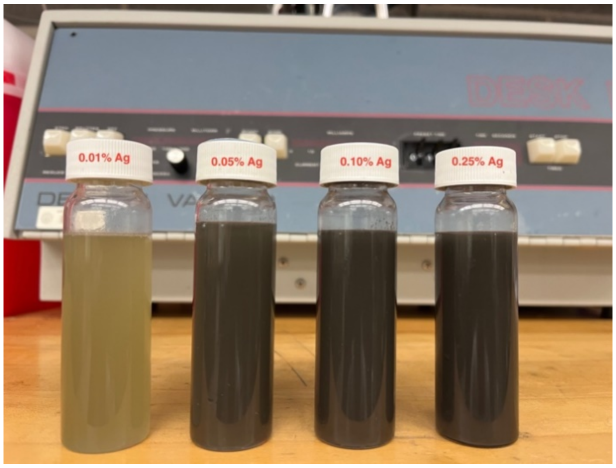
- The sample will be submerged into water in the sonicator. The sonicator will be prefilled with water up to the neck of the vials containing the sample. It will run for 1 hour at a time. Because of vibration, water will get warm and will be changed with fresh water before running the sonication for the second time. 6 cycles, each of 1 hour, in total, 6 hours of sonication will be needed to homogenize the fluid completely. The samples were visually checked to see if there is any settlement or deposition of nanoparticles, or the nanoparticles are distributed evenly thoughout the fluid to ensure the homogeneity. Finally, the samples will be prepared for tribological test.

Figure 6: Nanofluid sonication using Bransonic CPX5800 ultrasonic bath.

For thermal conductivity and viscosity measurement, another batch of 24 samples, each of 60 ml will be prepared using the same procedure described above. From this 60ml sample, 40ml will be used for thermal conductivity measurement and 20 ml will be used for viscosity measurement. As the samples were made for tribological test and for viscosity and thermal conductivity measurement following the exact same procedure and physical parameters, their property should be the same and shouldn't vary.The samples were contained in enclosed vials and kept out of any heat and light sources as well. As the nanoparticles used in this study are not reactive with vegetable oils used here as a function of time, the only parameter that could import any changes to the samples is settling of nanoparticles. As time went by, settling of nanoparticles occurred within the samples. To ensure the same properties as it was right after the samples were prepared, we sonicated each sample for 20 minutes to homozanize those completely before running each test; thermal conductivity measurement, viscosity measurement and tribological properties measurement.

Figure 7: Settling of nanoparticles(left) and complete hominization after 20 minutes of sonication nanoparticles(right) within 0.25wt% sunflower-h-BN nanofluid sample

Here, figure 8 to figure 9 depict the image of prepared nanofluid samples for testing. Each of these figure shows nanofluid with nanoparticle concentration increasing from left to right. Figure 8 and figure 9 display nanofluid samples prepared with soybean oil with Ag nanoparticle and sunflower with Ag nanoparticle, respectively. In both of the cases, as Ag concentration increases from 0.01 wt.% to 0.25 wt.%, the final fluid gets darker in color. In figure 10 and 11, we can see the color of soybean – h-BN and sunflower – h-BN nanofluid gets deeper, as in previous case, from left to right as h-BN concentration increases. In last two figures, figure 12 and figure 13, we experience the same nature, the color gets deeper as concentration of MgO increases in soybean



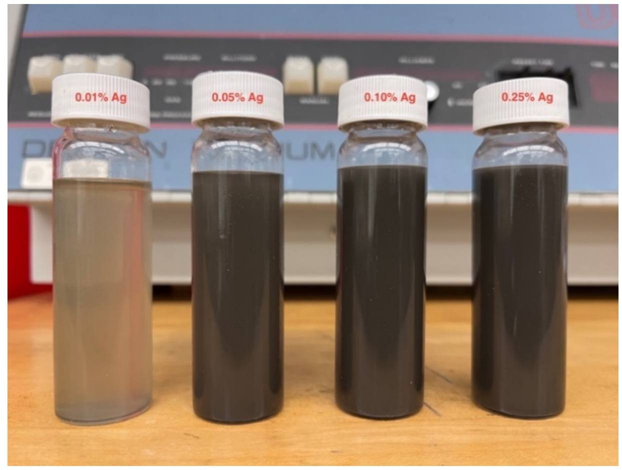
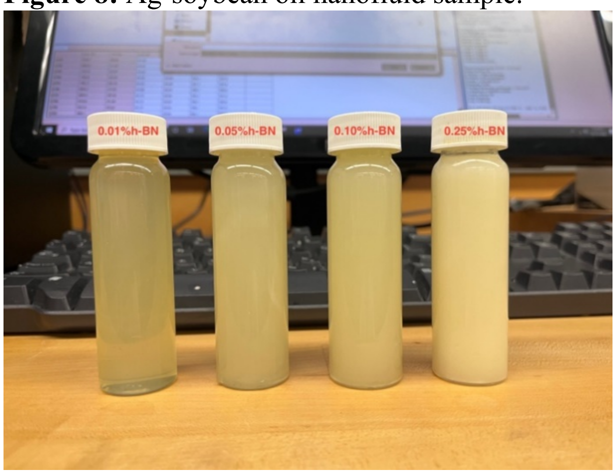


Figure 8: Ag-soybean oil nanofluid sample.

Figure 9: Ag-sunflower oil nanofluid sample.



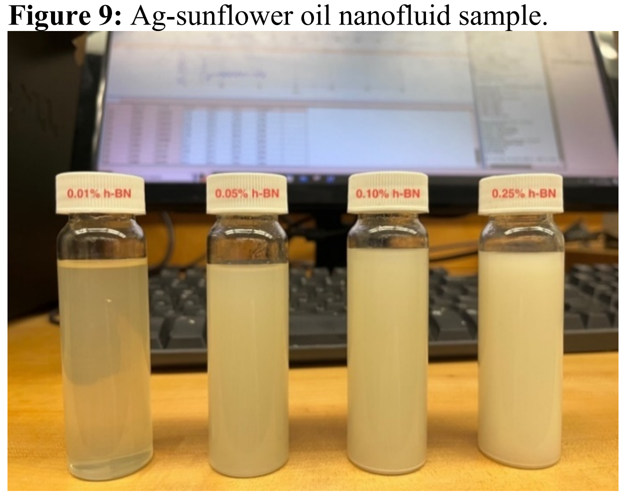
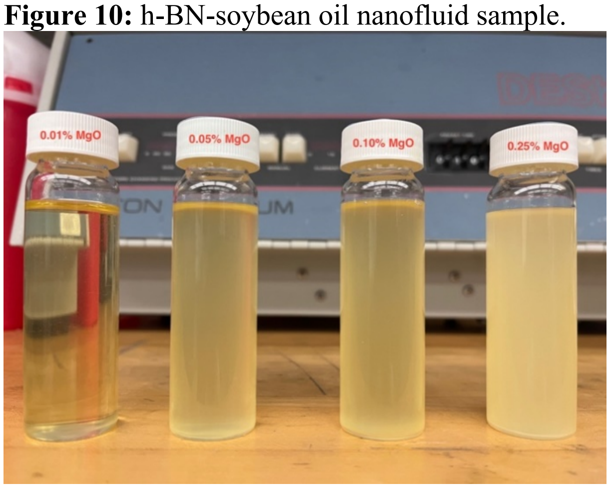


Figure 10: h-BN-soybean oil nanofluid sample.

Figure 11: h-BN-sunflower oil nanofluid sample.



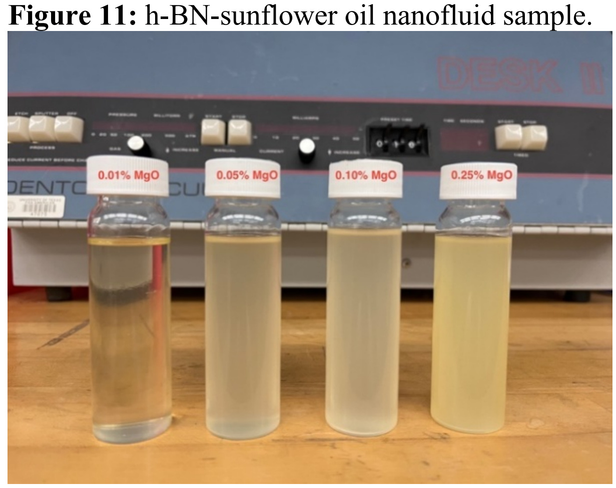


Figure 12: MgO-soybean oil nanofluid sample

Figure 13: MgO-sunflower oil nanofluid sample.

oil and sunflower oil. However, in case of sunflower – MgO nanofluid, the brownish color is a bit lighter than the color of soybean -MgO nanofluid.

To calculate the amount of nanoparticle needed to prepare each nanofluid sample, first we need to calculate density of each of the base oils. The following equation can be used to calcualte density of soybean and sunflower oil:

$$Density = \frac{Mass(\ gm)}{Volume\left(\ cm^{3}\right)}$$

Equation 4

The following table 6 shows the calculated density for soybean oil and sunflower oil. To measure the volume of the base oils, a 50 cm^3 vial, and to get the mass of the base oil we used Metler Toledo – ME204E weight balance machine.

Table 6: Density calculation of base oils.

Base Oil	Mass (gm)	Volume (cm^3)	Density (gm/cm^3)
Soybean Oil	18.2	20	0.91
Sunflower Oil	18.2	20	0.91

To calculate the amount of nanoparticle need to be used with base oil is calculted using the followign equation:

$$weight\ of\ \ nanoparticle = volume\ of\ \ base\ oil \times density\ of\ \ base\ oil \times nanoparticle\ concentration$$

Equation 5

For example, weight of Ag nanoparticle neededed to prepare a 0.05 wt% Ag-soybean nanofluid will require (120*0.91*0.0005) = 0.0546 gm or 54.6 mg Ag nanoparticle.

In table 7, we see the number of total sample for our study, amount of base oil needed to prepare the sample and the amount of each nanoparicle, Ag, h-BN and MgO needed to prepare 0.01 wt.%, 0.05 wt%, 0.10 wt.% and 0.25 wt.% nanofluid sample.

Table 7: Total amount of base oil and nanoparticles needed to conduct the whole research.

Sample number	Base Oil	Additive	Additive Concentration (%)	Properties to be measured	Amounts of Base Oil (ml)	Amount of Additive (mg)
1	Soybean Oil	None	0.00	Thermal Conductivity and Viscosity	60	0
2			0.00	COF and Wear Scar Diameter	120	0
3		Ag	0.01	Thermal Conductivity and Viscosity	60	5.46
4			0.05		60	27.3
5			0.10		60	54.6
6			0.25		60	136.5
7			0.01	COF and Wear Scar Diameter	120	10.92
8			0.05		120	54.6
9			0.10		120	109.2
10			0.25		120	273
11		MgO	0.01	Thermal Conductivity and Viscosity	60	5.46
12			0.05		60	27.3
13			0.10		60	54.6
14			0.25		60	136.5
15			0.01	COF and Wear Scar Diameter	120	10.92
16			0.05		120	54.6
17			0.10		120	109.2
18			0.25		120	273
19		h-BN	0.01	Thermal Conductivity and Viscosity	60	5.46
20			0.05		60	27.3
21			0.10		60	54.6
22			0.25		60	136.5
23			0.01	COF and Wear Scar Diameter	120	10.92
24			0.05		120	54.6
25			0.10		120	109.2
26			0.25		120	273

Table 7 : cont.

27	Sunflower Oil	None	0.00	Thermal Conductivity and Viscosity	60	0
28			0.00	COF and Wear Scar Diameter	120	0
29		Ag	0.01	Thermal Conductivity and Viscosity	60	5.46
30			0.05		60	27.3
31			0.10		60	54.6
32			0.25		60	136.5
33			0.01	COF and Wear Scar Diameter	120	10.92
34			0.05		120	54.6
35			0.10		120	109.2
36			0.25		120	273
37		MgO	0.01	Thermal Conductivity and Viscosity	60	5.46
38			0.05		60	27.3
39			0.10		60	54.6
40			0.25		60	136.5
41			0.01	COF and Wear Scar Diameter	120	10.92
42			0.05		120	54.6
43			0.10		120	109.2
44			0.25		120	273
45		h-BN	0.01	Thermal Conductivity and Viscosity	60	5.46
46			0.05		60	27.3
47			0.10		60	54.6
48			0.25		60	136.5
49			0.01	COF and Wear Scar Diameter	120	10.92
50			0.05		120	54.6
51			0.10		120	109.2
52			0.25		120	273

3.2 Measurement of Thermal Conductivity

The transient hot-wire approach will be utilized in a variety of temperatures in order to determine the thermal conductivity of vegetable nanofluids at a range of concentrations. The transient line heat source method involves applying heat to a heater that is housed inside of a very small needle (approximating a line heat source). The temperature inside the needle, and sometimes the temperature near to it, is monitored, and the data from both the temperature measurement and the heat input are used to infer the thermal properties of the material that is around the needle. The material is subjected to heat for only a brief period of time, and the temperature is recorded both during the heating and cooling phases. In this particular instance, a thermal analyzer known as a KD2 Pro equipped with a KS-3 sensor and facilitated by a single needle will be utilized. The KS-3 is a line-heat source with dimensions of 1.2 millimeters in diameter and 60 millimeters in length. The thermal conductivity might be determined by applying Equation 1 to the problem.

$$\Delta T = \frac{q}{4\pi k} \ln\left(t + t_0 \right) + C$$

Equation 6

Here,

Δ T = Temperature drift in probe

q = Heat applied in the probe (W/m)

k = Thermal conductivity of fluid(W/m.k)

t = time(s)

t_0 = Time of offset (s)

3.2.1 Apparatus

- Thermal properties analyzer – KD2 Pro, Decagon devices,INC.
- Electric heater – DLAB – MS7 – S550-S
- Thermometer
- Beaker
- Holding clamp

3.2.2 Test Condition

Room temperature, 30C, 40C and 50C

3.2.3 Work Procedure

Before starting the measurement, the equipment will be calibrated using glycerin provided by Meter Group, the same company which provided KD2 - the thermal properties analyzer. Here, thermal conductivity of glycerin is 0.282 W/m.K at 20C. It is ensured that the thermal conductivity matches exactly with this value at specified temperature. After calibrating the thermal analyzer, it will be used to measure thermal conductivity of the samples and results will be verified to three decimal points. Before measuring thermal conductivity, each sample will be sonicated for 20 minutes to homogenize the mixture again. After that the specimens will be kept aside until temperature comes to a steady-state condition close to room temperature. At least ten consequent readings will be measured for each set of experiment; the average values along with error will be reported and discussed for analysis.

