Production of Bio-lubricant from Non-Edible Oil (Castor Oil) Using Iron Oxide Nanoparticles

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Dedication

By the grace of Almighty Allah, who is the most Beneficent and the most merciful

This research is dedicated to my parents, who have always been my source of guidance and support.

To my supervisor who shared his knowledge, gave advice, and encouraged me to fulfill my tasks.

And to all my fellows, with whom I worked with and shared good memories.

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All praises to Almighty Allah, without His will nothing can happen, who favored us with the capacity to think and made us anxious to investigate this entire universe. Incalculable greetings upon the Holy Prophet Hazrat Muhammad (PBUH), the reason for the creation of the universe and wellspring of information and blessing for whole humankind.

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Uzair Ahmad

Abstract

Lubricants operate as anti-friction media, preserving machine reliability, facilitating smooth operation, and reducing the likelihood of frequent breakdowns. Petroleum-based reserves are decreasing globally, leading to price increases, and raising concerns about environmental degradation. Researchers are concentrating their efforts on developing and commercializing an environmentally friendly lubricant produced from renewable resources. Bio-lubricants derived from non-edible vegetable oils are environmentally favorable due to their non-toxicity, biodegradability, and net zero greenhouse gas emissions. The demand for bio-lubricants in industries and other sectors is increasing due to their nontoxic, renewable, and environment friendly nature. Good lubrication, anti-corrosion properties and high flammability are present in vegetable oil due to their unique structure.

The study reports first time the production of biolubricant from castor oil using Fe_3O_4 nanoparticles and ethylene glycol in a transesterification process, as an additive. Operational parameters such as FAME/alcohol, catalyst loading, and temperature were optimized. The reaction was complete after two hours at 160 °C, giving a yield of 94 %. To enhance the physiochemical properties of modified castor seed oil (MCSO), Fe_3O_4 nanoparticles and ethylene glycol were used. The biolubricant yield was also predicted using artificial neural networks (ANN). The multilayer perceptron (MLP)-based ANN showed a linear correlation between the output and target values at different temperatures, the amount of catalyst, and the alcohol/FAME ratios during training, testing, and validation. Finally, the tribological properties of the produced biolubricant (MCSO + ethylene glycol + 0.5 % Fe_3O_4 nanoparticles) showed lowest coefficient of friction (almost 50%) and 40% decreased in wear as compared raw oil and other biolubricant samples.

Keywords: Biolubricant, iron oxide, nanoparticle, additive, tribological properties.

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Acronym

ANN	Artificial neural network
CSO	Castor seed oil
DAGs	Diacylglycerols
EG	Ethylene glycol
FAs	Fatty acids
FAME	Fatty acid methyl esters
MAGs	Monoacylglycerols
MCSO	Modified castor seed oil
MLP	Multilayer perceptron
TE	Tri-esters
RCSO	Raw castor seed oil

Chapter 1

Introduction

1.1 Background

More than 80% of modern lubricants are made up of basic oil, with functional additives making up the remainder [1]. Lubricant qualities such as low-temperature flow properties, low-oxidative stability, and lubricity are all determined by the base oil. Mineral oils, synthetic oils, and vegetable oils are all subcategories of base oils. Traditional lubrication base oils have traditionally been processed from crude petroleum, but with diminishing petroleum sources and the high cost of synthetic lubricant, vegetable oils are being evaluated as viable alternatives. Because they are easily available, inexpensive, renewable, and good to the environment, vegetable oils have several advantages over other raw resources.

Although vegetable oils have several attractive properties, they are not frequently employed as lubricant base oils today. This is mostly because most vegetable oils have unfavorable physical qualities, such as a high melting point and inadequate thermal oxidative stability. A glycerol backbone holds three esterified long-chain fatty acids in natural triglycerides (TAGs), the primary constituent of vegetable oils. The glycerol structure and fatty acid profile of vegetable oils have a significant impact on their physical qualities. glycerol is an undesirable ingredient because of the potential for disintegration of the molecule due to the presence of an unstable hydrogen in the tri-esters (TE) of glycerol. But TAG's architecture comprises three ester groups that are organized to minimize steric hindrance between groupings of lipid acids. This configuration may lead to the creation of crystals as the molecules cool down. When vegetable oils are converted from natural fatty acyl esters to synthetic esters, their instability and high melting point can be greatly enhanced [1], [2].

Plant oil-based bio lubricants can be made from edible and non-edible tree-borne oils that are still underutilized in many countries, including the Canada, India, Brazil, Indonesia, USA, Malaysia, and so on. It is possible to boost farmers' incomes and maximize the use of agricultural products by increasing the market for unusual seed oils like rapeseeds and castor and plant oils like canola, sunflower, and palm oils. Because of their excellent environmental credentials, plant oils are widely used in a variety of industrial applications, including bio lubricants, emulsifiers, plasticizers, plastics, surfactants, resins, and solvents, as well as made from renewable resources and containing no volatile organic compounds.

1.2 Lubricant Demand

In 2022, the worldwide lubricants market is estimated to reach $68.54 billion, according to a new analysis from Grand View Research (Figure 1). Increased exploration and drilling are expected to have a favorable effect on the oilfield chemicals industry by increasing demand.

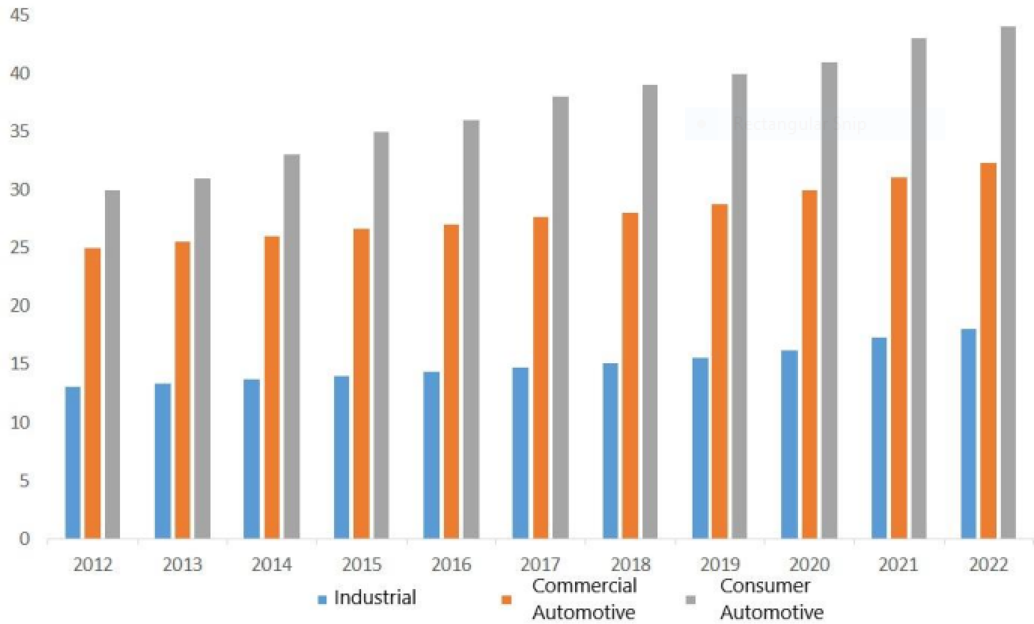


Figure 1: Global lubricants market volume by product, 2012 – 2022 (Million Tons)

Motorcycle sales, heavy-duty truck and other commercial vehicle demand, as well as light-passenger car sales, have boosted automotive manufacturing around the world, which is good news for the lubricants industry [3].

Every effort is taken to avoid spills and evaporation because almost 50 percent of all lubricants used in the world's manufacturing end up in landfills. Diesel engine particle emissions are one such example, with engine oil evaporation accounting for nearly a third of the total. The creation of environmentally friendly lubricants was motivated in part by the high levels of lubricant leakage into the environment. The rising expense of disposing or recycling leftover lubricants is another reason to minimize consumption. However, the lower leakage losses imply a reduction in the amount of wasted oil replenished and refreshed, which places additional demands on lubricants. As a result, the new oils must have excellent stability with time [4].

1.3 Feedstock

1.3.1 Plant Oil

The fat derived from plants is known as "plant oil." Seeds are the principal source of plant oil, however other sections of the plant can also yield oil. The classification of plant oils is based on the following criteria [22]:

- Classification based on source
- Classification based on availability
- Classification based on end use

1.3.2 Plant oils chemical structure

Plant oils and mineral oils are chemically distinct. Oils from plants include a high percentage (98%) of triacylglycerol (TAGs) with different compositions depending on many factors such as plant species and growing conditions. For the most part, plant oils are made up of fatty acids (FAs) (0.1%), monoacylglycerols (MAGs) (0.2%) diacylglycerols (DAGs) (0.5%), sterols, and tocopherols, which make up only 0.1% of plant oils [5] (Figure 3). Processing removes most of these small components, but some of them are useful by-products.

When describing the composition of plant oils, "fatty acids," long-chain molecules with 8-24 carbon atoms, are used to describe the oil's building blocks. Oils derived from plants differ in chemical composition from region to region due to climate, soil, and other geological factors. The chemical and physical properties of plant oils are largely determined by the fatty acids that make up the triacylglycerols.

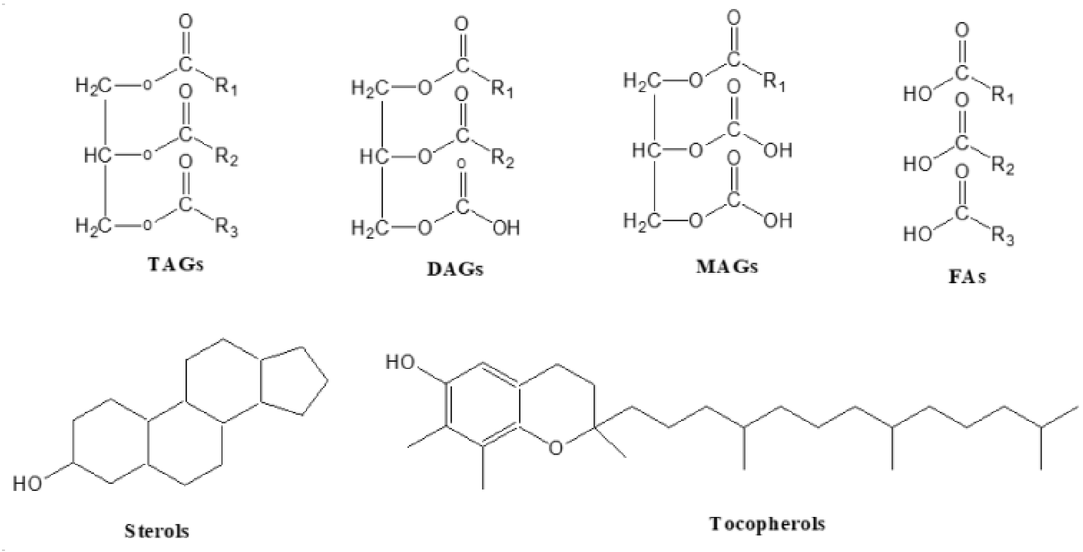


Figure 2: Systematic representation of the major component (TAG) and the minor components (FAs, MAG, DAG, tocopherols, sterols) of plant oils.

