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Review Article

Formulation of Lubricating Grease from Waste Oil: A Review

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ABSTRACT

This paper demonstrates the potential of waste turbine oil (WTBO) as a base oil to substitute for mineral oil, which is usually used in grease formulations. This study will analyze the characteristics of used turbine oil, including its chemical composition and physical characteristics, including kinematic viscosity, viscosity index, moisture content, contamination, and density. The presence of antioxidants (butylated hydroxytoluene (BHT) and amine or phenyl-a-naphthylamine (PANA), anti-wear, and corrosion-inhibiting additives that can improve the formulated lubricating grease performance and lengthen service life are just a few of the useful remaining WTBO characteristics that can be used wisely as the base oil. It is crucial to create more environmentally friendly, economically sensible, and thrifty grease formulations to adhere to Malaysia's Green Technology Master Plan, which has outlined the strategic plans for developing green technologies. The new inventions must establish a resource- and carbon- efficient economy. The abundance of WTBO in the aviation industry and the unique characteristics of WTBO itself promise a reliable supply of base oil for lubricating grease in the future.

Keywords: Additives, base oil, grease formulation, grease lubricants, spent bleaching earth (SBE), thickener, waste turbine oil

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INTRODUCTION

Basic Components in Grease

Grease's basic function is to stay in contact with and lubricate the moving surfaces without sweeping out due to pressure, centrifugal force, or gravity. It is an oil-

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based product that can form in solid to semifluid forms, and it is made up of base oil (70%–90%), thickener (5%–20%), and additives (1%–10%) (Rohim et al., 2021). The base oil, thickener and additive package significantly influence the behavior of grease. These three are the essential components on which grease formulas depend the most. The thickener is frequently described as a "sponge" that binds the base oil and additives (Alias et al., 2023). The thickener traps the oil that makes up most of the grease to stiffen or densify the finished product. Mineral oils and synthetic fluids are examples of base oils. The most used base is mineral oil. However, synthetic bases work best in extremely hot conditions (Suhaila et al., 2018).

Type of Grease

Grease is typically classified into two categories: soap-based and non-soap-based, depending on the thickener agent used in the lubricant. Soap-based grease uses a soap, such as lithium or sodium stearate, to maintain the even mixing of the oil and water components of the grease. In contrast, synthetic grease, also known as non-soap-based grease, employs a synthetic thickener, such as polyurea, to give the lubricant its structure (Aziz et al., 2017; Rawat & Harsha, 2019; Sofi et al., 2019).

Compared to soap-based grease, synthetic grease offers better lubrication, wear prevention, high-temperature stability, and higher resistance to water washout. Conversely, soap-based grease is commonly used in various industrial applications due to its good water resistance and ability to lubricate at low temperatures. Synthetic grease is often used in heavy-duty industrial and automotive applications with high temperatures and challenging operating conditions. In summary, the classification of grease as either soap-based or non-soap-based is based on the unique properties and capabilities of the two types of thickeners, as well as the specific applications in which they are used (Rahman & Aziz, 2022).

Based on a 2020 article from Tribology International, Figure 1 provides a mind map that displays some of the common types of oil greases (Chatra & Lugt, 2020; Johnson, 2008).

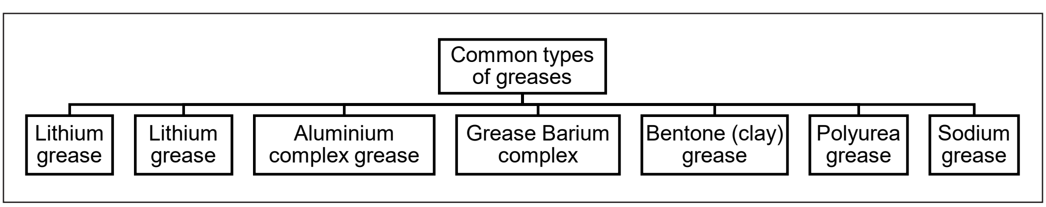

Figure 1. Common type of greases (Chatra & Lugt, 2020; Johnson, 2008)

General Grease Formulation from Waste Oil

The grease formulation is formed from a combination of base oils, additives and thickener. The mixture of the combination with the certain amounts will impact the characteristics of the grease performance. Genuine grease combines an oil or other liquid lubricant with a thickening, usually soap, to create a solid. Grease typically contains (1) 70%–90% base oil, (2) 5%–20% soap-like gelling agents (thickener), and (3) 1%–10% additives such as rust inhibitors, antioxidants, metal deactivators, and anti-wear agents (Mang & Dresel, 2007). The Industrial Revolution significantly impacted technology for grease enhancement formulation. Nowadays, many researchers are concerned about innovating a greener grease formulation by substituting the base oil that is frequently from the mineral source with the waste oil. Many successful stories of grease formulation from waste oil have been recorded, such as waste oil from waste engine oil, transformer oil and waste cooking oil (Japar et al., 2018, 2019, 2020).