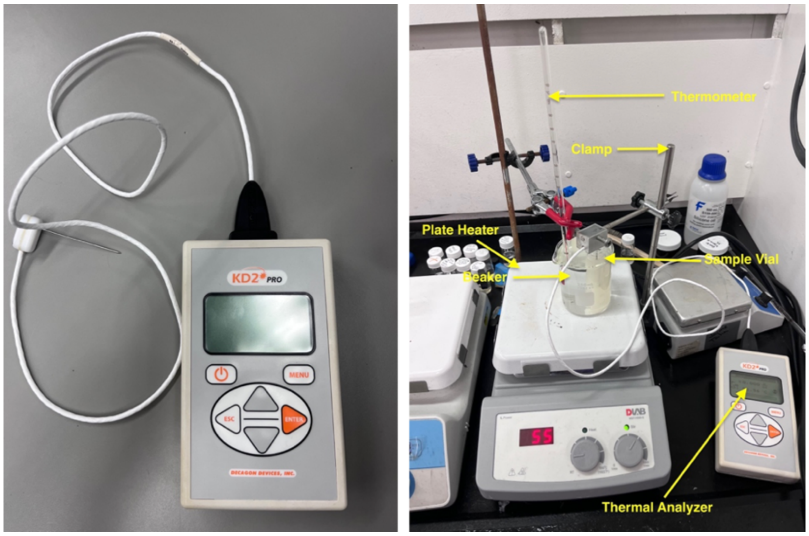


Figure 14: Thermal analyzer with measuring probe (left) and Thermal conductivity measuring setup at elevated temperature (right)

From this reading, the temperature, thermal conductivity of the sample and error of the evaluation are obtained directly from the thermal analyzer. In figure 14, we can see the thermal analyzer, KD2 Pro, used for thermal conductivity measurement. We can also see a probe, KS-3 attached to the analyzer which is inserted into the samples and collects essential data. In figure 14, we can see the setup for analyzing the samples. We observe the vial containing the sample submerged into a water containing beaker. Two holder is attached to hold thermometer and KS-3 probe in place. And the thermal analyzer is kept beside to record thermal conductivity of each sample.

To measure thermal conductivity at an elevated temperature (30°C, 40°C and 50°C), the vial containing the sample with be submerged into a water bath. This water bath will be placed on a plate heater, DLAB – MS7 – S550-S, which will be heated according to the desired temperature. A thermometer will be set to measure the temperature of the water bath, and thermal conductivity measuring probe will be kept inside the vial submerged into the sample to avoid free convection. When water temperature be stable at desired level, we'll wait 10 minutes to let temperature be stable in the oil sample inside the vial. We will ensure the temperature of the sample, as measured by the meter, is the same as the water bath before taking measurements, as measurement will be taken with the sample inside the water bath. Following that, 10 subsequent readings will be taken for thermal conductivity measurement. Again, the average of these 10 values along with the error will be recorded for further analysis. Following that, thermal conductivity of all the samples will be plotted as a function of temperature as well as nanoparticle concentration. Then, we will analyze the trend of the plot and try to understand the reasons behind a particular behavior of any sample.

3.3 Measurement of Tribological Properties

The test will be conducted using a four-ball wear testing machine in accordance with ASTM 4172. As test balls, chrome-alloy steel balls manufactured to AISI standard steel No. E-52100, with a diameter of 12.7 mm [0.5 in] and 25 extra polish grade will be used.

Three steel balls will be held together, lubricated, and subjected to testing. Before putting the nanofluid samples into the machine, they will be sonicated for twenty minutes. For three-point contact, a fourth steel ball, referred to as the top ball, is forced with 147N [15 kgf] into the cavity formed by the three clamped balls. The test lubricant is heated to 50 degrees Celsius, and the top ball is rotated at 1200 revolutions per minute for 60 minutes. Using the average size of the scar diameters worn on the three lowest clamped balls, samples will be compared.

3.3.1 Apparatus

- Wear Test Machine – Four Ball Tester – FBT3, Ducom
- Image Acquisition System – IAS3, Ducom, able to measure the sizes of the scars left on the three stationary balls
- Test balls: AISI standard steel No. E-52100, diameter - 12.7 mm [0.5 in.], 25 EP extra polish grade

- Cleaning fluid

3.3.2 Test Condition

Temperature: 50°C, speed: 1200 rpm, duration: 60 minutes, load: 147N

3.3.3 Procedure

- Before starting the experiment, it is ensured that the four-ball tester is properly calibrated. The four-ball tester – FBT3 is calibrated each year by Ducom, manufacturer of the machine, also before starting every new project in this machine. In this process, the load sensor, the temperature sensor and the speed sensor are calibrated properly.
- Properly clean four test balls, clamping components for holding upper and lower balls, and the oil cup using caution and the appropriate solvent or solvents. The components may be cleansed using a clean (unused) lint-free industrial wipe. Following the cleaning, only a new wipe should be used to handle each component. When the test oil is added and the machine is completed, there should be no sign of solvent.
- Tighten one of the clean balls into the test machine's spindle.
- Put three clean test balls in the test-oil cup and tighten by hand with the wrench that came with the equipment. The torque should be about 33.8 Nm to 67.7 Nm (25 ftlb to 50 ftlb).

Figure 15: Four ball tester - FBT 3.

Figure 16: Image acquisition system - IAS 3

- Pour the oil to be evaluated to a level at least 3 mm (18 in) above the top of the balls into the test-oil cup. Observe that this oil level remains after the test-oil has filled all holes.
- Place the test-oil cup and the three balls inside the machine, and make sure there is no shock loading by gradually applying the 15 kgf test load (147 N).
- Turn on the heaters, and adjust the dials so that the temperature is exactly 50 degrees. The voltage of the heater or the offset on the proportional controllers should be capable of bringing the temperature to a stable state.
- When the temperature of the test is reached, start the drive motor that was previously programmed to rotate the top ball at a rate of 1200 revolutions per minute for an hour. Every sample will undergo the evaluation process three times in accordance with the same protocol.
- We will obtain COF for each second for whole duration for each set of tests. After performing 3 consecutive tests for the same sample, we will take average of 3 values for the same time stamp and take an average again for all the data points which consist only the average values of the same time stamp.

- Finally, each value of COF will be plotted as a function of nanoparticle concentration.

In figure 15, we can see the four-ball tester – FBT 3 for tribological test. We can also see the sample holder where nanolubricant is put between 4 test balls before running the test. Figure 16 shows the Image Acquisition System – IAS 3 which was used to measure wear scar diameter of the test balls after running the four-ball test.

3.4 Measurement of Viscosity

On a Haake Mars 40 Rheometer with a high temperature measurement system, ceramic rotors, and electric heating, the viscosity will be measured. Utilizing a parallel-plate sensor, the rotational measurements will be taken. Each test will be conducted at a share rate ranging from 0.1 to 1,000 1/s, and samples will be evaluated at room temperature (23 ° C), 30 ℃, 40 ℃, and 50 ° C. The amount of sample required for each test is around 1 milliliter. Finally, viscosity as a function of share rate will be obtained, and a graph of viscosity versus share rate will be constructed.

3.4.1 Apparatus

- Rheometer **-** Haake Mars 40
- Measuring geometry (with a sensor) - P35/Ti-01210783
- Temperature controller – MTMC (MARS 40)
- Pipet
- Wiper paper

3.4.2 Test Condition

- Shear rate: 0.01 to 1000 s-1
- Temperature: Room Temperature (23C), 30C, 40C, 50C
- Duration: 10 minutes
- Distance between parallel plates: 0.5mm

3.4.3 Work Procedure

The overall work procedure is described below:

- The rheometer will initially be cleaned with acetone.
- The air pressure must be regulated between 1.8 and 2.0 bar; otherwise, the machine will be inoperable or excessive air pressure will cause damage to the instrument.

In figure 17, we can see the rheometer which was used to measure viscosity of our samples. We can also see the geometry attached with a sensor which was used to collect data and also the plate where the samples were put before running the test. Figure 17 displays the temperature controller which allowed us to raise the sample temperature to measure viscosity at elevated temperature. From figure 17, we can also see the pressure regulator where 2 bar was being maintained.

- Now, before proceeding further, at first the rheometer and temperature controller need to be turned on.
- After turning on the computer, "HAAKE RheoWin Job Manager" needs to be launched, and 'CS/CR – Rotation Step' should be selected from the measurement elements section.
- In the job editor box for the MARS 40 rheometer, we will choose (P35/Ti-01210783) as the measurement geometry, MTMC (MATS 40) as the temperature controller, and 0.5mm as the distance between two parallel plates.
- In the parameter window, we will be able to specify the beginning and ending shear rates (0.01 s-1 and 1000 s-1, respectively), as well as the number of steps into which the entire range of shear rates will be divided (200 in this instance). And we must decide the duration of each step; in our case, we will choose three seconds. In total, the duration of the experiment will be 600 seconds, or 10 minutes.

- By opening the manual control window, the sample needs to be loaded using a pipet.
- Before evaluating viscosity of the samples, the rheometer needs to be calibrated using viscosity standard solution from Brookfield Engineering Laboratories, Inc.
- The samples must completely touch both sides of the parallel plate.
- After positioning the sample carefully, the "Go to gap" button should be clicked. Therefore, the plates will be placed at a distance of 0.5mm from one another.
- After exiting the manual control panel, the experiment will ultimately be initiated (three trials for each one).
- As the rheometer starts to initiate the test, a set of records including shear stress and viscosity as a function of shear rate will starts to plot automatically. The corresponding values of the plot will also be recorded with corresponding temperature of the sample. As the shear rates increase, the value of viscosity stabilizes and approaches a value where the viscosity remains constant in spite of increasing shear rate. That is the value we will take as the viscosity of our sample at that temperature. In our study, we waited till 1000 s^{-1} share rate to obtain more accurate and consistent result for all the sample.

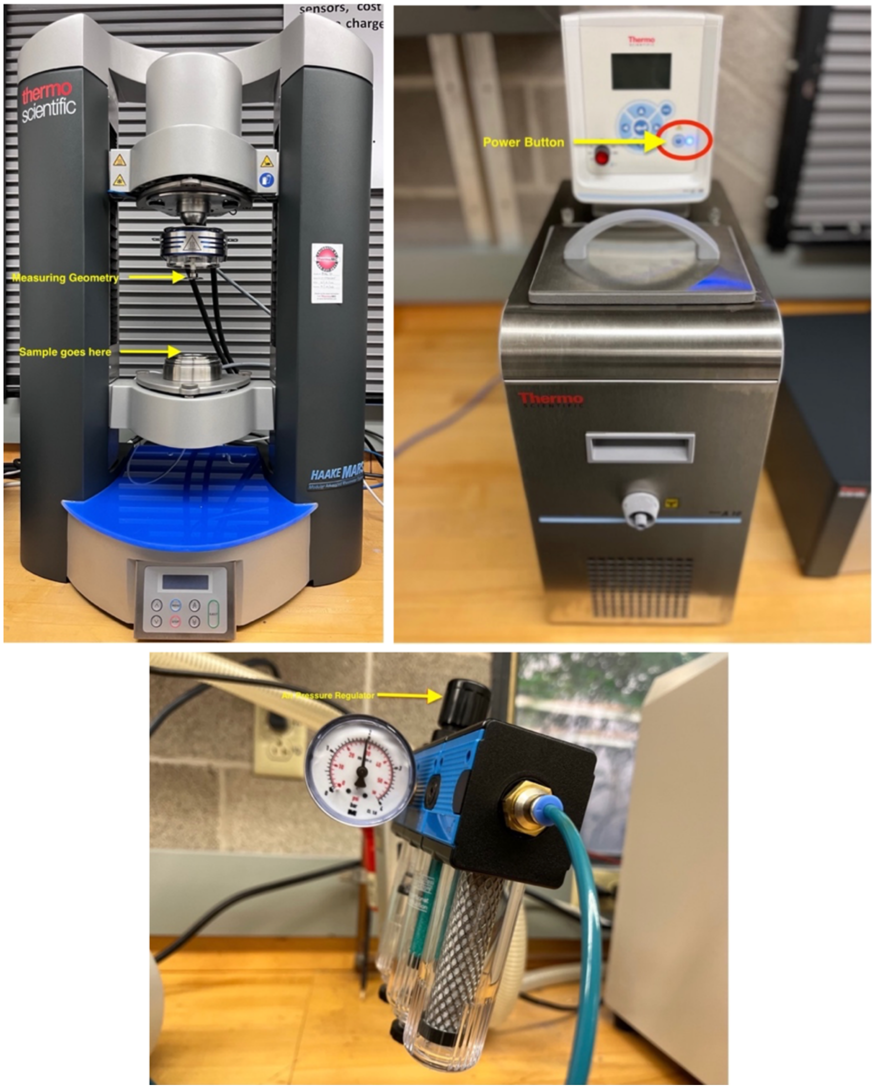


Figure 17: Rheometer - Haake Mars 40 (top-left), Temperature Controller (top-right), Air pressure controller (bottom).

