Bio-based hydrocarbon and Gas-to-Liquid (GTL) insulating liquids for power transformers: A comprehensive review

ABSTRACT

The increasing global focus on environmental impact and sustainable development has generated a growing demand from materials and power equipment manufacturers and owners to make a positive contribution towards these aspects. In this regard, new insulating liquids such as Bio-based hydrocarbon and Gas-to-Liquid (GTL) insulating liquids have been analyzed in this study, considering their biodegradation rate and technical characteristics. Also, the possibility of reusing aged mineral oil is emphasized as this makes it possible to change unsustainable patterns of consumption and production, in close connection with the advantages offered by the circular economy and the efficient use of resources in a systemic, cyclical and prospective approach. Imperatively, the push to improve sustainability credentials does not signify compromising the functional properties of the insulating liquid. Therefore, this paper will not only play a significant role in assessing the impact of incorporating these dielectric insulating liquids into power transformers but also analyze the trade-offs in employing any of these insulating liquids. Furthermore, the extensive assessment of their properties is part of the broader initiative to support a transition towards environmental sustainability, safety, and reliability of high-voltage equipment.

KEYWORDS:

insulation fluids, bio-based hydrocarbon, gas-to-liquid, biodegradability

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The normal operational life of a power transformer spans approximately 40 years, ranging more precisely from 32 to 55 years, with a standard deviation of 8 years

Synthetic and natural esters have gained attention as more environmentally friendly insulating liquids because of their high biodegradability

1. Introduction

Power transformers play a crucial role in worldwide electrical energy transport and distribution networks, and failures in this power equipment have a significant economic impact on electrical grid operation [1]. Therefore, it is essential to ensure their efficient operation to optimize investments and reduce associated operational costs. For high-power applications, oil-immersed transformers are preferred over dry-type transformers because oil serves both as an insulating medium and as a heat transfer or cooling medium. More so, despite technical advancements in transformers over the past century to meet evolving needs, their future availability depends on non-renewable petroleum resources [2, 3]. The lifespan of a transformer is directly related to its insulation system's lifespan, with the hot spot's temperature being one of the primary factors affecting this insulation system's degradation [4]. For instance, a hot spot temperature of 110 (with a maximum ambient temperature of 30) is considered the normal operating value, and any persistent increase of 6-7 above this temperature reduces the insulation's lifespan by half [5, 6]. Given the increasing universal demand for electrical energy, there is a risk of transformers becoming overloaded and overheating, causing most transformers worldwide to near the end of their useful life [7]. Therefore, it is essential to find new solutions to improve the design of power transformers and, most importantly, to extend their useful lifespan [8, 9].

The normal operational life of a power transformer spans approximately 40 years, ranging more precisely from 32 to 55 years, with a standard deviation of 8 years [10, 11]. Insulation failure can cause the lifespan of a transformer to be reduced to just 17.8 years, which marks about 50% of its originally estimated operational life [12]. The prediction for the lifetime of transformer insulating liquid stands at 20.55 years, but adverse circumstances may reduce it to as low as 5.5 years [13]. Therefore, there is a need for continuous research into insulating liquids, focusing on their improvement, analysis, and potential alternatives as insulating liquid serves as the backbone of transformer insulation systems, and billions of litres are in use in power equipment worldwide [14]. In recent decades, material advancements have allowed transformers to become more compact by reducing insulation distances, which has led to greater electrical stresses and temperature differences. Consequently, new materials need to serve two critical functions, which are to provide electrical insulation and efficient cooling for transformers, especially in cases of reduced insulation distances and higher voltages [15].

Petroleum-based oil was adopted as an insulating liquid in oil-immersed transformers in the early 1890s, and it was reported that paraffin-based oil was utilized in 1899. This was substituted after 1925 with naphtha-based oil as it generated a significant quantity of insoluble sludge and exhibited a high pour point. Polychlorinated biphenyl (PCB) was introduced in 1930 to address the high flammability nature of naphtha-based oil. PCBs were recognized as hazardous to people, animals, and the environment, particularly due to the potential release of dioxins during incomplete combustion [16]. Silicon oil was employed in 1970 to overcome the non-biodegradable and highly toxic PCB [17]. However, non-toxic silicon oil has restricted availability

At present, most power transformers are approaching or surpassing 25-30 years of use and simply replacing them due to their age is neither economically feasible nor technically practical

