

Review

Electrifying the Future: Second- and Third-Generation Derived Oils for Transformers

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Abstract

The reliability of power transmission and distribution depends on the proper functioning of power transformers, which use conventional mineral oil as an insulating fluid. The lower fire class and biodegradability of mineral oil have led to a shift towards second-generation oils from vegetable and plant crops. Ester fluids provide a better performance in combination with solid pressboard/paper insulation, increasing the lifetime of power transformers compared to those using mineral oil. Considering the need for sustainability in the near future, second-generation oils are no longer feasible, and hence, third-generation oils derived from microalgae species are suitable alternative fuels for the energy sector. The fatty acid methyl ester (FAME) content of algae is similar to that of biodiesel, making it a suitable fluid for power transformers. A detailed overview of third-generation feedstock (algae) for power transformer applications is provided, focusing on the extraction of algal oil, in conjunction with safety precautions and its fatty acid content, and a comparison with conventional vegetable and plant-based oils is presented. Various properties of algal oil (fatty acid composition, kinematic viscosity, oxidation stability, breakdown voltage, etc.) are analyzed to assess its suitability as a transformer fluid. This review article comprehensively analyzes the current research landscape surrounding the use of algal oil as an insulating fluid in transformers. It critically evaluates both the potential advantages and the unique challenges associated with this alternative to conventional mineral oil and second-generation vegetable and plant-based oils.

Keywords: transformers; biofuels; biodegradability; static charges; partial discharge; sustainability



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1. Introduction

Transformers form a major utility in the power system network, connecting transmission and distribution lines, and the reliability of electric supply in the network depends on their insulation [1]. Power transformers with higher ratings are mostly liquid-immersed, with an insulating fluid used as a coolant, combined with solid pressboard insulation to provide mechanical support to the winding conductor [2]. Most power transformers near coal-fired power plants are liquid-immersed and use different insulating fluids. The geological storage process is where carbon capture and storage (CCS) technology poses the most concern regarding possible environmental problems [3,4]. Because so much CO₂ will be

injected and kept underground for hundreds of years, storage locations must be extremely safe. An essential early warning system for the safety of oil field operations is corrosion monitoring. In order to evaluate the corrosion risk of important pipelines and equipment, including oilfield production systems, which are now a requirement for oilfield production, a variety of corrosion-monitoring techniques are frequently employed [5]. Since the early 1950s, there have been different insulating fluids tested for transformer applications, which include polychlorinated biphenyl (PCB), silicone oil (SO) and mineral oil (MO). Because of the risks associated with PCB discharge into the environment and its long-lasting adhesion to soil, it was outlawed for use in many applications in 1979 [6]. The methyl group in SO determines its viscosity, and it also results in a polymerization reaction during partial discharge (PD) activity, which limits its use to equipment operating below the inception voltage [7]. Due to the drawbacks associated with PCB and SO, MO has been in use for power transformers for the past 70 years. The MO produced through the distillation and refinement of crude petroleum consists of saturated and aromatic hydrocarbons [8]. MOs are complex mixtures of hundreds of distinct chemical components, primarily carbon and hydrogen in variously structured molecules. A portion of the hydrocarbons gathered during the distillation of petroleum crude stock are refined to create them. There are three different categories of crude oil, namely, paraffinic, naphthenic and mixed crude oils. Paraffinic oils contain small amounts of naphthenic hydrocarbons, which can be classified into normal paraffins and isoparaffins, the latter of which are mostly preferred due to their low pour points. Naphthenic oils have more naphthenic compounds than the paraffinic crudes, while mixed crude oils are intermediate between paraffinic and naphthenic compounds [9]. Compared to naphthenic-based transformer oil, paraffin-based transformer oil has superior density and antioxidation stability. Nevertheless, naphthenic-based oil has better low-temperature characteristics, respectable amounts of alkanes, cycloalkanes, and arenes, and a low wax content (usually less than 3%), and does not require a difficult, costly dewaxing procedure. Therefore, naphthenic-based crude oil has been the primary source of refinement for transformer insulating oil [10]. MO containing aromatic hydrocarbons provides a higher breakdown resistance to impulse voltages [8], whereas its lower biodegradability and flash point [11] are major disadvantages for power transformers. Furthermore, the sulfur compounds in MO lead to copper sulfide formation in the pressboard insulation and winding conductors [12], which then causes overall failure of transformer insulation. Aromatic hydrocarbons such as alkylbenzenes, polyarylalcanes and phthalates are used in capacitors and cables, per the technical specifications in IEC 60867. These insulating liquids also possess the disadvantages of lower-fire-class properties and non-biodegradability in nature. Hence, circumstances have led insulation engineers to focus on alternate dielectric fluids suitable for transformers.

The superior environmental characteristics of ester fluid (EF) over MO [10] have led to its application to transformers since 1998, and its behaviour under electrical and thermal loading conditions [13] has been the subject of ongoing research on a global scale. Synthetic esters are a large class of chemical compounds that are made from alcohols and organic acids. These liquids are designed to withstand oxidation and can absorb a lot more moisture than mineral oils before their effectiveness as insulants declines drastically. Vegetable oils are easily accessible natural ingredients; they should be regarded as the perfect starting point for completely biodegradable insulating liquids. Triglycerides, which are naturally produced by esterifying tri-alcohol glycerol with three fatty acids, make up their essential components. The fluids from various edible and non-edible crops are commissioned for transformers at both distribution and transmission levels [14]. Of the global oil produced from different crops in 2018 [15], the production of oil from palm, soyabean, sunflower and rapeseed accounted for a significant percentage compared to

other crops. EFs are in a better thermal class, which makes them a feasible choice for implementing near a utility, per the National Electrical Code (NFPA 70), which has added advantages of requiring less space and shorter cable length [16]. EFs are appropriate for non-breathing transformers due to their hygroscopic nature, which should be considered when making decisions about storage and handling issues [17]. Arief et al. [18] investigated the properties of palm fatty acid (PFAE) and FR3 oil with mineral oil. It was concluded that PFAE has a better insulation performance with a higher breakdown voltage and increased capacitance. Nevertheless, the higher dissipation factor of PFAE must be considered before its application to power transformers. Gómez et al. [19] studied different ester fluids, such as Bivolt A (from corn oil), Bivolt HW (from sunflower oil) and Envirotemp FR3 (soya oil), by performing dissolved gas analyses before and after thermal and electrical tests. Five different key gases (H_2 , CH_4 , C_2H_6 , C_2H_4 and C_2H_2) were used for predicting the fault gases, and the modified Duval triangle method predicted overheating and partial-discharge-based faults with better precision. Rozga et al. [20] examined synthetic ester fluids for lightning impulse breakdown voltage and static electrification to understand their potential to replace mineral oil. These analyses indicated greater development opportunities for synthetic esters for distribution transformers. Waste cooking oil holds great promise for resource recovery and environmental protection when used in non-fuel applications such as power transformers and their accessories. However, a successful transition necessitates a comprehensive research strategy with more focus on regulatory integration [21]. Based on results under laboratory and field conditions, it is possible to effectively integrate EFs into transformer insulation with minor adjustments to MO-based systems [22]. Natural ester fluid possesses a better performance up to the 420 kV transmission voltage level with stable working conditions [23]. The test results of EF have indicated a significant reduction in the hazards posed to the environment and show that it is easily compatible with the 100 MVA rating of mineral oil without compromising its performance [24].

With the advancements in artificial intelligence (AI) and the Internet of Things (IOT), it is currently possible to monitor the health indices of power transformers through remote monitoring [2]. A hybrid deep learning model combining the features of Graph Connection-Skip Neural Networks (GCSGCNs) and Gated Recurrent Units (GRUs) has been used to predict the gel points of mixed crude oils using technical data for gel point, viscosity and density from an oil mixing station in China [25]. The thermal ageing of ester fluids under laboratory conditions can be used to train the model and create a huge database for classification of faults under real-time operating conditions of power transformers [26]. Dissolved gas analysis can be performed using an INSULOGIX device installed within the transformer oil valve such that it is capable of analyzing the major gases (hydrogen and methane) formed during faults within the transformer [27]. Similarly, partial-discharge-monitoring units are currently installed on the walls of transformers with an in-built mobile communication interface for continuous monitoring of inception within transformer insulation [28]. Considering the availability of plant feedstock for the future generation, algal oil has been considered as a replacement for use with electrical components [29]. There are lab-scale experiments and patents on transformer fluids based on algae; however, there is currently no conclusive proof that industrial or pilot-scale transformers are using algae-derived insulating oil; all known commercial demonstrations utilize other vegetable oils. A specific patent describes “algae oil-based dielectric fluid for electrical components,” encompassing applications in distribution and power transformers, along with comprehensive property specifications (e.g., viscosity under about 50 cSt at 40 °C, biodegradability, and paper life extension). The patent text expressly addresses practical transformer designs (sealed tanks, radiators, forced oil circulation), suggesting intended real-world use, although it does not provide documentation of any constructed or field-tested pilot trans-

former; it is a technological disclosure rather than an operational case study. Evaluations of microalgae oils as industrial lubricants indicate that oils produced from microalgae can be developed into functioning lubricants; nonetheless, they only reference broad “industrial applications” and do not provide details on transformer testing [30]. In 2013, the Dow Chemical Company signed a joint agreement with Solazyme (currently TerraVia Holdings) to develop an algal-based dielectric fluid for next-generation transformer applications [31]. Algal species of various types (diatoms, green algae, blue-green algae, golden algae, brown algae, red algae) have been used for biodiesel production as a replacement for existing fuels [32,33]. Microalgae grow much faster than plant crops, with the anticipated annual output of oil from algae being 30 times higher than that of traditional palm oil [34]. Algae are a crucial form of biomass, and the properties of fluids derived from algae depend on the type of species. They are photosynthesizing creatures with a fast growth rate, capable of finishing their full cycle growth within a few days. Based on statistics, diatoms (unicellular microalgae) can generate 46 tons of oil per hectare in a year, depending on the algal species [35]. Unlike second-generation feedstock, algae do not need soil or agricultural land for their growth since they can flourish anywhere in rivers, wastewater and oceans [36]. Recently, genetically modified algal fuels have also been researched; these are considered fourth-generation feedstock and could soon be available for various applications. Algae mostly require a light source, minerals and CO₂ for growth, where the CO₂ released by power industries could be utilized, thereby preventing global warming. Considering the aforementioned aspects, algal oil can be used as a dielectric fluid for power transformer applications. The primary aim of this review article is to compare the characteristics of traditional biodegradable fluids from plant crops to oils derived from algae, examining their dielectric characteristics and other physico-chemical behaviour important for transformers. Furthermore, the design modifications of transformers for algal oils and standards that need to be developed to ensure their reliability with pressboard insulation are also within the scope of the present work.