1.4 Transesterification

Direct use of vegetable oil can be problematic at a high-temperature regime. The transesterification was therefore, performed to produce biodiesel by removing glycerol from the vegetable oils, from which bio-lubricants are produced by doing further modifications, that would be environmentally pleasant in its operations. For bio-lubricant productions, biodiesel is the efficient starting material [6]. The carboxylic in all the vegetable oils were modified through transesterification reaction to produce fatty acids methyl esters (FAMEs) and glycerol as a by-product.

Life cycle of a bio-based lubricant is shown in figure 3. It is quite clear that from plants biomass is collected which is used for the extraction of edible and non-edible oils which is used as a feedstock. Through transesterification this feedstock is converted into esters and glycerol. These esters and glycerol are than modified under different conditions to produce bio-based lubricants. These lubricants have several industrial uses. After usage these waste oils are biodegraded to produce carbon dioxide and water, through which plant is again produced and the cycle begins again.

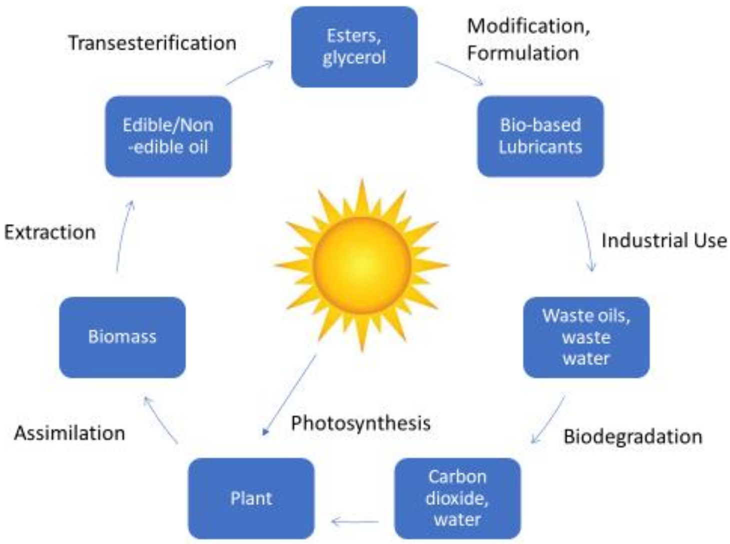


Figure 3: Life cycle of bio-based lubricants [7]

1.5 Problem Statement

Today most of the lubricant is produced from fossil fuels which is not environment friendly. These reservoirs are also depleted day by day. To overcome this problem alternative methods should be adopted to fulfil the requirements.

Nowadays lubricants are produced from petroleum products that are not safe for the environment and fossil fuel reservoirs are also depleted. Mineral oil also causes environmental issues because they are responsible for aquatic pollution when they spilled after their usage [8]. Considering these, there is a great need for an alternative lubricant that can reduce environmental issues and reduce the cost of petroleum products. Bio-lubricants have the capability of reducing the use of mineral oil due to their environment-friendly behaviour and are biodegradable and have higher viscosity index [9]–[11]

1.6 Research Objectives

To overcome the existing challenges in the field of lubricant, following objectives were identified.

1. To produce the bio lubricant from non-edible oil.

2. To investigate the physiochemical characterization of the biolubricant samples.
3. To benchmark the physiochemical characteristics of the synthesized bio lubricant with the commercial mineral lubricant.
4. To improve the physiochemical properties of the produced bio lubricant by using Iron oxide (Fe_3O_4) nanoparticles as a catalyst.
5. To enhance the tribological properties of the produced bio lubricant by using Iron oxide (Fe_3O_4) nanoparticles as a catalyst.

1.7 Scope of Study

The following scope was established to ensure that the research would be carried out in the time available:

- The vegetable oil used was limited to castor oil only.
- The analysis of physiochemical properties was carried out for limited samples.
- The catalyst used for the upgradation of bio lubricant was limited to Iron oxide (Fe_3O_4) nanoparticles only.
- Co-efficient of friction and Wear is studied in tribological properties.

1.8 Chapter Summary

This thesis comprises of five chapters. The exposure of each chapter is given in the following chapters.

- **Chapter 1** delivers vision of the subject, background and contemporary problems related to the work. It also clarifies the problem statement, research objectives and scope of the planned study.
- **Chapter 2** will sketch the literature review achieved to describe the previous work done on the transesterification of different vegetable oils. It also includes review based on feedstock and properties of different vegetable oils.
- **Chapter 3** covers the methodology related to the sample preparation and characterization, physiochemical properties and tribological analysis in the research. It will also give the related information about experimental procedure and the main equipment contributing to the experimental investigations.

- **Chapter 4** delivers results and discussions about the sample yields, physiochemical properties of the prepared samples and the tribological analysis.
- **Chapter 5** reviews all the findings and conclusions in the current study and provides the future recommendation for the related work.

Chapter 2

Literature Review

2.1 Lubrication and lubricants

Facilitation of the movement related to the surface when in contact with each other by the means of the lubricant substances is called as the lubrication. In all the mechanical system the presence of the lubricant is required between pieces that encounter one another. Wear and friction of the moving parts is reduced by the lubricants, and it can enhance the lifespan of the mechanical system [12], [13]. In all the form including solid, liquid, gases lubricants are available [14]. Generally, it can consist of two main parts which include additive and the base oil. Major component of the lubricant is base oil that certainly makes up to 70 -99% of the lubricant formation [15]. Additives which include dispersant, anti-wear, pour point viscosity index to improve the chemical and the physical properties. A very good lubricant is the excellent characteristics which include the pour point, flash point and the high viscosity index, and the prevention capability.

2.2 Bio lubricants from non-edible oils

2.2.1 Bio lubricants:

The lubricants based on the vegetable oils are the fats of animals are called as the bio-lubricants and due to their acceptance and the environment friendly properties it is gaining the popularity. Carbon dioxide that is being generated does not cause any harm to the environment [16]. In the manufacturing and the transportation industries and with the increase of the application of the bio lubricant, the market somehow expected to growth significantly [17].

2.2.2 Characteristics of non-edible oil

The degree and length of unsaturation of the fatty alkyl chains determine the characteristics of vegetable oil and fats. Fatty acid has significant part in figuring out the characteristics of products [18]. Most abundant fatty acids in the oil samples are stearic, palmitic, linolenic, oleic, linoleic.

Table 1: Fatty acid composition of non-edible [19]

Oil source	**Palmitic (16:0)**	**Stearic (18:0)**	**Oleic (18:1)**	**Linoleic (18:2)**	**Linolenic (18:3)**
Jatropha	16.0	6.5	43.5	34.4	0.80
Karanja	17.7	7.5	51.6	16.5	2.7
Polanga	12.0	12.9	34.1	38.3	0.30
Rubber	10.2	8.7	24.6	39.3	16.3
Mahua	17.8	14.0	46.3	17.9	------
Neem	14.9	14.4	61.9	7.5	------

2.2.3 Bio lubricant Resources

For their use as the bio lubricant, the non-edible vegetable oils are potential feedstocks due to their presence to overcome the problems that in correspondence to edible vegetable oil like the fuel vs food debate, energy issues and the environment. They are the less toxic and biodegradable in nature [20], [21]. Near the railways, roads, degraded forests they are planted. Moreover, they are well adapted to desiccate and semidessicate the conditions and their growth can be achieved without the moisture and the fertility. After the extraction from the oil-bearing seeds [22]. The subsequent table illustrates the statistics of oil content and geographic distribution of non-edible plant oils. Among the numerous non-edible oil yielding crops, Karanja and Jatropha are considered to be viable alternatives due to their widespread appeal. [23].

Table 2: Location and oil statistics of non-edible oils

Nonedible species	**Location**	**Seed wt%**	**Kernel wt %**	**References**
Salvadora oleoides (Pilu)	Western India and arid	40	--	[21], [24]

	regions of Punjab			
Ricinus communis (castor)	Chine, Brazil, China, France, Italy, India	45-55	--	[23], [25]
Pongammia pinnata (Karanja)	Malaysia, China and pacific islands	25-50	30-35	[21], [24]
Madhuca Indica (Mahua)	North and central India	32-50	55	[24], [26]
Guizotia abyssinica (Niger)	Ethiopia	42-60	53-50	[27], [28]
Jatropha curcas L (Jatropha)	Indonesia, India, Thailand, and Philippines.	20-60	42-60	[29], [30]
Garcinia indica (kokum)	Parts of India, tropical rain forests of western ghats, konkana	46.2	---	[22], [31]
Bombax malabaricum (cotton tree)	India	19-28	--	[32]
Balanites agyptiaca (desert, date)	Native parts of Asia and Africa	--	37-48	[33], [34]
Brassica carnita (Ethiopian mustard)	Native to Ethiopia	44	2.3-9.8	[31], [35]
Asclepias syriaca (milk weed)	Northeast and northcentral united states	21-26	0.017	[24], [31]

Aadirachta indica (Neem)	India, Pakistan, Malaysia, Bangladesh	27-32	28-48	[22], [31], [36]
Aphanamixis polystachya(pithraj)	Parts of China and India	---	36	[33], [37], [38]

2.2.4 Physiochemical Properties

Bio-lubricants derived from non-edible vegetable oils have valuable and beneficial physiochemical properties. They have several technical advantages over petroleum-based lubricants. They have a high degree of lubricity, a high viscosity index, a high flash point, and have fewer evaporative losses during storage [34], [39], [40]. Mineral oils' physical properties are generally determined by their carbon number distribution, which is specified by the crude oil source. Mineral oils are made up of straight and branched chain aromatic hydrocarbons, naphthenic, and paraffinic, with 15 or more carbons. As a result, these physical properties vary considerably: boiling points typically range between 300°C and 600°C, while specific gravities range from 0.820 for light paraffinic base/process oils to somewhat more than 1.0 for highly aromatic base/process oils [41]. The comparison of physiochemical properties of mineral oils with non-edible oils are shown in Table 3.

Table 3: Physiochemical properties comparison of mineral oils with non-edible oils

Properties	**Mineral Oils**	**Non-edible oils**
Density at 20°C (Kg/L)	0.890	0.950
Specific gravity	Less	More
Viscosity index	100	100-200
Pour point °C	-15	-22 to 12
Flash point °C	Lower	Higher
Cold flow behavior	Good	Poor
Oxidation stability	Good	Fair
Fire point °C	Lower	Higher
Biodegradability (%)	10-30	80-100

Sludge forming tendency	Good	Poor
Miscibility	---	Good

2.2.5 Castor

The scientific name of the castor seed oil is the Ricinus communis which somehow belongs to the Euphorbiaceae family. That seed oil can be found in Egypt in the lately 4000BC. South Asia and the East Africa are its native and it has spread to the many topological regions of the world. The shape of castor is like beans, lacks volatility, and has the light-yellow oil and it tastes sweet as well. Due to considerable amount of monosaturated fatty acid (MUFA) content it has the larger thermal oxidative stability, and it is widely used in the industries with the high temperature conditions as well. On the average the castor contains about 45-60% oil content.