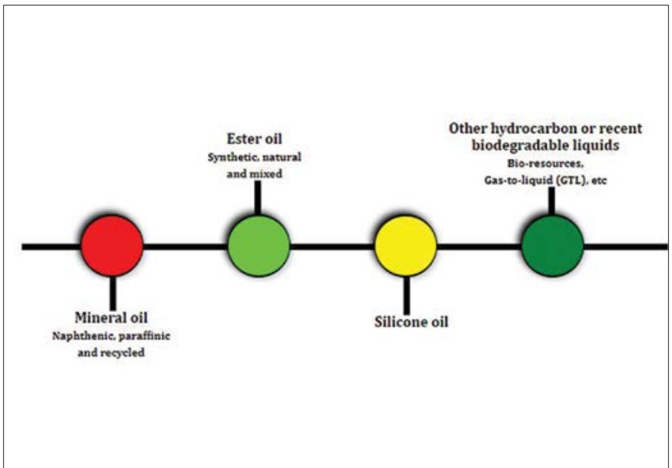


Figure 1. Overview of the currently available liquids

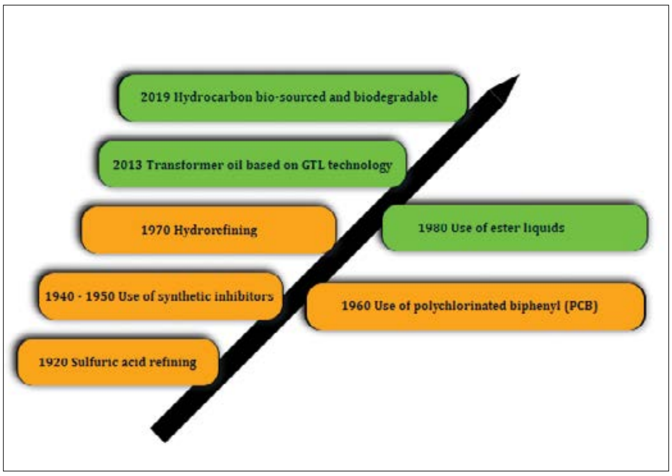


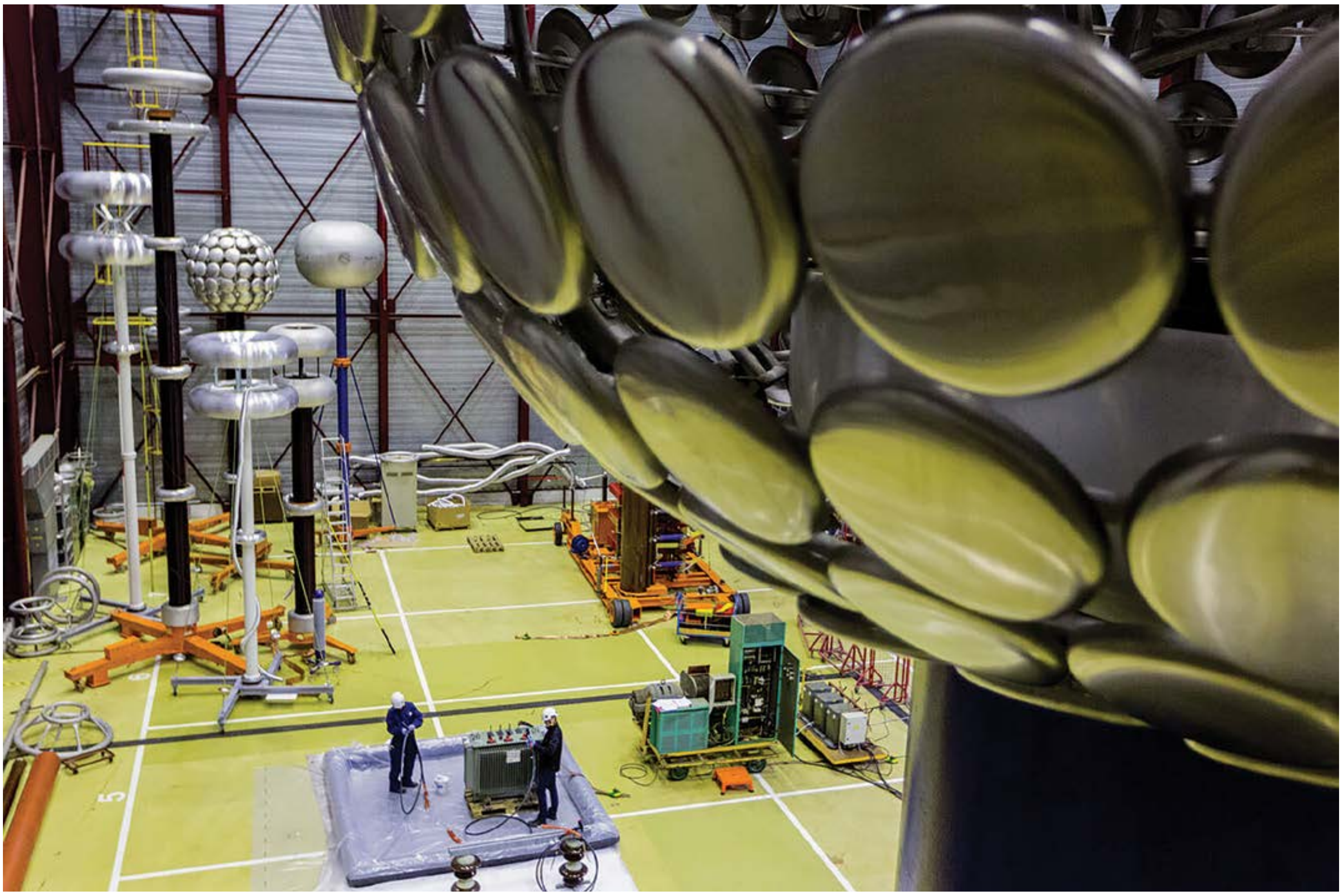
Figure 2. Evolution of insulating liquids for transformer