2. Algal Oil Extraction Process

Oil/lipid extraction from algal sources involves the processes of cell wall disruption and extraction of non-polar lipid molecules, which are then converted into fatty acid methyl esters via a transesterification reaction. The conventional process of lipid/oil extraction includes solvent extraction using chloroform and methanol, and in recent times, many extraction solvent systems containing hexane, CO₂-switchable solvents, ionic liquids, and deep eutectic solvents have been utilized for efficient lipid extraction. Also, cell disruption of algae plays a major role in extracting lipid/oil compounds with the highest potential yields. Physical and mechanical methods of algal cell disruption, such as ultrasonication, bead milling, microwave, electric pulse, etc., are still being utilized by many researchers [37–39]. Chemical and enzymatic methods (Figure 1) of cell disruption for lipid extraction using solvents, osmotic shock, supercritical fluids, or biological enzymes are being studied extensively for efficient and complete recovery of lipid molecules from algae [40].

2.1. Physical/Mechanical Methods of Oil/Lipid Extraction from Algae

Physical/mechanical methods involve utilizing techniques to rupture microalgal cells, releasing the lipid bodies stored within them. While these methods are not yet fully refined, solvent-free extraction shows promise as a viable technique for industrially producing primary extracted lipids. Ultrasonication is helpful when the cell wall in microalgal biomass is very thick, and the process of cell breakdown becomes more challenging. To prevent the generation of heat during crushing, ultrasound waves can be employed to generate cycles of high pressure and low pressure. These alternating waves penetrate the biomass,

move between cells, and create cycles of high and low pressure. This effectively crushes adjacent cells without the production of heat [41]. In the process of microwave treatment, electromagnetic waves traverse the extraction medium and penetrate the target. Polar molecules, including the water within the cells, absorb this energy and undergo rapid heating, resulting in an increase in pressure within the cell. This elevated pressure surpasses the maximum threshold that the cells can endure, causing cell rupture and the release of lipids in the solvent [42]. In the case of electric pulse treatment, transmembrane pores are created, which facilitate the dissolution of intracellular compounds such as lipids in the extracting solvent. These pores are transient and get rearranged with phospholipids and proteins. Osmotic shock involves subjecting a cell to a concentrated solution of a solute, such as dextran, salts, or polyethylene glycol, to decrease its osmotic pressure. This challenging environment has the potential to harm the cell walls of microalgae, leading to the release of their intracellular compounds [43].

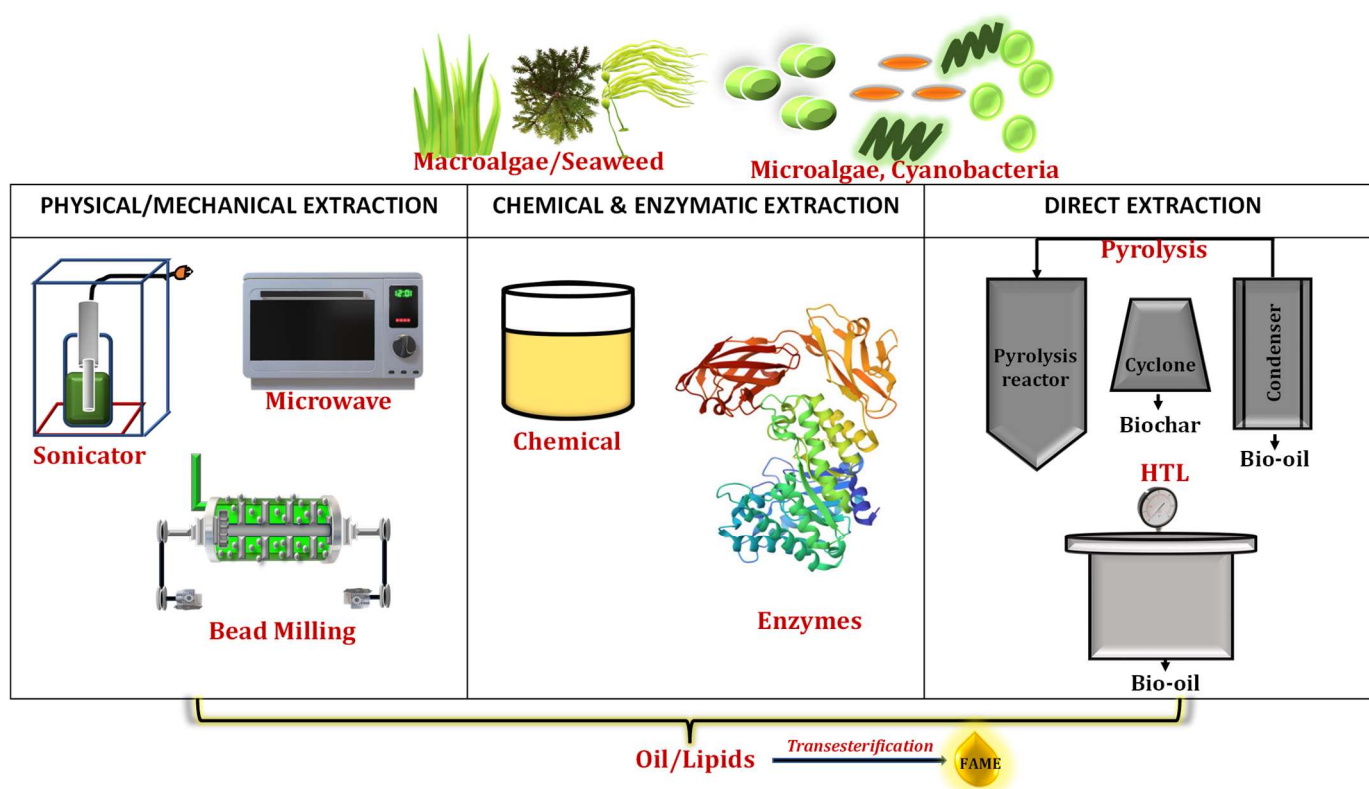


Figure 1. Methods of oil/lipid extraction from algae.

2.2. Chemical and Enzymatic Methods of Oil/Lipid Extraction from Algae

The fundamental principle underlying the extraction of lipids from microalgae through chemical methods using solvents is the concept of “like dissolves like” in chemistry. An optimal solvent for this process should exhibit a high level of specificity towards lipids, particularly acylglycerols. Additionally, the solvent must possess sufficient volatility to facilitate low-energy distillation, enabling the separation of lipids from the solvents. The extraction process for algal biomass can employ non-polar solvents like hexane, toluene, chloroform, and diethyl ether, as well as polar solvents such as acetone, methanol, ethanol, and ethyl acetate. Non-polar solvents play a crucial role in disrupting the hydrophobic interactions among non-polar and neutral lipids present in the algal biomass. Supercritical fluids serve as an effective extraction solvent because their solvent capabilities depend on density, allowing for adjustment by manipulating extraction pressure and temperature. They have the ability to yield crude lipids without the presence of solvents. Supercritical

CO₂ (SCCO₂) is the primary choice of solvent in supercritical fluid extractions due to its moderate critical pressure (around 7.4 MPa) and low critical temperature (around 31.1 °C). On the other hand, ionic liquids (for example, methanol and [Bmim][CF₃SO₃]) are appropriate for extracting lipids from algae because of their thermal stability, lack of volatility, and synthetic adaptability [40,43,44]. Cell disruption by biological enzymes is an environmentally friendly and relatively moderate method for extracting intracellular compounds from microalgae, offering high selectivity compared to solvent extraction techniques, particularly in lipid extraction. Lysozyme, glucanase, cellulase, and protease are utilized as commercial enzymes, typically in immobilized forms, to improve the stability and durability of disruptive actions during catalysis [43].

2.3. Direct Bio-Oil Extraction from Algae

Bio-oil, derived from algae, represents a sustainable and environmentally friendly energy alternative with the potential to replace traditional fossil fuels in the future. Algae-derived biomass has the capability to undergo two distinct processes to produce various biofuels. The first process involves the conversion of biomass into biofuels through biochemical methods, with microorganisms playing a key role. This conversion can be classified into four specific processes: alcohol fermentation, anaerobic digestion, transesterification and hydrogen production [45]. In the second approach, thermochemical methods are employed to apply heat and break down biomass in the presence of oxygen. Unlike biological processes, thermochemical techniques have the capacity to generate biofuels in solid, liquid, and gaseous forms. The thermochemical approach has proven to be more advantageous than biochemical processes due to its higher energy conversion, shorter reaction times, and more cost-effective production, addressing the limitations of low energy required for conversion, prolonged reaction times, and high production costs associated with biochemical conversion procedures [46]. Also, the thermochemical approach provides a more straightforward means of biofuel production compared to both chemical and biological processes. In chemical conversion, separation of biomass or purification of biomass is necessary, transesterification demands recycling of methanol, and the disposal process becomes intricate due to the production of soap. In the case of biochemical conversion processes like fermentation, biofuels are produced after a few days [47]. On the contrary, thermochemical conversion usually eliminates the requirement for chemicals and achieves its goals by transforming a diverse array of feedstocks from biomass, utilizing the entirety of the feedstock. The primary classifications of thermochemical conversion methods encompass hydrothermal liquefaction (HTL), direct combustion, pyrolysis, and gasification. Among these, pyrolysis and HTL stand out as the most notable and efficient approaches to bio-oil production [48].