Base Oil

The base oil in grease is a carrier for the lubricant and lubricates the machine's moving parts. It controls a lot of lubricant characteristics, including viscosity, volatility, and thermal stability. Grease performance can be impacted by the base oil's characteristics under various loads, temperatures, and environmental conditions (Aziz et al., 2017; Zhang et al., 2021). The characteristics and performance of the lubricant can be impacted by the base oil's carbon chain length.

A chain of carbon atoms joined in a linear or branched pattern is referred to as an aliphatic hydrocarbon chain. Many organic molecules, including the hydrocarbons in crude oil, natural gas, and coal, are composed of carbon chains as their fundamental constituents. A few to several hundred carbon atoms can make up the length of the carbon chain, which is determined by the number of carbon atoms. The number of carbon atoms in the hydrocarbon molecules that make up the base oil is referred to as the carbon chain length. In comparison to long-chain hydrocarbons, short-chain hydrocarbons, such as those in mineral oil, have a lower viscosity and are less stable at high temperatures. They are also more flammable since they have a lower flash point (Kaperick, 2013).

In comparison to short-chain hydrocarbons, long-chain hydrocarbons, such as those found in synthetic oils, have a higher viscosity and are more stable at high temperatures. They are also less prone to catch fire since they have a greater flash point. The properties of hydrocarbons can be influenced by the length of the carbon chain, the kind of chemical connection between the carbon atoms, the existence of double bonds, and the presence of functional groups (Niu et al., 2019).

Figure 2 shows a common variety of base oils, including mineral oil, synthetic oil, vegetable oil, biodegradable oil, food-grade oil, and high-temperature oil that can be utilized as a base oil in grease. The choice of base oil depends on the application and the operating circumstances to which the lubricant will be exposed. Each type of base oil has its distinct qualities and benefits (Suhaila et al., 2018). The creation of the thickening structure is substantially influenced by the type of base oil, which likely results in a distinct bleeding behavior and, consequently, a different lubricating mechanism (Fischer et al., 2018). Knowing that base oil provides lubrication, the viscosity factor will depend on it (the film thickness that depends on the base oil) (Kanazawa et al., 2017).

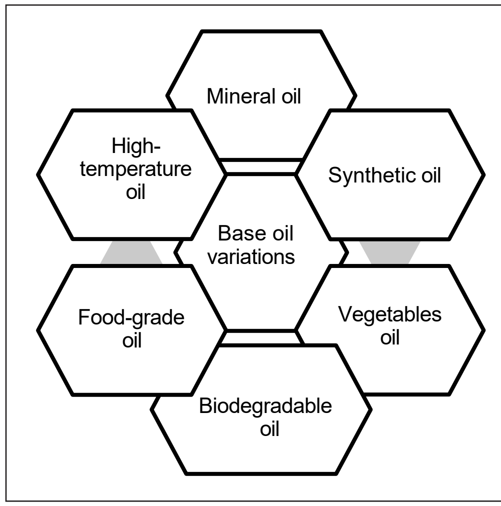

Figure 2. Base oil variations for grease formulation (Niu et al., 2019)

The most common base oil used in grease is mineral oil, derived from crude oil through refining. It is the cheapest and most widely used base oil in grease. However, they have disadvantages, such as less wear protection than synthetic-based greases, less thermal degradation and oxidation resistance, and not being biodegradable. If leaked or spilled, it can cause harm to the environment (Chandraseagar et al., 2019; Kuppusamy et al., 2020). Mineral oil can be further refined to create synthetic base oils (Rudnick, 2013).

Table 1 presents the API (American Petroleum Institute) classifications used to determine the level of refinement of base oils. Most industrial lubricants are derived from basic oils, and the API categorizes base oils into five groups based on their composition and how they are manufactured, as well as their response to different conditions, such as high temperatures. Groups I to III are produced by refining petroleum crude oil, while Group IV consists of fully synthetic (polyalphaolefin) base oils. Group V includes all other base oils that do not fall into Groups I to IV. Before any additives are mixed in, lubricating oils are initially categorized according to these five API groups (Aziz et al., 2017, 2018; Yano et al., 2013).