Round about the 1.8 M tons of the castor oil is produced annularly in the world. In the 30 different countries castor plant can grow which include Brazil, India, Russia, China, USA, and the Thailand and these are the countries that can make up to the 85% of the castor oil production. The firs and the second producer of the castor oil are the India and Brazil.

2.3 Methods for modification of Vegetable Oil

There are several methods which are used for the modification of non-edible oil. Esterification/Transesterification, estolide formation, epoxidation, and selective hydrogenation, are some the methods which are commonly used. These methods are used to improve the physiochemical properties of synthetic bio-lubricant. Some of the pros and cons are stated below in table 4.

Table 4: Methods for chemical modification of non-edible oil [6]

Methods	**Description**	**Pros**	**Cons**
Esterification/Transesterification	The conversion of an ester to another ester and has a	Low temperature properties	The reaction temperature is elevated.

	greater thermal stability.	are improved Thermo-oxidative stability is improved	A high oleic acid concentration in the feedstock is required.
Selective Hydrogenation	Hydrogenation of unsaturated and thermochemical cleavage of the ester	Oxidative stability is improved Degree of unsaturation is reduced	Reaction temperature is high Isomerization reactions
Epoxidation	Unsaturated C-C bonds, which are interconnected by an oxygen atom	Lubricity is improved Thermo-oxidative stability is improved Reaction temperature is low	The value of pour point is increased and the decrease in the value of Viscosity index
Estolide formation	Reaction between two similar or dissimilar acidic molecules	Thermo-oxidative stability is improved Reaction temperature is low Various types of vegetable oils can be used.	Production cost is high

2.4 Key process parameters for transesterification process

Transesterification processes should be carried out in the lowest possible time and temperature to make them economical. Room temperature to 65°C is commonly the most used temperature for transesterification process. Increase in temperature favours the transesterification reaction, however saponification also occurs due to the increase in temperature due to which less purity of the product and have a lower yield value.

Residence time also plays a significant part in the transesterification reactions. Reactions carrying out in the presence of homogenous and heterogeneous catalysts will have different residence time. Reaction time ranges from 30 mins to 2 hours can be observed in the presence of homogeneous catalyst while it can be increased for heterogeneous catalysts. In the presence of enzymatic catalysts, the reaction time may be up to one or two days [42], [43].

Due to the dispersion of alcohol molecules in the oil and mixing, the reaction takes place slowly in the start. The reaction occurs faster once the mixing is done. The reaction may proceed backwards if the reaction time is increase, due to which more fatty acids is produce which leads to the production of soap instead of alkyl esters. As triglycerides are immiscible in alcohols, mixing is very important in transesterification reactions.

Most of the transesterification reactions are carried out in the presence of homogeneous alkaline catalysts such as NaOH and KOH because as compared to acidic catalysts, they provide better and faster reaction [44]. To avoid low yield and side product formation, a low concentration of water and FFAs are preferred in a transesterification reaction using homogeneous alkaline catalysts. Some of the more frequently used acid catalysts are hydrochloric acid, sulfonic acid and sulfuric acid.

In the transesterification process, heterogeneous catalysts used are basically of three types namely base, acid, and enzyme [45]. For transesterification of vegetable oil many suitable heterogeneous catalysts are reported such as metal complexes, metal oxides, zeolites, membranes and resins [45]–[48].

The properties of bio-lubricant depend upon the type of raw material, which is used for production of bio-lubricant. Various properties such as viscosity Index (VI), viscosity pour point and flash point plays an important role to determine the quality of bio-lubricant. Higher the value of viscosity Index (VI), more the bio-lubricant will be preferred. Bio-lubricants lubricity is indicated by viscosity Index (VI).

Table 5: Physiochemical properties of non-edible oil [1], [6], [11], [49]–[51]

		Transesterification Operational Parameters					**Bio lubricant properties**				
Feed	**Catalyst**	**Catalyst ratio**	**Reaction Temp (°C)**	**Residence time (hr)**	**Yield %**	**Additive**	**Kinematic viscosity 40°C (cSt)**	**Flash Point (°C)**	**V.I**	**Pour point (°C)**	**Year**
Jatropha	KOH	1% KOH (w/w)	60	0.5	98	CaO	15		311	-12	2020
Jatropha seed	$NaOCH_3$	1%	150	3	47	TMP			178-183	-3	2019
Rubber seed	H_2SO_4	2%	150	5	79	TMP		310	283	-40	2019
Jatropha seed	$HClO_4$	2%	150	3	70	TMP		>300	150	-23	2019

Castor seed	o-phosphoric acid	0.8%	120	1	96.56	TMP	45.30	215	191	-8	2019
Castor oil	Amerlyst - 15/Dowex	10 wt %	100	4	90	TMP			132	-39	2018
Epoxidize jatropha oil	Sodium methoxide	1 wt%	60-65	-------	Not reported				139	0	2018
Jatropha oil	TMP	2 %(w/w)	150	3	55			>300		-30	2018
Jatropha	Sodium methoxide		150	3	>80	TMP	43.90		180	-6	2018
Rubber ME	P Toluensulphonic acid		140		95	TMP	23-62		206-222	-15 to -3	2018

Jatropha oil	Sodium meroide/TMP	2% w/w Jatropha/TMP=4/1	60-65	3	----	TMP	18.2		139	0	2018
Jatropha curcas	$NaOHCO_3$	3.9:1 to TMP	120	3	47		>28		183	-6	2013
Rubber seed	TMP	3.9:1	60	2	48.4		8.6		271	-40	2013
Karanja	TMP	4:1	30	1	---	TMP	4.8		--	3	2013
Crude Jatropha oil	NaOH	1wt %	60	1		Not reported	51.73		186	8	2011
Jatropha	NaOH	3.9:1 1(w/w)%	120	3		Not reported	43.68		186	-3	2011

Jatropha oil is trans esterified in the presence of KOH catalyst. The reaction temperature of this process is 60°C with the residence time of 60 min. Under these conditions, the yield is 98%. Jatropha oil is treated in the presence of sodium methoxide catalyst at different temperatures resulting in different yield percentage. When it is treated at 150°C the yield of the product is 47% and >80% this is because of the source from which jatropha is extracted.

The residence time and reaction temperature also affect the properties of the bio lubricant. When jatropha is treated in the presence of NaOH catalyst at different temperatures and residence time the resulting bio lubricant will have different properties. At 60°C and 1hr residence time, the pour point of the bio lubricant is 8°C while when this process occurs at 120°C with residence time of 3 hrs the resulting bio lubricant will have the pour point of -3°C.

Castor oil in the presence of o-phosphoric acid at 120°C with the residence time of 1hr the resulting product will have a yield of 96.56%. The yield of the product drops down to 90% when castor oil is treated in the presence of Amerlyst-15 catalyst at 100°C with the residence time of 4 hrs.

Similarly, rubber seed oil gives different yields under different operational parameters. In the presence of H_2SO_4 catalyst at 150°C with the residence time of 5hrs the yield of the product is 79%, but in the presence of TMP catalyst the yield drops down to 48.4% at 60°C with the residence time of 2 hrs.

Beauty leaf oil is a non-edible oil, and its colour is dark green. It has many attributes to be used as a feedstock. The seed has an average oil content of about 70%. The physiochemical properties of oil able to meet almost all the standards. The flash point is 106 °C and has a pour point of 12 °C. The kinematic viscosity of beauty leaf biodiesel at 40 °C is4.20 mm^2/s [52].

2.5 Comparison of tribological properties

Tribological properties like coefficient of friction and wear plays an important part in load-bearing applications especially. Around 15-20%, wastage of fuel energy occurs to overcome the frictional forces in Internal combustion engines [53]. This wastage of energy can be reduced by the usage of lubricants having a low coefficient of friction. Monolayer film is formed due to the presence of polar heads of the saturated and monounsaturated fatty acids, with metal surfaces and stick away from the non-polar end. The coefficient of friction is reduced, as a result. The close packing of carbon-chains is prevented in polyunsaturated fatty acids, increasing the co-efficient of friction and wear rate and weakening the monolayer film.

Bio-lubricants shows better anti-wear properties when compared to mineral oil [7], [54]. Tribological properties of some non-edible are shown Table [55]. Co-efficient of friction and wear scar properties of some of non-edible oils are shown in Table 6.

Table 6: Comparison of tribological properties of commercial lubricant with non-edible oil

Reference Lubricant	**Testing method**	**Biolubricant**	**Result obtained**	**Reference**
SAE20W40	Pin on disc machine	Jatropha oil	Less wear, low frictional losses	[56]
SAE 40	Pin on disc machine	Cottonseed oil	Low co-efficient of friction, less wear at high speed	[34]
SAE20W40	Single cylinder, direct injection CI engine	Pongamia oil	Friction losses are lower	[57]
SAE20W40	Pin on disc machine	Jatropha oil	At high velocity, wear rate is minimum	[58]
SAE20W40	Pin on disc machine	Pongamia oil	Less surface wear	---

2.6 Bio-lubricant Industrial Perspective

Bio lubricant provides many advantages as alternative lubricants for maintenance and industrial applications due to their environment friendly behaviour. Bio lubricants, because of their environmental benefits, they can prevent pollution and can be used in sensitive environments. Bio lubricants can be used in various maintenance and industrial applications. Generally, bio-lubricants are used as hydraulic fluids, two-stroke engines, in power equipment, craft jet engine, chain saw oils, marines, engine oils, aviation oil, greases [7].