- Finally, viscosity of all the samples at room temperature, 30C, 40C and 50C will be plotted as a function of nanoparticle concentration and will be analyzed further for finding our possible reasoning behind the particular behavior possessed by a specific nanolubricant sample.
- Apart from these, density of the sample also needs to be specified before starting the measurement.

$$Density\ of\ \ the\ sample\ =\frac{total\ weight\ of\ \ the\ nanolubricant(\ g)}{(\ volume\ of\ \ lubricant+volume\ of\ \ nanoparticle)\left(\ cm^{3}\right)}$$

Equation 7

- The result must be multiplied by 1,000 to obtain the density in kilograms per cubic meter.
- Before moving to the next set of experiments, the spindle must be moved higher to clean the plate as well as the spindle itself.
- After all the tests have been completed, the temperature controller and rheometer need to be turned off.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Thermal Conductivity

The thermal conductivity of soybean and sunflower oils have been found to improve with the addition of several types of nanoparticles.

From table 8-10, we can see the change of thermal conductivity of soybean-Ag, soybean-h-BN and soybean-MgO as a function of temperature and nanoparticle concentration.

Table 8: Thermal conductivity of soybean-Ag nanofluid at different temperature and different nanoparticle concentration

Fluid	TC at Room Temperature	30C	40C	50C
Soybean Base	0.162	0.1621	0.1622	0.1627
Soybean+0.01% Ag	0.162	0.1622	0.1643	0.1667
Soybean+0.05% Ag	0.1618	0.163	0.1676	0.1743
Soybean+0.10% Ag	0.1618	0.1664	0.1721	0.1788
Soybean+0.25% Ag	0.162	0.1671	0.1792	0.1937

Table 9: Thermal conductivity of soybean-h-BN nanofluid at different temperature and different nanoparticle concentration

Fluid	TC at Room Temperature	30C	40C	50C
Soybean Base	0.162	0.1621	0.1622	0.1627
Soybean+0.01% h-BN	0.162	0.1633	0.1653	0.1681
Soybean+0.05% h-BN	0.1624	0.1638	0.1699	0.1727
Soybean+0.10% h-BN	0.1619	0.1644	0.1717	0.1824
Soybean+0.25% h-BN	0.162	0.1686	0.1824	0.1983

Table 10: Thermal conductivity of soybean-MgO nanofluid at different temperature and different nanoparticle concentration

Fluid	TC at Room Temperature	30C	40C	50C
soybean Base	0.162	0.162	0.162	0.163
soybean+0.01% MgO	0.162	0.164	0.1651	0.1648
soybean+0.05% MgO	0.1617	0.164	0.1678	0.1688
soybean+0.10% MgO	0.1624	0.165	0.172	0.1748
soybean+0.25% MgO	0.1622	0.166	0.1764	0.1863

In figure 18, change of thermal conductivity of soybean nanofluids as a function of temperature and Ag, h-BN and MgO filler fraction is depicted. Soybean base oil – without being reinforced with any nanoparticle, did not exhibit a major temperature dependency. Its thermal conductivity remained practically almost the same across the entire range of temperature increments from room temperature to 50°C, which is similar to the findings of prior studies(Jaime Taha-Tijerina, Shaji, et al. 2020a). It was found to be 0.162 W/m.K at room temperature and 0.1627 W/m.K at 50C, which is an improvement of only 0.4%. Taha et al. in 2020 found only less than 2% improvement of thermal conductivity of soybean oil and sunflower oil which is well aligned with the result found from our study(Jaime Taha-Tijerina, Shaji, et al. 2020a). In their study, the improvement of thermal conductivity of soybean oil was from 0.156 W/m.K to 0.158 W/m.K and for sunflower oil it was from 0.1605 W/m.K to 0.162 W/m.K, from room temperature to 50C respectively. This result is a little different from our study. The possible reason for this could be because the source of soybean oil and sunflower oil was different; as a result the chemical structure and composition of these two oil samples were not exactly the same, which might have an impact on thermal conductivity of the oils. When temperature was increased, the overall trend of thermal conductivity was steadily upward for all of the fillers and concentrations that were being studied. Figure 18a. displays the influence of Ag nanoparticle while used with soybean oil. It is evident that, as the filler fraction and temperature went up, thermal conductivity, as a consequence, also improved steadily. For instance, with Ag nanoparticle, at 50C temperature, thermal conductivity was improved 2.9%, 7.5%, 10.3% and 19.6% with 0.01 wt.%, 0.05 wt.%, 0.10 wt.% and 0.25 wt.% respectively. A similar kind of trend was observed in case of soybean oil reinforced with h-BN nanoparticle. It showed even higher thermal conductivity improvement, 22.4%, at 50C with 0.25 wt.% h-BN nanoparticle concentration. In case of soybean oil with MgO nanoparticle, improvement in thermal conductivity is also significant. It showed 1.73%, 4.2%, 7.9% and 15% improvement with 0.01 wt.%, 0.05 wt.%, 0.10 wt.% and 0.25 wt.% MgO concentration, respectively.

The results found from this study are similar to the results from the studies with similar base oils and nanoparticles. Taha-Tijerina et al. found 24%, 18% and 21% thermal conductivity improvement from soybean-Ag, sunflower-Ag and corn-Ag nanofluid at 50C, respectively at 0.25 wt.% concentration(Jaime Taha-Tijerina, Shaji, et al. 2020a).

Nanofluid samples made out from sunflower oil and with the same nanoparticles demonstrated a similar behavior. The following tables 11-13, display the change of thermal conductivity as a function of temperature and nanoparticle concentration.

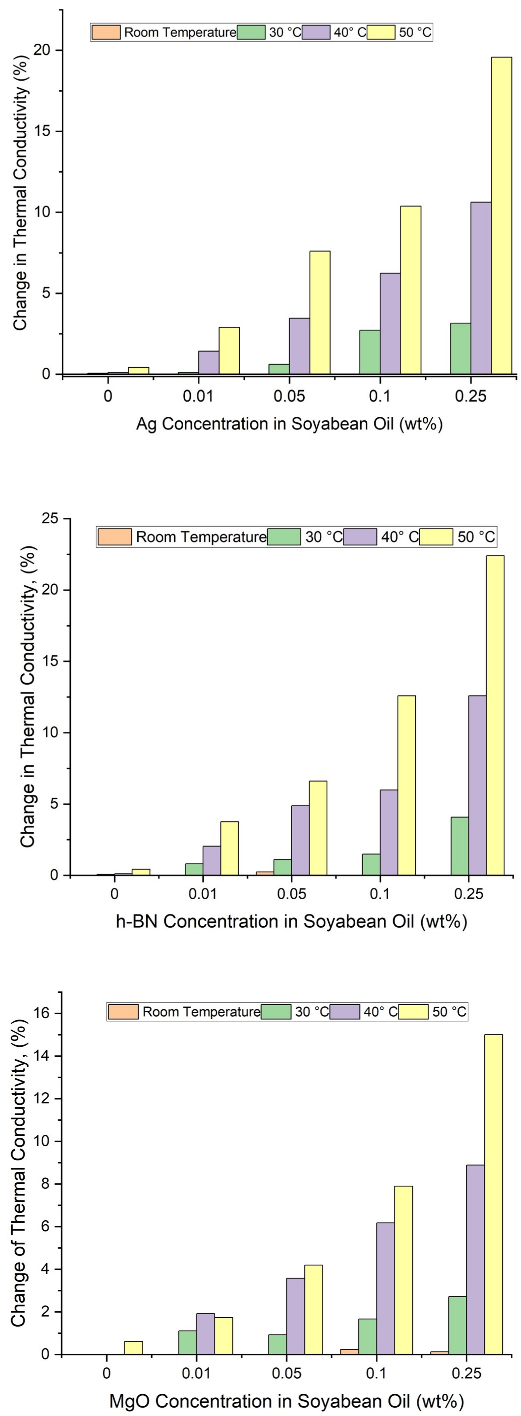


Figure 18: Thermal conductivity of soybean-Ag nanofluid(top), soybean-h-BN nanofluid(middle) and soybean-MgO nanofluid(bottom) as a function of concentration (temperature is mentioned).

Table 11: Thermal conductivity of sunflower-Ag nanofluid at different temperature and different nanoparticle concentration.

Fluid	TC at Room Temperature	30C	40C	50C
Sunflower Base	0.163	0.163	0.163	0.163
Sunflower+0.01% Ag	0.163	0.163	0.165	0.167
Sunflower+0.05% Ag	0.163	0.164	0.168	0.176
Sunflower+0.10% Ag	0.163	0.167	0.174	0.182
Sunflower+0.25% Ag	0.163	0.170	0.179	0.206

Table 12: Thermal conductivity of sunflower-h-BN nanofluid at different temperature and different nanoparticle concentration.

Fluid	TC at Room Temperature	30C	40C	50C
Sunflower Base	0.1633	0.163	0.1634	0.1632
Sunflower+0.01% h-BN	0.1632	0.1635	0.1637	0.1655
Sunflower+0.05% h-BN	0.1633	0.1643	0.1691	0.1784
Sunflower+0.10% h-BN	0.1634	0.1644	0.1739	0.1853
Sunflower+0.25% h-BN	0.163	0.1661	0.1811	0.2022

Table 13: Thermal conductivity of sunflower-MgO nanofluid at different temperature and different nanoparticle concentration.

Fluid	TC at Room Temperature	30C	40C	50C
sunflower Base	0.1633	0.163	0.1634	0.1632

sunflower+0.01% MgO	0.1626	0.1638	0.1651	0.1652
sunflower+0.05% MgO	0.1632	0.1635	0.1678	0.1708
sunflower+0.10% MgO	0.163	0.1647	0.172	0.1781
sunflower+0.25% MgO	0.1629	0.1664	0.1764	0.1905

In figure 19, we can observe the change of thermal conductivity of sunflower oil nano lubricant. The overall thermal conductivity trend here is upward as a response of increased temperature and filler concentration. From figure 19a, it is evident that Ag nanoparticles contributed to improve thermal conductivity of sunflower oil, maximum 26.15% at 50C with 0.25 wt.% concentration. Similar result is noticed with nano lubricant of sunflower oil with h-BN filler fraction. It showed 2.45%, 7.53%, 11.57% and 26.15% improvement of thermal conductivity, increasing steadily with filler concentration and temperature, with 0.01 wt.%, 0.05 wt.%, 0.10 wt.% and 0.25 wt.% h-BN respectively. In the case of sunflower-Mgo oil nanofluid, the highest thermal conductivity was obtained at 0.25 wt.% at 50C. It is also evident that the result aligns well with the previous studies, sometimes even better with similar kinds of materials. Yao et al. in 2018 developed a nano lubricant with FR3 oil and 0.1 vol.% h-BN, where they observed an improvement of 14% thermal conductivity at 90C(Yao et al. 2018b). However, at room temperature, the developed nano lubricant showed a 11.9% improvement at room temperature, which in our case, both soybean oil and sunflower oil nano lubricant, was almost unchanged in response to the addition on nanoparticles.

Taha-Tijerina et al. were able to improve thermal conductivity of VG-100 (a vegetable oil)-h-BN and VG-100-h-BN 21% and 23%, respectively, with 0.25 wt% at 50C compared to room temperature.(Jaime Taha-Tijerina, Ribeiro, et al. 2020).

It is clear that the inclusion of Ag, h-BN, and MgO nanoparticles considerably increased the thermal conductivity of the nano lubricant. A possible explanation for this improvement of thermal conductivity could be the aggregation of particle molecules, Brownian motion of nanoparticles within the fluid phase as well as because of particle and liquid interface(Das 2017). When van dar walls attraction between molecules is larger than intermolecular repulsion force, they prone to grow together and form nanoparticle clusters (Riahi et al. 2020). And when they create clusters, nanoparticles within the base fluid create a chain like formation. This chain-like structure has lower thermal resistance and hence creates a path of higher thermal conductance. This mechanism could also be a possible mechanism behind all these improved thermal performance(Keblinski et al. 2002). On top of it, liquid molecules stacking at the vicinity of the surface of solid particles may contribute to create a thermal bridge between solid particles and fluid phase, hence, facilitating higher heat conductance within two fluid points (Murshed, Leong, and Yang 2008).

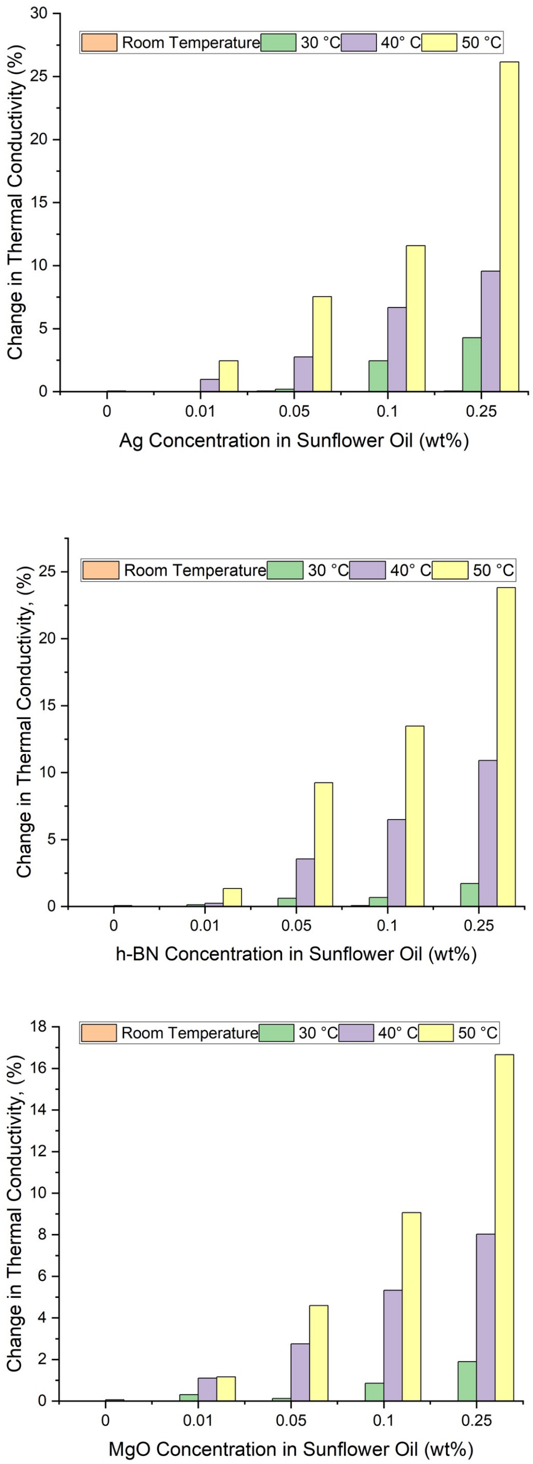


Figure 19: Thermal conductivity of sunflower-Ag nanofluid (top), sunflower-h-BN nanofluid (middle) and sunflower-MgO nanofluid (bottom) as a function of concentration (temperature is mentioned).