Turbine oil is a highly refined mineral produced from properly selected crude oil (ENEOS Corporation, 2018). It falls into Group 1 as it consists of mineral oil. Due to its strong oxidation stability and high viscosity index, it can be utilized as a lubricant for many

Table 1
API base stock categories

Groups	Base Oil	Viscosity Index	Vol % of Saturates	Mass of % Sulphur
I.	Mineral Oil	$80 \leq V1 < 120$	and < 90	> 0.03
II.		$80 \leq V1 < 120$	and ≥ 90	≤ 0.03
III.			≥ 90	≤ 0.03
IV.	Polyalphaoelfin (PAO)	≤ 120		
V.	All other base stocks			

different types of machinery, particularly for compressors and general industrial equipment. The best viscosity grade can be selected because it ranges in viscosity from 32 to 220.

Thickener

The thickener is a substance that will create a solid or semifluid structure when it is combined with the chosen lubricant. The thickener provides grease by being a sponge that holds the lubricant in place by holding the combination of base oil and additives together. Thus, the stability and consistency of the grease will be directly impacted by the amount and type of thickener present (Razali et al., 2018). It has been discovered that the structure of the thickener and the viscosity of the base oil mostly affect how elastohydrodynamic lubrication films behave. The structure of the thickener, base oil viscosity, and rolling speed all have an impact on how the thickener adheres to or deposits on contacting surfaces, as well as how oil starvation affects film formation (Sta˚hl & Jacobson 2003; Wu et al., 2023). Elastohydrodynamic Lubrication (EHL), a type of hydrodynamic lubrication (HL), is a lubrication regime where there is significant elastic deformation of the surfaces, which significantly changes the shape and thickness of the lubricant film in the contact (Mahadeshwara et al., 2023).

One of the most common types of thickener used in grease is metallic soap, which currently contains calcium, sodium, lithium, aluminum, clay, polyurea, and sodium. The traditional metallic soap is combined with a complexion of ingredients to create complex greases. Lithium-based is the most popular type as it has widely been used. These are produced using a low-molecular-weight organic acid as the complexing agent in addition to normal lithium soap (Arkı & Balköse, 2013). A soap is a metal salt of fatty acid by definition(Russo et al., 2023). If the grease contains soap, fatty acids are added; if not, basic oil is filled with the remaining elements. The long chain with complexion of azelaic acid, acids tallow and sebacic acid (such as instances of typical acids) as well as the high-molecular-weight fatty acids,stearic acid and 12-hydroxystearic acid are the remaining elements. The metal base is added once the acid reaches the proper temperature, at which point the fatty acid melts. Making soap is referred to as saponification (Figure 3). In essence, it is a mix of acid and base equal/produces soap and water.

Then, all the water is removed because lubricants should have very little water. After finishing, the substance is cooled and allowed to gel; at this point, the mixture turns into grease. Next, base oil is added to the

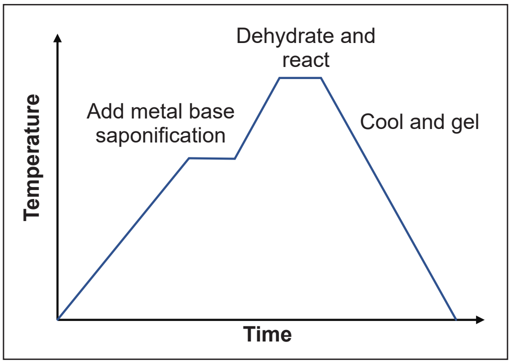

Figure 3. Grease essential process: acid + base = soap + water

mixture to modify consistency (additives might also be added). To achieve the consistency needed for the product, it might need to be heated, cooled, and tested multiple times. Most people mistakenly believe that grease is largely a thickener, whereas it is mostly oil. Usually, 10%– 20% of the oil in a container contains soap (Jeanna, 2017; Rawat & Harsha, 2019).

Non-soap thickeners are also becoming more and more common in specialized applications, like high- temperature settings. Two examples of thickeners that do not melt at high temperatures are bentonite and silica aerogel (Rawat & Harsha, 2019).

Figure 4 shows the crystalline structure of a few common thickeners that have always been used in the grease industry. Different crystalline structures are produced depending on the thickener's component chemistry, which changes the qualities of the grease made with those thickeners. The crystals get denser and thicken less effectively, but they also get more thermal and shear stable. However, greases with a larger thickener content have worse pumpability and torque characteristics, as one might anticipate (Fan et al., 2018).