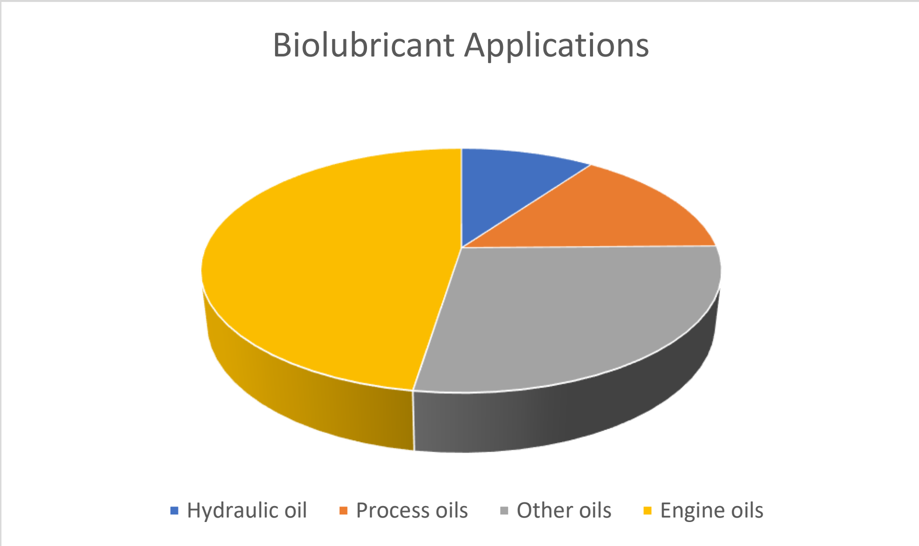


Figure 4: Bio-lubricant applications

2.6.1 Hydraulic Fluids

Hydraulic fluids are used in hydraulic system to transfer the energy. Compressibility is one of important parameter of hydraulic fluids, lower compressible hydraulic fluid has a better pressure transmission velocity, due to which better use of energy and great response can be seen [59]. Power transmitting properties has been enhanced when soybean oil is used as compared to mineral oil [59]. Many edible and non-edible oils such as rubber seed oil, palm oil, rapeseed oil have exhibit better properties as compared to mineral oils, when used as a hydraulic fluid [60], [61]. Now a days many companies are making hydraulic fluids using vegetable oil due to their better properties and environment friendly behaviour.

Mobil, Shell, and Chevron Texaco are important companies that are marketing hydraulic fluids with approved several pump standards using environment friendly vegetable oils.

2.6.2 Engine Oils

Severe temperature and/or pressure conditions are required for the lubricants to be used in engine systems. Many vegetable oil such as palm castor and coconut oil can be used as an alternative in two-stroke engines [62]. Volatile organic compounds emission is reduced by 5% when castor oil is used as a bio-lubricant in engine [62]. Masjuki et al. also stated that the emission of hydrocarbons and CO is reduced when palm oil is used as a lubricant in two-stroke engine as compared to mineral oils [63].

Thermo-oxidative stability is one of important parameter of lubricants. In four-stroke engine, coconut and palm oil shows good behaviour. Because of absence of additive their behaviour is worsened and have poorer oxidative stability [64], when prolonged used.

Bio-lubricants are used as an engine oil which is prepared by many companies like Biosynthetic technologies (USA), Green Earth Technologies (USA) and Renewable Lubricants Inc. (USA).

Some of the top manufacturers of bio-lubricant production are listed below in Table 7.

Table 7: Manufacturers of bio-lubricants

Brand name	**Product description**	**Characteristics and environmentally related information**	**Applications**	**Manufacturer**	**Manufacturer country**
KLUBERBIO RM 2-100	Stern tube oil	ISO-VG 100/150 Biodegradability > 60%	Stern tube bearings Propellers Shaft seal	KLUBER	Germany
KLUBERBIO EG 2-68 KLUBERBIO EG 2-100	Gear oil	ISO-VG 68/100/150 Biodegradability >60%	Gear set, bearings and seal	KLUBER	Germany
KLUBERBIO LR 9-32 KLUBERBIO LR 9-46	Hydraulic oil	ISO-VG 32/46/68 Biodegradability > 60%	Hydraulic motors, hydraulic components	KLUBER	Germany

KLUBERBIO C 2-46	Chain oil	ISO-VG 46 Biodegradability >60%	Chain	KLUBER	Germany
PLANTOHYD 40N	Hydraulic oil	Vegetable oil based hydraulic oil Biodegradability >60%	Hydraulic Systems	FUCHS	Germany
PLANTOHYD 15S	Hydraulic oil	Synthetic ester oils with additives. Biodegradability > 60%	Usable as lubricating and hydraulic oil	FUCHS	Germany
PLANTOSYS 32 HVI	Hydraulic oil	Environment friendly. Biodegradability > 60%	Usable in all mobile and stationary hydraulic system	FUCHS	Germany
PLANTOLUBE CGLP 68 S	Machine oil	Oils based on synthetic esters with very good biodegradability	Used in modern machine tools	FUCHS	Germany
PLANTOLUBE SC46 S	Compressor oil	Fully synthetic, rapidly biodegradable compressor oil	Used in screw compressors	FUCHS	Germany

PLANTOTAC HV 220N	Adhesive oil	High quality adhesive oils based in vegetable oil, and rapidly biodegradable	Joints bolts etc.	FUCHS	Germany
MULTIS COMPLEX SHD 220	Grease oil	Used for greasing intervals because of synthetic formula	Plain bearing, chassis	TOTAL	France
BIOMULTIS SEP2	Grease oil	Handle extreme pressure and biodegradable	Used for lubricating rolling bearings	TOTAL	France

Chapter 3

Materials and Methods

3.1 Raw material

The raw material which was used in this project is castor seed oil (CSO) and was obtained from the local market. Methyl alcohol was purchased from a local vendor. Iron oxide (99 % purity) nanoparticles and ethylene glycol were obtained from the vendor as an additive. Iso-octyl alcohol was obtained from a local chemical supplier.

3.2 Development of a biobased lubricant

The fatty acid methyl ester (FAME) was produced via a transesterification procedure using a base catalyst. **Figure 5** presents the experimental setup of the transesterification process. The procedure of transesterification was carried out in a double-neck round-bottom flask and sealed with a Graham condenser. Oil and alcohol; methanol with a molar ratio of 1:6 was pumped into a collar flask and sunk into a dehydrator. A 1-percent potassium hydroxide (KOH) substrate was introduced into the oil to improve the interaction between the mixes. The reaction temperature was maintained stable at 60 °C for 1 hour in the dehydrator. After that, the sample was poured into a separate funnel and allowed to settle to differentiate between FAME and glycerol. The bulky material, which was glycerol, would sink to the base, while the FAME stayed at the top. Therefore, glucose was extracted, and FAME was passed through a cleaning procedure. This method was carried out by pumping warm water into the FAME in the measuring cylinder. Thus, such mixes are agitated with the introduction of phosphoric acid until the mixture reaches pH 7. The samples were allowed to remain at a temperature in the range of 120 °C to eliminate additional methanol and water material.

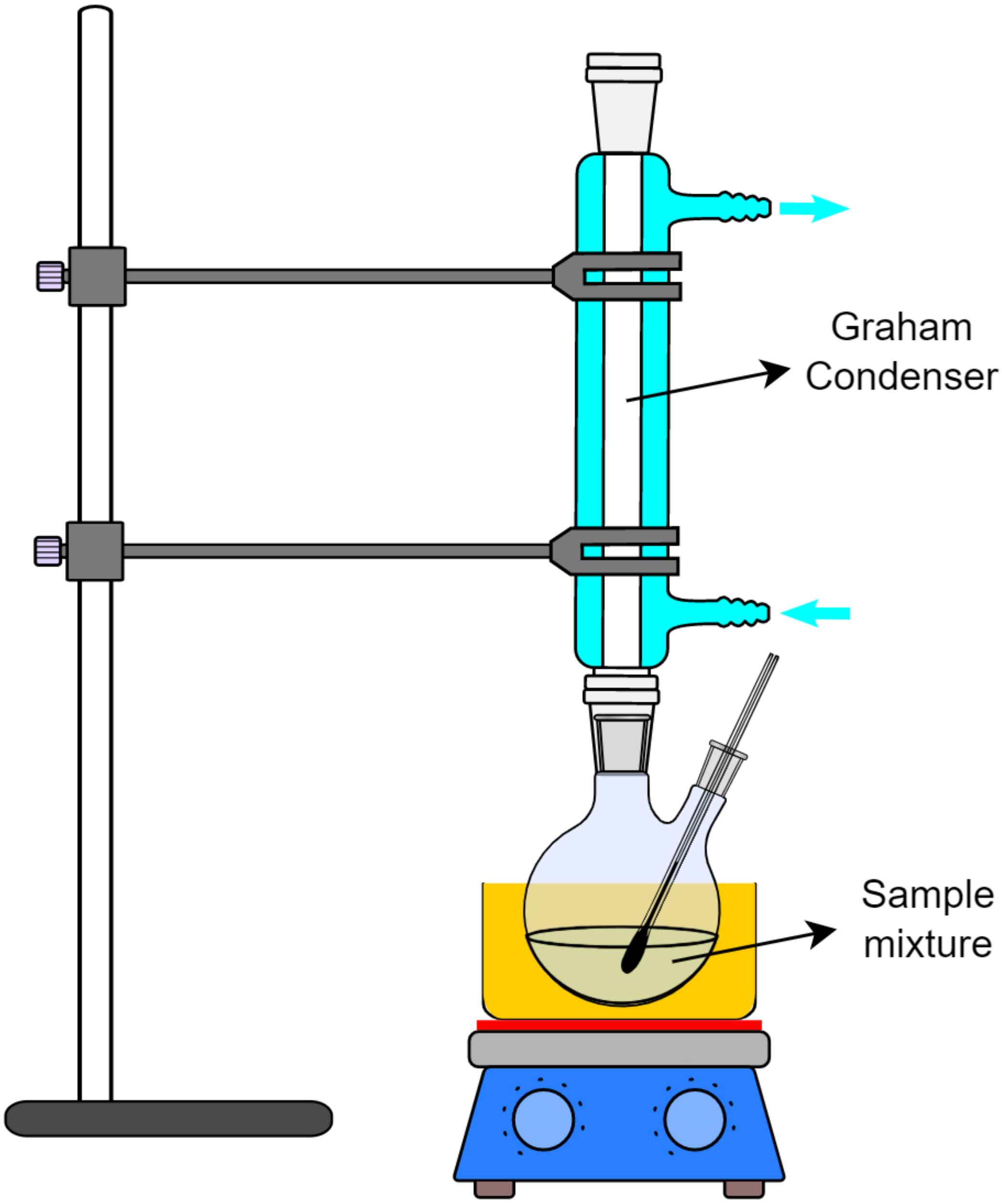


Figure 5: Experimental setup of the transesterification process

Finally, to develop a biolubricant, the FAME developed in the first step of transesterification was used. The process was carried out in a 1000 ml double-neck round bottom flask with a thermometer, a measuring outlet, and a Graham condenser. The flask was placed on a heating mantle at a temperature of 160 °C. FAME and isooctyl alcohol were pumped into the round bottom double neck flask and steadily heated to 160 °C. Electromagnetic mixers have been utilized to ensure that both formulations have been adequately blended. Sodium methoxide was used as a precursor and mixed with a solvent for 2 hours to finish the process and become a biolubricant known as modified Castor seed oil (MCSO). After the transesterification process, the MCSO was mixed with additives. The additives used were ethylene glycol and iron oxide (Fe_3O_4) nanoparticles. The surface modulation device was used to ensure the stabilization of the additives with the modified liquid. For a consistent suspension of the additives, they are mixed with a magnetic stirrer of 750 rpm for a duration of 3.5 h. The mixture was stirred again through the ultrasonic sonicator for 1 hour. **Table 8** illustrates the samples prepared with and without additives. The complete schematic experimental procedure is illustrated in **Figure 6**.