to transformer users due to economic considerations. Some acids and alcohols were synthesized in 1990 to produce synthetic ester oil which possesses a high fire point, high dielectric strength, high viscosity, and are readily biodegradable [18]. However, mineral oil remains the most commonly used insulating liquid, accounting for approximately 90 to 95% of global consumption in electrical power equipment. When this oil leaks, it causes an adverse impact on the surroundings as it has a very low biodegradation rate. Also, it has a low fire point and flash point that could lead to an increased fire risk for the power equipment [19, 20]. Therefore, synthetic and natural esters have gained attention as more environmentally friendly insulating liquids because of their high biodegradability. Synthetic esters are produced from chemicals that are quite expensive, and their content is questionable. Also, natural ester liquids cause remarkable decreases in the cooling efficiency of transformers, as they possess high viscosity and pour points [10, 21]. Furthermore, the oxidation stability of natural ester liquid is poor, and it is more prominent in unsaturated esters than saturated ester liquids [22, 23]. This led to the advent of some alternative liquids, such as bio-based hydrocarbon and gas-to-liquid insulating oil, which can contribute to improving and overcoming these drawbacks. These liquids exhibit good thermal properties such as low viscosity and have a high biodegradation rate [10, 21, 24]. Figures 1 and 2 show the insulating liquids used in electrotechnics and the evolution of hydrocarbon oil for power transformers, respectively [25].

Bio-based hydrocarbon liquid is a bio-based insulating oil product containing material from a biological source, such as residues and byproducts, which are mainly plants

At present, most power transformers are approaching or surpassing 25-30 years of use. Simply replacing them due to their age is neither economically feasible nor technically practical. Therefore, the primary goal of power transformer owners is to explore solutions to extend their lifespan without compromising on reliability while reducing operating costs and improving the electrical insulation system to optimize safety factors. Furthermore,

The Gas-to-liquid isoparaffinic technology is a newly proposed insulating liquid derived from natural gas instead of crude oil and is compatible with dissolved gas analysis tools



Insulating liquid experiences oxidative deterioration in the presence of oxygen to produce several oxidation contaminants, which can be mitigated using oil additives in breathing units

by 2050, the world population has been projected to increase from 8 billion to 9.7 billion [26]. Likewise, the percentage of people living in the cities and the energy demand are expected to increase by 68% and 47%, respectively [27, 28]. Therefore, our study is carried out with this perspective in mind, namely, achieving net zero CO_2 emission. Also, this comprehensive review elaborates on the state-of-the-art knowledge regarding the essential characteristics of transformer insulating liquid. We conducted a comparative literature review on new bio-based hydrocarbon and GTL oils to achieve this.

2. Bio-based hydrocarbon and GTL oils

2.1. Bio-based hydrocarbon oil

Bio-based hydrocarbon liquids are the recent type of insulating liquids based on bio-based feedstock [29] that is easily biodegradable [30, 31]. They have a very low viscosity, which could be beneficial to improving the power transformer's thermal behaviour [30, 32]. The liquids are said to have similarities with hydrocarbon-containing non-aromatic components, which are in line with the IEC 60296 standards, and their renewability and biodegradability are confirmed according to OECD 301 specifications [31, 32]. Their biodegradability, carbon content, recyclability, and eco-toxicity are important physicochemical parameters that need to be studied to determine these insulating liquids' environmental friendliness and sustainability. Bio-based hydrocarbon liquid is a bio-based insulating oil product containing material from a biological source, such as residues and byproducts, which are mainly plants [33]. It is generated using intense hydro-processing together with isomerization. The insulating liquid is a hydrocarbon with non-toxic components that have an approximately low molecular weight relative to petroleum-based model mineral oil [34]. This liquid enhances the cooling ability of the transformer windings, as it possesses a very low viscosity value, which could improve the transformer cooling properties. It is also biodegradable with improved oxidative stability [33], since it is mainly hydrocarbons with a relatively low molecular weight [30].