Again, the Brownian motion can explain how increment in temperature can contribute to increase in thermal conductivity of a fluid(Chon et al. 2005). Brownian motion is defined as the random movement of nanoparticles that occurs from their collision with one another and their thermal interaction with the molecules of the base fluid (Riahi et al. 2020). The mobility of individual nanoparticles allows for collisions between them, which may transfer energy. Additionally, the base fluid that is surrounding the nanoparticles at the nanoscale level will convict as a result of interaction between solid and fluid particles(Riahi et al. 2020). By this way, it is able to effectively combine base fluid molecules that are at different temperatures, which accelerates the flow of thermal energy within the fluid.

When nanoparticle concentration is higher along with higher fluid temperature, improvement of thermal conductivity is more rapid. As the temperature rises, the movement of nanoparticles increases as well as the kinetic energy they possess(Riahi et al. 2020). As the temperature increases, increased Brownian motion results in more nanoparticles motion, as a result, a significant improvement in thermal conductivity. Additionally, more nanoparticles are dispersed throughout the base fluid as a consequence of a larger solid volume percentage. It aids in more frequent collision between suspended nanoparticles which results in even better thermal conductivity improvement(Riahi et al. 2020).

Analyzing the improvement of thermal conductivity, we can see that sunflower oil nanofluid have experienced more improvement than soybean oil nanofluids. The reason behind this could be because sunflower oil had initially slightly better thermal conductivity than soybean oil. As temperature and nanoparticle concentration went up, the difference became more obvious. Apart from this, we can also see that MgO nanofluids have a considerably lower thermal conductivity improvement than Ag and h-BN nanofluids. The reason could be MgO has a much lower thermal conductivity, around 30 W/m.K at room temperature which is much lower in comparison to Ag and h-BN nanoparticles(Slifka, Filla, and Phelps 1998).

4.2 Viscosity

To understand the lubricants behavior when added with nanoparticles, we studied the effect of Ag, h-BN and MgO concentration in the viscosity performance, under temperature-dependent evaluation from room temperature (24°C to 50°C). In the following table 14-16, viscosity of soybean oil nanofluids at different temperature and nanoparticle concentration is demonstrated in detail.

Table 14: Viscosity of soybean oil nanofluid as a function of Ag nanoparticle concentration at different temperature.

Concentration (%)	Room Temperature	30C	40C	50C
0	57.41	44.76333333	31.82	23.59333333
0.01	55.80666667	42.61333333	31.10333333	22.62
0.05	59.27	42.10666667	31.06333333	22.80333333
0.1	64.12666667	43.55333333	31.53	22.94333333
0.25	62.24333333	43.55333333	31.54	23.38

Table 15: Viscosity of soybean oil nanofluid as a function of h-BN nanoparticle concentration at different temperature.

Concentration (%)	Room Temperature	30C	40C	50C
0	57.41	44.76333333	31.82	23.593333
0.01	57.46666667	45.15666667	30.91666667	23.833333
0.05	57.56666667	45.2	31.46333333	23.843333
0.1	55.65666667	44.42666667	30.71333333	22.883333
0.25	56.87333333	44.26666667	30.14666667	23.68

Table 16: Viscosity of soybean oil nanofluid as a function of MgO nanoparticle concentration at different temperature.

Concentration (%)	Room Temperature	30C	40C	50C
0	57.41	44.76333333	31.82	23.59333333
0.01	59.1	45.49333333	32.35	23.83333333
0.05	59.19	45.30333333	32.11	23.84333333
0.1	57.00333333	44.05666667	31.42	22.88333333
0.25	73.66666667	45.82666667	32.59	23.68

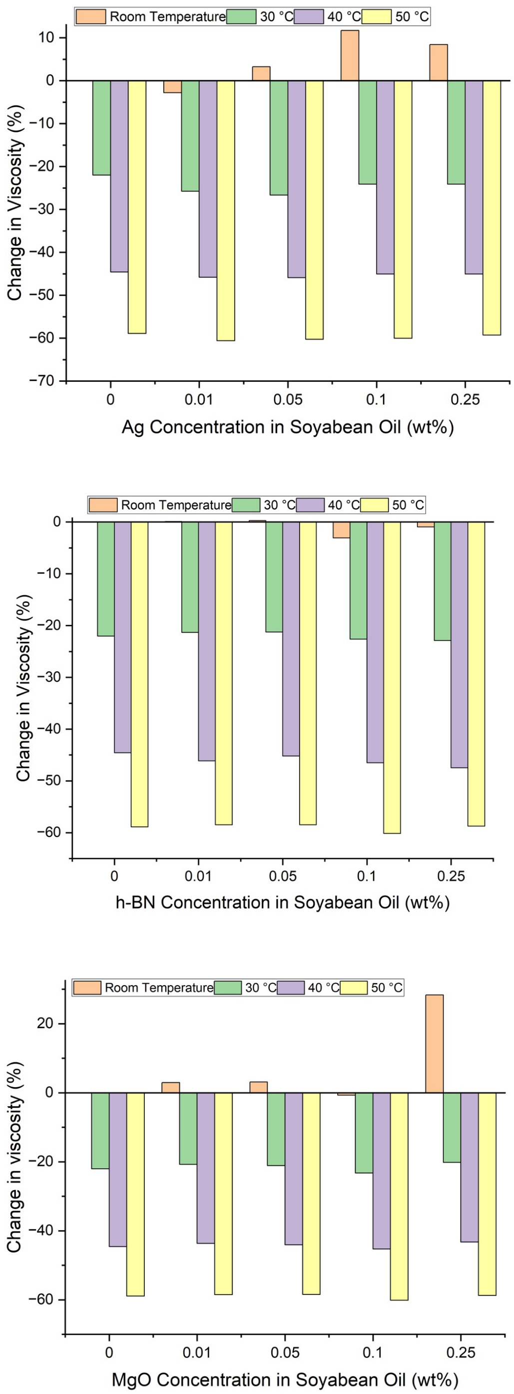


Figure 20: Viscosity of Soybean oil nanofluid as a function of Ag nanoparticle(top), h-BN nanoparticle(middle) and MgO nanoparticle(bottom) at different temperature.

Figure 20 displays the change of viscosity of soybean nano lubricant as the temperature increases. It is evident that as the temperature increases from room temperature to 50°C, the overall trend for all the fluids is downward.

Soybean oil reinforced with MgO nanoparticles, figure 20 (bottom), shows similar trend except at room temperature. At room temperature, viscosity of soybean oil – MgO nanofluid displays a fluctuation reaching the lowest point, 57 cP at 0.10 wt.% MgO concentration. Following that, viscosity goes up steadily reaching the highest point, 73.67cP at 0.25 wt.%. When temperature rises, viscosity decreases for all the nanofluids with different filler fractions. For 30°C, 40°C and 50°C, as the concentration of nanoparticles goes up, viscosity remained stable comparatively. In the following table 17-19, viscosity of sunflower oil nanofluids at different temperature and nanoparticle concentration is demonstrated in detail.

Table 17: Viscosity of sunflower oil nanofluid as a function of Ag nanoparticle concentration at fdifferent temperature.

Concentration (%)	Room Temperature	30C	40C	50C
0	72.65	57.33	39.67333333	28.50333333
0.01	76.3	54.69666667	38.52666667	27.92666667
0.05	76.14333333	56.25333333	39.77333333	28.58666667
0.1	75.83	57.1	39.74333333	28.38
0.25	74.64	56.36333333	39.30333333	27.70666667

Table 18: Viscosity of sunflower oil nanofluid as a function of h-BN nanoparticle concentration at different temperature.

Concentration (%)	Room Temperature	30C	40C	50C
0	72.65	57.33	39.67333333	28.503333
0.01	75.68666667	56.10666667	39.57	28.59
0.05	75.50333333	55.90666667	39.23	28.303333
0.1	75.17333333	56.17333333	38.94	28.283333
0.25	74.88	55.98	38.71666667	28.08

Table 19: Viscosity of sunflower oil nanofluid as a function of MgO nanoparticle concentration at different temperature.

Concentration (%)	Room Temperature	30C	40C	50C
0	72.65	57.33	39.67333333	28.50333333
0.01	77.02333333	57.25	39.61	28.12333333
0.05	76.77333333	54.78	37.86666667	27.22
0.1	75.84	56.86666667	39.19666667	27.89666667
0.25	74.46333333	55.94666667	38.61333333	27.47666667

Figure 21 shows sunflower oil nanofluids viscosity as a function of different filler fraction. It also displays the effect of temperature on viscosity as the filler fraction changes. From figure 21 (top), it is clear that viscosity remained almost the same at all concentration. However, as temperature raised from room temperature to 50°C, it dropped dramatically as in case of soybean oil nanofluids. At room temperature, viscosity went up a little from 72.65 cP to 76.30 cP, at 0.01 wt.% concentration. However, it remained stable for all the remaining Ag nanoparticle concentration. Although the overall trend for all temperature is straight line, they show a little valley at 0.01 wt.% except at room temperature and stayed the same for all other concentrations. For this sunflower – Ag nanofluid system, the highest viscosity is 76.30 cP at room temperature and 0.01 wt.% Ag and the lowest viscosity is 27.71 cP at 50°C with 0.25 wt.% Ag concentration.

In figure 21 (middle), sunflower oil – h-BN nanofluid shows the similar trend. Viscosity doesn't change much as h-BN concentration increases. However, it dives down as temperature goes up, till 50°C. Similar to the sunflower oil – Ag nanofluid case, at room temperature, viscosity reaches it’s peak, 75.69 cP at 0.01 wt.%, following that it drops gradually until it reaches 74.88 cP at 0.25 wt.%.

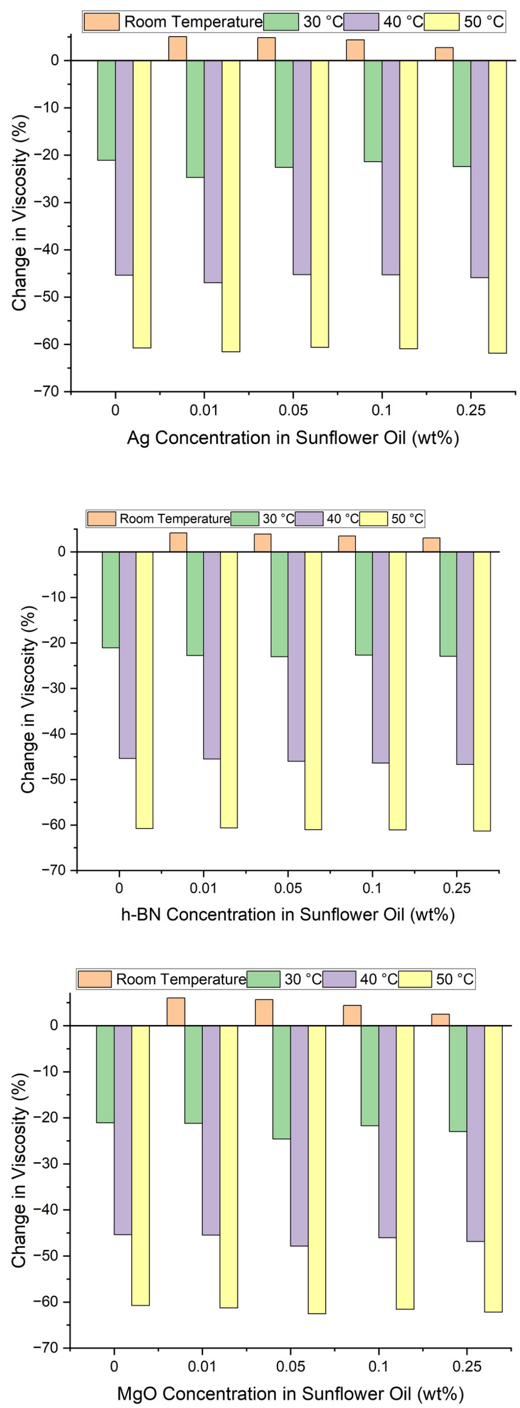


Figure 21: Viscosity of sunflower oil nanofluid as a function of Ag nanoparticle (top), h-BN nanoparticle (middle) and MgO nanoparticle (bottom) at different temperature.

For the other temperatures, 30°C, 40°C and 50°C, viscosity remains nearly the same throughout the change of h-BN nanoparticle concentration. The highest viscosity here observed is 75.69 cP in room temperature with 0.01 wt.% h-BN and the lowest one measured was 28.08 cP at 50°C with 0.25 wt.% h-BN.

In case of sunflower oil – MgO nanofluid, figure 21 (bottom), viscosity shows a similar behavior in response to added nanoparticles and temperature. Like two other previous cases of sunflower oil nanofluid, viscosity doesn't change that much in response to filler fraction. Although, it takes a dip as soon as the temperature rises. At room temperature, initially, viscosity rises a little reaching 77.02 cP at 0.01 wt.% from 72.65 cP. Following that it stayed stable getting at 74.46 cP at 0.25 wt.%. At 30°C, as well as 40°C and 50°C, viscosity didn't change much as a function of changing filler fraction. It reaches 28.12 cP, 27.22 cP, 27.9 cP with 0.01 wt.%, 0.05 wt.%, 0.10 wt.% and 0.25 wt.% at 50°C temperature, respectively.