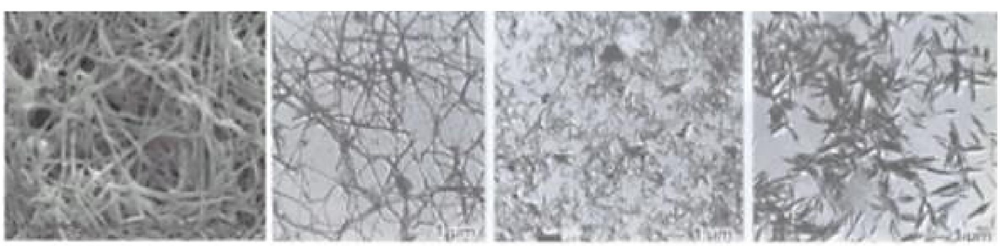

Figure 4. Crystalline structure in different thickener

Additives

Today, a wide range of additives are utilized to improve the service characteristics of lubricating grease. These additions alter the interfacial energy between the base oil and the thickening agent particles in a certain range and degree, and the volumetric fraction and nature of the additives have a major impact on their success. The characteristics of lubricating grease components and the microstructure attained during the production will determine how good the grease's performance will be (Chatra & Lugt, 2020). There are a few ways to categorize additives that have been characterized, such as whether they work in the fluid's center or on the surface, chemically active or inert, or via physical touch. Table 2 shows that the additives could be divided into two categories: performing in bulk or at a surface (Bhat & Charoo, 2019; Canter, 2012).

The grease formulation's primary goal is to be able to choose additives that will not damage the grease. Hence, the choice of additives must take into consideration the structural stability of the thickener system that was used in the grease formulation. One of

Table 2
Additives category (Bhat & Charoo, 2019; Canter, 2012)

Additives performing in the bulk of the grease	
Antioxidants	Extend the life of the lubricant by inhibiting oxidation, thus minimizing base oil thickening, sludging and deposits
Scavengers	Chosen to react with undesirable contaminants such as acids or sulfur to render them less harmful.
Additives performing at a surface	
Anti-wear Agents	Inhibit wear typically under high-speed, low-load operating conditions.
Corrosion Inhibitors	Inhibit the corrosion of metals in contact with the lubricant, protecting equipment and extending the useful life of the lubricant.
Extreme Pressure (EP) Agents	Inhibit seizure under high loads and temperatures
Friction Modifiers	Reduce the friction between moving parts by surface adsorption
Metal Deactivators	Inhibit the metals from contacting the lubricant and catalyzing the oxidation of the lubricant.
Seal Swell Agents	Assist elastomer seals and gaskets in performing their function.

the thickener's characteristics that usually hinders the movement of additives is the polarity of the thickener. Inappropriate additives will create a physical barrier (Kaperick, 2013). Besides, it also can cause grease to soften, odor, corrosion with the intact surface, low-temperature performance, and decrease permeability (Bhat & Charoo, 2019; Canter, 2012).

PROBLEM STATEMENTS

Grease formulations based on mineral oil are frequently employed in a wide range of industrial and automotive applications because they effectively lubricate and safeguard moving parts. The base oil that is most generally used in the formation of grease is mineral oil, which is made from petroleum. The current trend in grease formulation nowadays is to create greases that are more sustainable and environmentally friendly while yet delivering the performance demands of various applications. Other than that, it needs to be cheap as well. One of the most cost-effective and sustainable methods of grease formulation that has been identified and is ongoing is using waste oil as a base oil in the grease formulation, where the typical base oil, usually from mineral oil, will be substituted with the waste oil (Okal et al., 2022). Research and development to employ waste oil as a base oil for grease formulation is actively happening. Numerous results and findings in the research that look into the performance and viability of using waste oil as a base oil have typically been encouraging. Studies demonstrated that in terms of wear resistance, load-carrying capacity, and high-temperature stability, waste oil used as a base oil in greases could perform on par with or even better than standard mineral oil-based greases. Besides, it is also mixed with selected thickeners and additives to enhance performance and increase service life, such as antioxidants, rust inhibitors, and anti-wear agents (Japar et al., 2020).