2.3.1. Pyrolysis for Bio-Oil Production

Pyrolysis serves as the initial stage preceding any thermochemical conversions and is succeeded by the combustion of char or gasification. During the pyrolysis process, intricate reactions such as rearrangement, fragmentation, polymerization, dehydration, and decarboxylation occur. The presence of lipids, carbohydrates, and proteins in microalgae renders them suitable for the energy production process through pyrolysis. Given its yield efficiency and energy, pyrolysis is regarded as a cost-effective approach for converting algal biomass into fuel [49]. Pyrolysis of algae is classified into two primary types based on operational parameters such as heating rate and residence time: slow pyrolysis (typically employing a rate of 10 °C/min) and fast pyrolysis (usually requiring a temperature increase exceeding 100 °C/s). Fast pyrolysis is a systematic procedure wherein biomass is heated to the ideal pyrolysis temperature before undergoing complete decomposition. It

is characterized by the swift cooling of pyrolysis vapours, coupled with extremely high temperatures and heating rates in the reaction [50]. To produce bio-oil, the temperature must fall within the range of 300 to 600 °C. In contrast to fast pyrolysis, slow pyrolysis yields a significantly higher amount of biochar due to its production of fewer alternative gaseous and liquid products. Therefore, fast pyrolysis is highly recommended for bio-oil production from algal sources [51].

2.3.2. Hydrothermal Liquefaction for Bio-Oil Production

The hydrothermal liquefaction (HTL) of biomass stands out as an early and successful thermal conversion technology, effectively enhancing the value of various biomass feedstocks. It exhibits remarkable flexibility in handling various feedstocks, offering the potential to reduce oxygen levels and process wet biomass. HTL relies on a fundamental reaction involving biomass or other organic materials in the presence of water under standard hydrothermal conditions. Under these conditions, water persists in either a liquid form or in a supercritical state characterized by high density [52]. The incorporation of a wet reaction environment makes HTL suitable for moist feedstocks, eliminating the need for drying. In the HTL refining process, biomass or organic material undergoes various depolymerization reactions, such as hydrolysis, decarboxylation, and dehydration, yielding water-soluble compounds. Subsequent repolymerization involves multiple condensation mechanisms to form non-water-soluble substances, including biochar and bio-crude [53]. Bio-oil from algal sources has the following characteristics: (i) higher heating value, in the range of 30 to 38 MJ/Kg; (ii) presence of esters and phenolic compounds; (iii) presence of aldehydes, ketones, etc.; (iv) presence of volatile compounds [54]. The major compounds found in bio-oil obtained from various algae species are presented in Table 1.

Table 1. Bio-oil characterization using gas chromatography [55–61].

Algal Species	Major Compounds Found in Bio-Oil
<i>Nannochloropsis</i> sp.	Myristic acid, palmitoleic acid, palmitic acid
<i>Dunaliella tertiolecta</i>	Palmitic acid, octadecadienoic acid
<i>Dunaliella</i> sp.	Palmitic acid, linoleic acid, oleic acid
Blue-green algae blooms	Palmitic acid
<i>Spirulina</i>	Tert-hexadecanethiol
<i>Saccharina japonica</i>	Heterocyclic aromatic compounds such as cyclopentanes, cyclohexanes
<i>Enteromorpha clathrate</i> , <i>Sargassum natans</i>	C16 to C20 hydrocarbons

3. Precautionary Measures for Using Biodegradable Fluids in Power Transformers

Biodegradable EFs should be tested to determine their compatibility with different transformer materials and establish precautionary measures associated with their physico-chemical properties before introducing them into transformers. Despite the benefits of EFs compared with petroleum-based oils, the servicing of liquid and storage challenges must be managed cautiously to prevent equipment failures brought on by inappropriately applying limitations of MO to EFs. To address this issue, separate requirements and guidelines have been established for EFs [62,63]. The use of EFs under frigid climate conditions poses a serious problem since their pour points, regardless of added depressants, are around −30 °C [64]. Ester liquids are only appropriate for sealed power transformer units due to their reduced oxidation stability, which may be overcome by adding sufficient antioxidants below the permitted limit [28]. The typical gaskets allowed for on-load tap changers (OLTCs) with MO have been found to be incompatible with EFs, but fluorosilicone rubber can be used as a replacement without incurring any undesirable

effects [65]. Cellulosic impregnation in EFs should be allowed to occur for a longer time in a temperature range of 60–80 °C [66]. Corrosive sulfur exists naturally in MO, and though EFs are non-corrosive, they can absorb sulfur from the adsorbents used for reclaiming aged fluids. Thus, insulation engineers should determine the elemental composition of reclaimed EFs before reusing them in power transformers to avoid sulfur deposition on pressboard and winding conductors [67]. The insulating fluid experiences numerous stresses (electric, thermal, chemical) during the transformer's operational lifetime, and thus, it is essential to understand ageing characteristics of EFs, especially their dielectric properties and associated decay products [68]. Specific standards have been created for EFs with higher-fire-class properties [69,70] for performing accelerated thermal ageing tests with a defined temperature and duration. Experiments on natural EFs should be performed only in a nitrogen atmosphere, whereas synthetic esters (SEs) can be used in either an air or nitrogen atmosphere. To date, there are no precautionary measures available for algal biofluid in high-voltage applications, but investigation into its physico-chemical and dielectric properties could provide more information before its application in real-time power transformer networks.

4. Properties of Biodegradable Fluids for Power Transformers

4.1. Composition of Fatty Acids

Vegetable oils derived from different plant crops are shown in Table 2 with their fatty acid compositions. The glycerol backbone of natural ester (NE) is attached to various fatty acid groups (saturated, monounsaturated and polyunsaturated). Figure 2a presents the structure of NE, where the different alkyl groups (R, R' and R'') are involved in double bonds (C=C). The physical properties of the vegetable oils depend on their chemical composition.

Table 2. Fatty acid composition of vegetable oils.

Oil	Saturated Fatty Acid		Monounsaturated Fatty Acid	Polyunsaturated Fatty Acid	
	Palmitic (C16:0)	Stearic (C18:0)	Oleic (C18:1)	Linoleic (C18:2)	Linolenic (C18:3)
Palm [71]	44.4	4.3	39.9	9.4	-
Olive [72]	15.8	3	71	13.2	1
Rapeseed [73]	4	2	56	26	10
Pongamia pinnata oil [74]	11.65	7.5	51.5	16.64	-
Sunflower [75]	7	5	19	68	1
Coconut [76]	10	4	10	2.5	0.2
Soyabean [77]	9	4	28.5	49.5	8

EFs with higher saturated fatty acid content are preferred for transformer applications since they have lower viscosity and higher stability towards the oxidation process compared to those with unsaturated fatty acids [27]. Despite the production of natural EFs from a wide range of plant crops, only those derived from specific oils (soyabean, rapeseed and sunflower) are permitted for use in transformers because of their better insulating properties. Most commonly, carboxylic acids and multiple alcohol functional groups are combined to form SEs. Specifically, SEs are characterized as a group of polyol esters (Figure 2b). Currently, there are numerous EFs (NE-BIOTEMP, NE-Envirotemp FR3, NE-MIDEL 1204, NE-MIDEL 1215 and SE-MIDEL 7131, SE-ProEco TR3746, SE-Envirotemp 200) used for transformer applications. In general, algal oil consists of a large quantity of polyunsaturated fatty acids, which has an impact on the stability of biofuel. Nevertheless,

the lower melting point of polyunsaturated fatty acids compared to monounsaturated or saturated fatty acids results in better properties of algal oil for use under cold weather conditions [35]. But microalgal oils containing high levels of saturated fatty acids (SFAs) exhibit enhanced stability, attributed to their increased resistance to oxidation when contrasted with oils containing abundant unsaturated fatty acids (UFAs). This quality renders them potentially valuable in scenarios prioritizing extended shelf life and resilience against deterioration. The absence of double bonds in the carbon chain of SFAs contributes to their enhanced resistance to oxidation. Double bonds are susceptible to attack by reactive oxygen species, leading to degradation. Many microalgal species have shown a remarkably high content of saturated fatty acids and comparatively less unsaturated fatty acids (Table 3). This is exemplified by *Chlorella vulgaris*, which exhibits a noteworthy 60.1% SFA content, with UFAs constituting the remaining 39.7% [78]. Similarly, another study documented that *Scenedesmus* sp. possessed a substantial proportion of SFAs (52.3%), with UFAs making up the balance (47.7%) [79]. The prominent presence of saturated fatty acids (SFAs) in many microalgae species (as shown in Table 3) makes them attractive candidates for producing stable oils, rendering them suitable for a range of industrial applications.

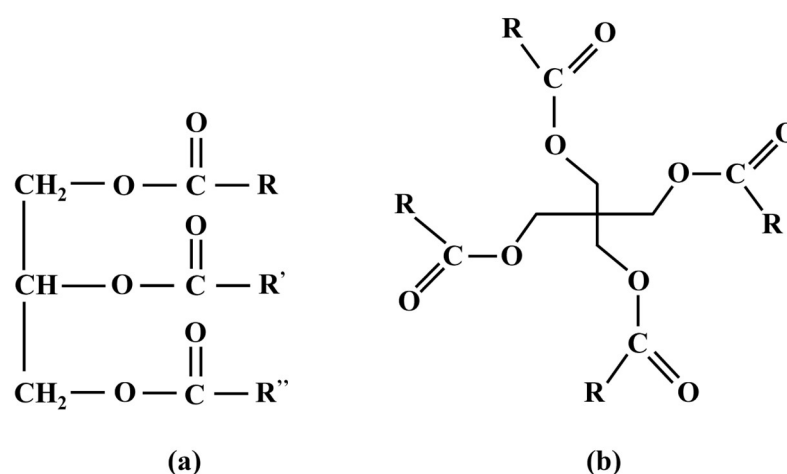


Figure 2. Structures of (a) NE and (b) SE.

Table 3. Fatty acid composition of algal oils from different species.