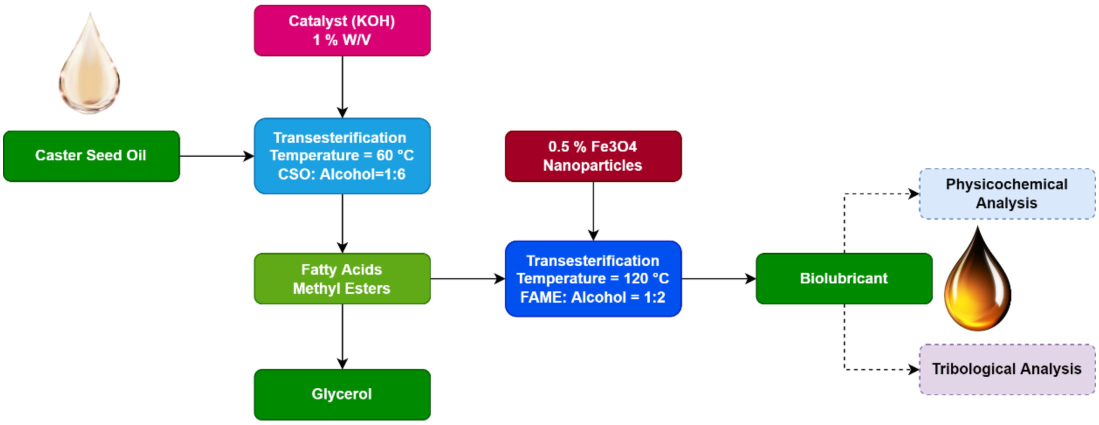


Figure 6: Experimental setup of research methodology

Table 8: Samples prepared for analysis

Symbol	Description	Sample
RCSO	Raw Castor Seed Oil	

MCSO	Modified Castor Seed Oil	
MCSO + 0.5 % Fe_3O_4 nanoparticles	Modified Castor Seed Oil with 0.5 % iron oxide nanoparticles	
MCSO + ethylene glycol	Modified Castor seed oil with ethylene glycol	
MCSO + ethylene glycol + 0.5 % Fe_3O_4 nanoparticles	Modified castor seed oil with ethylene glycol and 0.5 % iron oxide nanoparticles.	

3.3 Methodology for Artificial Neural Networks

Artificial neural networks (ANN) are useful tools for non-linear regression. An advantage of ANNs is that they can be trained on any data set without prior knowledge of the modelled phenomenon. In this study, ANN based on multilayer perceptron (MLP) is used for non-linear regression. MLP consists of input, hidden layer, and output layers. The hidden and output layers are made up of artificial neurons. The input layer transfers the input signals through the hidden layers to the output layer in feedforward mode. The connection weights were then adjusted using an error backpropagation algorithm while training from the randomly assigned initial values. During data set training, the error between the target and output signals is minimized by adjusting the number of neurons in the hidden layers and the transfer functions of the neurons. For this study, the Statistica Automatic Neural Networks (SANN) present in the TIBCO Statistica 13.5 software was used. SANN uses the Broyden-Fletcher-Goldfarb-Shanno (BFGS) iterative algorithm to minimize the error function of ANN [24]. The Automated Network Search (ANS) feature of SANN compares various networks and selects five models based on the best performance criteria, saving time by avoiding the lengthy trial-and-error process. The activation functions used in ANS for the hidden and output layers are identity, tanh, logistic, sigmoid, exponential, Softmax, sine, and Gaussian. The flow chart for the ANN modelling is shown in **Figure 7**. The relative influence of the input variables on the output parameter is assessed in terms of relative sensitivity. ANN based on MLP has been used to model, optimize, and predict the yield of biofuels [25-27].

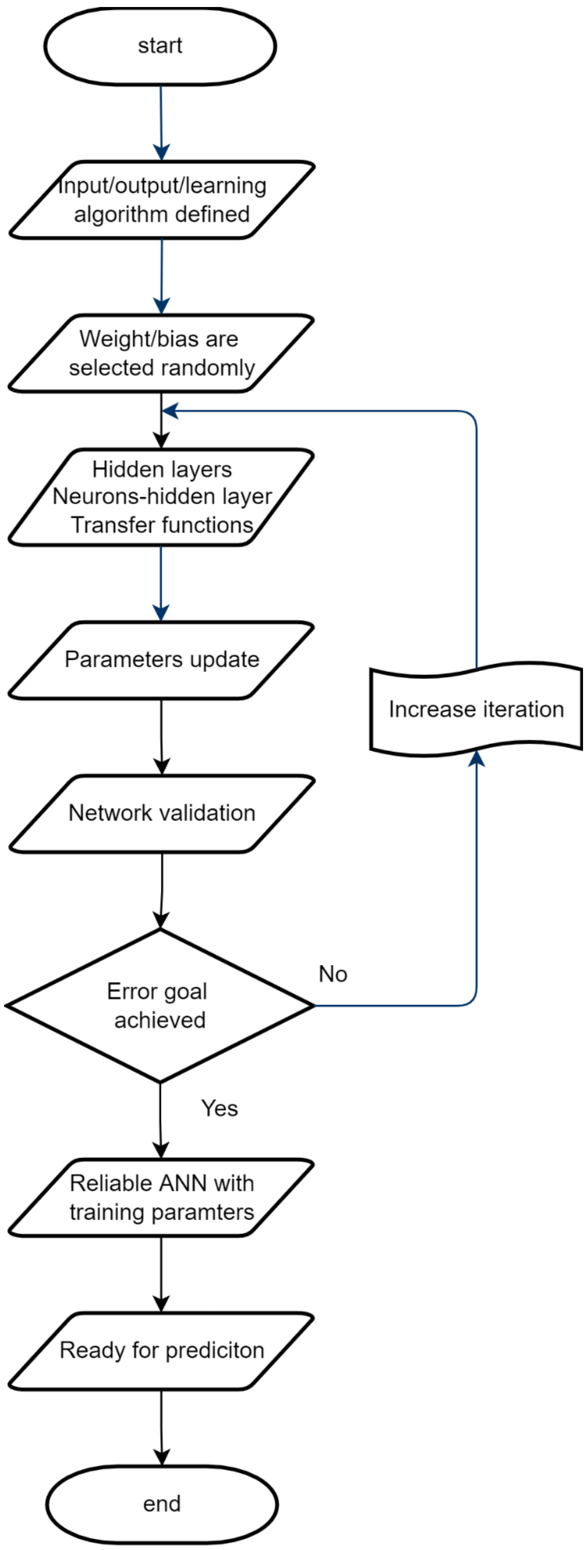


Figure 7: Generic flow chart for ANN modeling

3.4 Physiochemical Characterization

The characteristics of each lubricant sample were determined and confirmed according to the American Society of Testing and Materials (ASTM). To evaluate the buoyancy of the oils, density tests were performed. The samples were weighed using a pycnometer at a temperature of 20 °C according to ASTM 4502. Viscosity was determined using an Ostwald viscometer and according to ASTM D445 [35] at 40 °C and 100 °C for the oil. The flashpoint was defined as the temperature at which a sample of oil began to vaporize and form an ignitable mixture in the air. It was determined using an ASTM D92 [36] closed cup flash point tester (Pensky-Martens). The lubricant samples were placed in the cup, heated, and then regularly opened to initiate ignition. According to the ATSM D-97 standard [37], the pour point of the samples was measured.

3.5 Tribological Characterization

The pin-on-disc machine has been used to explore the wear and friction parameters under lubricant deployment. The friction force was measured in the operating application of the device using the load cell coupled to the tribo machine. The applied load was used to normalise the friction forces in order to determine the friction coefficient. The lubricant was supplied to the interface dropwise in conjunction with a pump powered by an electric motor (**Figure 8**).

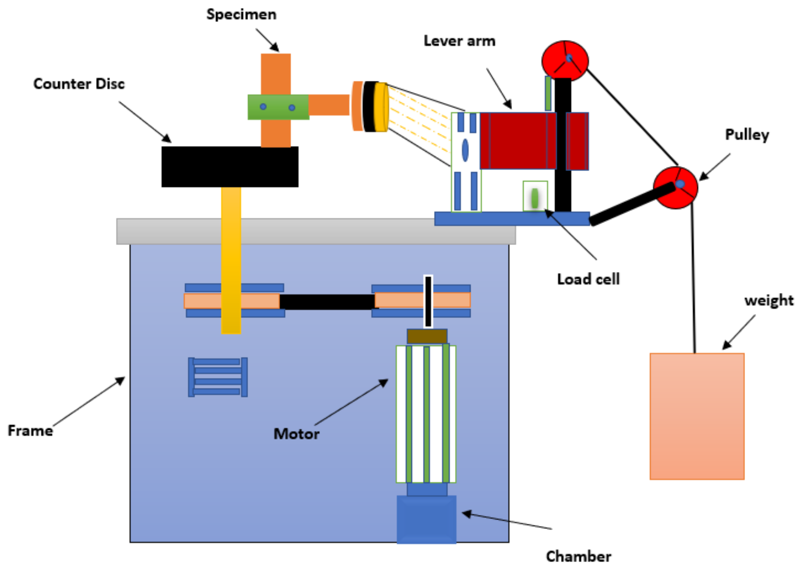


Figure 8: Experimental setup of tribological analysis

Chapter 4

Results and discussion

4.1 Effect of temperature on yield

As shown in **Figure 9**, the biolubricant yield was the lowest at 150 °C, giving only 83 % at the completion of the experiment. For 160 °C and 170 °C, the yields were increased to 90 % at 100 min. At the end of the experiment, the yield was 94.5 % and 94.8 % at 160 °C and 170 °C, respectively. As the temperature increase, reaction conversion also increases, hence the biolubricant yield is also increased. Thus, a distinct effect of temperature was observed on the final yield and kinetics, particularly at low temperatures. Similar trend was reported by published studies [28, 29].

