



ENVIRONMENTALLY ACCEPTABLE LUBRICANTS: LATEST ADVANCEMENTS

Introduction

Environmentally Acceptable Lubricants (EALs) developed from biogenic materials and synthetic esters meet stringent environmental standards set by the Organization for Economic Cooperation and Development (OECD), the Coordinating European Council (CEC), and the American Society for Testing and Materials (ASTM), ensuring they are readily biodegradable, non-toxic to aquatic life, and non-bioaccumulative. Within the last few years, the field of EALs has rapidly expanded to combat growing environmental concerns surrounding conventional mineral oil-based lubricants, including oxygen starvation in marine ecosystems, soil contamination and toxicity, and health risks associated with air-borne particles. EALs have demonstrated promising anti-friction properties superior to that of standard mineral oil-based lubricants that can further augment their industrial applications and consumer market. Currently, many government-funded projects and research are exploring the possibilities of using agricultural waste for EAL raw materials, applying EALs to hydroelectric power industries, and reinforcing the tribological properties of EALs with multi-functional additive technologies. This paper highlights important transition from traditional lubricants to EALs by exploring the environmental risks posed by current lubricant applications, governmental regulations promoting EALs, and recent government-funded projects and research on EALs.

Conventional Lubricants Categorization and Applications

Lubricants are substances that reduce friction between material surfaces, regulating power transmission and preventing corrosion. Various industries, such as automotives, aerospace, medicine, and food processing, utilize different classes of lubricants. These lubricants create a thin barrier over the microscopic roughness of surfaces, facilitating the smooth movement of mechanical parts and protecting machinery from wear and tear.[1][2]

Lubricants are classified into four major main categories: oils, greases, penetrating lubricants, and dry lubricants.[3] Oils, also referred to as liquid lubricants, consist of long polymer chains and detergent additives that protect the oil from oxidation and metal deposits. Oils have low viscosity and resistance, rendering them optimal for operations requiring minimal friction. For example,

Test Type	Test Name	Measured Parameter ^a	Pass Level ^b	Method
Ready Biodegradability (A substance is considered to be inherently biodegradable using any of these tests if it shows ≥20% biodegradability within the test duration)	DDAT	DOC	≥70%	OECD 301A
	Strum test	CO ₂	≥60%	OECD 301B
	MITI test	DOC	≥70%	OECD 301C
	Closed bottle test	BOD/COD	≥60%	OECD 301D
	MOST	DOC	≥70%	OECD 301E
	Sapromat	BOD/COD	≥60%	OECD 301F
	Strum test	CO ₂	≥60%	ASTM D-5864
	Shake flask test	CO ₂	≥60%	EPA 560/6-82-003
	BODIS test	BOD/COD	≥60%	ISO 10708
Hydrocarbon degradability	CEC test	Infrared Spectrum	≥80%	CEC L-33-A-934
Screening tests (semi-official)	CO ₂ headspace test	CO ₂	≥60%	ISO 14593

Figure 1. Standard Biodegradability Tests[10]

circulation oils are used for bevel and worm gears in automobiles; compressor oils are applied to vacuum pumps, pistons, and rotary vane compressors in aviation; and slideway oils are suitable for lathes, cutting, grinding, and milling machines in medicine and food productions.[4] These oils are tailored to meet specific applications set forth by industries reliant on efficient machinery.

Greases are blends of base oils and thickeners, typically comprising mineral oil and lithium-based soaps. The thickeners provide grease with a sticky, thick, and viscous consistency that prevents leaking or dripping. Greases are long-lasting lubricants that adhere to surfaces like gears, chains, and linkages that defend against contaminants and integrate well with other lubricants. These characteristics make greases ideal for infrequently used machinery and extremely dry conditions. For instance, water-resistant calcium greases are used for low-speed and low-load bearings in marine applications; aluminum complex soap greases are suitable for high thermal environments in food productions and pharmaceutical oils; and urea greases are employed in casting lines and iron mills in construction and infrastructure industries.[5] Greases are a reliable solution for various environments where long-lasting protection is essential.