In most of the previous studies, viscosity increases as a result of increased nanoparticle concentration(Murshed, Leong, and Yang 2008). However, in our study, for all of the nano lubricant samples, adding nanoparticles has practically no contribution in changing viscosity. When nanoparticles are added within fluid, they agglomerate and trap liquid inside of a large, agglomerated porous particle. As a result, effective volume of the particle increases which eventually contributes to increase viscosity(Anoop et al. 2009). However, in our study, viscosity didn't increase. Rather it remained comparatively unchanged. Another effect which can reduce viscosity is weakening of intermolecular hydrogen bond within the base fluid. If the hydrogen bonds present in soybean oil and sunflower oil are disturbed or weakened by the addition of Ag, h-BN or MgO nanoparticles, the resultant fluid could possess less viscosity than their pure base oils(Suganthi, Anusha, and Rajan 2013). Suganthi et al. in 2013, experienced a similar phenomenon (Suganthi, Anusha, and Rajan 2013). However, in their experiment, viscosity of nano lubricant decreased as a function of increased filler fraction rather that remaining unchanged. In our study, the unchanged viscosity can be explained by cancelling out each other's outcome, increase of viscosity by nanoparticle agglomeration and decrease of viscosity by weakening hydrogen bond of base fluid.

While increasing nanofluid temperature, bond between two molecules get weakened and sometimes the molecules get separated. When this happens, molecules are able to move more freely(Nguyen et al. 2008; Elena V. Timofeeva et al. 2010). This can happen the other way as well. As temperature goes up, molecules move faster which results in weakening of intermolecular bond, hence, lower viscosity(Ma and Fang 2017). Similar result by simulation was achieved by Tijerina et al. where they simulated viscosity of h-BN reinforced mineral oil(José Taha-Tijerina et al. 2017). They observed a comparatively no change of viscosity as the nanoparticle concentration goes up, which is similar to our study.

4.3 Tribological Properties

To understand tribological performance of prepared soybean and sunflower nano lubricants, we evaluated coefficient of friction (COF) and wear scar diameter (WSD) for each set of samples. In the following tables 20-22, WSD and COF of soybean oil nanofluids at different nanoparticle concentration is demonstrated in detail.

Table 20: WSD and COF of soybean oil-Ag nanofluids at different nanoparticle concentration.

Concentration (%)	WSD (μm)	COF (μm)
0	510.9	0.1861
0.01	507.3	0.1338
0.05	473.4	0.1463
0.1	520.8	0.1439
0.25	527.0	0.1591

Table 21: WSD and COF of soybean oil-h-BN nanofluids at different nanoparticle concentration.

Concentration (%)	WSD (μm)	COF (μm)
0	510.9	0.1861
0.01	525.2	0.1844
0.05	480.3	0.1784
0.1	485.2	0.1660
0.25	470.8	0.1680

Table 22: WSD and COF of soybean oil-MgO nanofluids at different nanoparticle concentration.

Concentration (%)	WSD (μm)	COF (μm)
0	510.9	0.1861
0.01	464.1	0.1577
0.05	470.7	0.1607
0.1	469.9	0.1585
0.25	537.8	0.1647

Figure 22 displays the change of WSD and COF as the concentration of filler fraction changes. It is evident that, overall, there is no general trend of WSD as the concentration of nanoparticles changes. We can see that as the h-BN concentration increases, soybean-h-BN initially shows an increment in WSD, 525.2 μm from 510.9 μm at 0.01wt.% h-BN. However, following that it decreases as the concentration increases to 0.05wt.% and reaches 470.8 μm at 0.25 wt.% concentration after showing a fluctuation of WSD at 0.10wt.% concentration. In case of soybean-Ag nanofluid, WSD decreases steadily showing 507.3 μm and 473.4 μm at 0.01wt.% and 0.05wt.% Ag concentration, respectively. Conversely, WSD rises rapidly at 0.05wt.% having 520.8 μm diameter and remained comparatively flat for rest of the concentrations. Among these three nanofluids, MgO shows the least WSD, 464.1 μm at 0.01 wt.% MgO concentration, however, following that it rises abruptly and exhibited 470.7 μm, 469.9 μm and 537.8 μm of WSD with 0.05 wt.%, 0.10 wt.% and 0.25wt.% MgO concentration.

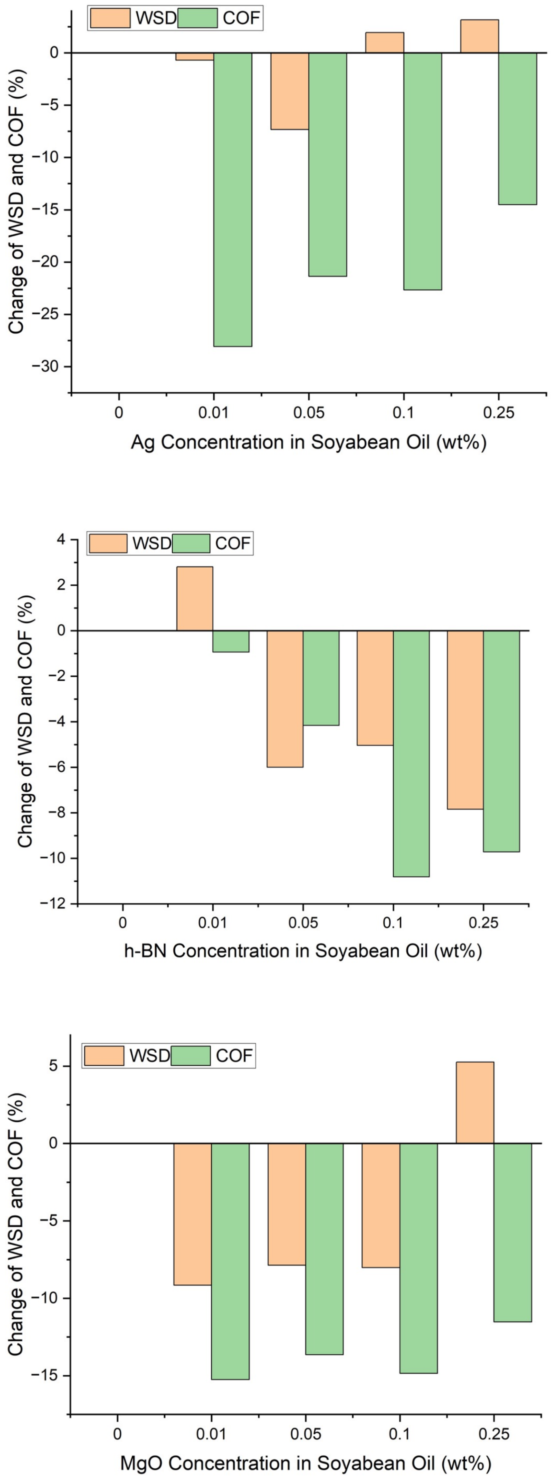


Figure 22: WSD and COF of soybean-Ag nanofluid (top), soybean-h-BN nanofluid (middle) and soybean-MgO nanofluid (bottom).

Here, we can observe that WSD decreases down to a point in response to increased nanoparticle concentration. This can be explained by different lubrication effect like ball bearing effect, protective film formation, mending effect and polishing effect. When two moving surfaces moves against each other, nanoparticles on the lubricant stuck on the surface of the metal balls, hence create a protective film. This film prevents the metal balls from wearing. However, after reaching up to a certain concentration, aggregation and entanglement of the nanostructures cause the discontinuation of the protective film. As a result, the balls get direct contact with each other and get worn.

We can see that COF decreases from 0.1861 to 0.1338 while pure soybean oil is added with 0.01wt.% Ag nanoparticle. Following that COF remained comparatively the same – 0.1463 and 0.1439 at 0.05wt.% and 0.10wt.% Ag nanostructure filler fraction, respectively. And finally, it increased to 0.1591 at 0.25wt.% Ag concentration.

It is shown that when soybean oil was added with h-BN nanoparticle, COF dropped gradually until reaching 0.1660 at 0.10wt.% from 0.1861 at pure soybean oil. Following that COF increased again up to 0.1680 at 0.25wt.% h-BN concentration. When soybean oil was reinforced with MgO nanoparticle it showed its lowest COF, 0.1577 at 0.01wt.% concentration. However, it showed fluctuation of COF but remained comparatively unchanged as MgO concentration increased from 0.01 wt.% to 0.25wt.%. From COF results of soybean oil nanofluids we can see that, out of these three nanoparticles, Ag outperformed the other two causing 28.1% reduction in COF, while, h-BN had the least impact, 10.8% reduction in COF. In all of the cases, the highest impact of nanoparticles in reducing COF was witnessed within 0.1 wt.% concentration. As concentration went up above 0.1 wt.%, COF increased in all of the cases. Here, a 'U' shape trend of COF as a function of nanoparticle concentration can be explained at the same way we explained protective film preventing the metal balls from wearing. In case of soybean-h-BN nanofluid sample, because of the laminar structure of h-BN, the particles are able to slide upon each other in response to the rubbing force. Hence, COF of the lubricant gets decreased. As the critical concentration is reached, h-BN particles pile upon each other, hence, the protective layer gets discontinuous which hampers the tribological performance of the lubricant. The other two samples, soybean-Ag and soybean-MgO reduce COF value the same way, creating protective layer, by the addition of Ag and MgO nanoparticles, respectively.

In the following tables 23-25, WSD and COF of sunflower oil nanofluids at different nanoparticle concentration is demonstrated in detail.

Table 23: WSD and COF of sunflower oil-Ag nanofluids at different nanoparticle concentration.

Concentration (%)	WSD (μm)	COF (μm)
0	451.6	0.1761
0.01	429.722222	0.19085237
0.05	455.611111	0.17409874
0.1	415.5	0.18457388
0.25	448.833333	0.17686693

Table 24: WSD and COF of sunflower oil-h-BN nanofluids at different nanoparticle concentration.

Concentration (%)	WSD (μm)	COF (μm)
0	451.6	0.1761
0.01	419.416667	0.14365685
0.05	415.055556	0.13840688
0.1	437.333333	0.14052818
0.25	410.333333	0.188589

Table 25: WSD and COF of sunflower oil-MgO nanofluids at different nanoparticle concentration.

Concentration (%)	WSD (μm)	COF (μm)
0	451.6	0.1761
0.01	439.222222	0.1765932
0.05	422.115741	0.17658985
0.1	454.148148	0.18125426
0.25	449.611111	0.1733198

Figure 23 depicts the effect of filler fraction with sunflower oil as a change in WSD and COF. When Ag is added with sunflower oil, initially WSD decreases from 451.6 μm to 429.7 μm at 0.01wt.% Ag. It increased again at 0.05wt% Ag concentration, following a dip at 415.5 μm with 0.10wt.% Ag concentration. And finally, WSD reached 448.8 μm at 0.25 wt.% Ag filler fraction. Similar abrupt changes were witnessed in case of sunflower oil reinforced with h-BN nanoparticle. As h-BN concentration increased to 0.01 wt.%, WSD was 419.4 μm. Following that, WSD slightly reduced to 415.1 μm at 0.05 wt.%. However, after that, we can see WSD increased to 437.3 μm at 0.10 wt.% h-BN. Finally, WSD gradually reduced and settled at 410.3 μm with 0.25wt.% h-BN. In case of sunflower – MgO nanofluid, WSD dropped down consecutively at 0.01wt.% and 0.05 wt.% reaching at 422.1 μm and following that it increased 7.6% and reached 454.1 μm. As MgO concentration increased further, WSD dropped 0.9% having WSD 449.6 μm.

Figure 23 displays the effect of nanoparticles on COF while added with sunflower oil. From figure 4a, we can observe that unlike soybean-Ag nanofluid, sunflower-Ag nanofluid showed a fluctuation right after Ag concentration started to increase. Pure sunflower oil exhibited 0.1761 COF, while it increased to 0.1909 and decreased to 0.1741 at 0.01wt.% and 0.05wt.% respectively. However, after that, it decreased and increased again, showing COF of 0.1741 and

0.1846 at 0.05 wt.% and 0.10 wt.% respectively and decreased again as concentration went up to 0.25wt.% having COF value of 0.1769.

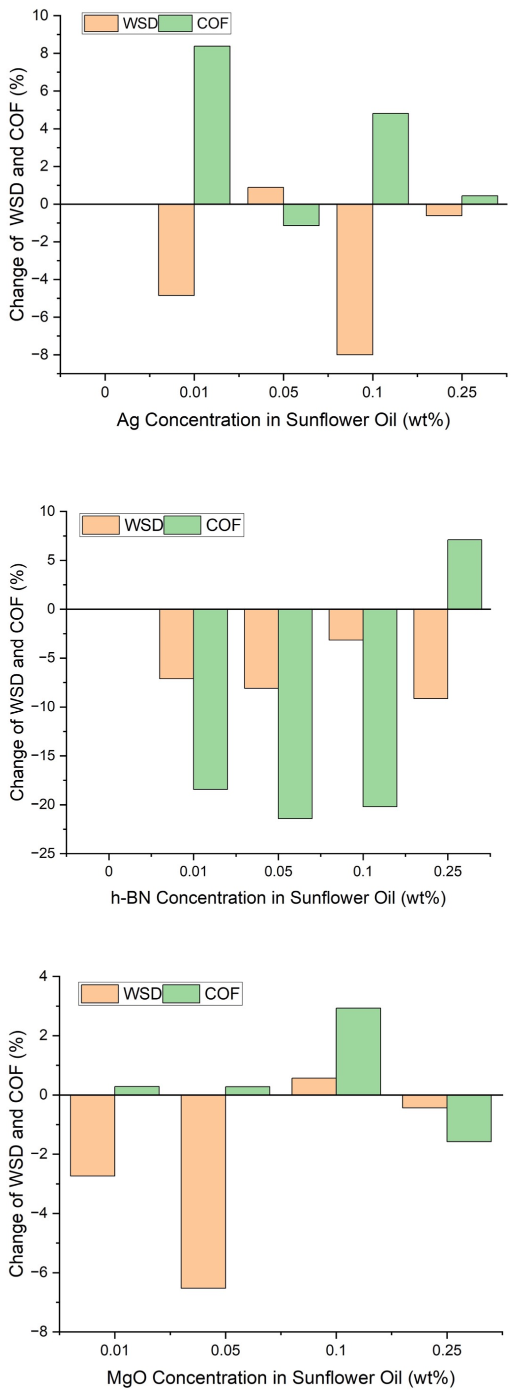


Figure 23: WSD and COF of sunflower-Ag nanofluid (top), sunflower -h-BN nanofluid (middle) and sunflower -MgO nanofluid (bottom).