2.2. GTL isoparaffinic liquid

The Gas-to-liquid (GTL) isoparaffinic technology is a newly proposed insulating liquid derived from natural gas instead of crude oil, with a more uniform chemical structure, high resistance to oxidation and very low sulphur content of less than 1 ppm, which helps prevent copper and silver corrosion in oil-immersed transformers [35]. This liquid lacks aromatic molecules and complies with IEC 60296 standards, having low viscosity and pour points that could improve the cooling properties, even during cold startups [34]. This gas-to-liquid insulating liquid is collected from natural gas (methane), with hydrocarbon being the base oil that is majorly saturated iso-paraffinic. It has fewer impurities than mineral oil and is compatible with dissolved gas analysis (DGA) tools as it produces gases similar to traditional transformer-insulating liquids [36]. GTL can come in different varieties, and it could be readily biodegradable or a high-performance inhibited liquid [37]. GTL is produced using the Fisher-Tropsch process considering three-stage procedures, where natural gas is transformed into liquid and solid hydrocarbons with high purity or through direct partial combustion of methane to methanol [38]. The Fischer-Tropsch (F-T) process, illustrated in Figure 3, is the most widely used technology today. At first, methane reacts with oxygen to produce synthesis gas, a mixture of hydrogen and carbon monoxide. Subsequently, the resulting gas is catalytically transformed into wax through the F-T process. This wax hydrocarbon is then refined with new catalysts, which are distilled into a variety of products using a standardized technique. Therefore, this process ascertains that saturated paraffins are only the hydrocarbon produced as the liquid base component is mainly hydrogen and carbon [37, 39]. A GTL insulating liquid

Table 1. Beneficial prospects of GTL

Liquid	Benefits
GTL iso-paraffinic oil	- Sulphur free - Reduced aromatic content - Recyclable - Lower density - Robust compatibility - inherently biodegradable - Arctic applications - Readily biodegradable

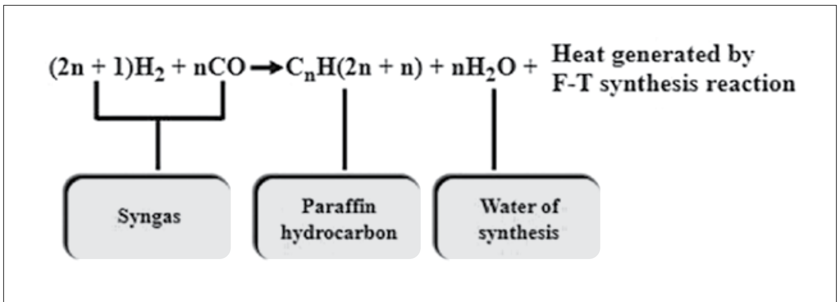


Figure 3. Fischer-Tropsch reaction process [41]

was reported to have enhanced low-temperature fluidity. This liquid is 7.3 to 8.5% less dense relative to traditional oil with a pour point less than -42°C to -48°C with a viscosity lower than 253 mm^2s^{-1} -381 mm^2s^{-1} and 1000 mm^2s^{-1}-1157 mm^2s^{-1} at -30°C and -40°C respectively [36]. Table 1 gives some of the benefits of GTL as an insulating liquid for power transformers [36, 40].

Bio-based hydrocarbon oil exhibits significantly lower viscosity compared to mineral oil, natural ester, and synthetic ester, making it suitable for low-temperature applications

3. Oil additives

Insulating liquid experiences oxidative deterioration in the presence of oxygen to produce several oxidation contaminants, such as acid and sludge, that can reduce the performance of the insulating liquid, thereby leading to the accelerated degradation of the power equipment insulation system. Therefore, oxidation inhibitors (antioxidants) are used to mitigate this oxidation reaction, which helps to prolong the life of the insulating liquid. The primary operational mechanisms of these antioxidants involve the scavenging of free electrons, synergistic actions, and chelation of metals [42]. Also, maintaining the optimal concentration level of inhibitors is crucial to guarantee the effective performance of insulating liquid within transformer units, whether serving as an insulating or cooling agent. Common inhibitors that are used as antioxidants are 2,6-di-tertiary-butyl-para-cresol (DBPC), 2,6-di-tertiary-butylphenol (DBP), ascorbic acid (AA), propyl gallate (PG), butylated hydroxytoluene (BHT), alpha-tocopherol (α-T) butylated hydroxy anisole (BHA) and citric acid (CA) [43-45]. According to their source and mechanisms, they can be classified into three groups, as shown in Table 2. Therefore, the optimal efficiency of antioxidants can only be achieved by employing the combination of three or more antioxidants with different classes and mechanisms [42, 45, 46]. It was reported in [46, 47] that reclamation of aged service insulating liquid without the addition of an inhibitor may experience a short post-reclamation lifespan based on the oxidation level of the liquid. Therefore, reclaimed insulating liquid should be treated with an inhibitor and its content should be kept between the range of 0.25% to 0.3% by weight of the inhibitor. Furthermore, the rate at which inhibitors deplete the oil depends on several factors, including oxygen levels, soluble contaminants, catalytic agents and temperature. Consequently, routine testing of inhibitors in electrical insulating liquid is important to ensure the dependable functioning of high-value assets like transformer units. The use of infrared spectroscopy (IR) and gas chromatography-mass spectroscopy (GC-MS) technology can be employed to monitor and measure the concentration of these additives in the insulating liquid according to IEC 60666 and ASTM 2668 [48-50].