Penetrating lubricants are specialized oils designed to penetrate tight spaces and dissolve rust. These short-lasting lubricants are effective at strengthening wood and loosening rusted or

stuck mechanical fasteners, making them perfect candidates for maintenance work and corrosion removal. WD-40 is a widely used and versatile penetrating lubricant for a myriad of applications in woodwork, hand tools, firearms, and mining, and military applications.[6] Penetrating lubricants’ accessibility to confined spaces and instant results make them a user-friendly tool for anyone.

Finally, dry lubricants, such as silicon, graphite, and polytetrafluoroethylene (PTFE), are spray lubricants mixed with volatile substances like alcohol or water. These readily evaporating lubricants are specific to threaded rods or locks, clean and dust-free surfaces, and high-temperature and high-pressure environments. For example, graphite is used on locks and hinges in transportations; PTFE or Teflon are applied to non-stick coatings in household cookware and food processing equipment; and hexagonal boron nitride or micro-ceramic are included in skin-care products, tissue scaffolds, and lithium-ion batteries.[7][8] Despite their solid state, dry lubricants’ unique properties allow them to tolerate extreme conditions that are otherwise unachievable by common oils and greases.

Applicational Threats and Health Hazards

Conventional lubricants are composed of base oils, thickeners for greases, and additives that are non-renewable, non-

Test Title, with Species	Test Number
Growth Inhibition Test, Alga	OECD 201
Acute Immobilization Test, <i>Daphnia</i> sp.	OECD 202
Acute Toxicity Test, Fish	OECD 203
Prolonged Toxicity Test: 14-Day Study, Fish	OECD 204
Respiration Inhibition Test, Bacteria	OECD 209
Early-Life Stage Toxicity Test, Fish	OECD 210
Reproduction Test, <i>Daphnia magna</i>	OECD 211
Short-term Toxicity Test on Embryo and Sac-fry Stages, Fish	OECD 212

Figure 2. OECD Aquatic Toxicity Tests[10]

biodegradable, and toxic to the environment.[2] Base oils, which make up 75% to 90% of lubricants, can be classified into three main varieties: mineral oils, synthetic oils, and natural oils. With modern technological advancements and increasing industrial demands, efficient lubricant production is essential to appease the increasing energy consumption of machinery and equipment. Most base oils in lubricants are mineral oils produced during crude oil refining processes at a favorably low cost compared to the natural gas conversions or petrochemical synthesis of synthetic oils and natural base oils in EALs.[9] Greases contain up to 10% thickeners, such as graphite and lithium-based soaps, alongside the base oil.[10] The rest of a lubricant contains hundreds of performance-enhancing additives made of metal-organic chemicals or chemical processed natural raw materials that serve as antioxidants, anti-wear agents, pour-point depressants, and viscosity-index improvers, among other functions to enhance lubrication.

According to a 2019 article published in the International Journal of Environmental Research and Public Health, humans and ecosystems are continually exposed to pernicious chemicals in conventional lubricants that can be fatal to us in the long run. Open cutting systems like chainsaws and harvesters that are commonly used in forestry, households, urban greenery, and roadworks all require the application of lubricants. Lubricant oil mist or droplets can infiltrate soils and groundwater, causing oxygen impermeability by clogging soil pores and crevices between soil particles, disrupting water infiltration, and contaminating water with just 1 ppm (part per million) of oil. Moreover, millions of liters of lubricants enter connected waterways and marine ecosystems annually through operational discharge, leakage, accidental spills, and vessel cleanings that initiate unknown pollution sprawls. Oil pollution in this way produces a petroleum film on water surfaces that disrupts gas exchange between the water and atmosphere, leading to oxygen starvation, reduced photosynthesis, increased temperatures, and adverse effects on microorganisms, aquatic plants, and deep-sea life.

Exacerbated situations include eutrophication, a phenomenon in which excessive nitrogen and phosphorus nutrients from oils proliferate sea life and lead to eventual oxygen shortages and dead zones, a problem applicable to many water reservoirs worldwide. Furthermore, petroleum compounds in lubricants degrade over time and undergo chemical transformations when exposed to environmental factors, yielding secondary chemicals that are more toxic than their predecessors. Thus, proper caution must be observed to avert oil mist penetration into human skin or airways which can cause hazards ranging from short-term irritation and allergic reactions to long-term skin cancer and adverse effects on respiratory tracts and the nervous system.[9]