In the recently published study, many researchers claimed to have been able to develop grease using various waste oils such as waste cooking oil (WCO), waste engine oil (WEO), and waste transformer oil (WTO) as the base oil (Japar et al., 2019; Rahman & Aziz, 2022; Whitby, 2020). The performance of the produced grease may differ depending on the chemical qualities and composition of these three forms of waste oil. Usually, a vegetable oil, like WCO, that is used for frying food and is primarily made up of triglycerides, which are esters of glycerol and fatty, will create grease with low toxicity, good oxidation stability, high flash point, low pour point and high Viscosity Index (VI) (Herman et al., 2021). Meanwhile, WTO, an insulating and cooling fluid made primarily of paraffin, naphthene, and aromatics, is used in electrical transformers, and WEO is a lubricant that is used to lubricate internal combustion engines; it is primarily made up of hydrocarbons such as paraffins, naphthenes, and aromatics (Mahmud et al., 2019). Since both WTO and WEO are made up of almost similar hydrocarbon properties, they share almost similar properties of the grease produced, such as high viscosity, good lubrication, high-temperature resistance, good water resistance and good corrosion resistance (Japar et al., 2019; Rahman & Aziz, 2022).

Modern grease formulations employ waste oil as a base oil for its sustainability, cost-effectiveness, promising performance, and environmental-friendliness. Other than that, it is due to their availability, too. As numerous industrial processes constantly produce it, waste oil is readily available on the market and can serve as a reliable source of base oil. Although the idea of recycling waste oil to make new products has been put into practice in Malaysia (Razali et al., 2018, 2020), regretfully, WTBO has not discovered a means to recycle in any application despite the growing markets of turbine oil. WTBO is a useful by-product of turbine oil that is unavoidable while lubricating turbines for chemical synthesis (Glushkov et al., 2020). It is, nevertheless, can cause a serious environmental issue. Abundant WTBOs worldwide, present significant environmental, economic, and social problems (Liu et al., 2013).

A few research have found some valuable chemical and physical characteristics of waste turbine oil that can be utilized to formulate a high-quality grade at a low cost. WTBO also had been found to have a similar hydrocarbon chain as WEO and WTO, where WTBO also consisted of paraffins, naphthenes, and aromatics. Furthermore, as waste aviation turbine oil already contains a number of additives like antioxidants, rust inhibitors, and anti-wear agents that can enhance performance and lengthen service life, it can be thought of as a potential replacement for mineral oil as a base oil in grease composition (Vershinina et al., 2019). Additionally, it is designed to offer lubrication and protection in extreme pressure, high load, and high-temperature circumstances typical of airplanes and other aircraft. Although no research claims that WTBO can be used as a base oil in grease formulations, its properties look promising in the grease formulation. Hence, this proposal will be the first research paper to initiate this study.

OBJECTIVE

The objective of this review paper is to study whether the recycling of WTBO as a base oil in the grease formulation (replacing the mineral oil as a common base oil) will be able to produce an industrial standard grease or not by evaluating the physical and chemical properties of WTBO.

Grease Formulation from Waste Oil

Greener alternatives began to become more and more popular in grease formulation. Due to urbanization and industrialization, waste oil production keeps increasing. The possibility to reuse waste oil as grease base oil has been demonstrated by research; nevertheless, the variable composition of waste oil upon collection, particularly for waste oil produced by the aviation industries, would result in uneven grease quality when employed in the formulation of grease (Rahman & Aziz, 2022). Research on current developments is actively carried out by utilizing and analyzing a variety of chemical compounds to follow the green trends. Environmental pollution is one such issue that has been and will continue to be. In connection with this, studies on creating new environmentally friendly grease formulations are carried out by utilizing waste, such as used oil and industrial waste and by investigating potential environmentally friendly grease components, such as the base fluid, thickener, or additive (Japar et al., 2020). Table 3 shows the successful research on grease formulation from waste oil.

Table 3
Successful grease formulation from waste oil

Aim	Grease Formulation	Parameter	Author/Ref
Formulation of grease using waste from a palm oil refinery.	Base oil: waste cooking oil thickener spent bleaching earth Additive: fumed silica	1. Consistency and dropping point 2. Corrosiveness on copper 3. Tribological properties	Waste-based, base oil and thickener (Japar et al., 2020)
Develop grease from waste oils as the base oil and red gypsum as one of the thickeners.	Base oil: waste oils Thickener: red gypsum/ fumed silica Additive: MoS_2	1. Consistency and dropping point 2. Separation of oil	Waste-based base oil and thickener (Razali et al., 2018)
Formulation of lubricating grease from waste transformer oil	Waste Oil: WTO Thickener: fumed silica & sodium stearate Additives: molybdenum disulfate (MoS_2)	1. Consistency and dropping point 2. Separation of oil	Nur Suhaila binti Anang Japar (Japar et al., 2019)
Characterization of lubricating grease formulated from waste engine oil	Waste Oil: WEO Thickener: fumed silica & sodium stearate Additives: molybdenum disulfate (MoS_2)	1. Consistency and dropping point 2. Separation of oil	N. W. Abdu Rahman. (Rahman & Aziz 2022)