4. Characteristics of GTL and bio-based hydrocarbon

4.1. Bio-based hydrocarbon

Viscosity: The cooling properties of bio-based hydrocarbon oil (BBHO) were examined in [51] by measuring the viscosity of the insulating liquid at 40 per ASTM D7042 standard. The viscosity measured was compared to that of standard non-inhibited mineral oil (NMO), soybean-based natural ester (SNE), and pentaerythritol synthetic ester (PSE). The result of the study shows that the viscosity of bio-based hydrocarbon oil is lower relative to its counterpart, with decrements of 59.3%, 88.4%, and 87.2% observed in NMO, SNE, and PSE, respectively. The kinematic viscosity of bio-based hydrocarbon oil was measured in centistoke at a temperature of 20°C, 40°C and 100°C in [52]. It was reported that the kinematic viscosity of bio-based hydrocarbon oil decreases over the mineral oil by 70.3%,

The activation energy of bio-based hydrocarbon oil-impregnated insulation shows a marked improvement over synthetic ester and mineral oil, enhancing its dielectric properties

Table 2. Mechanisms, classes, and functions of some antioxidants

Mechanisms		Classes		Functions
	Natural	Synthetic	Secondary	
Free radical scavenging	-	DBPC, BHA, BHT, PG, DBP	-	Delay of electrons, trapping of electrons
Metal chelation	-	BHA, BHT, PG	-	Increase induction period, decrease maximum oxidation rate
Synergism	α-T	-	AA and CA	Improved the performance of other antioxidants

Bio-based hydrocarbon oil demonstrates superior dielectric performance and breakdown voltage compared to conventional insulating oils, attributed to the absence of aromatic hydrocarbons

60.6%, and 41.2% at 20°C, 40°C, and 100°C respectively, it decreases over soybean ester by 91.6%, 89.2%, and 82% at 20°C, 40°C, and 100°C respectively, and decreases over synthetic ester by 91.8%, 87.2%, and 72.8% at 20°C, 40°C, and 100°C respectively. The thermal properties of four insulating liquids (mineral oil, bio-based hydrocarbon oil, synthetic ester and natural ester) were analyzed under different climate conditions of -10°C, 20°C, and 30°C in [53]. It was reported that bio-based hydrocarbon insulating liquid exhibits the lowest temperature for both HV and LV windings. This is a result of the high specific heat capacity and low viscosity of the bio-based hydrocarbon oil relative to other coolants used. Also, at 30°C, all the coolants have close winding temperatures except the bio-based hydrocarbon. This confirms that bio-based hydrocarbon insulating liquid is more suitable for use in low-temperature regions.

Activation energy: In [54], the activation energy from the DC conductivity of a bio-based hydrocarbon oil-impregnated pressboard insulation was measured and determined from the Arrhenius plot of the sample. The result obtained was compared with the activation energy of the pressboard impregnated with synthetic ester and mineral oil. From their results, the activation energy of the bio-based hydrocarbon oil-impregnated pressboard insulation had the highest activation energy, with 56.4% and 8.4% improvement observed over the pressboard impregnated in synthetic ester and mineral oil, respectively.

Dielectric dissipation factor: In [55], the dielectric dissipation factor of bio-based hydrocarbon and synthetic ester was tested in four different transformer types. The dissipation factor was measured per IEC 61869, IEC 60076, IEEE C57.13, and IEEE C57.12.00 specifications. It was reported that the bio-based hydrocarbon liquid has a lower dielectric dissipation factor than the synthetic ester in all the transformer types used. Also, the dielectric dissipation factor of bio-based hydrocarbon oil and inhibited mineral oil was measured with and without impregnated insulating pressboard [56]. The result of the study indicates that the dissipation factor in bio-based hydrocarbon oil without and with impregnation is decreased by 33.3% and 16.7%, respectively, relative to inhibited mineral oil. Furthermore, the dielectric constant of bio-based hydrocarbon oil was measured at 90°C according to IEC 60247 in [51]. The result shows that the dielectric constant of the bio-based hydrocarbon oil, which is measured to be 1.99, is the lowest among other insulating liquids utilized.