Environmentally Acceptable Lubricants Classification and Applications

Recognizing the plethora of health alerts associated with conventional lubricants, the United States Environmental Protection Agency (US EPA) responded with a revised Vessel General Permit in 2013, mandating the use of EAL for all oil-to-water interfaces on vessels 79 feet or longer in U.S. coastal and inland waters.[11] The US EPA is currently in collaboration with the US Coast Guard to develop new national standards for commercial vessel incident discharges. The 2013 Vessel General Permit is in effect until new regulations anticipated in 2026 are enforceable.[12]

According to the US EPA, an EAL satisfies the criteria for biodegradability, minimal toxicity, and low bioaccumulation potential in marine vessels and machinery. EALs are formulated from three biodegradable oils that are low in toxicity: vegetable oils, synthetic esters, and polyalkylene glycols.

Common plants, such as canola, rapeseeds, and sunflowers, are used for extracting vegetable oils that contain natural esters called triglycerides. According to the US EPA, vegetable oils are commonly implemented as oil-based lubricants and comprise a small fraction of EALs due to their high-cost scarcity, low thermo-oxidative stability, and poor cold flow properties. Nonetheless, they find applications in hydraulic fluids and wire rope greases

and are deemed a promising source for biolubricants due to their high lubricity, high flash point, and extreme pressure endurance.

Conversely, synthetic ester-based lubricants, created through the esterification of modified animal fats and vegetable oils, have existed since the 1950s as jet engine lubricants, making them the oldest source of biolubricant production. The US EPA labels them as the most commercially available class of EALs due to their sheer malleability, functioning as hydraulic oils, thruster oils, and gear lubricants. Synthetic esters are known for their high viscosity index, corrosion protection, and high oxidative stability. However, they are less biodegradable than vegetable oil-based lubricants and are incompatible with certain paints and seal materials. Moreover, they are the most expensive alternative, costing two to three times more than mineral oil.

Finally, polyalkylene glycols (PAG) are created through the polymerization of either ethylene oxide or propylene oxide, which are soluble in water and oil, respectively. Despite their petroleum-based origins, the US EPA proclaims PAGs to be highly biodegradable, offering the best low and high-temperature viscosity performances and protection against wear and water ingress. PAGs are suitable as stern tube and thruster lubricants but are incompatible with mineral oils, paints, varnishes, and seals as well as having the highest changeover costs.

Besides base oil ramifications, manufacturers strive to use ashless or non-metal additives (other than Ca, Na, K, MG) and non-toxic additives alongside less toxic calcium-based soaps thickeners in EALs to lessen their environmental impact.[10]

Environmentally Acceptable Criteria

In accordance with the EPA, a lubricant is “environmentally acceptable” after passing standardized test methods in three parameters: biodegradability, aquatic toxicity, and bioaccumulation.

Common test methods for biodegradability are developed by the Organization for Economic Cooperation and Development (OECD), the Coordinating European Council (CEC), and the American Society for Testing and Materials (ASTM). Test methods OECD 301B and ASTM D-5864 set the threshold for readily biodegradable substances at 60% conversion to carbon dioxide within ten days of biodegradation initiation and 28 days after test initiation. On the other hand, CEC test methods

respective percentage of mineralization threshold or “pass level” for a substance to be considered readily biodegradable. According to the US EPA’s most current Vessel General Permit in 2013, oils must be at least 90% biodegradable and up to 5% non-biodegradable and non-bioaccumulative, with the remainder being inherently biodegradable. With greases, at least 75% must be biodegradable with up to 25% either inherently biodegradable or non-biodegradable and not bioaccumulative.[13]

Next, EALs must undergo aquatic toxicity testing, including OECD tests 201-204 and 209-212, to exemplify low toxicities to marine organisms in case of oil spills or pollution. Figure 2 lists all eight OECD tests with the most common procedures evaluating the 72-hour growth of algae (OECD 201), the 48-hour acute immobilization test for daphnia (OECD 202), and the 96-hour acute toxicity test for fish (OECD 203). Overall, vegetable oil and synthetic ester base oils exhibit lower toxicity levels at a Lethal Concentration 50 (LC50), the amount of chemicals needed to cause 50% mortality in test organisms, around 10,000 ppm for fish. Water-soluble PAGs, on the other hand, show increased toxicity towards marine animals by directly seeping into sediments and water columns rather than residing on water surfaces.