When sunflower oil was added with h-BN nanoparticle, COF gradually decreased down to a point where the value reached 0.1384 at 0.05 wt.%. Following that, it increased a little at 0.10 wt.% and leaped to 0.1886 at 0.25 wt.%, exhibiting the highest among sunflower-h-BN samples. In contrast to soybean-h-BN samples, COF value didn't reduce gradually, rather it reached to an optimum point and following that COF started to rise again.

In case of sunflower-MgO nanofluid, COF remained almost the same until MgO concentration went up to 0.05 wt.% showing COF 0.1766. After that, it increased to 0.1813 at 0.10 wt.% and reduced to 0.1733 at 0.25 wt.%. Unlike while added with soybean oil, effect of MgO on sunflower oil is combatively minute in case of reducing COF.

From COF values of sunflower nanofluid samples, it is clear that h-BN nanoparticle outperformed Ag and MgO nanoparticles while mixed with sunflower oil to reduce COF. Here, h-BN nanoparticles pile upon each other while sliding force acts upon the steel balls. These piled up nanoparticles slide past each other hence reduce the COF. Sunflower–Ag and sunflower–MgO comparatively remained unresponsive to reduce COF. This reason can be explained by aggregation of Ag and MgO nanoparticles while they are mixed with the sunflower oil. This aggregation prevented the formation of protective film which would have aided reducing COF for these nanolubricant samples. In case of h-BN nanofluid, sunflower oil showed better performance than its soybean oil counterpart. Sunflower–h-BN showed maximum 21.4% reduction in COF, with 0.05 wt.% concentration.

While there are only a very few studies on vegetable oils reinforced with the same nanoparticles as in our study, some studies are narrated below to get an idea how addition of nanoparticles has affected the tribological properties of our base oils. Taha et al. found a 10.3%

reduction in COF when soybean oil was added with Ag nanoparticle(Jaime Taha-Tijerina, Shaji, et al. 2020b). From another study conducted by Kashyap and Harsha, we can see that chemically modified rapeseed oil reinforced with TiO_2 reduced COF around 15%(Kashyap and Harsha 2016). In a different research, soybean oil modified with MoS_2 showed maximum, around 25% reduction of COF(Xu et al. 2014). A separate study carried out by Arumugam and Sriram, TMP ester added with TiO_2 displayed a 15% reduced COF(Arumugam and Sriram 2013). These results comply well with the results from our soybean nanofluid samples where we got significant reduction in COF from all three samples. On the other hand, there are also studies which showed a very little COF improvement, around 2-5% while vegetable oils were reinforced with different nanoparticles[5] [6]. These studies show that even though it is likely that COF will come down significantly in response to the addition of nanoparticles, sometimes it doesn't happen, like in case of our sunflower-Ag and sunflower-MgO nanofluid where the maximum reduction of COF is 1.14% and 1.6% respectively. Like explained before,

In general, tribological performance depends on the size, shape, morphology, chemical composition of the particles(Akbulut 2012). Usually, as the concentration of nanoparticles increases up to a certain point, coefficient of friction (COF) decreases(Shafi and Charoo 2021). In some of our samples, we observe the same phenomenon. Soybean-Ag, soybean-h-BN and soybean-MgO nanofluid showed their lowest COF at 0.01wt.%, 0.01wt.% and 0.10wt.% with their respective nanoparticle concentration. After that COF increased again in response to increased nanoparticle concentration. In case of sunflower-h-BN, the lowest COF was observed at 0.05 wt.% h-BN concentration and COF increased again as nanoparticle concentration increased further. However, sunflower-Ag and sunflower-MgO showed fluctuation of COF and remained almost unchanged in response to the added nanoparticles. The reason behind the success of h-BN nanoparticles with sunflower oil in reducing COF is the same as in case of soybean-h-BN nanofluid, piling up of h-BN nanoparticles and sliding over each other in response to sliding force. However, Ag and h-BN nanoparticle couldn't contribute much in reducing COF while mixed with sunflower oil. The agglomeration of Ag and MgO nanoparticles in their respective nanofluid prevented the origination of protective film which could reduce COF by displaying ball bearing effect.

CHAPTER V

CONCLUSION

Here in our study, the goal was to develop a nano lubricant with base oil and nanoparticles, both of which should be bio-compatible and environment friendly. For these reasons, we chose soybean oil and sunflower oil as base lubricants, and Ag, h-BN and MgO as nanoparticles. We used water-based ultrasonication for several hours (8 – 10 hr.) to homogeneously dispersed the selected lubricants and nanostructures at various filler fraction. Once we obtained the nanolubricants, we performed thermal conductivity, viscosity and tribological measurements to evaluate their characteristics. Overall, inclusion of nanostructures in vegetable oils showed a positive result.

The effect of addition of nanoparticles on thermal conductivity was positive. For both base oils, as the concentration of nanoparticles and temperature of the lubricant increased, their thermal conductivity also increased in response. For instance, soybean oil showed 19.56%, 22.41% and 15% overall improvement in thermal conductivity as the inclusion of 0.25 wt.% Ag, h-BN and MgO at 50°C. On the other hand, sunflower oil showed 26.25%, 23.82 and 16.67% of overall thermal conductivity improvement as sunflower oil was added with the same nanoparticles respectively at 50°C. This improvement could be explained with improving Brownian motion of nanoparticles as the temperature went up, aggregation of nanoparticles within nanofluid and stacking of liquid molecules at the vicinity of solid particles creating thermal bridge as well.

On the other hand, in case of viscosity, it showed a little change in response to the inclusion of nanoparticles. For example, viscosity of soybean oil at room temperature changed from 57.41 cP to 62.24 cP and 57.87 cP with the addition of 0.25 wt.% Ag and h-BN, respectively. However, soybean oil had a large change of viscosity from 57.41 cP to 73 cP at 0.25 wt.% MgO concentration. Similarly sunflower oil also showed a little change in response to the inclusion of Ag, h-BN and MgO nanoparticles; their viscosity changed from 72.65 cP to around 74.5 cP for all the nanoparticles at 0.25 wt.% concentration. This unchanged viscosity can be explained by increase of viscosity as a result of nanoparticle agglomeration and decrease of viscosity by weakening hydrogen bond of base fluid, canceling out each other's effect. This unchanged viscosity has a overall positive effect on industrial application. As a result of lower viscosity, there will be a need of lower pump efficiency to pump this lubricant and this lower viscosity does facilitate higher thermal performance as well. Besides that, because of this lower viscosity flow characteristics of the fluid will also be improved and there should be a less pressure drop within the fluid system. However, temperature had a great effect on all types of nanofluid samples. As the temperature went up from room temperature to 50°C, viscosity dramatically dropped and showed 23.38 cP, 23.38 cP and 23.68 cP for 0.25 wt.% soybean-Ag, soybean-MgO and soybean-h-BN nanofluid. And in the case of sunflower base oil, the values were 27.7 cP, 28.5 cP and 28.08 cP for 0.25 wt.% Ag, MgO and h-BN inclusion. The reason behind this can be explained by breaking of molecular bond within oil as temperature went up, which facilitated more frequent movement of molecules facing less resistance.

In the case of tribological properties, inclusion of nanoparticles had an overall positive impact. As nanoparticles concentration went up, wear scar diameter (WSD) and coefficient of friction (COF) decreased up to a certain concentration. For example, sunflower oil showed its lowest COF at 0.05 wt.%, 0.05 wt.% and 0.25 wt.% with Ag, h-BN and MgO nanoparticle inclusion. However, the reductio of COF was not always the same for all the nanofluid. In case of soybean oil nanofluids, the maximum reduction of COF was 28.1%, 10.8% and 16.33% with Ag, h-BN and MgO addition.

From this study, it is clear that environmentally friendly oils and nanoparticles have the potential to improve lubricant's quality. However, there are still some drawbacks which should be addressed. For example, settling nanoparticles over time is a great concern. Further research can be carried out to find out how to minimize the settling of nanoparticles and maintain the overall lubricant properties. Using surfactant with nanoparticles could be a possible option. It is also worth understanding if the lubricating properties of these lubricants do diminish over time or not. However, as a starting point this research will help others to further carry it out and find out it's usability in actual industrial practices.

REFERENCES

Abosede, Ewetola E. 2013. “Effect of Crude Oil Pollution on Some Soil Physical Properties.” *IOSR Journal of Agriculture and Veterinary Science*. http://www.iosrjournals.org/iosr-javs/papers/vol6-issue3/D0631417.pdf?id=7269 (August 22, 2021).

Ahmed, Siraj Ali et al. 2018. “Improving Car Radiator Performance by Using TiO2-Water Nanofluid.” *Engineering Science and Technology, an International Journal* 21(5): 996–1005.

Akbulut, Mustafa. 2012. “Nanoparticle-Based Lubrication Systems.” *Journal of Powder Metallurgy and Mining* 01(01). https://www.omicsonline.org/open-access/nanoparticle-based-lubrication-systems-2168-9806.1000e101.php?aid=3298 (October 29, 2022).

Ali, Mohamed Kamal Ahmed et al. 2016. “Improving the Tribological Characteristics of Piston Ring Assembly in Automotive Engines Using Al2O3 and TiO2 Nanomaterials as Nano-Lubricant Additives.” *Tribology International* 103: 540–54.

Aluyor, E. O., and M. Ori-jesu. 2009. “Biodegradation of Mineral Oils – A Review.” *African Journal of Biotechnology* 8(6). https://www.ajol.info/index.php/ajb/article/view/59986 (August 22, 2021).

Anoop, K. B., S. Kabelac, T. Sundararajan, and Sarit K. Das. 2009. “Rheological and Flow Characteristics of Nanofluids: Influence of Electroviscous Effects and Particle Agglomeration.” *Journal of Applied Physics* 106(3): 034909.

Arumugam, S., and G. Sriram. 2013. “Preliminary Study of Nano- and Microscale TiO2 Additives on Tribological Behavior of Chemically Modified Rapeseed Oil.” *Tribology Transactions* 56(5): 797–805.

Arumugam, S, and G Sriram. 2014. “Synthesis and Characterization of Rapeseed Oil Bio-Lubricant Dispersed with Nano Copper Oxide: Its Effect on Wear and Frictional Behavior of Piston Ring–Cylinder Liner Combination.” *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology* 228(11): 1308–18.

Baranowska-Wójcik, Ewa, Dominik Szwajgier, Patryk Oleszczuk, and Anna Winiarska-Mieczan. 2020. “Effects of Titanium Dioxide Nanoparticles Exposure on Human Health—a Review.” *Biological Trace Element Research* 193(1): 118–29.

Barker, Colin. 1985. “Chapter 2 Origin, Composition and Properties of Petroleum.” In *Developments in Petroleum Science*, Enhanced Oil Recovew, I, eds. Erle C. Donaldson, George V. Chilingarian, and Teh Fu Yen. Elsevier, 11–45.

https://www.sciencedirect.com/science/article/pii/S0376736108705648 (February 27, 2022).

Belluco, W, and L De Chiffre. 2002. "Surface Integrity and Part Accuracy in Reaming and Tapping Stainless Steel with New Vegetable Based Cutting Oils." *Tribology International* 35(12): 865–70.

Bhanvase, Bharat, and Divya Barai. 2021. "5 - Electrical, Optical, and Tribological Properties of the Nanofluids." In *Nanofluids for Heat and Mass Transfer*, eds. Bharat Bhanvase and Divya Barai. Academic Press, 167–90. https://www.sciencedirect.com/science/article/pii/B9780128219553000133 (October 31, 2022).

Bindhu, M. R. et al. 2016. "Structural, Morphological and Optical Properties of MgO Nanoparticles for Antibacterial Applications." *Materials Letters* 166: 19–22.

Bird, J O, and P J Chivers. 1993. "28 - Friction." In *Newnes Engineering and Physical Science Pocket Book*, eds. J O Bird and P J Chivers. Newnes, 235–37. https://www.sciencedirect.com/science/article/pii/B978075061683650031X (October 31, 2022).

Biresaw, Girma, Grigor B. Bantchev, and Steven C. Cermak. 2011. "Tribological Properties of Vegetable Oils Modified by Reaction with Butanethiol." *Tribology Letters* 43(1): 17–32.

Brevedan, Marta Ingrid Victoria, Guillermo Hector Crapiste, and Amalia Antonia Carelli Albarracin. 2000. "Changes in Composition and Quality of Sunflower Oils during Extraction and Degumming." https://ri.conicet.gov.ar/handle/11336/40570 (October 19, 2022).

Calabi-Floody, Marcela, Benny Theng, and Maria Luz Mora. 2009. "Natural Nanoclays: Applications and Future Trends- A Chilean Perspective." *Clay Minerals - CLAY MINER* 44: 161–76.

Carelli, Amalia A., Marta I. V. Brevedan, and Guillermo H. Crapiste. 1997. "Quantitative Determination of Phospholipids in Sunflower Oil." *Journal of the American Oil Chemists' Society* 74(5): 511–14.