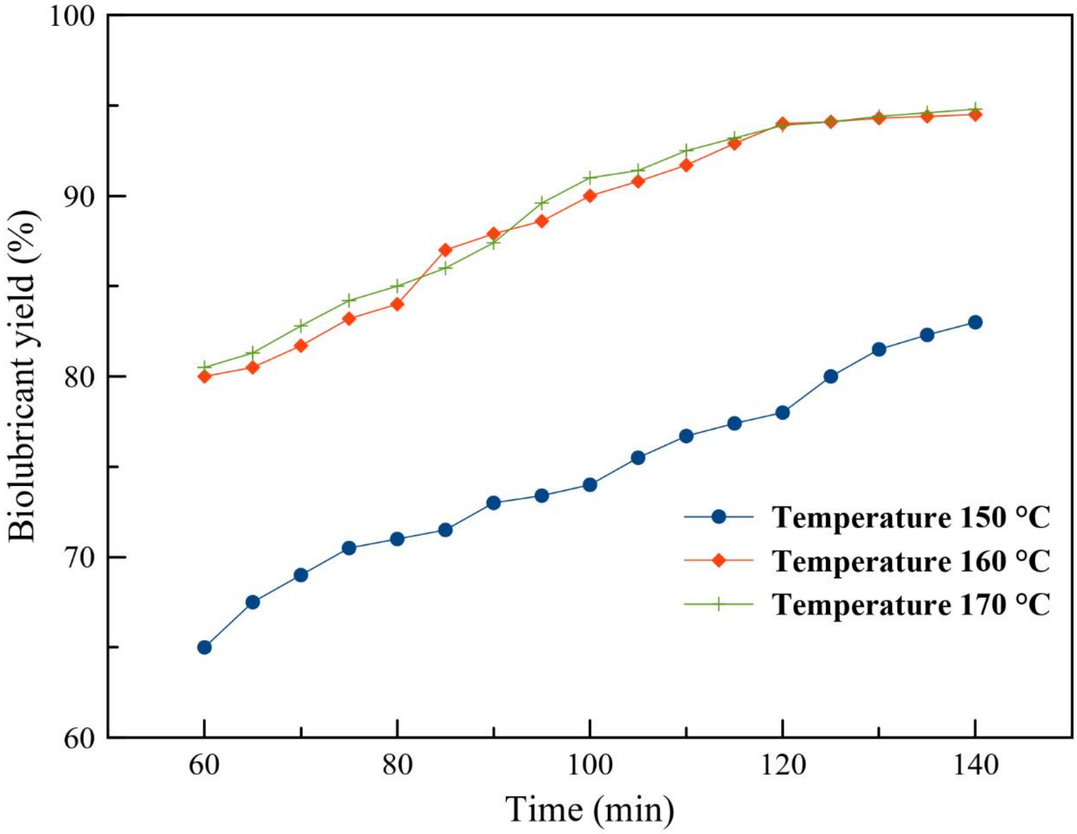


Figure 9: Biolubricant production at different temperatures (Catalyst 1 % w/v and Alcohol to FAME ratio of 2:1)

4.2 Effect of catalyst concentration on yield

The effect of catalyst concentration was determined at 160 °C, under the assumption that the catalyst concentration would be more effective at lower temperatures (**Figure 10**). From a kinetic point of view, the increase in catalyst concentration increased the reaction rate. Considering the biolubricant yield, the final conversion was too low (less than 80 %) using a 0.5 % catalyst (w/v) compared to 1 % and 2 %. (94.5 and 95 %, respectively). For 1 and 2 % of the catalyst loading, the completion was achieved only after two hours as shown by an asymptote. There seems to be a concentration of catalyst limit beyond which no increase in conversion was detected. As a result, a concentration of 1 % w/v of the catalyst was observed as most viable to get maximum yield. Similar findings was reported by other researchers [30, 31].

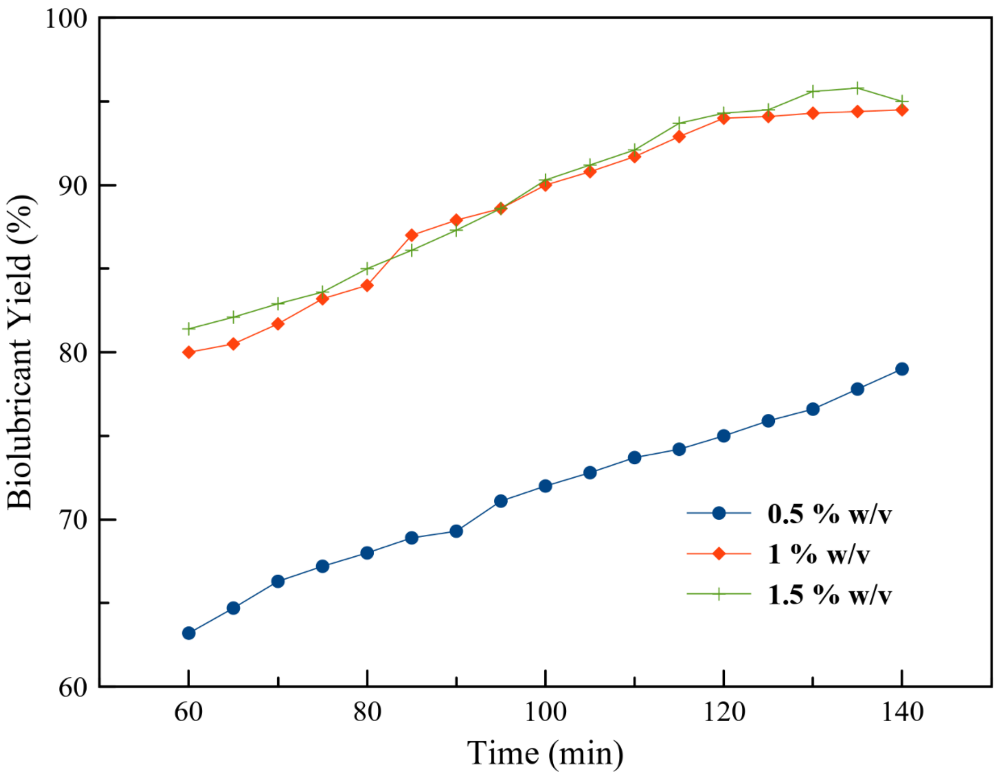


Figure 10: Biolubricant production as a function of catalyst concentration (Temp 160 °C and alcohol to FAME 2:1)

4.3 Effect of alcohol/FAME on yield

Regarding the molar ratio of Iso octyl alcohol/FAME, there were differences, especially for the equimolar concentration (1:1) (**Figure 11**). With this value, a yield of hardly 80.5 % was obtained, while for the molar ratios of 2:1 and 3:1, the yield improved significantly (94.5 % and 95 %, respectively). These findings revealed that the alcohol content had a significant effect on the equilibrium, rerouting the process toward the production of the biolubricant. In terms of kinetics, the alcohol content had a favorable effect, increasing the rate of creation of the product. As a result, some authors recommend using an amount of alcohol greater than a 1:1 molar ratio [32, 33]. In this study, the most suitable molar ratio was found to be 2:1.

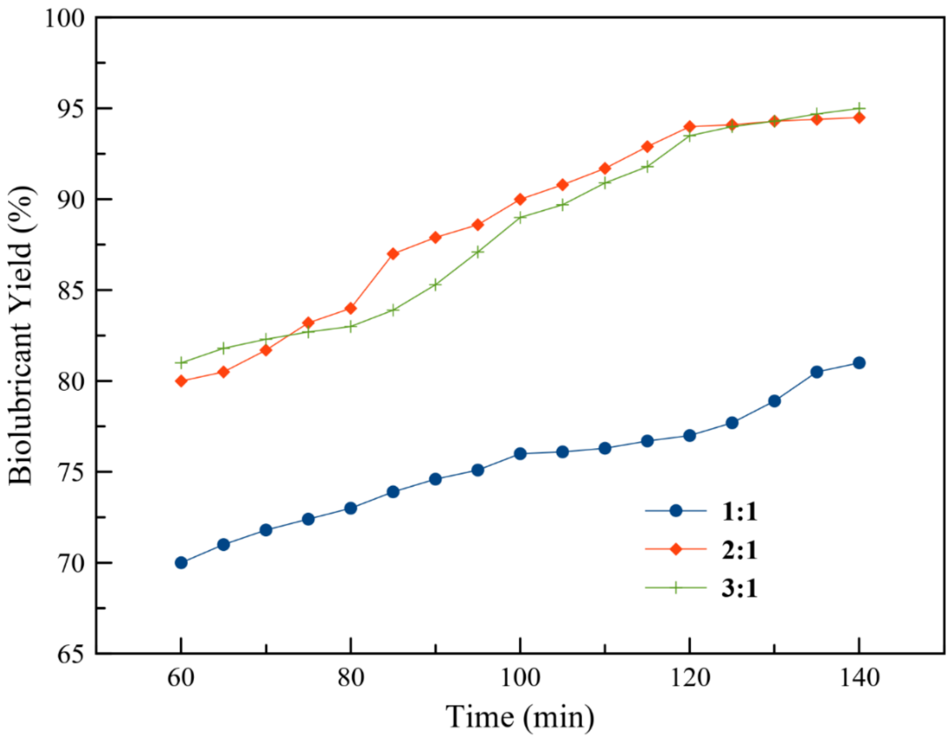


Figure 11: Biolubricant production according to the alcohol/FAME molar ratio (Temp 160 °C and catalyst 1 % w/v)

In summary, considering the relationship between the economic factors and yield, the following values were chosen for the biolubricant production: 160 °C of temperature, 1 % of catalyst (w/v) and a 2:1 molar ratio of alcohol/FAME.

4.4 Performance prediction using Artificial Neural Networks

The output parameter (bio lubricant yield %) was modelled for the input (temperature, catalyst loading, and alcohol/FAME ratio) [34]. To design the neural network, the data set was randomly distributed into three sets of training (70 %), testing (15 %), and validation (15 %). **Table 9** lists the best neural model structure with quality metrics during training, testing, and validation. The model structure represents the corresponding neurons used in the input, hidden, and output layers, respectively. The nodes in the input layer are equal to the input variables of the model, which are two in this case. Neuron no. and the activation function in the hidden layer were obtained by the BFGS iterative algorithm for better predictability. The only neuron in the output corresponds to the target.

Table 9: Structures and performance metrics of the five best neural networks for each variable

Variables	**Structure**	**Train**		**Test**		**Validation**		**Activation Functions**	
		R	Error	R	Error	R	Error	Hidden Layer	Output Layer
Temperature	2-11-1	0.999183	0.057807	0.998997	0.057807	0.999848	0.043174	Tanh	Tanh
	2-11-1	0.999086	0.064494	0.998581	0.071514	0.999439	0.094270	Logistic	Tanh
	2-7-1	0.998518	0.104536	0.998689	0.068659	0.998826	0.189274	Exponential	Tanh
	2-3-1	0.998720	0.090927	0.998250	0.076732	0.999286	0.169229	Tanh	Tanh
	2-3-1	0.997338	0.187546	0.996087	0.145784	0.998399	0.423223	Tanh	Identity
Catalyst	2-11-1	0.999444	0.050274	0.999442	0.048043	0.999483	0.060261	Tanh	Logistic
	2-5-1	0.998610	0.140608	0.999294	0.081079	0.999460	0.065348	Tanh	Logistic
	2-11-1	0.999241	0.069111	0.999756	0.017111	0.999277	0.101026	Exponential	Tanh
	2-9-1	0.998830	0.105978	0.999873	0.015749	0.999025	0.096932	Logistic	Identity
	2-11-1	0.999565	0.039480	0.999830	0.024003	0.999290	0.079727	Tanh	Exponential

Alcohol /FAME ratio	2-4-1	0.999021	0.059502	0.997975	0.083490	0.998777	0.074705	Logistic	Logistic
	2-3-1	0.997971	0.120359	0.997364	0.090246	0.997868	0.140045	Tanh	Sine
	2-10-1	0.998627	0.081591	0.999332	0.124295	0.998301	0.098053	Tanh	Logistic
	2-3-1	0.998107	0.111453	0.999854	0.021593	0.999114	0.081839	Tanh	Identity
	2-6-1	0.998767	0.073367	0.999772	0.057083	0.997935	0.114007	Tanh	Logistic

Figure 12 shows the correlation of the output with the target values. The models showed good fits of the data during the training, testing, and validation of ANN. ANN architectures were trained to predict biolubricant yield. The five-best MLP-based ANN structure to predict the effect of temperature on biolubricant yield required 3-11 neurons in the hidden layer with tanh and exponential as activation functions. A higher R value and low error during training, testing, and validation of the data set make these structures the best suited for prediction. MLP-based ANN with 5-11 hidden layers using tanh, exponential, and logistic functions performed well in predicting the effect of catalyst loading.