Finally, all lubricants have bioaccumulation potential or the possible accumulation of chemicals within organism tissue over time. Base oils in conventional lubricants contain 90% water-insoluble, lipophilic chemicals like alkanes that can withdraw from water bodies and enter fatty tissues, posing a high bioaccumulation risk and harming biological functions. Meanwhile, many natural base oils in lubricants consist of carboxylic acids that increase water solubility, degradation, and depuration rates within an organism, presenting themselves as favorable alternatives and key components in determining an EAL.

Two common bioaccumulation tests, OECD 117 and 107, observe the dissolution of a substance mixed with octanol and water via gas chromatography or infrared detectors and calculate the partition coefficient of octanol and water (Kow). Octanol exhibits fatty tissue-like properties and dissolves bioaccumulative chemicals more readily than water. Hence, a greater log Kow value implies a greater bioaccumulation potential in substances. Logarithms of partition coefficients for marine environments are measured on a scale of 0 to 6. Substances scoring log Kow < 3 are considered non-bioaccumulative while those whose log Kow > 3 are bioaccumulative. Despite these standard bioaccumulation tests, environmental variables, like lipophilic compounds’ reaction to seawater and freshwater, organisms’ metabolism of chemicals, and the substances’ intrinsic chemical nature, are equally important metrics that define an EAL.[10]

Sample #	Grease Composition	Penetration for the Unworked Grease, dmm	NLGI Grade	Penetration for the Worked Grease, dmm	NLGI Grade
Sunflower oil with cu 20% lithium stearate					
1	Simple	240	3	347	1
2	With 15% cellulose	204	4	329	1
3	With 15% lignin	188.5	4	329	1
Sunflower oil with cu 20% calcium stearate					
4	Simple	170	5	355	0
5	With 15% cellulose	165	5	348	1
6	With 15% lignin	160	5	353	1
Palm oil with cu 20% lithium stearate					
7	Simple	171	5	364	0
8	With 15% cellulose	154	5	342	1
9	With 15% lignin	184	4	324	1
Palm oil with cu 20% calcium stearate					
10	Simple	156	5	358	0
11	With 15% cellulose	117	6	316	1
12	With 15% lignin	184	4	315	1

Figure 3. Worked and Unworked Fried Sunflower and Palm Oil-based Greases Penetration Test Results[20]

assess biodegradability via levels of infrared absorbance of extractable lipophilic compounds, accounting for the overall biodegradability of a substance with at least 80% performance.

Figure 1 summarizes the frequently used test methods for ultimate biodegradability. Each test measures biodegradable activity via specific parameters, such as dissolved organic carbon (DOC), carbon dioxide (CO2), biochemical oxygen demand (BOD), and chemical oxygen demand (COD), and has a

Sample #	Grease Composition	Dropping Point, °C
Sunflower oil with cu 20% lithium stearate		
1	Simple	98
2	With 15% cellulose	101.5
3	With 15% lignin	101
Sunflower oil with cu 20% calcium stearate		
4	Simple	99
5	With 15% cellulose	100
6	With 15% lignin	91.5
Palm oil with cu 20% lithium stearate		
7	Simple	101
8	With 15% cellulose	102
9	With 15% lignin	102
Palm oil with cu 20% calcium stearate		
10	Simple	87.5
11	With 15% cellulose	100
12	With 15% lignin	104.5

Figure 4. Dropping Point Results of Grease Samples[20]

Sample #	Avg COF *	Avg Film (%) **	WSD (µm) ***
1	0.062	58	180.0
2	0.042	89	173.0
3	0.046	76	168.5
4	0.047	100	63.0
5	0.041	97	189.0
6	0.033	93	194.0
7	0.051	35	243.5
8	0.044	45	250.0
9	0.059	6	197.5
10	0.050	14	218.0
11	0.042	92	186.0
12	0.030	50	193.0

* Avg COF—average values for the coefficients of friction; ** Avg Film (%)—average values for the contact resistance of the grease film; *** WSD (µm)—wear scar diameters.