Algal Oil Species	Saturated Fatty Acid		Monounsaturated Fatty Acid	Polyunsaturated Fatty Acid	
	Palmitic (C16:0)	Stearic (C18:0)	Oleic (C18:1)	Linoleic (C18:2)	Linolenic (C18:3)
<i>Chlorella vulgaris</i> [79]	45.2	8.4	1.2	6.3	32.2
<i>Scenedesmus</i> sp. [79]	48.42	6.7	16.8	18.1	5.9
<i>Nannochloropsis oceanica</i> [80]	45.9	0.6	22.2	0.7	0.5
<i>Thalassiosira weissflogii</i> [81]	11.73	-	0.98	3.57	-
<i>Chaetoceros calcitrant</i> [82]	47.68	4.6	6.67	1.6	0.02
<i>Schizochytrium</i> sp. [83]	52.4	1.9	0.2	0.3	0.4

4.2. Biodegradability

Oil spillage from transformers is one of the most common events occurring in power networks and, if not adequately managed, might pose a serious environmental risk. The biodegradability of fluid depends on the metabolism of naturally existing bacteria present in the soil. Naturally, it is advantageous if spilled liquids immediately perish without the need for expensive clean-up procedures. A substance is said to be biodegradable if 60% of its biodegradation occurs within a time span of 10 days or at the end of 28 days [84].

The Organisation for Economic Co-operation and Development (OECD) aims to create standards and improved regulations for testing chemicals under environmental conditions. OECD 301 provides guidelines [85] on various test techniques involved in determining the biodegradability of different materials, as shown in Figure 3. The tests that are applicable to transformer fluids are indicated in green colour (301B, 301D, 301F). OECD 301A [86] measures the fluid's biodegradability based on the variation in its dissolved organic carbon (DOC) during a test period of 28 days. This technique is mostly used for chemicals that are non-volatile and soluble. OECD 301B [87], also known as the Modified Sturm Test, measures CO₂ evolution in a constantly aerated container to assess the material's readiness for biodegradation, with its use targeted towards both highly soluble and insoluble materials. OECD 301C [88] is a modified MITI (Ministry of International Trade and Industry, Japan) method that uses oxygen consumption as a measure of biodegradability, and it is suitable for volatile and poorly soluble materials. OECD 301D [89] analyzes biodegradation in a closed bottle by measuring the dissolved oxygen throughout the test period, and it is applicable to both volatile and absorbing materials. OECD 301E [90] is similar to OECD 301A but varies in the concentration of microorganisms, which is lower in the former compared to the latter. OECD 301F [91] determines biodegradability by measuring the consumption of oxygen in a closed respirometer. The test sample is added to a diluted solution, and oxygen consumption is measured through CO₂ formation in the solution. This technique for testing biodegradability is mostly used for hardly soluble substances, specifically for wastewater applications.

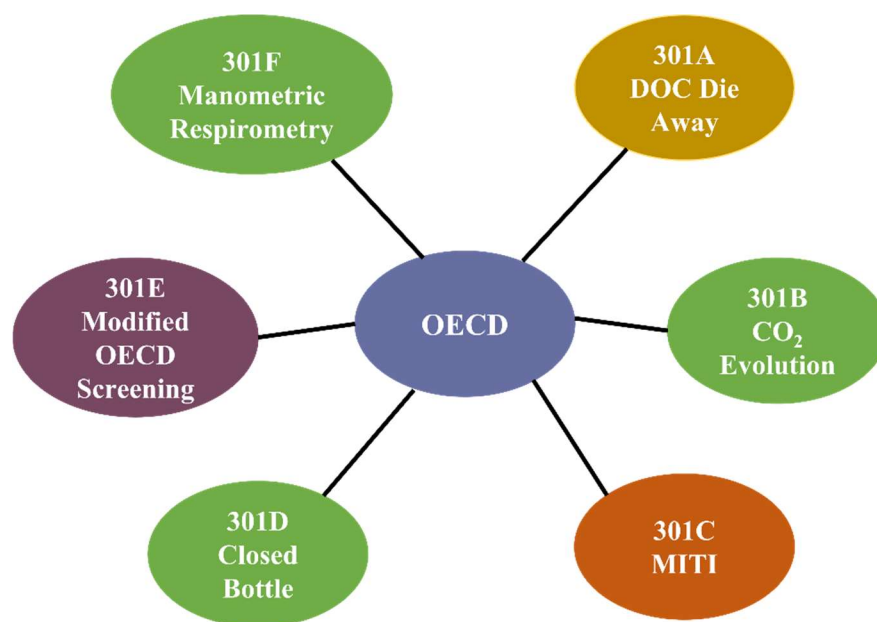


Figure 3. OECD tests for biodegradability.

A comparison of dielectric fluids used in transformers tested for their biodegradability per OECD guidelines for a test duration of 28 days [92,93] is shown in Figure 4. The EFs (NE, SE) have been concluded to be “readily biodegradable”, as their biodegradability has reached more than 60% within 10 days, whereas MO (10%) and SO (5%) are more resistant to biodegradation. MO has lower biodegradability due to the presence of aromatic hydrocarbons in its chemical composition, which have an adverse impact on soil organisms and are considered environmental contaminants [94]. SO does not biodegrade rapidly when evaluated using standard recognized procedures, with polydimethylsiloxane (PDMS) initially hydrolyzing to form siloxanols along with dimethylsilanediol (DMSD). These reactions can take years in wet soil and only a few days in the case of dry soil. Finally, DMSD

undergoes degradation to produce CO_2 and inorganic silicate [95]. As a consequence, SO has a more complicated environmental impact beyond its biodegradability.

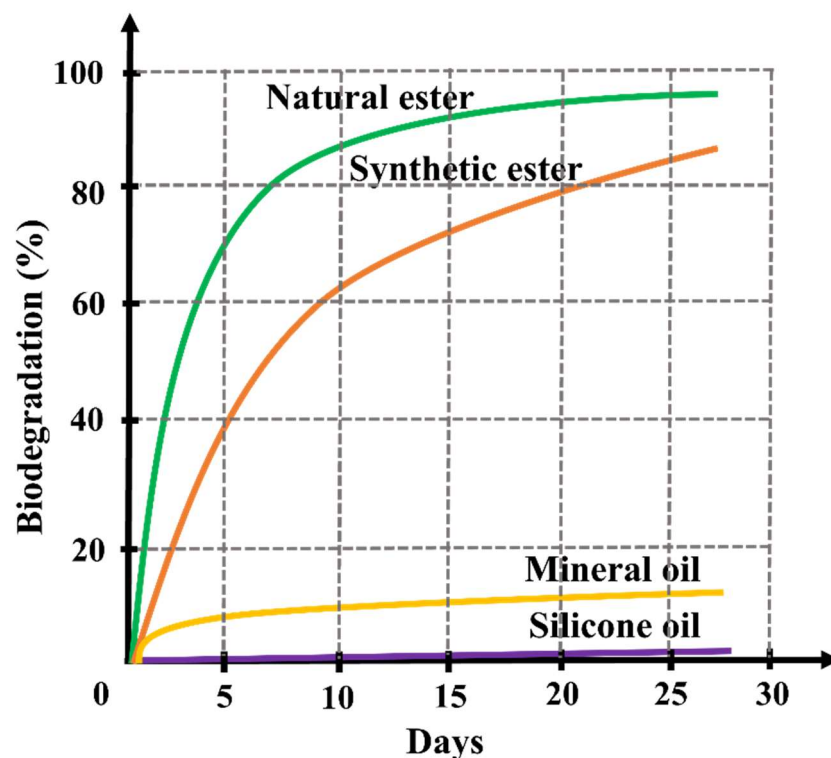


Figure 4. Biodegradation of different dielectric liquids.

Natural EFs are 95% biodegradable, and SEs derived from pentaerythritol and monounsaturated fatty acids also exhibit high biodegradation (89%), although the addition of low concentrations of stabilizers can reduce their biodegradability [96]. Biofuels derived from algae are also biodegradable, and their percentage of degradation and time duration depend on the algal species. *Arthrospira maxima* is a microalgae species that results in 70% biodegradation, whereas the *Nannochloropsis* sp. is only 40% degradable due to the presence of higher lipid content, slowing down the biodegradation process. *Cladophora glomerata* is a macroalgae species with only 48% biodegradation due to a large ash content, but *Gelidium corneum*, being a red algae fibre, is 77% degradable within a time span of 20 days, which is faster than microalgal species and biofuels from vegetable and plant crops [97]. Apart from the OECD 301 guidelines on testing of biodegradability, the Coordinating European Council method (CEC L-33-A-94), with a test period of 21 days [98], and Biological Oxygen Demand (BOD) are also widely used to assess the biodegradability of insulating fluids.

4.3. Kinematic Viscosity

The essential characteristics of an insulating fluid that influence the thermal heat exchange process within the power transformer are quantified by kinematic viscosity. This parameter measures the resistance opposing the fluid motion, where a higher viscosity reduces the flow through the pressboard ducts of transformer winding, raising its nominal temperature level [99]. ASTM D445 [100] is used to measure the kinematic viscosity of transformer insulating fluids, which exhibit Newtonian flow behaviour. Using this technique, the time taken for a constant volume of fluid to flow through a capillary tube under gravity at a controlled temperature is measured using a viscometer. Apart from the above standards, recently an open cone–plate geometry [101] and a closed cylindrical geometry [102] with a double gap have been used for rheological testing of insulating fluids. The

kinematic viscosity of different vegetable oils used for transformer applications is indicated in Figure 5. The vegetable oils from sunflower, soyabean, rapeseed and palm fatty acid ester (PFAE) have viscosity ranges more suitable for transformer applications compared to oils from castor, mustard, rice husk and Pongamia Pinnata. Chen et al. [103] have developed a quartz tuning fork technique for measuring the viscosity of transformer oil, and it provided an error deviation of less than 2.52% compared to the existing measurement methodology. The viscosity of EF is four times higher than that of MO [104], and its trend remains the same with ageing under a nitrogen atmosphere. It was confirmed that the viscosity of EFs remains stable with ageing temperature in the presence of pressboard insulating material and metals. Significant differences in the viscosities of MO and EF have been reported in various studies [105,106]. The viscosity undergoes a significant change only at ambient temperature and minimally varies at the operating temperature of the transformer [107]. Recently, research from the Technical Committee on Liquid Dielectrics indicated that NEs could polymerize via oxidation processes, making the fluid more viscous in nature, which could lead to gel formation on the core winding [108]. But this solid gel formation depends on the fatty acid composition of different vegetable oils, and higher concentrations of oleic acid in EFs can prevent the oxidation process and gelling compared to polyunsaturated acids [109]. Yusof et al. [110] studied the impact of ultrasonic radiation on palm oil at different temperatures by utilizing a sonicator for varying time intervals. It was found that viscosity was reduced under the impact of ultrasonic radiation, and the highest reduction of 44.9% was measured at 75 °C.