Breakdown voltage: In [56], the AC breakdown voltage of bio-based hydrocarbon oil was measured and compared with inhibited mineral oil with and without impregnated insulating pressboard. The results indicate that the breakdown voltage of bio-based hydrocarbon oil before and after impregnation is improved over the mineral oil by 5.2% and 2.3%, respectively. The work in [57] reported that the breakdown voltage of bio-based hydrocarbon oil measured per IEC 60156 standard is 12.7% and 29.2% above the mineral oil and natural ester (NE) used, respectively. Furthermore, the compatibility of bio-based hydrocarbon oil with an electro-technical pressboard containing 4% water content by weight was examined in this study. According to the authors, the enhanced dielectric performance of bio-based hydrocarbon over conventional mineral oil can be a result of the absence of aromatic hydrocarbon that is known to initiate the propagation of streamers.

Lightning impulse breakdown voltage (LIBV): The lightning impulse breakdown voltage of mineral oil (MO), synthetic ester (SE), and bio-based hydrocarbon was measured in [58] under negative polarity. In this work, the mineral oil was taken as a standard for the other two liquids due to its known specifications. The mean LIBV of bio-based hydrocarbon oil and synthetic ester is 2% and 15% less than the standard value of LIBV for mineral oil, respectively. Also, a research group measured the lightning impulse breakdown voltage of bio-based hydrocarbon liquid and three other types of insulating liquids in [31] under positive polarity. The measurement was done according to IEC 60897 for 25 mm and 40 mm point-to-sphere electrode gaps. It was analyzed that the behaviour of bio-based hydrocarbon oil is close to the mineral oil used, as they are both hydrocarbon-based liquids. Furthermore, a different observation, which can be seen in [59], was reported for bio-based hydrocarbon oil under negative polarity. In [55], the LIBV of the two bio-degradable liquids was measured. According to the study, the observed LIBV in bio-based hydrocarbon oil is 8.1% higher relative to the LIBV in the synthetic ester. Bio-based hydrocarbon liquid performances are summarized and compared in Table 3 relative to some conventional insulating oils.

During ageing, GTL oil demonstrates slower reduction in interfacial tension than mineral oil, indicating better resistance to paper deterioration and oil oxidation, which enhances its cooling performance in power transformers

4.2. GTL liquids

Interfacial tension: The interfacial tension of GTL and mineral oil with impregnated insulating paper was compared and analyzed in [60]. It was observed that the interfacial tension in GTL is higher than in mineral oil. This implies that products of paper deterioration and oil oxidation are more available in mineral oil. There-

Table 3. Summary of some bio-based hydrocarbon characteristics compared to different liquids

Reference	Properties	Insulating liquid	Compared liquid	Standard	Optimal performance
[51]	Viscosity	Bio-based hydrocarbon oil	NMO, SNE, PSE	ASTM D7042	-59.8% of NMO, -88.4% over SNE, and -87.2% over PSE
[52]			MO, SE	Not stated	-89.2% over MO, and -87.2% over SE at 40°C
[56]	Dielectric dissipation factor		MO + pressboard	Not stated	-33% over MO, and -16.7% over MO+paper
	AC Breakdown voltage			IEC 60156	+5.2% over MO, and +2.3% over MO+paper
[57]			MO, NE	IEC 60156	+12.7% over MO and 29.2% over NE
[55]	Lightning breakdown voltage		SE	IEC 60897	+8.1% over SE

The breakdown voltage of GTL oil shows greater stability and resilience under thermal ageing compared to mineral oil, with significant improvements observed after prolonged exposure

fore, lesser force is needed to break the interface of mineral oil as the insulating liquid strength has been debilitated, resulting in reduced interfacial tension in the liquid. It was noted that low interfacial tension diminishes insulating liquid cooling performance in power transformers.

Dielectric dissipation factor: In [61], the author reported that the dielectric dissipation factor of impregnated Kraft paper in GTL and mineral oils has similar characteristics. Furthermore, the dielectric dissipation factor of mineral oil and GTL subjected to accelerated thermal ageing at 120°C for 3 to 10 days is measured according to IEC 60247 standard in [40] by utilizing a Keysight E4980A precision LCR meter.

In this study, it was reported that the dielectric dissipation factor of mineral oil increases with ageing relative to the pristine sample, while the dielectric dissipation factor of GTL initially decreases relative to the pristine sample and remains unaffected till 6 days of ageing, but a further decrease was observed in the 10 days aged sample. The stable dielectric dissipation factor experienced in GTL up until 6 days may be a result of lower generation and accumulation of aged byproducts in the insulating liquid.