Figure 5. Mechanical Test Results of Grease Samples[20]

EAL Developments Within the Last Three Years:

1. Government-Funded Research

Since June 2024, the United States Department of Energy's Water Power Technologies Office (WPTO) has leveraged five million dollars to fund small business-led projects advancing EAL research in marine energy and hydropower and further promote commercialization.[14] Below are public updates on three projects that have received nearly \$1 million in funding to continue their Phase II research.[15]

a) RiKarbon

RiKarbon, a Delaware-based biotech company focused on manufacturing renewable products from unconventional carbon feedstock, is redesigning conventional poly-alpha-olefin (PAO) synthetic lubricants from petroleum feedstocks into a 100% bio-based EAL or BioLube, derived from agricultural wastes like corn stover and corn cobs. Their patent-pending technology creates PAO-like lubricants that satisfy petroleum standards and offer a favorable, lower viscosity index than conventional PAOs. Currently, RiKarbon is partnering with Pacific Northwest National Laboratory, Germany-based chemicals company BASF, and hydropower manufacturers to implement Phase II of their research development, which involves introducing BioLubes to hydropower facilities. Their goal is to transition agricultural waste-derived EALs into the global market while simultaneously combating climate change by reducing carbon emissions from conventional lubricant manufacturing and usage.[15][16]

b) Tetramer

Tetramer, a South Carolina-based advanced materials company specializing in converting lab researched materials into market or battlefield applications, aims to commercialize esterified propoxylated glycerol (EPG) as a bio-derived, biodegradable, non-toxic, and non-bioaccumulating base oil and EAL for hydroelectric applications. In Phase I of the research, EPG exhibited a unique low pour point value of -9oC that could endure extreme cold conditions, prepared a lubricant that outperformed the petroleum industry gold standard via a rig test conducted by GE Hydro Solutions Global Center for Excellence in Switzerland, and demonstrated potential large-scale production capacity with 750,000 gallons produced annually. Tetramer will proceed to Phase II of their project at Porjus Hydroelectric Power Station in Sweden with plans to develop various viscosity grade EALs, install facilities in the U.S., seek turbine original equipment manufacturer approvals, and conduct extensive tests on seals, paints, and oils in turbines.[15][17][18]

c) Polnox Corporation

Polnox Corporation, a Massachusetts-based organization centered on designing and commercializing industrial additives for lubricants, plastics, and other organic materials, is using its multifunctional, safer additive development technology to complement biodegradable oils in EALs. Their Mcln (multifunctional corrosion inhibitor) and DT-mPM (antioxidant) additive technologies can substitute four integral additives in EAL formations. In Phase I of their research, they successfully paired their multifunctional additives with biodegradable oil to create an EAL that met and exceeded the primary specifications set by the United States Army Corps of Engineers. During Phase II of their project, Polnox will continue to formulate and upscale EAL production for hydropower applications using their latest multifunctional additives development technology to ensure the safety of aquatic ecosystems and waterways.[15][19]

2. Fried Vegetable Oil-Derived EAL

A major concern with the usage of vegetable oils in EAL

production is the dedication of valuable farmland for cultivating feedstock. To avoid the allotment of agricultural land for vegetable oils in EAL production and prevent competition with food resources, Săpunaru et al. from the University of Constanta in Romania published their research on a modern, second-generation material to synthesize EALs in Lubricants, an international tribology journal. In 2024, the team acquired sunflower and palm oil waste from restaurants to develop

their own environmentally friendly greases and evaluated their consistencies, high-temperature stabilities, and contact resistances. The obtained fried sunflower and palm oils were filtered before adding stearic acid, 20 wt.% lithium or calcium soap, and 15 wt.% environmental-friendly cellulose or lignin additives/thickeners, thereby formulating an array of different grease samples. The grease samples were subjected to an ASTM 217-02 penetration test to assess consistency with values as summarized in Figure 3, where all worked greases displayed consistent penetration values of 320 dmm to 360 dmm. Greases containing cellulose or lignin additives were labeled as grade 1 (soft) while those without additives were categorized as grade 0 (very soft). Comparably, mineral oils with lithium soap fall within grades 1 to 2, portraying these fried vegetable oil-derived greases as having similar consistencies to commercialized greases.