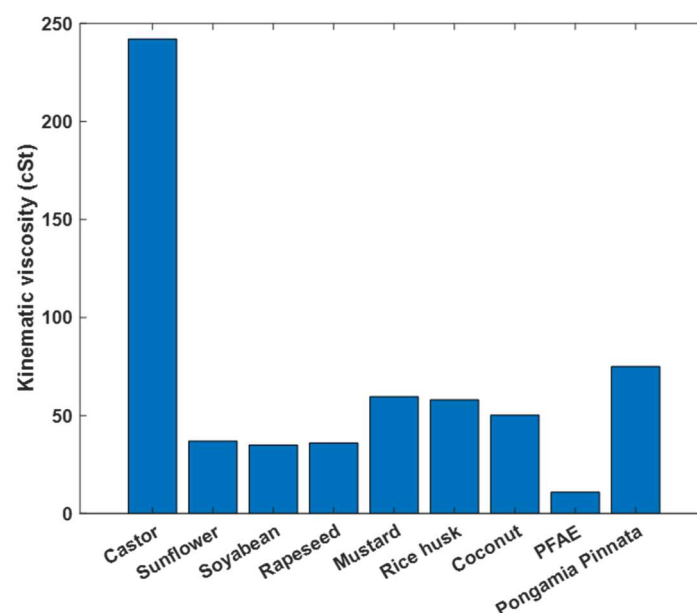


Figure 5. Kinematic viscosity of vegetable oils at 40 °C [111–113].

Srinivasa et al. [114] experimentally analyzed the impact of moisture content on the viscosity of EFs (palm oil, sunflower oil) and inferred that moisture increases the intermolecular forces in the fluids, causing a rise in viscosity. Zheng et al. [115] used a molecular dynamic simulation along with free volume theory to predict the viscosities of natural EFs, and the simulation outcomes exhibited a good correlation with experimental results in the lower temperature range (−20 °C to 20 °C), whereas at higher temperatures (−40 °C, −50 °C), higher error was observed. The primary objective of thermally designing liquid-filled power transformers is to ensure they can withstand the temperature rise test. It is crucial for the manufacturers of ester transformers to determine the heat generated during power loss that is dispersed during cooling mechanisms [116]. In an oil-directed cooling

mechanism, the EF's viscosity has an impact on the pressure drop occurring in the winding ducts, as well as on the flow velocity. The effects of flow rate and temperature on different ester-filled transformers have been studied, with a clear information on the inlet velocity before the retro-filling of the EF [117]. The weak interactions related to viscosity in fatty acid methyl esters (FAMES) in EFs have been explored using the electrostatic potential, van der Waals potential and average local ionization energy, with a microscopic effect at the sites of C=C bonds [118]. A higher number of these bonds weakens the molecular interactions in the fluid, causing a decrease in viscosity. The operation of a 50 MVA transformer loaded with both NE and MO was tested by Girgis et al. [119], who noted a considerable rise in tank oil temperature. Further, the EFs showed an increased hot-spot temperature in the winding, with a higher impact in air-forced cooling compared to natural air cooling in transformers. Also, while loading a 90 MVA transformer, the top oil temperature in an ester-filled transformer was 4.4 °C higher than that of a transformer filled with MO. Currently, the blending of different insulating fluids is being considered to reduce the overall cost and maintain better dielectric properties inside the transformer [120]. The blending of vegetable oil (80% rapeseed oil, 20% PFAE) improved the kinematic viscosity by 51.3% [112], where the change in the molecular size increased diffusion, and a reduction in the interaction between the fluids due to free volume was inferred to be the cause of lower kinematic viscosity. The above studies on viscosity suggest that thermal model flow in the winding and its losses should be analyzed based on multiple parameters (pressure head, tank volume, radiators). Thus, while designing the cooling mechanism for ester-filled transformers, insulation engineers should consider the higher viscous parameter of EFs before their installation for real-time application. Algal oils have been tested for their viscous properties mainly for biodiesel applications, and the typical kinematic viscosities of oils from different species are indicated in Table 4. The viscosities of oils from the majority of algal species lie between 1.1 cSt and 10 cSt, which is similar to the range observed in conventional mineral oil used for power transformers and below the limit of oils derived from vegetable and plant crops. This gives an initial suggestion for power engineers that algal oil could provide better heat transfer between winding conductors. Paisan et al. [121] have investigated crude algal oil (*Chlorella* sp.) with palm oil in a weight ratio of 30:70 and observed a viscosity of around 122 cSt. The mixture of two different oils impacts the viscous flow behaviour [122,123], and thus a suitable combination of algal oils with better stability should be selected for better thermal performance in high-voltage applications.

Table 4. Kinematic viscosities of biofuels from algal species [81,124–127].

Algae Species Name	Kinematic Viscosity (cSt) @ 40 °C
<i>Ulva fasciata</i>	35.2
<i>Thalassiosira</i> sp.	1.151
<i>Chlorella vulgaris</i>	5.2
<i>Rhizoclonium hieroglyphicum</i>	5.0
<i>Caulerpa racemosa</i>	4.30
<i>Sargassum myriocystum</i>	7.89

4.4. Flow Electrification

Flow electrification is a key issue that requires attention in a liquid-immersed power transformer [128]. The insulating liquid used for heat transfer at the pressboard spacers and copper winding causes polarization in the interfacial regions, forming an electrical double layer (EDL) with opposite charges at liquid and solid insulation [129,130]. Power transformer failures caused by the flow electrification mechanism are not an abrupt phenomenon since these static electric charges developed on the pressboard ducts lead to discharges

along its surface and a subsequent breakdown process over a longer time period [131]. A typical diagram representing the dissociation of charges at the interfaces in a model test transformer is shown in Figure 6. Based on the physico-chemical interactions, the layer close to the solid surface is the fixed layer (compact layer) that is tightly packed, and the next layer is the diffuse layer, where the ions are not tightly packed and are free to move into the fluid [132].

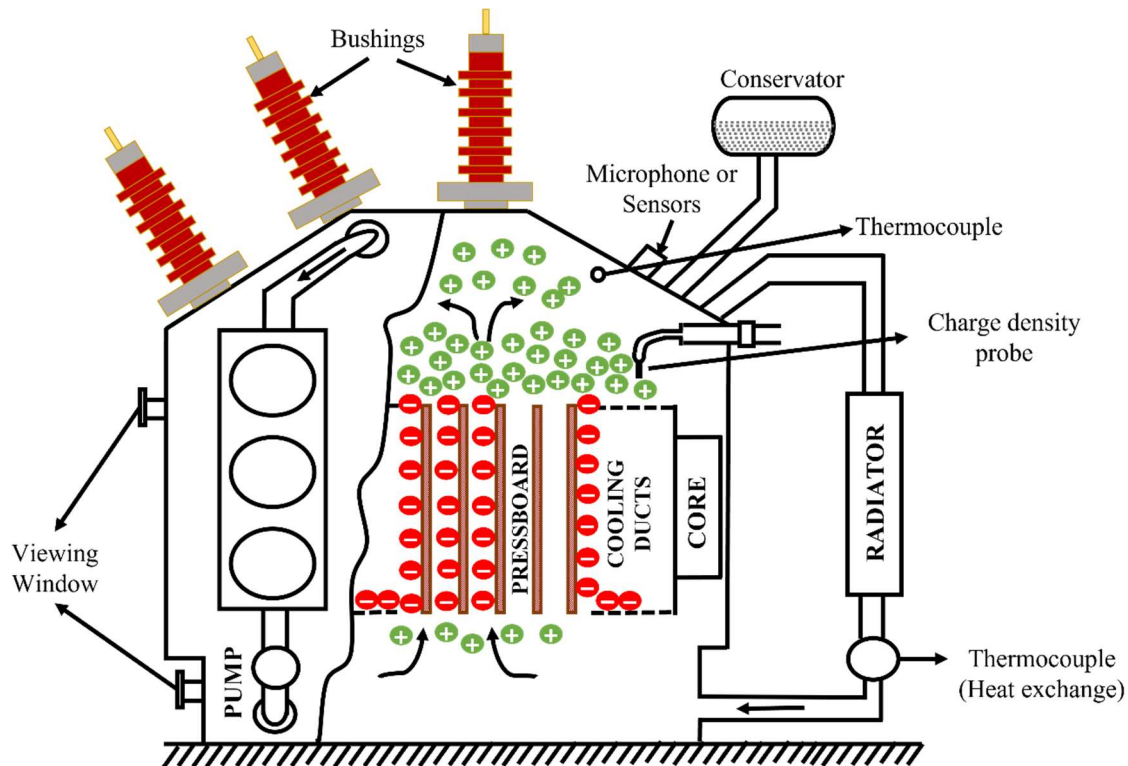


Figure 6. Mechanism of flow electrification at interfaces.