The similarities of all the waste oils listed in Table 3 that qualify them for grease formulation are due to their significant potential as a base fluid and/or a substitute for mineral oil. The variety of fatty acids present in each of the chemical compositions in each waste oil of each research will contribute to different values of grease formulated (Japar et al., 2019).

Turbine Oil

The main purpose of turbine oil is to lubricate the bearings and auxiliary machinery in steam and hydraulic turbines, turbo pumps, and air, gas, and refrigeration turbo compressors. Hence, it could be said that the primary purposes of turbine oil are for lubrication, speed control, and cooling (Fuskele et al., 2022). Basically, turbine oil is made from a combination of relatively simple ingredients: Base oil, oxidation, corrosion, defoaming inhibitors, and demulsifiers. The turbine oil formula typically makes up 97% or more of the base oil. A mineral or synthetic hydrocarbon base oil makes up the majority of turbine oil composition.

Additives are blended into the base oil at low amounts to preserve the oil and the turbine parts. According to OEM specifications, additives should give the turbine optimal performance. Original equipment manufacturer (OEM) lubrication requirements are designed to give the end user some assurance that the equipment will function properly and last as the specified amount of time stated if a certain lubricant is used. For example, antioxidants are one of the additives widely used in turbine oil. Antioxidants are a group of substances that have the capacity to inhibit oxidation. As a result, they can stop the turbine oil from breaking down and thickening (raising viscosity), improving the turbine's performance and extending its life too (Soleimani et al., 2018). The phenol and amine combinations are noteworthy for being utilized in turbine oil as antioxidants regularly (Shahnazar et al., 2016; Yano et al., 2013)

The turbine oil consumption is usually huge, approximately 3,700 gallons or 14,000 liters. That is an expensive oil supply of nearly 67 drums (Shekarchian et al., 2012). It typically lasts 3–5 years in a turbine, but this relies on the internal conditions of the system. Degradation would happen more quickly in a filthy system than in a clean one if the system encounters temperatures over the threshold, forms deposits, and otherwise is in good condition (Pirro et al., 2016; Vandervort et al., 2021). Turbine oils are recommended for use in situations where hydraulic oils, air compressor and vacuum pump oils, general shop lubricants, bearing lubricants, and heat transfer oils (Verified Market Research, 2022).

Figure 5. Turbine oil market size and forecast 2020–2028 (Verified Market Research, 2022)

According to Esomar Verified Market research, turbine oil was estimated to be worth USD 1.3 billion in 2020 and is expected to grow to USD 1.7 billion by 2028 (Figure 5). It will also grow at a compound annual growth rate (CAGR) of 3.7% from 2021 to 2028. The average price for turbine oil per gallon is 81.7 USD, and it is estimated that almost 1.5 million gallons of turbine oil will be widely produced in 2020 (Verified Market Research, 2022).

Properties of Used Turbine Oil

When evaluating grease performance, the qualities of the turbine oil used are crucial. Used turbine oil is an oil that no longer satisfies the quality requirement and has reduced qualities. An oil analysis needs to be done to guarantee the condition of the used turbine oil, as the characteristics of the used turbine oil were unknown at the time of collection. The properties of the turbine oil used, including kinematic viscosity, viscosity index, moisture content, and density, were examined in this study. Elemental analysis and FTIR characterization were also carried out to look for contamination, additives, or wear metal in used turbine oil (Tichy et al., 2021). In terms of chemical characteristics from Tables 5 and 6, it was found that the main constituents of the WTBO were C, O, and N, with metals making up only 4% of the sludge's mass. According to the analytical results, demulsifiers, defoamer, antirust, and antioxidants are also available. It is, therefore, practically a hydrocarbon (an organic substance made only of carbon and hydrogen (Gupta, 2017; Liu et al., 2016; Mortier et al., 2011).