Carelli, Amalia A., Lorna M. Frizzera, Pedro R. Forbito, and Guillermo H. Crapiste. 2002. "Wax Composition of Sunflower Seed Oils." *Journal of the American Oil Chemists' Society* 79(8): 763–68.

Çelik, O. N., N. Ay, and Y. Göncü. 2013. "Effect of Nano Hexagonal Boron Nitride Lubricant Additives on the Friction and Wear Properties of AISI 4140 Steel." *Particulate Science and Technology* 31(5): 501–6.

Charoo, M. S., and M. F. Wani. 2017. "Tribological Properties of H-BN Nanoparticles as Lubricant Additive on Cylinder Liner and Piston Ring." *Lubrication Science* 29(4): 241–54.

Chen, Yan et al. 2020. "Performance Characteristics of Lubricants in Electric and Hybrid Vehicles: A Review of Current and Future Needs." *Frontiers in Mechanical Engineering* 6. https://www.frontiersin.org/articles/10.3389/fmech.2020.571464 (October 19, 2022).

Chon, Chan Hee, Kenneth D. Kihm, Shin Pyo Lee, and Stephen U. S. Choi. 2005. "Empirical Correlation Finding the Role of Temperature and Particle Size for Nanofluid (Al2O3) Thermal Conductivity Enhancement." *Applied Physics Letters* 87(15): 153107.

Cortes, Vicente et al. 2020. "The Performance of SiO2 and TiO2 Nanoparticles as Lubricant Additives in Sunflower Oil." *Lubricants* 8(1): 10.

Cortes, Vicente, and Javier A. Ortega. 2019. "Evaluating the Rheological and Tribological Behaviors of Coconut Oil Modified with Nanoparticles as Lubricant Additives." *Lubricants* 7(9): 76.

D'Andrea, Mark A., and G. Kesava Reddy. 2018. "Health Risks Associated With Benzene Exposure in Children: A Systematic Review." *Global Pediatric Health* 5: 2333794X18789275.

Das, Pritam Kumar. 2017. "A Review Based on the Effect and Mechanism of Thermal Conductivity of Normal Nanofluids and Hybrid Nanofluids." *Journal of Molecular Liquids* 240: 420–46.

Dayana, Indri et al. 2020. "Study of Thermal Conductivity of Fe3O4 Nanoparticles Coated with TEOS." In Medan, Indonesia, 110015. http://aip.scitation.org/doi/abs/10.1063/5.0003795 (October 30, 2022).

Desai, Nilesh, A. M. Nagaraj, and Nilesh Sabnis. 2021. "Analysis of Thermo-Physical Properties of SAE20W40 Engine Oil by the Addition of SiO2 Nanoparticles." *Materials Today: Proceedings* 47: 5646–51.

Dev Choudhury, Nabajit, Niharendu Saha, Shubrajit Bhaumik, and Rupam Kataki. 2021. "Production and Evaluation of Physicochemical, Rheological, and Tribological Properties of Cucurbita Pepo L. Seed Oil." *Biomass Conversion and Biorefinery*.

Dos Santos, Carolina Alves et al. 2014. "Silver Nanoparticles: Therapeutical Uses, Toxicity, and Safety Issues." *Journal of Pharmaceutical Sciences* 103(7): 1931–44.

Duangthongsuk, Weerapun, and Somchai Wongwises. 2009. "Measurement of Temperature-Dependent Thermal Conductivity and Viscosity of TiO2-Water Nanofluids." *Experimental Thermal and Fluid Science* 33(4): 706–14.

Emanet Ciofani, Melis, Özlem Şen, and Mustafa Çulha. 2020. "Hexagonal Boron Nitride Nanoparticles for Prostate Cancer Treatment." *ACS Applied Nano Materials* 3(3): 2364–72.

Ettefaghi, Ehsan-o-llah et al. 2013. “Experimental Evaluation of Engine Oil Properties Containing Copper Oxide Nanoparticles as a Nanoadditive.” *International Journal of Industrial Chemistry* 4(1): 28.

Farade, Rizwan A. et al. 2020. “Investigation of the Dielectric and Thermal Properties of Non-Edible Cottonseed Oil by Infusing h-BN Nanoparticles.” *IEEE Access* 8: 76204–17.

Farbod, Mansoor, Razieh Kouhpeymani asl, and Amin Reza Noghreh abadi. 2015. “Morphology Dependence of Thermal and Rheological Properties of Oil-Based Nanofluids of CuO Nanostructures.” *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 474: 71–75.

Favi, Pelagie Marlene et al. 2015. “Shape and Surface Effects on the Cytotoxicity of Nanoparticles: Gold Nanospheres versus Gold Nanostars.” *Journal of Biomedical Materials Research Part A* 103(11): 3449–62.

“FoodData Central.” 2018. https://fdc.nal.usda.gov/fdc-app.html#/food-details/171411/nutrients (October 19, 2022).

“Full Text.” https://engineering.purdue.edu/NanoLab/PDF/1999.Thermal Conductivity of Nanoparticle Fluid Mixture.pdf (August 27, 2021).

Ganguly, Priyanka, Ailish Breen, and Suresh C. Pillai. 2018. “Toxicity of Nanomaterials: Exposure, Pathways, Assessment, and Recent Advances.” *ACS Biomaterials Science & Engineering* 4(7): 2237–75.

Gawęda, E., K. Bednarek, and Z. Szydło. 2005. “Oznaczanie mgły olejowej w powietrzu na stanowiskach pracy metodą wagową.” *Bezpieczeństwo Pracy : nauka i praktyka* nr 12: 11–14.

“Global Vegetable Oil Consumption, 2019/20.” *Statista*. https://www.statista.com/statistics/263937/vegetable-oils-global-consumption/ (March 10, 2022).

Guimarey, M. J. et al. 2018. “Effect of ZrO2 Nanoparticles on Thermophysical and Rheological Properties of Three Synthetic Oils.”

Hemmat Esfe, Mohammad, Seyfolah Saedodin, Mousa Rejvani, and Jalal Shahram. 2017. “Experimental Investigation, Model Development and Sensitivity Analysis of Rheological Behavior of ZnO/10W40 Nano-Lubricants for Automotive Applications.” *Physica E: Low-dimensional Systems and Nanostructures* 90: 194–203.

“ISO Grade Oils - Viscosities and Densities.” 2008. https://www.engineeringtoolbox.com/iso-grade-oil-d_1207.html (October 19, 2022).

Iyahraja, S., and J. Selwin Rajadurai. 2015. “Study of Thermal Conductivity Enhancement of Aqueous Suspensions Containing Silver Nanoparticles.” *AIP Advances* 5(5): 057103.

Janke, Isabel et al. 2013. “VISCOSITY AND THERMAL CONDUCTIVITY OF SOYBEAN OIL-DIESEL BLENDS BETWEEN 293 AND 353 K.” : 6.

Järvholm, B. et al. 1982. “Respiratory Symptoms and Lung Function in Oil Mist-Exposed Workers.” *Journal of Occupational Medicine.: Official Publication of the Industrial Medical Association* 24(6): 473–79.

Kashyap, Amod, and AP Harsha. 2016. “Tribological Studies on Chemically Modified Rapeseed Oil with CuO and CeO2 Nanoparticles.” *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology* 230(12): 1562–71.

Kasolang, Salmiah, Mohamad Ali Ahmad, Mimi Bakar, and Ahmad Hussein Abdul Hamid. 2012. “Specific Wear Rate of Kenaf Epoxy Composite and Oil Palm Empty Fruit Bunch (OPEFB) Epoxy Composite in Dry Sliding.” *Jurnal Teknologi* 58.

Keblinski, P, S. R Phillpot, S. U. S Choi, and J. A Eastman. 2002. “Mechanisms of Heat Flow in Suspensions of Nano-Sized Particles (Nanofluids).” *International Journal of Heat and Mass Transfer* 45(4): 855–63.

Khalafvandi, Seyed Ali, Muhammad Ali Pazokian, and Ehsan Fathollahi. 2022. “The Investigation of Viscometric Properties of the Most Reputable Types of Viscosity Index Improvers in Different Lubricant Base Oils: API Groups I, II, and III.” *Lubricants* 10(1): 6.

Khalil, Waleed, Alaa Mohamed, Mohamed Bayoumi, and T. A. Osman. 2018. “Thermal and Rheological Properties of Industrial Mineral Gear Oil and Paraffinic Oil/CNTs Nanolubricants.” *Iranian Journal of Science and Technology, Transactions of Mechanical Engineering* 42(4): 355.

Khan, Ibrahim, Khalid Saeed, and Idrees Khan. 2019. “Nanoparticles: Properties, Applications and Toxicities.” *Arabian Journal of Chemistry* 12(7): 908–31.

Kumar Gajrani, Kishor, and M. Ravi Sankar. 2017. “Past and Current Status of Eco-Friendly Vegetable Oil Based Metal Cutting Fluids.” *Materials Today: Proceedings* 4(2, Part A): 3786–95.

Lansdown, Alan B. G. 2006. “Silver in Health Care: Antimicrobial Effects and Safety in Use.” *Current Problems in Dermatology* 33: 17–34.

Lee, Kwangho et al. 2009. “Understanding the Role of Nanoparticles in Nano-Oil Lubrication.” *Tribology Letters* 35(2): 127–31.

Liñeira del Río, José M. et al. 2019. “Tribological and Thermophysical Properties of Environmentally-Friendly Lubricants Based on Trimethylolpropane Trioleate with Hexagonal Boron Nitride Nanoparticles as an Additive.” *Coatings* 9(8): 509.

Liu, G. et al. 2004. “Investigation of the Mending Effect and Mechanism of Copper Nano-Particles on a Tribologically Stressed Surface.” *Tribology Letters* 17(4): 961–66.

Lu, Tun et al. 2016. “Hexagonal Boron Nitride Nanoplates as Emerging Biological Nanovectors and Their Potential Applications in Biomedicine.” *Journal of Materials Chemistry B* 4(36): 6103–10.

M., Maheshwar. 2018. “A REVIEW ARTICLE ON MEASUREMENT OF VISCOSITY.” *International Journal of Research in Pharmacy and Chemistry* 8(1): 69–77.

Ma, Qianli, and Haisheng Fang. 2017. “Viscosity Prediction of Water-Based Silver Nanofluid Using Equilibrium Molecular Dynamics.” In American Society of Mechanical Engineers Digital Collection. https://asmedigitalcollection.asme.org/IMECE/proceedings/IMECE2016/50619/V007T09A048/262682 (October 25, 2022).

Madhujith, Terrence, and Subajiny Sivakanthan. 2018. “Oxidative Stability of Edible Plant Oils.” In *Bioactive Molecules in Food*, Reference Series in Phytochemistry, eds. Jean-Michel Mérillon and K.G. Ramawat. Cham: Springer International Publishing, 1–23. https://doi.org/10.1007/978-3-319-54528-8_94-1 (September 9, 2021).

“Magnesium Oxide (MgO) Nanoparticles - Properties, Applications.” 2013. *AZoNano.com*. https://www.azonano.com/article.aspx?ArticleID=3353 (October 19, 2022).

Malakar, Arindam et al. 2020. “Ferrihydrite Reduction Increases Arsenic and Uranium Bioavailability in Unsaturated Soil.” *Environmental Science & Technology* 54(21): 13839–48.

Marquis, Fernand, and Felipe Chibante. 2005. “Improving the Heat Transfer of Nanofluids and Nanolubricants with Carbon Nanotubes.” *JOM* 57: 32–43.

Maszewska, Magdalena et al. 2018. “Oxidative Stability of Selected Edible Oils.” *Molecules : A Journal of Synthetic Chemistry and Natural Product Chemistry* 23(7): 1746.

Mechiri, S. K., V. Vasu, and A. Venu Gopal. 2017. “Investigation of Thermal Conductivity and Rheological Properties of Vegetable Oil Based Hybrid Nanofluids Containing Cu–Zn Hybrid Nanoparticles.” *Experimental Heat Transfer* 30(3): 205–17.

Meng, Yuan, Fenghua Su, and Yangzhi Chen. 2018. “Effective Lubricant Additive of Nano-Ag/MWCNTs Nanocomposite Produced by Supercritical CO2 Synthesis.” *Tribology International* 118: 180–88.

Murshed, S. M. S., K. C. Leong, and C. Yang. 2008. “Investigations of Thermal Conductivity and Viscosity of Nanofluids.” *International Journal of Thermal Sciences* 47(5): 560–68.

Nair, Sabarinath Sankaran, Kumarapillai Prabhakaran Nair, and Perikinalil Krishnan Rajendrakumar. 2017. “Evaluation of Physicochemical, Thermal and Tribological Properties of Sesame Oil (Sesamum Indicum L.): A Potential Agricultural Crop Base Stock for Eco-Friendly Industrial Lubricants.” *International Journal of Agricultural Resources, Governance and Ecology* 13(1): 77.

Nallusamy, Dr, and J. Logeshwaran. 2017. "Experimental Analysis on Nanolubricants Used in Multi Cylinder Petrol Engine with Copper Oxide as Nanoparticle." *RASĀYAN Journal of Chemistry* 10: 1050–55.

Neri, F. et al. 2016. "Determining Exhaust Fumes Exposure in Chainsaw Operations." *Environmental Pollution* 218: 1162–69.

Nguyen, C. T. et al. 2008. "Viscosity Data for Al2O3–Water Nanofluid—Hysteresis: Is Heat Transfer Enhancement Using Nanofluids Reliable?" *International Journal of Thermal Sciences* 47(2): 103–11.

Nowak, Paulina, Karolina Kucharska, and Marian Kamiński. 2019. "Ecological and Health Effects of Lubricant Oils Emitted into the Environment." *International Journal of Environmental Research and Public Health* 16(16): 3002.

Nwoguh, Theodore O., Anthony C. Okafor, and Hilary A. Onyishi. 2021. "Enhancement of Viscosity and Thermal Conductivity of Soybean Vegetable Oil Using Nanoparticles to Form Nanofluids for Minimum Quantity Lubrication Machining of Difficult-to-Cut Metals." *The International Journal of Advanced Manufacturing Technology* 113(11): 3377–88.