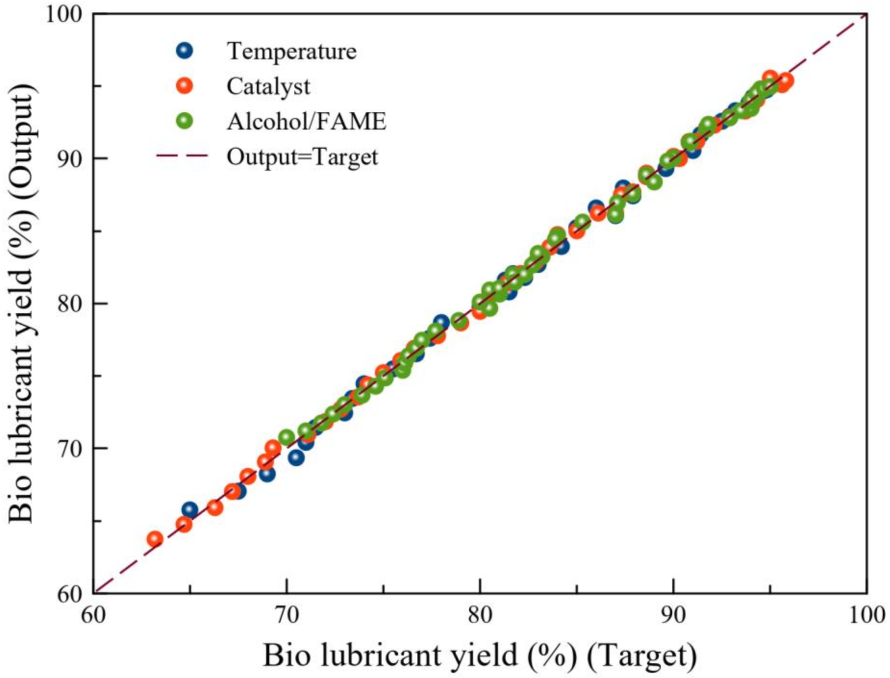


Figure 12**:** Correlation between output and target for different input parameters with ensemble best-fit MLP-based ANN

The biolubricant yield as a function of the alcohol/FAME ratio was best described by a model containing 3-10 hidden layers using tanh and logistic as the activation function. The best models were used for the sensitivity analysis. The results are presented as a relative influence of the input parameters on the yield of the biolubricant. As shown in **Figure 13**, catalyst loading and the alcohol/FAME ratio influence the yield equally by 38 % compared to temperature, which influences by 24 %.

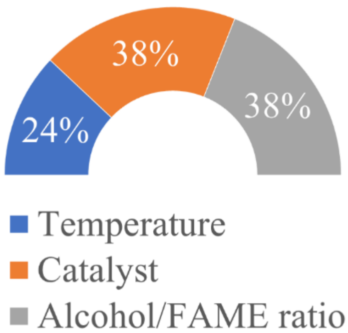
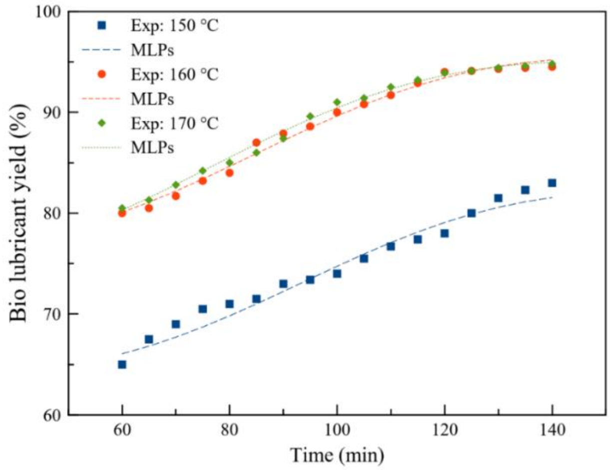


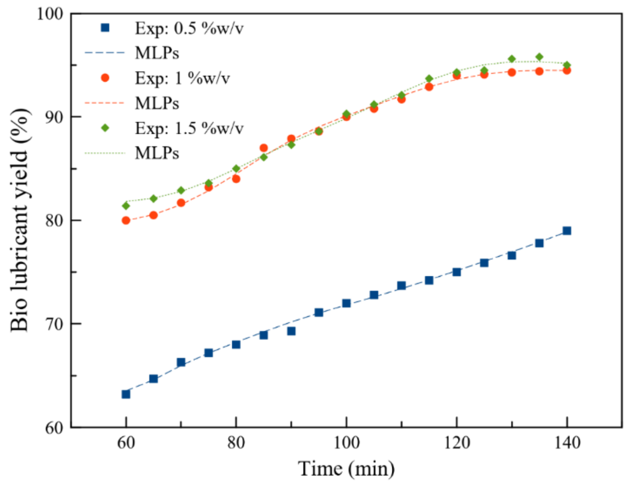
Figure 13: Relative sensitivity of input variables to biolubricant oil yield

The generated model codes were used to verify the accuracy of the internally trained, tested, and validated models using the complete data set. **Figure 14** (a) shows the comparison of the experimental and simulated values of biolubricant yield for different times at different temperatures. It is evident that the model accurately simulated the measured values. Similar observations can be made for the influence of catalyst loading and alcohol/FAME ratios in **Figure 14 (b&c).**

(a)



(b)



(c)

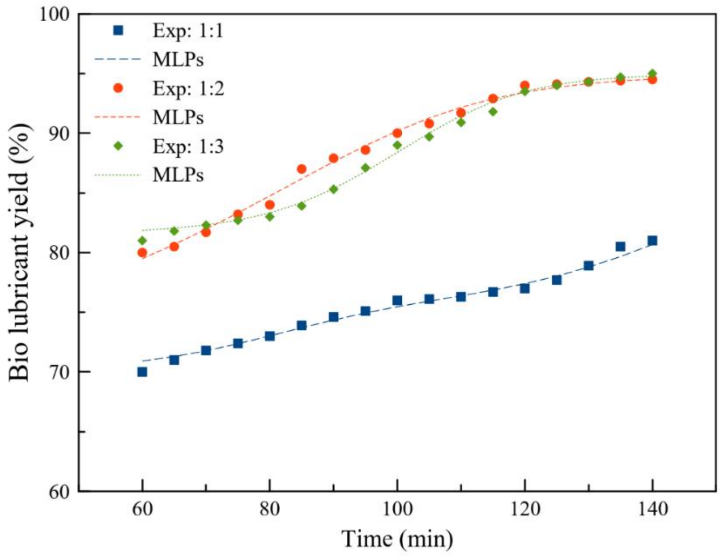


Figure 14: Biolubricant yields measured and simulated at different (a) temperatures, (b) catalyst loadings, and (c) alcohol/FAME ratios

4.5 Physiochemical Properties

The synthesized biolubricant was analyzed in terms of density, flash point, pour point, and kinematic viscosity at 40 °C and 100 °C. The results of the lubricants were compared with those of the commercial lubricants (75W-140 and AG100). We can see a decrease in the viscosity values as the temperature is increased. **Table 10** shows the physiochemical properties of all lubricants. It is quite clear that MCSO with ethylene glycol and 0.5 % Fe_3O_4 nanoparticles shows a better flash point result compared to MCSO with 0.5 % Fe_3O_4 nanoparticles.

Table 10: Physiochemical properties of lubricant samples

Oil Type	**Density (kg/m^3) at 20 (°C)**	**Flash Point (°C)**	**Pour point (°C)**	**Kinematic viscosity cSt at 40 (°C)**	**Kinematic viscosity cSt at 100 (°C)**	**Ref.**
Raw Castor Oil	959	147	-5	193	20	This study
Modified Lubricant	890	243	-15	210	22	

Modified Lubricant + Fe_3O_4	894	266	-16	216	25	
Modified Lubricant + Ethylene Glycol (EG)	891	259	-14	213	23	
Modified Lubricant + Fe_3O_4 + EG	893	272	-18	218	27	
AG100		244	-18	216	19.6	[38]
75W-140		174	-54	175	24.7	[39]

Figure 15 illustrates the relationship between kinematic viscosity and temperature for all lubricant samples. Most lubricants showed similar patterns. Under such circumstances, the viscosity decreased as the temperature increased. Repetitive contact with rubbing surfaces shortened the useful life of lubricating chemicals. It may lead to the creation of carbonate shale, induce wear, and impair the device's performance. It must be recognised that higher temperatures at the molecular level are required to break covalent bonds, initiate free-radical processes, and cause the viscosity of the lubricating material to decline. The kinematic viscosity of (75W-140 and AG100) was found to be 216 cSt and 175 cSt at 40 °C [39]. However, RCSO and MSCO show better kinematic viscosity at 40 °C (193 and 210 cSt, respectively) than the commercial lubricant AG100. **Figure 15** shows that with the addition of 0.5 % Fe_3O_4 nanoparticles to MCSO, the kinematic viscosity increases compared to RCSO and MCSO. The addition of ethylene glycol and 0.5 % Fe_3O_4 nanoparticles to MCSO shows the highest value of kinematic viscosity.