Breakdown voltage: In [60], the breakdown voltage of mineral oil and GTL with impregnated insulating paper was compared and analysed. It was reported that the breakdown voltage of the mineral oil increased only by approximately 0.7% over the GTL, which is considered an insignificant increase. Also, the breakdown voltage of mineral oil and GTL was measured per IEC 60156 standard under accelerated thermal ageing in [40] by utilizing Model BAUR DTA 100 C automatic oil tester. According to the authors, it was reported that the mean breakdown voltage of mineral oil decreases consistently with ageing relative to the pristine oil sample, while the mean breakdown voltage of GTL decreased during the first 3 to 6 days, after which it starts increasing after 10 days. The decrease of GTL relative to the pristine sample can be a result of the presence of moisture in the sample which gradually evaporate as ageing period increases leading to increase in the breakdown voltage of GTL after 10 days.

Lightning impulse breakdown voltage (LIBV): In [37], the lightning impulse breakdown voltage of two GTL oils (Biodegradable and non-biodegradable) was analysed for negative polarity. The study compares their LIBV with three other mineral oil-based insulating liquids produced by the same manufacturer. The authors employed a point-to-sphere electrode system with a gap of 25 mm, according to IEC 60897. Their result shows that the LIBV voltage of the biodegradable GTL is greater than the non-biodegradable one and other mineral-based insulating liquids used except for one of the mineral oils with a difference LIBV of only 6 kV. In addition, GTL's low sulphur content and its miscibility ability are factors that constitute a potential advantage over mineral oil. Similarly, the LIBV of six samples (consisting of inhibited and uninhibited

GTL oil outperforms mineral oil in lightning impulse breakdown voltage, attributed to its low aromatic content, which reduces the risk of streamer propagation

Transformer insulating liquids are experiencing a rapid progressive move towards more sustainable and environmentally friendly alternatives

GTL and mineral oil) were measured under positive polarity in [62]. The samples show a close range of LIBV except for the inhibited GTL, which displays a low value. This was reported to be a result of an absence of aromatic hydrocarbon in its composition. Also, the lightning impulse breakdown voltage (LIBV) of GTL was measured under positive and negative polarity in [63] and compared with conventional mineral oil. It was reported that the LIBV of GTL is greater than that of the mineral oil, with an improvement of 23% and 36% under positive polarity and negative polarity, respectively. This observation was explained to be a result of GTL having a very low aromatic component, as aromatic molecules are said to possess low ionization energy that enhances the propagation of positive streamer.

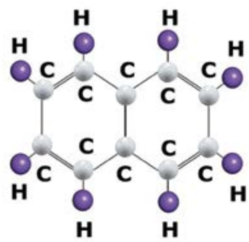
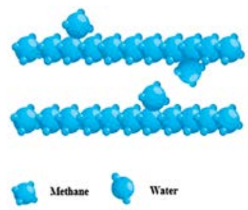
Partial discharges: In [64], the partial discharges of GTL were observed to be greater than that of synthetic ester. It was reported that the maximum electric field strength takes place in synthetic ester and GTL at different locations. The distribution of electric field strength in GTL is uniform between the insulating liquid and the paper layer. Likewise, the electric field strength in synthetic ester at the point where the transition occurs from paper to liquid is significantly lower than that at the inner layer of the paper winding. It was said that the different dielectric constants of GTL and synthetic ester are the reason for this observation.

Bio-based hydrocarbon liquids have promising properties when compared to conventional solutions, mainly due to very low viscosity, which could significantly improve their cooling properties

5. Comparison with conventional oils

Transformer insulating liquids are experiencing a rapid progressive move towards more sustainable and environmentally friendly alternatives. Conventional mineral oils, widely employed by many, are now facing challenges from insulating liquids like bio-based hydrocarbon and GTL oils that are obtained from different sources to meet the rapidly evolving demands, including environmental requirements. Table 4 presents some comparisons of bio-based and GTL liquids aiming to spell out their types, origins, characteristics, compositions, means of production, and chemical formulations [14, 51, 65-68]. Furthermore, Tables 5 and 6 show the use trend of these insulating liquids in transformers and some of the important properties of insulating liquids based on performance, respectively.