In the transformer tank, the liquid transports the negative ions, while the positive ions are pulled toward the electrons. But this is generally negligible due to the grounding of the transformer walls [133]. On the other hand, the pressboard structure holds a negative charge on its layer, diffusing the positive charges into the fluid. This is because the cellulosic pressboard structure has a higher affinity towards positive charges due to the presence of hydroxyl groups [134]. There are numerous methodologies for measuring the electrostatic tendency of dielectric fluids based on experimental models (planar flow, centrifugal flow) used for their movement [135]. Capacitive Sensors [136,137] were first used to mimic the flow looping of insulating fluids, similarly to real-time power transformers, using various electrical and mechanical systems to execute the charge separation mechanism at the pressboard insulation. The charge developed on the solid pressboard insulation was detected using a picoammeter, and the remaining residual charges were then permitted to proceed in the direction of the relaxation vessel for measuring the leakage current (upstream, downstream). This method requires a huge quantity of insulating liquid, and more time is required for processing the experimental conditions. So, the Ministatic charge test [138], used to evaluate the charging of fuels in the aviation industry, was adapted for transformer insulating liquids. A 50 mL plastic syringe is used to force the oil through a cellulosic filter (high porosity and increased surface area) and thus could not be correlated with the actual system in transformers. To address the shortcomings of the above methods, models based on a circular flow were developed in a later stage. The Couette charger

test system [139] fills the spacings between the internal and external cylinders with the insulating fluids, and the pressboard stackings are folded to create the interfacing of the power transformer. This experimental model can measure the static charge under different flow regimes (laminar, turbulent) by spinning the interior cylinder at a defined velocity. This method, as opposed to the other techniques, considers the impact of the applied electric field on the charging mechanism but requires a higher volume of liquid, like planar flow. A compact model like the spinning disc methodology was later adopted per CIGRE standards [140] to measure the static electrification of insulating fluids, considering the effect of different parameters (surface roughness, thickness and temperature). Later, an oscillatory system [141] was created to investigate the flow current of dielectric fluids with a parallel metal electrode system coated with pressboard material and housed in a metal tank. The stepper motor was used to oscillate the electrode, and the streaming current was measured for different oscillation frequencies.

The EFs were first evaluated for electrification using a planar flow model, and it was concluded that they resulted in a higher flow current, but they could dissipate the charge developed on pressboard insulation due to its enhanced conductivity [138]. This early investigation into EFs could not provide a clear idea of the exact physico-chemical parameters affecting the generation of charges at the interfaces. MO and SO provided a lower current magnitude when tested with the Ministatic tester [142] compared to EFs. The hypothesis initially related the viscosity as a dependent parameter to the streaming current, but it was later found that highly viscous SO resulted in a lower current. Later, a comparison of MO and EFs for streaming electrification was performed using a circular disc system [143]. A higher current magnitude was noticed in EFs under the effects of temperature and velocity at different interfaces (fibreglass/Cu, pressboard/Cu), but their minimal difference from MO and higher biodegradability make them suitable fluids for transformer insulation. Talhi et al. [144] studied the streaming current using the spinning disc system, indicating an increased current magnitude of SE compared to MO. Further, the streaming current was found to vary as a function of moisture, impurities and dissolved oxygen. Streaming electrification under ageing conditions was analyzed using both SE and MO using the rotating disc and pipe flow technique [145,146]. Under unaged conditions, the MO exhibited a lower current than SE due to its polar nature, whereas with ageing conditions, the EF showed a lower current magnitude. This implies that ageing of insulating fluid could respond differently to static electrification in EFs, with their lower relaxation time and volume resistivity. Huang et al. [147] examined various EFs for streaming phenomena and concluded that SEs were three times more powerful than NEs at the time. Also, the charging potentials of both MO and EF were found to be identical, thus proving the potential of EFs in power transformers. Rouabeh et al. [148] examined the correlation of electrostatic charging tendency (ECT) of different vegetable oils with their electro-hydrodynamic (EHD) properties. The relation was observed to be strong, with the fluid being sensitive to static electrification, experiencing a lesser tendency towards movement in the presence of an electric field. Both of these physical mechanisms depend on the Debye length, which plays a major part in the diffusion of charges from the interfaces and reduces the field intensity in the electro-convection process. The ECT of a mixture of PFAE and MO was measured to understand the retro-filling aspects in transformers [149]. An increased ratio of PFAE to MO resulted in a higher current, which decreased after a certain concentration due to resistivity and moisture affinity of PFAE towards the mixed fluid. The impact of flow electrification in MO [150,151] under the influence of AC and DC voltages is well known, but with current research trends moving towards alternate EFs and their mixtures, much more data from electrical field studies on flow electrification of EFs is required. There is no data on the flow electrification of algal oil

with any solid interfaces, and hence it is not possible to comment on its charge dissociation at the pressboard interfaces in transformers. Nevertheless, the surface of microalgae is negatively charged due to the nature of its functional groups (amine, carboxylic, hydroxyl) and several other factors (pH, ionic strength, light intensity) involved in their growth [152].

4.5. Dielectric Permittivity and Dissipation Factor

The dielectric permittivity of insulating fluids is determined by their tendency to become polarized under the influence of an external electric field. Transformers designed with a mixed insulation (pressboard/paper, fluid) system should have a dielectric fluid with increased permittivity and a lower dissipation factor. The IEC 61620 [153], IEC 60247 [154] and ASTM D924 [155] standards are used for the measurement of dielectric behaviour of insulating fluids with respect to frequency and temperature. The dielectric parameters (ϵ_r , $\tan \delta$) for different insulating fluids are shown in Table 5. The permittivity of insulating fluids in power transformer applications should be close to the permittivity of cellulosic pressboard/paper insulation, minimizing the tangential electric field stress between the interfaces and avoiding the creeping discharges involved in pressboard insulation [156,157]. Considering this statement, EFs (NE, SE) have permittivities closer to that of solid insulation in transformers compared to those of SO and MO. Divergent AC fields are more prominent in power transformers, and their field distribution is mostly dependent on the permittivity of the liquid insulation [17]. EFs have a 40% higher permittivity than MO, and the lower permittivity ratio of solid–liquid insulation means that EFs experience a different electric field than MO. The permittivity is dependent on the temperature, as, at higher temperatures, the molecules in the fluid become agitated and have a low propensity for orientation towards the electric field [158]. The permittivity of insulating fluids can change during the ageing phenomenon inside transformers due to dissolved decay products (DDPs) from winding and pressboard insulation. Palm oil, which is the most researched among the EFs, has a geometric imbalance in its molecules, leading to higher polarity and dipole formation, resulting in increased permittivity [159]. Also, the dissipation factor of PFAE is found to be lower than that of FR3 fluid until an ageing duration of 1920 h at an ageing temperature of 160 °C [92]. Singha et al. [104] compared the ageing characteristics of high-oleic NE (HONE) and MO (150 °C, 3000 h), inferring a stable magnitude of their permittivities for the entire ageing duration. The dissipation factor of an insulating fluid depends on its conductivity and the composition of additives present in its structure, which can slow down contamination during the ageing process [160]. A natural EF aged without Kraft paper insulation resulted in a lower loss factor compared to its influence with the addition of Kraft paper. It was inferred that at higher temperatures (70 °C), the NE has a higher probability of extracting more water from the Kraft paper, resulting in an increased dissipation factor compared to MO and SE [161,162]. Bandara et al. [163] investigated a similar phenomenon to that discussed above but indicated that pressboard aged along with MO and EF resulted in a lower dissipation factor, which is contradictory to the conclusions from the above study. The oxidation process during ageing could result in radical formation, which results in a reduction in ionic mobility in the EF, resulting in a reduction in the loss factor, but in the presence of pressboard, these radicals are absorbed by pressboard material, and thus a constant loss factor is observed. In addition, it is concluded that greater dissociation of ionic particles occurs in EFs with higher permittivity, which results in an increased dissipation factor compared to MO. The magnitude of the loss factor is not favourable for comparison of different insulating fluids, but it is required to understand their rate of change to assess their level of ageing. Mostly, the acidity of the fluid is found to be responsible for the increase in $\tan \delta$, but there could be compounds that are non-acidic that also develop during ageing. The hydrolysis of the insulating fluid during degradation can result in constant $\tan \delta$ with

increased acidity, and the oxidation reaction can result in constant acidity with increased $\tan \delta$ [161]. Thus, acidity is not the only dependent parameter associated with $\tan \delta$ of the insulating fluid, but other physico-chemical properties also need to be understood. Martin et al. [164] experimentally analyzed FR3 fluid filling two transformers of the same design, operating for a duration of 25 months. It was found that the dissipation factor lay around the limit of 0.05 suggested for a natural EF by the standard formulated by IEEE [63].

Table 5. Dielectric parameters of transformers' insulating fluids.

Oil	ϵ_r		$\tan \delta$		Comments
	20 °C	90 °C	20 °C	90 °C	
MO [17]	2.20	2.10	0.00012	0.0011	The permittivity of the EF is higher than those of SO and MO, whereas the dissipation factor is lower for MO compared to other fluids. There is not much variation in the permittivity of different vegetable oils, but there is variation in the dissipation factor due to a change in the composition of fatty acids.
SO [64]	2.70	2.5	0.01	-	
NE [140]	3.2	2.93	0.002	0.016	
SE [73]	3.30	2.95	0.0008	0.0212	
Vegetable oils					
Oil Type	ϵ_r (25 °C)		$\tan \delta$ (90 °C)		
Palm [92]	2.94		0.0051		
Sunflower [165]	3.1		0.0093		
Canola [158]	2.01		0.0009		
Soyabean [166]	3.1		0.061		
Camellia [167]	3.19		0.0088		
Karanji [168]	2.02		0.0002		
Rapeseed [169]	2.93		0.0017		

The $\tan \delta$ of natural EFs is divided into three different regions with temperature variation (20–180 °C): The initial rise is very small until 70 °C, and then it slightly increases until 110 °C. Further, the rate of the rise in $\tan \delta$ increases to a higher magnitude after 130 °C [170]. The higher hygroscopicity of EFs results in a higher loss factor with the addition of water content compared to MO, and 743 ppm of moisture content in an EF increases $\tan \delta$ to ten-fold its initial magnitude. Gutiérrez et al. [171] experimentally tested the effect of ageing on different vegetable oils, inferring a higher $\tan \delta$ for palm oil compared to sunflower, soyabean and rapeseed, with no major variation detected in their permittivities. A mixture of 50% EF and 50% MO resulted in the highest permittivity [124] among all combinations, with twice the dissipation factor of MO. The dielectric parameters of the mixed fluid were found to be within the limits specified by IEEE for a new insulating fluid, but its stability and $\tan \delta$ at higher ageing temperatures still require more research before its application to power transformers. Biofuel from green algae species [172] was found to have a smaller penetration depth, indicating its lower permittivity and lower dissipation factor compared to palm oil, which can impact the degradation of cellulosic pressboard insulation inside the transformers. Currently, there is a patent on algal species for electrical components, where the reported dissipation factor is less than 0.5% at 25 °C [29]. This value is not limited to a single algal species; rather it may be single cells, colonies, clumps, filaments or any combination of these. Based on the chemical structure of triglycerides present in algal species, the dielectric constant could vary between 2.5 and 3.1, which is a similar range to that of natural and synthetic esters. Algal oils are widely explored in the area of biodiesel, along with their co-products, in applications in industries such as medicine, food and cosmetics. There should also be more of a focus on dielectric aspects of algal oils, which could lead to a more sustainable impact on the energy sector.