Tables 4 and 5 list the qualities and capabilities of both fresh and used turbine oil. In-service turbine oil keeps its excellent properties even after extensive use. Kinematic viscosity, the flow resistance brought on by gravity, increased from 45.20 to 46.68 mm2 s-1 at a particular temperature. After serving for a long period, alcohols, aldehydes, carboxylic acid, and other oxides were created (Hsu & Gates, 2000; Liu et al., 2016). The synthesis of carboxylic acids resulted in a small increase in acid number value (ASTM D974,2014). Based on how quickly viscosity changes with temperature, The viscosity index (VI) is one of the most crucial elements in determining lubrication quality.

The term "viscosity index" refers to how the viscosity of an oil changes with temperature. For instance, high-VI oils experience less temperature-related viscosity change than low-VI oil. High-VI base oils are a prerequisite for the multigrade engine oils that vehicle manufacturers demand as a starting point in the formulation process. High-VI base oils have minimal volatility and are designed to work at low and high temperatures (Mang & Dresel, 2007). These oils are suitable for usage at temperatures between 32- and 150 degrees Fahrenheit. Group I base oils are refined using a solvent, a less complex refining procedure (Brown, 2015). Grease and gear lubricants frequently contain Group I base oils.

In other studies of the physical properties of the used turbine oil, the WTBO could be described as per Table 6, named Oil F. The viscosity of the used turbine oil is the lowest compared to other used oils, such as engine oil, hydraulic oil, bearing oil and gear oil (Liu et al., 2013). Viscosity is the single most important performance property of a lubricant. The higher the viscosity, the greater the resistance to flow. The lower viscosity of these oils will result in less resistance and faster flow. In order to produce a great grease formulation that is high in viscosity, an extra thickener will be added (Tichy et al., 2021).

Table 4
Fresh turbine oil and in-service turbine oil (Properties and performance) (Liu et al., 2016)

Description		**Fresh Oil**	**In Service Oil**	
Kinematic Viscosity (40°C)/mm² s⁻¹	41.4-50.6	45.2	46.68	ASTM D445
Viscosity Index	≥95	125	123	ASTM D2270
Acid Numbering KOH g⁻¹	≤0.3	0.07	0.08	ASTM D974
Water Separability (54°C, 40-37-3 mL)/min	≤30	10	20	ASTM D1401
RPVOT/min	Report	788	470	ASTM D2272
Watering kg⁻¹	≤100	90	158	ASTM D6304
Air Release (50°C)/min	≤10	1.7	4.9	ASTM D3427
Ruler/%	Amine	100%	52%	ASTM D6971
	Phenol	100%	31%	
Content/ppm				
Zn		0	1.7	ASTM D4951
Cu		-	0.15	
Fe		-	0.61	
Na		-	0.08	
P		22.38	26.62	
Si		<0.48	<0.48	
Ci		<0.0015	<0.0015	

Table 5
Sulphur content in the turbine oil residue (Liu et al., 2016)

	C	**O**	**N**	**P**	**S**	**Ca**	**Fe**	**Zn**	**Si**	**Ai**
Sludge/mass %	61.4	20.8	5.54	2.81	1.84	0.46	1.31	4.52	0.64	0.28
Residues of sludge after TG/ mass%	50.53	31.79	-	0.69	0.85	1.01	3.17	9.81	1.46	0.69

Table 6
Physical and chemical: properties of fresh, used and refortified oils (Liu et al., 2013)

Samples		**Viscosity 40°C (mm²/s)**	**TAN (mgKOH/g)**	**H_2O Content (vol%)**	**H_2O Separability at 54°C (min)**	**Cu Corrosion**	**Mechanical Impurities (wt%)**
Oil F	Fresh Oil	32.56	0.02	-	40–37–3 (6.5)	1b	/
	Used Oil	31.68	0.03	0.01	40–40–0 (20)	3b	/
	Refortified Oil	32.08	0.02	0.01	40–40–0 (20)	1b	/

TAN is the Total Acid Number. It is a measure of acidity that is defined by the amount of potassium hydroxide in milligrammes that is required to neutralise the acids in one gram of oil (Decote et al., 2021). The standard acid value for lubricating is 0.1 (> 0.1 so corrosive and < 0.1 so non-corrosive). Oil F has recorded 0.03 mgKOH/g. Hence, a non-corrosive grease will be expected to be produced from this formulation.

The permissible water content in grease must be only 0.15% to 0.3% (Ismail et al., 2019; Sharma et al., 2022). The used turbine oil in Table 7 stated that only 0.01% of water content is found in it. Few costs will be saved as unnecessary processes like grease water washout need to be done to remove the water.