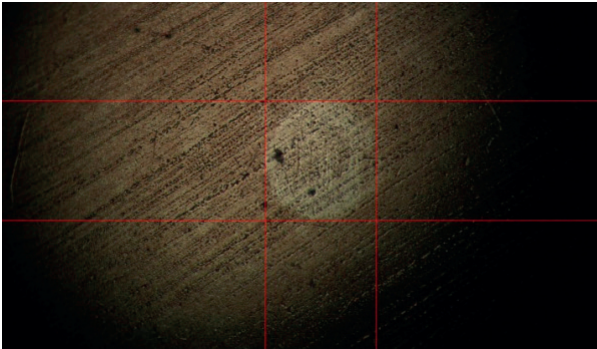


Figure 6. Wear Scar Diameter of a Sampled Grease after HFRR Analysis[20]

Next, dropping point tests were performed to test grease stability at high temperatures. Figure 4 displays the grease samples' dropping points ranging from 87.5oC to 104.5oC. Although this interval is rather low for mechanisms that deal with light loads, oil separation after a period of operation could be advantageous. Lastly, the grease samples underwent high-frequency reciprocating rig (HFRR) tests and wear scar microscopy to observe their contact resistance. Figure 5 summarizes the data obtained and parameters considered: average coefficient of friction, contact resistance, and wear scar diameter. The average coefficients of friction for all samples were calculated and varied from 0.030 to 0.062, but the range was comparative to that of commercialized mineral oil-based greases (0.030-0.060). The contact resistances of the grease films were vastly different, ranging from 6% to 100%, and indicated the soft consistency in fried-vegetable oil-based greases. Overall, sunflower oil-based greases were more resistant than those made from palm oil. Nearly all grease samples demonstrated low wear scar diameters ranging from 168.5 µm to 250 µm, indicating quality lubrication and displaying mechanical test data comparable to commercial soft greases (Figure 6). Ultimately, the best grease samples were sunflower oil-based with 20 wt.% calcium soaps with and without cellulose additives that offered consistency grades, thermal stability, and wear resistance standards on par with industry standards for light-load mechanisms. Still, further efforts are necessary to compete against the finest mineral oil-based lubricating greases.[20]

3. Nile Tilapia Fish Organs-Derived EAL

In 2018, the United Nations Food and Agriculture Organization recognized the Nile tilapia, seen in Figure 7, as the third most produced fish species in the world with 4.5 million tons produced and more than 100% growth over the last ten years. The increased consumption rate of tilapia leads to higher amounts of fish waste after filleting, as the waste totals more than 65% of the fish's original weight and 7% waste obtained from the viscera or internal organs alone. Tilapia waste is a valuable commodity since the extracted inedible oils can weigh up to 58% of the fish's mass and thus serves as viable sources for biolubricant production. In



Figure 7. Nile Tilapia[22]

2022, Moreira et al. from the Federal University of Ceará in Brazil attempted to modify tilapia oil extracted from the viscera and assess its lubrication properties via rheological tests, molecular dynamics simulations, and toxicity tests against Artemia salina, a saline shrimp species.

Figure 8 depicts the chemical process of transforming extracted tilapia oil into the esters trimethylolpropane (TMP) and pentaerythritol (PE) with conversion rates of 98.0% and 98.2%, respectively. These esters were then subjected to lubricant rheological tests to assess their flow characteristics. Both esters behaved as Newtonian liquids, characteristic in most lubricants, in which a fluid's viscosity is not affected by shear rate, at 40oC to 60oC and 20-1000s-1 shear range. Next, molecular dynamics simulations were used to validate the experimental ester synthesis and determine the physical properties of tilapia oil lubricants. The models displayed T-TMPE in a liquid state and T-PEE in a gel-like state, observations identical to the experimental products shown in Figure 9.

Finally, toxicity tests against A. salina were measured in LC50 with a toxicity threshold greater than 1000 ppm. In Figure 10, mineral oil displayed an LC50 of 335 ppm while T-TMPE and T-PEE presented LC50s of 2460 ppm and 2531 ppm, respectively, proving the non-toxicity of chemically modified tilapia oil that is almost eight times safer than mineral oil. The esterification of tilapia waste oil successfully portrayed lubricant-like properties with Newtonian fluid behavior at moderate temperatures and low toxicity rates with aquatic microorganisms, reaching rudimentary standards for the classification of an EAL and reinforcing its potential to become one. In addition, tilapia waste offers a resourceful, sustainable feedstock for EAL production that could be cost-efficient and highly productive on an industrial scale.[21]