4.6. Flash Point and Fire Point

The major concern that should be considered with the liquid-immersed power transformer is its fire properties. The temperature inside power transformers can increase to more than 200 °C due to localized hotspots, damaging both the solid and liquid insulants [173]. This phenomenon over a long time interval could lead to complete flashover of the solid insulation spacers, causing a major fire hazard and complete breakdown in the power system network. There are ASTM standards for measuring the fire classes of insulating fluids. ASTM D92 [174] is the Cleveland Open-Cup (COC) method: a test cup is filled with a test sample (70 mL), and then the temperature is allowed to increase at a high rate for the initial duration and then decrease once the flash point is reached. A flame is swept across the cup at predetermined intervals, and the lowest temperature at which both air and vapour pressure combine to ignite the mixture near the fluid's surface is quantified as the flash point. The experiment is further continued until the test specimen ignites and the burning is sustained for at least five seconds, and the temperature during this process is considered the fire point. ASTM D93 [175] is the Pensky-Martens Closed-Cup (PMCC) method, which involves a test cup made of brass filled with a test specimen and closed. The specimen is heated and stirred at a specific rate through two different procedures, and a flame is ignited by directing an ignition source at the test cup at intermittent time spans, with an interruption in the stirring process once the flame is detected. Considering the above standards developed for both the flash point and fire point, a wide range of literature is available for different transformer insulating fluids. Cai et al. [176] tested the fire-retardant characteristics of MO and NE. To assess the combustion of these two fluids, heating was performed with an oxyacetylene flame. It was concluded that MO continuously burned, whereas NE exhibited self-extinguishing behaviour after the flame was put out in five minutes. The reason for this phenomenon is the improved ignition characteristics of NE compared to MO. Mazzaro et al. [177] performed the spray test at 25 °C to determine the fire properties of NE and MO. The fluxing of oils was done in the form of a spray (50 °C, 7 bar) with a propane flame. MO exhibited flame maintenance for longer, with no fire extinguishing or dark smoke, whereas NE was less capable of maintaining a flame, with a shut-down time of less than two seconds and the release of grey smoke. Daghrhah [178] studied the reproducibility of the flash point and fire point of NE under laboratory conditions for both the open-cup and closed-cup methods. The COC technique showed a higher deviation in both flash point and fire point compared to the PMCC method. It was further confirmed that ageing of the NE fluid would not affect its fire class, but more data from testing of in-service EFs is still suggested to verify the findings obtained under laboratory conditions. Now, a mixture of NE and SE has also been investigated [179], providing no improvement in the fire point or flash point. Similarly to the above findings, the flash points and fire points of different vegetable oils for power transformer applications are shown in Table 6.

Table 6. Flash points and fire points of vegetable oils.

Oil	Flash Point (°C)	Fire Point (°C)
Palm [180]	295	315
Olive [181]	330	355
Rapeseed [182]	325	340
Pongamia Pinnata [73]	240	255
Sunflower [182]	270	285
Castor oil [183]	210	230
Coconut [184]	335	350
Soyabean [184]	>315	>350

Table 7 indicates the flash points and fire points of algal oils, where the maximum limit obtained depends on the algal species. Most of the species have still not been tested for their fire class properties in engine applications or confirmed as replacements for conventional diesel oil. The flash point and fire properties of algal oil depend on the chain lengths of fatty acid methyl esters and the degree of unsaturation. Algae containing more saturated fatty acids have higher flash points and release less harmful gases, whereas algae with more unsaturated fatty acids have lower flash points and release more smoke [185]. Biofuels from algal species tested for their fire class properties were not found to be in the range suitable for power transformer applications. Depending on the characteristics of the algal species, some of the biofuels had fire class properties closer to those of mineral oil and much lower than those of fuels extracted from vegetable and plant crops. However, the blending of biofuels with conventional mineral oil is a possible solution to improve the flash point and fire point of algal oil [186,187]. Thus, considering the present data available on flash point and fire point, it is not possible to draw conclusions about the application of algal oils to transformers.

Table 7. Flash points and fire points of algal oils.

Algae Species Name	Flash Point (°C)	Fire Point (°C)
<i>Botryococcus</i> sp. [188]	144	-
<i>Ulva fasciata</i> [124]	51	57
<i>Spirulina</i> [189]	130	-
<i>Monoraphidium</i> sp. [190]	99	102
<i>Chlorella sorokiniana</i> [190]	94	97
<i>Spirogyra</i> [191]	78	-
<i>Lyngbya</i> sp. [192]	74	76
<i>Synechococcus</i> [192]	71	73
<i>Chlorella vulgaris</i> [193]	217	235

4.7. Oxidation Stability

The key factor influencing the effectiveness of insulating fluids in transformers is their oxidation stability. The dissolved oxygen present naturally in the fluid and its inflow from the external environment into transformers can increase the acidity and dissipation factor of insulating fluids [194]. The capability of the insulating fluid to resist oxidation under thermal stress, along with the presence of oxygen and copper coil, is inferred as its oxidation stability. ASTM D2440 [195] provides the procedure for the determination of oxidation stability in MO while maintaining a temperature of 110 °C for 72 h or 164 h. The fluid is examined at the end of the ageing period to check for sludge formation and measure acidity as an indirect quantification of oxidation stability. ASTM D1934 [69] presents the open-beaker method for determining oxidative ageing of insulating fluids with and without a metal catalyst and is applicable only to fluids with flash points higher than 130 °C. IEC 61125 [196] provides a similar methodology for materials to be diffused in the test specimen, but at 120 °C and 100 °C in oxygen and air, depending on the method. The Rotating Bomb Oxidation Test (RBOT), mostly used for MO, evaluates the time it takes for oxygen pressure to drop to a predetermined threshold. Although efforts are being made to develop better tests for NEs, a recognized standard for these fluids has yet to be published. MO oxidizes at a much lower temperature (105 °C), leading to the formation of sludge, thereby worsening its dielectric properties [197]. SO oxidizes at a temperature of 175 °C, increasing the viscosity, followed by thermal breakdown at 230 °C [84]. NEs tend to be more prone to oxidation because their molecular structure contains more fatty acid chains, as opposed to SEs, which begin oxidation at 125 °C, based on the percentage of saturated fatty acid content [198]. The occurrence of byproducts in

natural EFs due to oxygen (alcohols, aldehydes, acids, and ketones) and their increase in viscosity can be attributed to the existence of carbon–carbon double bonds, which serve as the primary sites for oxidation reactions [17]. The polyunsaturated fatty acids present in EFs are oxidized much more quickly compared to monounsaturated fatty acids. Thus, NEs are best suited for sealed power transformers with nitrogen as a headspace due to its lower oxidation stability compared with other dielectric fluids. To increase the oxidation stability of NE, considerable research has been conducted recently with the inclusion of different antioxidants [199]. Biofuels derived from algae species containing higher amounts of docosahexaenoic acid (DHA) have better oxidation stability, but there is still no physical explanation for these results [200]. There has been various research on the addition of antioxidants and esters [201,202] to enhance the oxidation stability, but the functionality of algal oils should be verified for standards developed for power transformers.

4.8. Partial Discharge

The localized electrical discharges that partially bridge the insulation barrier are known as partial discharges (PDs) and have been found to be a major cause of failure in transformer insulation [203]. These discharges occur due to projections in the copper winding and electric field enhancement at weak spots and edges within the transformer [204,205]. There are different discharge sources (voids, surface, corona) that can result in PDs inside the transformer [206], and multiple techniques have been investigated for the isolation of these discharges [207,208]. Identifying these incipient discharges is a major difficulty, with no particular standards defined for their detection. IEC 61294 [209] and IEC 60270 [210] were the initial standards intended for PD quantification in transformers based on the magnitude of apparent charge and repetitive pulses formed during discharges. Later, additional approaches [211,212] (acoustic emission (AE), radio frequency (RF), ultra-high frequency (UHF) and optical fibre), as shown in Figure 7, were investigated in laboratory conditions and utilized in field power transformers. The PD in a transformer generates energy near its source due to mechanical stress, resulting in AE [213], which is detected by a piezoelectric sensor (AE sensor). The transformer unit is provided with a specific window for the installation of RF [214] and UHF sensors [215] for PD detection and localization. The frequency characteristics of PDs inside the transformer are in the UV region [216], and their emission intensity can be related to the intensity of discharges. Thus, an optical fibre [217,218] can also be used for indirect PD measurement by detecting absorption characteristics matching the emission wavelength regions of different discharges occurring inside the power transformer.

These new methodologies should be compared with the conventional PD measurement unit [219], which uses a coupling capacitor, to determine their accuracy. The various factors that could possibly initiate PDs in transformers are shown in Figure 8. Chandrasekar et al. [220] studied the PD characteristics of palm oil and corn oil for their comparison with MO, finding lower PD activity in the former compared to the latter. Also, a frequency analysis revealed PD pulses with different defects (rod–plane, needle–plane) to be negligible for both EF and MO. The Rogowski coil provided better accuracy than the shunt sensor in detecting PDs in palm oil and MO [221]. The PD burst characteristics examined in EF and MO using a non-homogeneous field (needle–plane electrode) with different PD parameters (charge transfer, time interval between subsequent discharges, average number of PD pulses) did not exhibit any differences between different transformer dielectric fluids [222].