The 3b of copper corrosion recorded by Oil F is quite worrisome because it indicates an intermediate potential for Oil F to corrode the turbine (Tańczuk et al., 2017). Nevertheless, the additives like antioxidants and corrosion inhibitors used in the turbine oil were found to be hardly removed, although after going through the reclamation (the removal of water and particulate contamination from oil products and refortification process). Thus, the outcome of the grease formulation from the turbine oil used is predicted to not be corrosive.

FUTURE PROSPECT

Traditionally, mineral oils have been employed for lubrication purposes. Nevertheless, the long-term viability of fossil fuel-based energy sources is a significant concern. Moreover, the improper disposal of mineral oils can lead to environmental contamination in aquatic and terrestrial ecosystems(Borras et al., 2018). The combustion of mineral oils utilized as lubricants has the potential to release a tiny number of metallic elements, including phosphorus, zinc, calcium, magnesium, and iron nanoparticles (Cecilia et al., 2020). In this particular setting, using environmentally sustainable and non-hazardous bio-lubricants becomes essential. The utilization of bio-lubricants remains somewhat constrained compared to mineral oils, but this trajectory is growing and is contingent upon investments in research and development (R&D). The surge in demand for biodegradable lubricants can be attributed to the progression of environmental regulations, which have become increasingly stringent to mitigate the adverse environmental consequences of improper disposal practices (Negi et al., 2021).

The future prospects of bio-lubricants should prioritize enhanced lubricating qualities and reduced toxicity compared to conventional mineral oils. In addition to stringent environmental restrictions, there is an anticipation for developing more sustainable formulations utilizing WTBO as a fundamental base oil. The anticipated physical and chemical characteristics of WTBO following the treatment outlined in this study suggest a favorable potential to produce industrial grease.

Based on the findings of the Esomar Verified Market research, as depicted in Figure 6, it was projected that the market for turbine oil will have significant growth in the next years. The production of waste turbine base oil (WTBO) is expected to expand significantly due to the global rise in turbine oil consumption over time (Efimov, 2020). The estimated proportion of waste oil in relation to the whole consumption of commercial products is approximately 50%, with waste oils specifically accounting for approximately 30% of this total (Hester & Harrison, 2010). The aviation industry has experienced a significant evolution in the aftermath of the Covid-19 pandemic. This transformation has led to an increased need for sustainable aviation oils. However, this surge in demand has also resulted in the generation and accumulation of WTBO. Consequently, it becomes imperative to ensure the proper disposal of these waste oils (Gong et al., 2020).

Table 7
2007 production of worldwide used oil source and classifications (Yu, Ma & Wang, 2012)

The Classification and Source of *Worldwide Used oil Source*	**Production of Used oil (Million Ton)**	**Explanations**
Used lubricating oil, chainsaw oil, Hydraulic fluid and lubricating grease	2925	According to a 45% efficiency factor, the Total National Production of Used Lubricants, hydraulic fluid, and lubricating grease is estimated to be around 2925 million tons.
Total of Worldwide Used oil Source	3753.7	Including other used oil likes (petroleum mining oil, dye, and ship industry)

Waste oil is harmful in two ways: it can be toxic to people and damage the natural environment. In 2007, the production of used oil in China was 37.537 million tons, with turbine oil falling under the lubricating oil category, contributing to 29.25 million tons of used oil production (Table 7). Different types of oil have various levels of additives, such as heavy metals, chlorine, and sulfur, which can be harmful to humans. When turbine oil is used, it can produce harmful substances due to high temperatures and oxidation, such as 3,4-Benzypyrene (PAH) and polychlorobiphenyl (PCB), which can seriously harm human health. Used oil pollution can also harm the ecosystem, soil, water, and plants (Aganbi et al., 2019; Ismail et al., 2021). A small amount of used turbine oil can contaminate a large amount of water, and waste oils can endanger aquatic life in rivers, lakes, and streams.

CONCLUSION

In conclusion, the idea of utilizing treated waste turbine oil for the grease formulation is promising to be viable based on the theoretical properties that have been analyzed. But a few things might need added for more valuable grease production. However, in this paper, the study covers only the grease formulation part. Hence, the WTBO collected from the supplier needs to be treated first before being substituted as a base oil to remove any impurities, such as metal, dust, debris, or moisture content. The formulated grease is expected to be long lasting due to the "natural" existence of antioxidants in the used oil and useful to the moving machinery that metal made. Besides, the increased production of worldwide turbine oil means the increased amount of the used turbine oil will be in now and future is expected. Thus, this grease formulation is necessary for reducing the environmental impact and cost of the disposal process of used oil, which involves money and energy.

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