Oommen, T.V. 2002. "Vegetable Oils for Liquid-Filled Transformers." *IEEE Electrical Insulation Magazine* 18(1): 6–11.

Pal, U. S. et al. 2015. "Effect of Refining on Quality and Composition of Sunflower Oil." *Journal of Food Science and Technology* 52(7): 4613–18.

Palacios, Anabel et al. 2019. "Thermal Conductivity Measurement Techniques for Characterizing Thermal Energy Storage Materials – A Review." *Renewable and Sustainable Energy Reviews* 108: 32–52.

Poth, Ulrich. 2001. "Drying Oils and Related Products." In *Ullmann's Encyclopedia of Industrial Chemistry*, John Wiley & Sons, Ltd. https://onlinelibrary.wiley.com/doi/abs/10.1002/14356007.a09_055 (October 18, 2022).

Proctor, Andrew. 1997. "Soybean Oil Extraction and Processing." In *Soybeans*, Boston, MA: Springer US, 297–346. http://link.springer.com/10.1007/978-1-4615-1763-4_6 (October 18, 2022).

Pullen, James, and Khizer Saeed. 2012. "An Overview of Biodiesel Oxidation Stability." *Renewable and Sustainable Energy Reviews* 16(8): 5924–50.

Rafiq, M. et al. 2015. "Use of Vegetable Oils as Transformer Oils – a Review." *Renewable and Sustainable Energy Reviews* 52: 308–24.

Rafiq, Muhammad, Muhammad Shafique, Anam Azam, and Muhammad Ateeq. 2021. "Transformer Oil-Based Nanofluid: The Application of Nanomaterials on Thermal, Electrical and Physicochemical Properties of Liquid Insulation-A Review.” *Ain Shams Engineering Journal* 12(1): 555–76.

Ramteke, Sangharatna, and H Chelladurai. 2020. “Examining the Role of Hexagonal Boron Nitride Nanoparticles as an Additive in the Lubricating Oil and Studying Its Application.” *Proceedings of the Institution of Mechanical Engineers, Part N: Journal of Nanomaterials, Nanoengineering and Nanosystems* 234(1–2): 19–36.

Reddy, K. S. V. Krishna, Naval Kabra, Umesh Kunchum, and T. Vijayakumar. 2014. “Experimental Investigation on Usage of Palm Oil as a Lubricant to Substitute Mineral Oil in CI Engines.” *Chinese Journal of Engineering* 2014: e643521.

Riahi, Afifa et al. 2020. “Study of Thermal Conductivity of Synthesized Al2O3-Water Nanofluid by Pulsed Laser Ablation in Liquid.” *Journal of Molecular Liquids* 304: 112694.

Rogoś, E., and A. Urbański. 2010. “Charakterystyki tribologiczne roślinnych olejów bazowych dla olejów hydraulicznych.” *Tribologia* nr 5: 201–11.

Rojas, Edwin E. Garcia, Jane S.R. Coimbra, and Javier Telis-Romero. 2013. “Thermophysical Properties of Cotton, Canola, Sunflower and Soybean Oils as a Function of Temperature.” *International Journal of Food Properties* 16(7): 1620–29.

Rojas, Edwin, Jane Coimbra, and Javier telis-Romero. 2013. “Thermophysical Properties of Cotton, Canola, Sunflower and Soybean Oils as a Function of Temperature.” *International Journal of Food Properties* 16.

Rukunudin, I. H., P. J. White, C. J. Bern, and T. B. Bailey. 1998. “A Modified Method for Determining Free Fatty Acids from Small Soybean Oil Sample Sizes.” *Journal of the American Oil Chemists’ Society* 75(5): 563–68.

Sadiq, Ibrahim Ogu et al. 2018. “Enhancement of Thermo-Physical and Lubricating Properties of SiC Nanolubricants for Machining Operation.” *Procedia Manufacturing* 17: 166–73.

Sajid, Muhammad et al. 2015. “Impact of Nanoparticles on Human and Environment: Review of Toxicity Factors, Exposures, Control Strategies, and Future Prospects.” *Environmental Science and Pollution Research* 22(6): 4122–43.

Salimon, Jumat, Nadia Salih, and Emad Yousif. 2011. “Chemically Modified Biolubricant Basestocks from Epoxidized Oleic Acid: Improved Low Temperature Properties and Oxidative Stability.” *Journal of Saudi Chemical Society* 15(3): 195–201.

Samion, Syahrullail, K. Nakanishi, and S. Kamitani. 2005. “Investigation of the Effects of Frictional Constraint with Application of Palm Olein Oil Lubricant and Paraffin Mineral Oil Lubricant on Plastic Deformation by Plane Strain Extrusion [Investigation of the Effects of Frictional Constraint with Application of Palm Olein Oil Lubricant and Paraffin Mineral Oil Lubricant on Plastic Deformation by Plane Strain Extrusion].” *Toraibarojisuto/Journal of Japanese Society of Tribologists* 50: 877–85.

Sanni, Samuel Eshorame, Joseph Obofon Odigure, Vincent Efeovbokhan, and Moses Eterigho Emetere. 2017. "Comparative Study of Lube Oils Syhthesized from Chemically Modified Castor and Soybean Oils Using Additive." *Science and Engineering Applications* 2(2): 134.

Savva, S. C., and A. Kafatos. 2016. "Vegetable Oils: Dietary Importance." In *Encyclopedia of Food and Health*, eds. Benjamin Caballero, Paul M. Finglas, and Fidel Toldrá. Oxford: Academic Press, 365–72. https://www.sciencedirect.com/science/article/pii/B9780123849472007091 (October 19, 2022).

Sepyani, Kamran, Masoud Afrand, and Mohammad Hemmat Esfe. 2017. "An Experimental Evaluation of the Effect of ZnO Nanoparticles on the Rheological Behavior of Engine Oil." *Journal of Molecular Liquids* 236: 198–204.

Shaari, Mohd et al. 2015. "Investigation of Tribological Properties of Palm Oil Biolubricant Modified Nanoparticles." *Jurnal Teknologi* 76: 69–73.

Shafi, Wani Khalid, and M. S. Charoo. 2021. "An Overall Review on the Tribological, Thermal and Rheological Properties of Nanolubricants." *Tribology - Materials, Surfaces & Interfaces* 15(1): 20–54.

Shajahan, Tariq, and Wim-Paul Breugem. 2020. "Influence of Concentration on Sedimentation of a Dense Suspension in a Viscous Fluid." *Flow, Turbulence and Combustion* 105(2): 537–54.

Singh, Yashvir et al. 2021. "Magnesium Oxide (MgO) as an Additive to the Neem Oil for Efficient Lubrication." *Materials Today: Proceedings* 46: 10478–81.

Slifka, A. J., B. J. Filla, and J. M. Phelps. 1998. "Thermal Conductivity of Magnesium Oxide From Absolute, Steady-State Measurements." *Journal of Research of the National Institute of Standards and Technology* 103(4): 357–63.

Specialties, Twin. 2020. "What Are Biodegradable Lubricants?" *Twin Specialties Corp.* https://www.twinoils.com/news/what-are-biodegradable-lubricants/ (August 22, 2021).

Suganthi, Kuppusamy Swaminathan, Natarajan Anusha, and Kalpoondi Sekar Rajan. 2013. "Low Viscous ZnO–Propylene Glycol Nanofluid: A Potential Coolant Candidate." *Journal of Nanoparticle Research* 15(10): 1986.

Syahrullail, S., B. M. Zubil, C. S. N. Azwadi, and M. J. M. Ridzuan. 2011. "Experimental Evaluation of Palm Oil as Lubricant in Cold Forward Extrusion Process." *International Journal of Mechanical Sciences* 53(7): 549–55.

Taha-Tijerina, Jaime, Hélio Ribeiro, et al. 2020. "Thermal Conductivity Performance of 2D H-BN/MoS2/-Hybrid Nanostructures Used on Natural and Synthetic Esters." *Nanomaterials* 10(6). https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7353450/ (June 12, 2021).

Taha-Tijerina, Jaime, Sadasivan Shaji, et al. 2020a. “Tribological and Thermal Transport of Ag-Vegetable Nanofluids Prepared by Laser Ablation.” *Applied Sciences* 10(5): 1779.

———. 2020b. “Tribological and Thermal Transport of Ag-Vegetable Nanofluids Prepared by Laser Ablation.” *Applied Sciences* 10(5): 1779.

Taha-Tijerina, José et al. 2017. “Theoretical Prediction of Physical Properties (Viscosity) on 2D-Based Nanofluids.” *Ingeniería, investigación y tecnología* 18(1): 101–9.

Tahir, Awais, Petr Pokorny, and Naveed Malek. 2021. “Butane Toxicity: The Curse of Volatile Solvent Abuse.” *Dubai Medical Journal* 4(4): 344–47.

Takeuchi, Y et al. 1980. “A Comparative Study on the Neurotoxicity of N-Pentane, n-Hexane, and n-Heptane in the Rat.” *British Journal of Industrial Medicine* 37(3): 241–47.

Tang, Zhenglin, and Shaohui Li. 2014. “A Review of Recent Developments of Friction Modifiers for Liquid Lubricants (2007–Present).” *Current Opinion in Solid State and Materials Science* 18(3): 119–39.

Tao, Xu, Zhao Jiazheng, and Xu Kang. 1996. “The Ball-Bearing Effect of Diamond Nanoparticles as an Oil Additive.” *Journal of Physics D: Applied Physics* 29(11): 2932–37.

Tenbohlen, Stefan, and Maik Koch. 2010. “Aging Performance and Moisture Solubility of Vegetable Oils for Power Transformers.” *IEEE Transactions on Power Delivery* 25(2): 825–30.

“Thermal Conductivity of Fresh and Used Engine Oil.” *Thermtest*. https://thermtest.com/application/thermal-conductivity-of-fresh-and-used-engine-oil (November 8, 2022).

Timofeeva, E. V., M. R. Moravek, D. Singh, and (Ne). 2011. “Improving the Heat Transfer Efficiency of Synthetic Oil With Silica Nanoparticles.” *Journal of Colloid and Interface Science* 364(1; Dec. 2011). https://www.osti.gov/biblio/1089120-improving-heat-transfer-efficiency-synthetic-oil-silica-nanoparticles (August 27, 2021).

Timofeeva, Elena V. et al. 2010. “Particle Size and Interfacial Effects on Thermo-Physical and Heat Transfer Characteristics of Water-Based α-SiC Nanofluids.” *Nanotechnology* 21(21): 215703.

Tiong, Chiong Ing, Yahya Azli, Mohammed Rafiq Abdul Kadir, and Samion Syahrullail. 2012. “Tribological Evaluation of Refined, Bleached and Deodorized Palm Stearin Using Four-Ball Tribotester with Different Normal Loads.” *Journal of Zhejiang University SCIENCE A* 13(8): 633–40.

Verma, Puneet, M. P. Sharma, and Gaurav Dwivedi. 2016. “Evaluation and Enhancement of Cold Flow Properties of Palm Oil and Its Biodiesel.” *Energy Reports* 2: 8–13.

Vowles, Hugh P. 1932. “Early Evolution of Power Engineering.” *Isis* 17(2): 412–20.

Wan, Qingming, Yi Jin, Pengcheng Sun, and Yulong Ding. 2015. “Tribological Behaviour of a Lubricant Oil Containing Boron Nitride Nanoparticles.” *Procedia Engineering* 102: 1038–45.

Wang, Li et al. 2020. “Mono-Dispersed Ag/Graphene Nanocomposite as Lubricant Additive to Reduce Friction and Wear.” *Tribology International* 146: 106228.

Włodarczyk-Makuła, M. 2016. “Zagrożenie zanieczyszczenia środowiska wodnego związkami ropopochodnymi.” *LAB Laboratoria, Aparatura, Badania* R. 21, nr 1. http://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-70aae97e-1564-4a4a-9468-0308b8f2438f (October 19, 2022).

Woma, Timothy Yakubu et al. 2019. “Vegetable Oil Based Lubricants: Challenges and Prospects.” *Tribology Online* 14(2): 60–70.

“World Oil Statistics - Worldometer.” https://www.worldometers.info/oil/ (March 10, 2022).

Xie, Huaqing, Wei Yu, and Wei Chen. 2010. “MgO Nanofluids: Higher Thermal Conductivity and Lower Viscosity among Ethylene Glycol-Based Nanofluids Containing Oxide Nanoparticles.” *Journal of Experimental Nanoscience* 5(5): 463–72.

Xu, Z. Y. et al. 2014. “Tribological Properties of Molybdenum Disulphide Nanoparticles in Soybean Oil.” *Tribology - Materials, Surfaces & Interfaces* 8(4): 179–86.

Yao, Wei et al. 2018a. “Enhanced Electrical Insulation and Heat Transfer Performance of Vegetable Oil Based Nanofluids.” *Journal of Nanomaterials* 2018: e4504208.

———. 2018b. “Enhanced Electrical Insulation and Heat Transfer Performance of Vegetable Oil Based Nanofluids.” *Journal of Nanomaterials* 2018: e4504208.

Yuan, Chao et al. 2019. “Modulating the Thermal Conductivity in Hexagonal Boron Nitride via Controlled Boron Isotope Concentration.” *Communications Physics* 2(1): 1–8.

Zhang, Xi-Feng, Zhi-Guo Liu, Wei Shen, and Sangiliyandi Gurunathan. 2016. “Silver Nanoparticles: Synthesis, Characterization, Properties, Applications, and Therapeutic Approaches.” *International Journal of Molecular Sciences* 17(9): 1534.

Zin, V. et al. 2016. “Improved Tribological and Thermal Properties of Lubricants by Graphene Based Nano-Additives.” *RSC Advances* 6(64): 59477–86.

BIOGRAPHICAL SKETCH

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