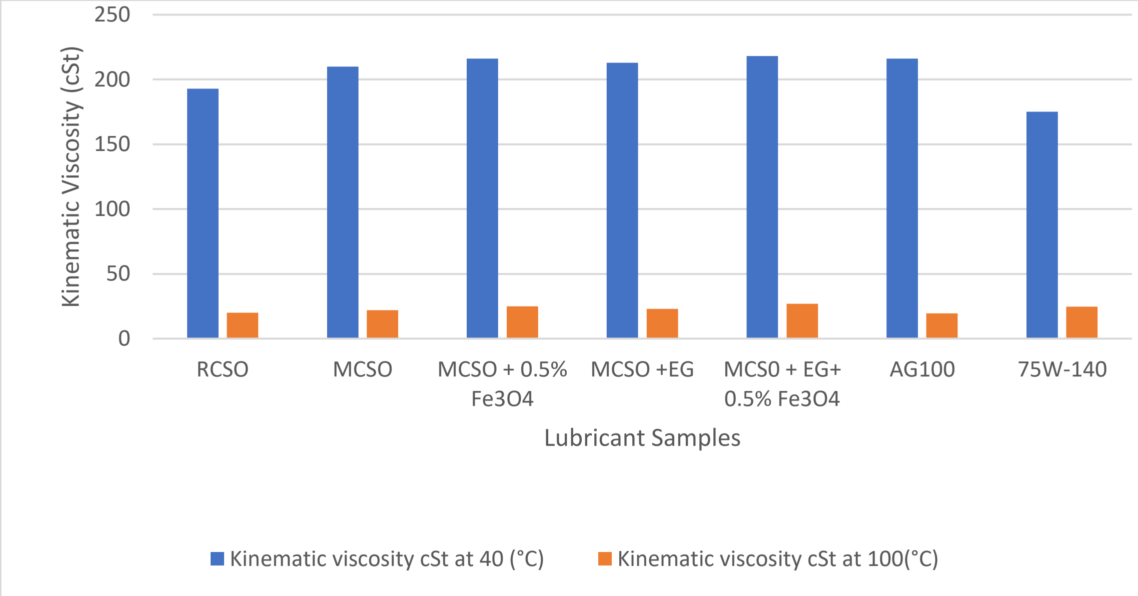


Figure 15: Kinematic viscosity of lubricant samples

4.6 Tribological Analysis

4.6.1 Coefficient of friction

The coefficient of friction for various lubricant samples is shown in **Figure 16**. Esters have been shown to develop in the formation of an effective layer on the surface during movement. The presence of a long chain molecules strengthens the load capacity of the lubricating coating [40]. Improvement in results has been observed in the case of additive addition. The addition of additives, ethylene glycol and Fe_3O_4 nanoparticles, to MCSO shows better friction coefficient results compared to RCSO and MCSO. Chemically treated vegetable oil provides better lubrication and enhanced film adsorption on metallic surfaces. The adsorption coating reduced friction between the surfaces, resulting in a decrease in the cutting forces.

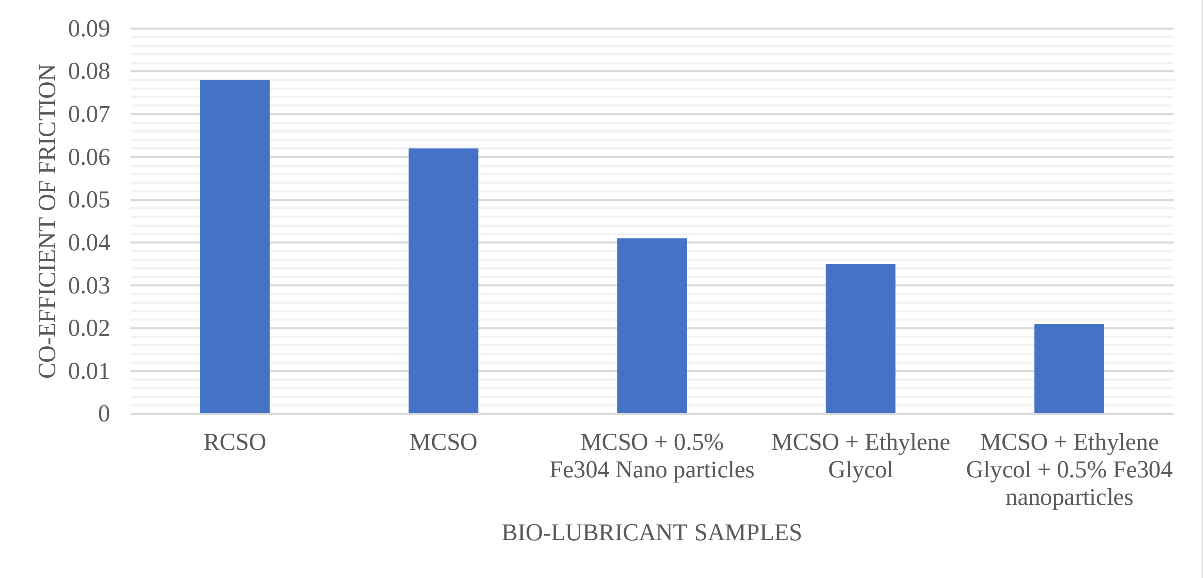


Figure 16: Coefficient of friction of different biolubricant samples

4.6.2 Wear

To determine pin wear, the samples were thoroughly cleaned with acetone and dried in a preheated oven prior to weighing. **Figure 17** clearly illustrates the wear of the pin. RCSO and MCSO show almost the same wear behavior. The additives ethylene glycol and Fe_3O_4 nanoparticles show better wear compared to RCSO and MCSO. The effect of nanoparticles on corrosion and wear characteristics depends on the dispersion of the particles within the epoxydated oil. Fe_3O_4 nanoparticles have a greater ability to disperse in solution, allowing the anti-wear mechanism to function properly. The tricarbamyl alcohol reaction occurs between the transcription factors of the components and the metal atoms during their interaction, resulting in the formation of an extraordinarily excellent lubricant coating. The better performance of MCSO + ethylene glycol + 0.5 % Fe_3O_4 nanoparticles is mainly due to the production of thin lubricating films with metals in contact. The creation of a thin molecular lubricant coating assisted in reducing friction, thus preventing premature material wear. The development of a protective lubricating layer on the surfaces was anticipated to reduce the forces operating on them.

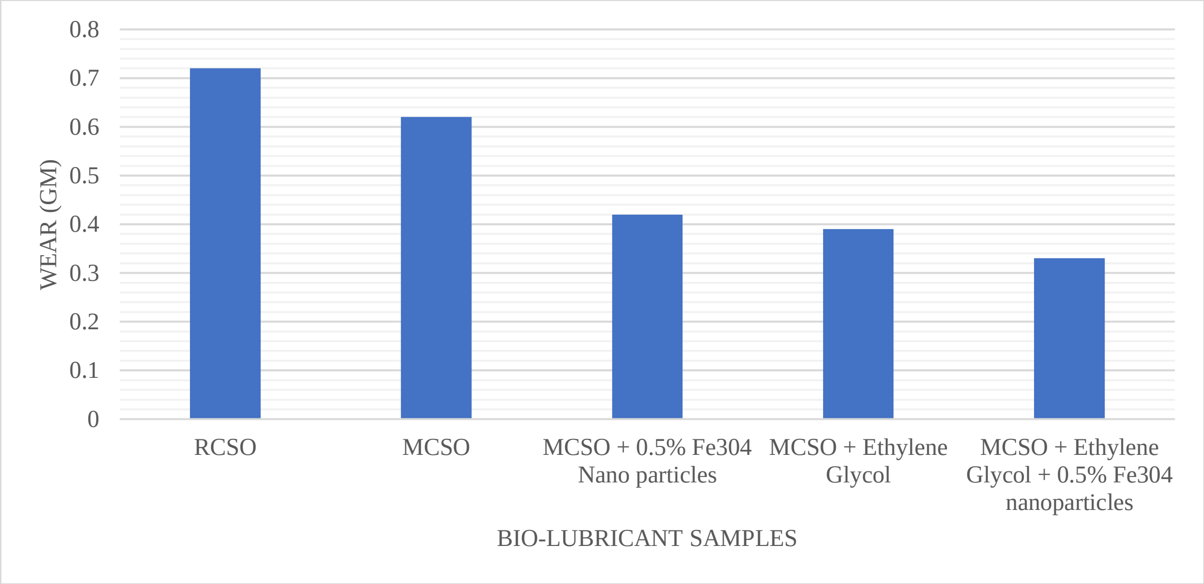


Figure 17: Wear material for biolubricant samples produced

Conclusion and Recommendations

Conclusion

Bio-lubricants have stable low-temperature properties and improved tribological characteristics. Bio-lubricants derived from non-edible oils may be a viable option for automotive applications. They have inherent technical characteristics that outperform fossil oils, such as high ignition temperature, increased lubricity, better service life of equipment, low evaporation rate, better anti-wear properties, viscosity, increased viscosity index, reduce traces of metal emission into the atmosphere, high load carrying capacity, excellent coefficient of friction, and biodegradability.

The preparation of biolubricants (conversion and kinetics) was affected by the FAME/alcohol molar ratio, catalyst concentration (Fe_3O_4), and temperature. Thus, the temperature increased the final yield, with kinetic shifts at higher temperatures. As the molar ratio of FAME/alcohol increased, the yield improved. Similarly, as the catalyst loadings increased from low to intermediate values, the ultimate conversion increased. To optimize yield and economics, intermediate temperature, and catalyst concentrations (T = 160 °C, catalyst = 1 % w/v) were used, as well as the maximum alcohol/FAME ratio (2:1). Once the critical conditions for biolubricant production were established, the yield of the castor oils obtained was acceptable, approximately 94 %. When additives are added to the MCSO, the physiochemical properties of the biolubricants produced are enhanced. The MCSO + ethylene glycol + 0.5 % Fe_3O_4 nanoparticles show the best results among the other biolubricant samples produced. Training, testing, and validation of the artificial neural network (ANN) showed a high linear regression coefficient (more than 0.997) for biolubricant yield as a function of temperature, catalyst loading, and alcohol/FAME ratio. The results obtained from the developed ANN models were found to agree well, and hence, it can be concluded that the ANN models can effectively predict the biolubricant yield for varying temperatures, catalyst loading, and alcohol/FAME ratios for different time durations. The relative sensitivity of the temperature to the biolubricant yield was found to be lower than that of the catalyst loadings and the alcohol/FAME ratios.

Future Recommendations

- The selection of non-edible oil is another big challenge. Earlier most of the research is carried out using edible oil which causes the shortage of food, so to overcome this, there is a great increase in the cultivation of non-edible oils, such as castor, jatropha.
- The use of nanoparticles can cause adverse effects, so the production of harmless bio-lubricant using nanoparticles is a major challenge.
- In comparison with mineral oil, bio-lubricant production should focus on non-toxicity and better lubrication properties than mineral oil.
- The production cost increases in case of non-edible oils because of presence of high content of FFAs.
- It is necessary to ensure continued availability of vegetable oils before replacing bio-lubricants with mineral oil for use in machines. Need to develop additives for improvingmaterial compatibility and oxidation stability.
- To improve bio-lubricants shelf life, more research should be done.
- The lack of technology affects the production of bio-lubricants on a large scale with comparative prices. Continuous supply of vegetable oils which are the main source of bio-lubricants production is very necessary to control its price.
- At low temperature bio lubricants tend to form a solid residue, due to which lubricant movement decreases. They require further improvement.

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