Table 4. Comparison of bio-based hydrocarbon and GTL insulating liquids with conventional mineral oil

Insulating liquid	Type	Origin	Characteristics	Composition	Mean of production	Chemical formulation
Mineral oil	Refined crude oil	Crude petroleum oil distillation	Clean, bright, colourless	Straight and branched alkanes, cyclic paraffin, and aromatic hydrocarbon	Distillation	
Bio-based hydrocarbon	Pyrolyzed biomass	Bio-based feedstock	Readily biodegradable, clear, free from sediment, yellow/amber	Hydrotreated bio-hydrocarbon	Catalytic cracking	Not available
GTL	Refined natural gas	Natural gas or gaseous hydrocarbons (methane)	Readily biodegradable, clean, odourless, and colourless	Natural gas, coal, and biomass	Fisher-Tropsch process	

Even though the price of new insulating liquids is high, it may be balanced by long-term savings due to the attractive environmental and technical properties

6. Challenge for alternative solutions

The findings presented in this paper show that bio-based hydrocarbon liquids have promising properties when compared to conventional solutions. These are mainly attributed to the liquid having very low viscosity, which could significantly improve its cooling properties. Furthermore, it has a high biodegradation rate, is recyclable and has a reduced carbon footprint compared to mineral oil derived from crude oil. However, to advance in the full adoption of these new insulating liquids, especially in large power transformers, researchers must focus on using advanced observation techniques and parameter measurement to improve the chemical, physical, and dielectric characteristics of these new insulating liquids. Therefore, extensive studies should be conducted to check the ability of new oils to function properly with materials in transformers such as cellulose, gasket, paints or other materials that influence the lifespan of the liquid and the transformers. Additionally, the focus should be on accelerated ageing insulation systems involving these liquids to evaluate their performance under severe conditions, thus providing insight into their evolutionary performance.

Table 5. The use trend of insulating liquids in transformers version 2022 [69, 70]

Kind of transformer	Mineral Oil	Bio-based hydrocarbon	GTL Biodegradable
Power	Generally used	Rarely used	Rarely used
Traction	Rarely used	Not currently used	Not currently used
Distribution	Generally used	Rarely used	Rarely used
Instrumentation	Generally used	Not currently used	Rarely used

Note: This may not cover all potential uses as it is only based on known applications documented in the literature

Table 6. Outline of some important properties of insulating liquids based on performance

Insulating liquid	Mineral Oil	GTL (BD)	Bio-based hydrocarbon
Low temperature	Good	Good	Good
Eco-friendly	Bad	Good	Good
Water resistance	Bad	Medium	Good
Oxidation stability	Medium	Good	Good
Fire safety	Bad	Good	Good

represents good   represents medium   represents bad

In terms of market acceptance, customers are inclined to opt for new insulating liquids over conventional mineral oil primarily when they offer a cost-effective advantage. Although the initially higher purchase price of these new insulating liquids may discourage potential buyers, this may be balanced in theory by the long-term savings on energy expenses due to the promising environmental and physicochemical properties of these new insulating liquids. However, these benefits need to be practically demonstrated to convince transformer users and manufacturers to adopt these alternative solutions.

Although oil additives are primarily employed to enhance the oxidation stability of insulating liquids, they undergo depletion over time. Therefore, it is imperative to meticulously monitor them closely as they can inadvertently stimulate the formation of insoluble deposits, thereby accelerating insulation degradation and corrosion. Consequently, alternative techniques beyond the ASTM and IEC methods (expensive and tedious) may be developed that will potentially harness higher wavelengths to facilitate early detection of inhibitor depletion. Furthermore, the conventional techniques for detecting inhibitor content in the insulating liquid need to undergo validation when applied to these new insulating liquids. It is pertinent to ascertain whether these techniques are suitable for adoption as an international standard method or if new techniques should be considered.

7. Conclusion

Without compromising the technical and thermal facets of oil-immersed transformers, sustainability and environmental considerations are a major concern to engineers and researchers as the most widely used mineral oil is produced from non-renewal fossil resources. The development of vegetable oil, which is renewable and biodegradable, seems to be the most achievable solution. However, the presence of free fatty acid in the liquid leads to an increase in viscosity and tends to have a high pour point, making them unsuitable for low-climate regions. Therefore, a new bio-based hydrocarbon liquid and mineral oil derived from GTL technology has recently entered the market. These insulating liquids have a good biodegradation rate and oxidation stability, with attractive carbon footprint measured from their carbon (IV)oxide equivalent emission and high Grashof number, which enable them to be suitable as a natural convective coolant.

However, in terms of market acceptance and massive adoption of these liquids, transformer manufacturers and owners are inclined to opt for new solutions primarily when they offer cost-effectiveness. Even though the initially higher purchase price may discourage potential buyers, this may be balanced in theory by the long-term savings due to the attractive environmental and technical properties of these liquids. In this regard, this trade-off needs to be practically demonstrated to convince transformer users and manufacturers. Furthermore, an extensive study should be conducted to evaluate the ability of these insulating liquids to operate effectively without adversely affecting the short and long-term reliability of power transformers.

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