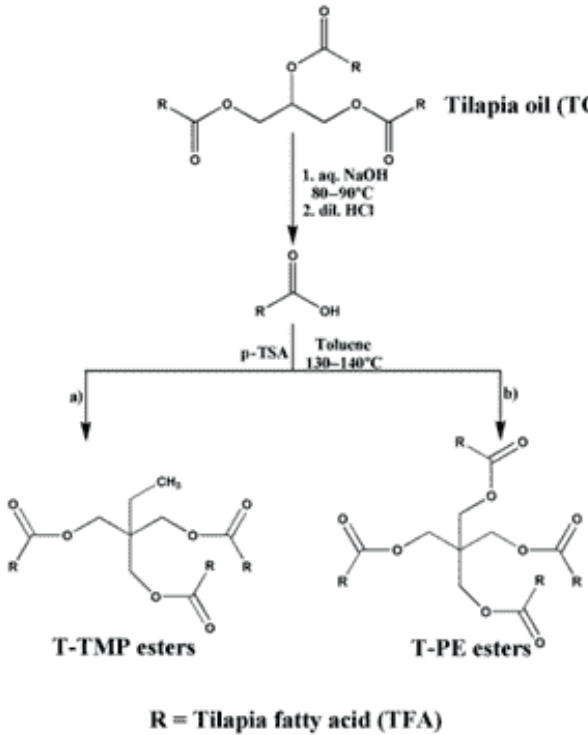


Figure 8. Chemical Process of Tilapia Oil Extracts to Trimethylolpropane (TMP) and Pentaerythritol (PE) Esters[21]

Conclusion

Whether it is the United States Department of Energy's multimillion projects with multifunctional additives technology and or research labs across the globe developing their own EALs using local fish and fried vegetable oil wastes, Environmentally Acceptable Lubricants are gaining popularity due to the foreseeable detrimental consequences of long-term production and applications of conventional lubricants. The transition to widespread EAL production is essential to protect ourselves,

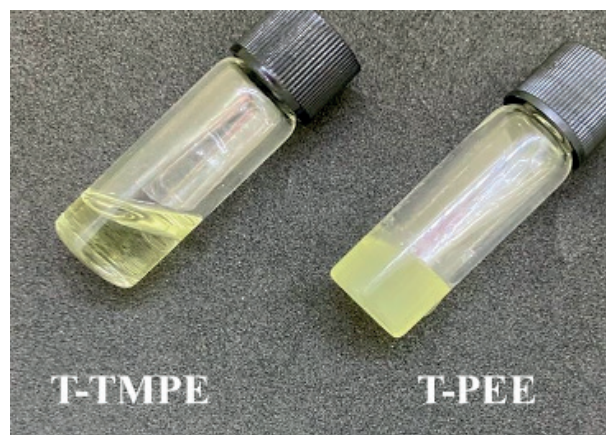


Figure 9. Experimental Trimethylolpropane (TMP) and Pentaerythritol (PE) Esters[21]

organisms, and the environment from irreversible damage and extinction. The implementation of a green lubricant demonstrates our appreciation for the natural assets granted to us and resolves our exploitation on natural capital. Although the journey from formulating a competing biolubricant that conforms with industrial standards to achieving large-scale production and commercialization is an arduous endeavor, modern research results suggest a promising future in creating safer, cleaner habitats for all its inhabitants.

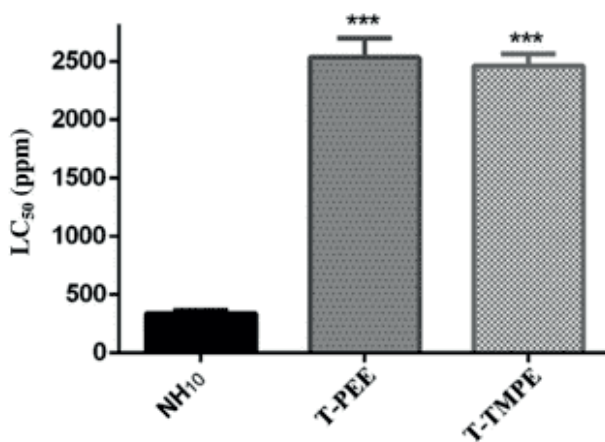


Figure 10. Comparative LC50 Levels in Mineral Oil, T-PEE, and T-TMPE[21]

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