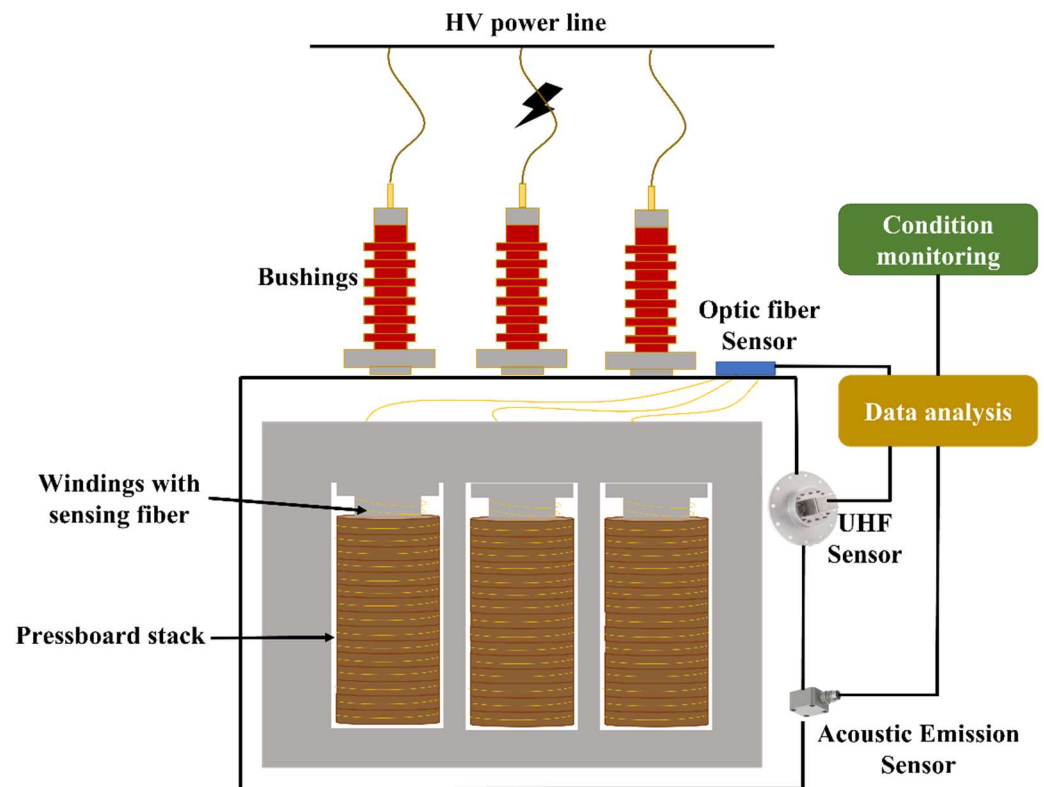


Figure 7. Sensors used for PD detection in power transformers.

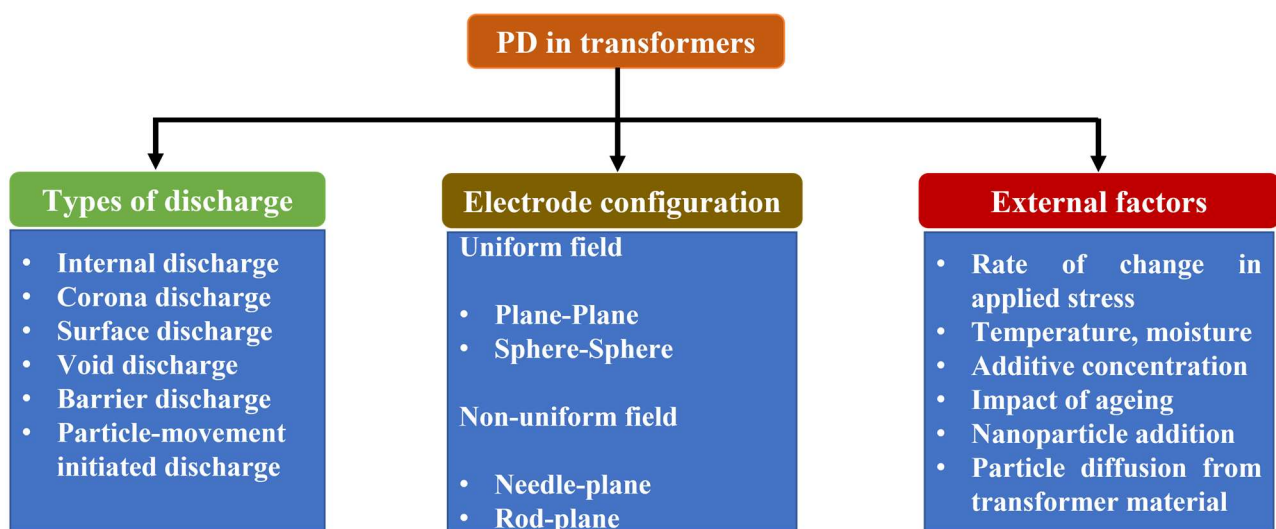


Figure 8. Factors affecting PD formation in power transformers.

Huang et al. [223] investigated the effect of different temperatures on PDs of SE under AC voltages. The PD magnitude and its repetition rate increased with temperature, and a drop in PD pulses occurring in the negative cycle was observed. The PD assessment of barriers in MO and SE [224] indicated better detection using a photo-multiplier tube (PMT) with lower discharges in EF, concluding the optical technique to be a useful method for non-sinusoidal waveforms. The impact of moisture content on PDIV indicated a lower voltage for MO compared to EF [225], and this proves the negligible levels of polymerization reactions and wax formation. The PD pattern is altered with higher moisture content, indicating lower PDIV for MO compared to synthetic EF [226]. The PDIV of NE was higher for different discharges (surface discharges, barrier discharges with pressboard) compared

to that of MO, whereas the PD pattern was the same in both fluids [227]. Similarly, the PD trends with PFAE and MO were similar, but for soyabean oil, a higher magnitude was deduced from the NQP (N-PD occurrence, Q-PD magnitude, P-PD phase angle) patterns [228]. Jaroszewski et al. [229] investigated the effect of different test methods and various electrode configurations for PD measurement of NE in the presence of dissolved water. NE exhibited changes in its molecular structure, ionization energy and mobility with the addition of water content, indicating a reduction in PDIV in the moist condition compared to the dry condition. Kanakambaran et al. [230] studied the identification of PD using Fibre Bragg Gratings (FBGs) and inferred that frequency spectra for different discharges were separable with the use of a Ternary plot and provided better accuracy in the localization of multiple discharges [231]. Rice bran and sunflower oils for transformer insulation have been compared with MO by Mariprasath et al. [232] for their PD activity. It was concluded that both EFs (rice bran, sunflower) provided better stability and dielectric strength upon ageing. The rice bran oil provided better resistance to PD characteristics with a lower number of discharges than sunflower and MO, but it is necessary to perform continuous monitoring of the viscosity of EFs with ageing of transformer insulation. The rate of change in the applied voltage profile plays a major role in the initiation of PD activity in transformers [233]. The advancement of decentralized power generation into the grid can result in harmonic voltages, with higher total harmonic distortion (THD) observed to be around 60% [234]. Soyabean oil tested for ageing performance for use in transformers [68] showed a higher PDIV under DC voltages compared to AC voltages. Also, the effect of the AC voltage profile under harmonic frequencies and the impact of overlapping harmonic frequencies with different distortions on thermally aged soyabean oil led to only a minimal change in its PDIV, and thus the oil could be concluded to resist harmonic voltages. Soumya et al. [235] investigated EF FR3 Envirotemp for its thermal ageing performance under different atmospheres (Air, He and N₂), concluding that an air medium results in more degradation than the others. Also, the harmonic voltages with THD in FR3 oil decreased with thermal ageing, whereas their dominance in the frequency characteristics was measured at 1 GHz, irrespective of the voltage profiles. A proportion of 20% SE with MO [236] exhibited a higher PDIV than MO, with fewer discharges under DC and AC with different harmonics distortion percentages. The flux densities in the transformer have been found to be in the range of 700 mT, and thus, an understanding of the impact of the magnetic field on the PD phenomenon is required, along with the addition of an electric field [237]. Amizhtan et al. [238] studied this impact on MO with AC voltages using two sensors (UHF, optical fibre), indicating a lower PDIV with the influence of a magnetic field. Srinivasan et al. [239] investigated the behaviour of punga oil as a transformer insulant by testing it under both AC and DC voltages with the impact of a magnetic field (85 mT). The identification of PDs in punga oil using the white fibre was more accurate than that using the red fibre and the UHF sensor. Gautam et al. [240] investigated the effect of the magnetic field on particle movement in EF with PD activity using a UHF sensor and fluorescent fibre. The PDIV decreased with ageing duration for different voltage profiles, and the accuracy of the fluorescent fibre in PD detection declined during the ageing process due to variation in the emission characteristics of EF. Similar studies were performed on a synthetic EF with the addition of zeolite [241], resulting in a change in the frequency characteristics of PDs with the impact of the magnetic field. Apart from transformer applications, PD detection based on fluorescence emission [242] can be used in high-temperature superconductor-based power applications. The PD mechanism of fluids requires intensive studies with different simulated faulty conditions to assess their performance, and algal oils still require more data before their application to power transformers.

4.9. Breakdown Voltage

A liquid-immersed power transformer containing an insulating fluid as a coolant should possess a high breakdown strength under electrical stresses occurring during its operation. The requirement for high resistance of EFs to breakdown increases with the transition of power networks to higher-voltage transmission lines, along with the rise in costs of insulation design [243]. This necessitates a substantial effort by insulation engineers to improve the quality of insulating fluid, considering its limitations regarding the environment. Mostly, the liquid is tested for BD phenomena under nominal voltage profiles (AC, DC) [244] and transient voltage profiles (lightning impulse (LI) voltage, switching impulse (SI) voltage) [245,246]. The standards for testing the BDV of insulating fluid specify measurements under homogeneous field conditions [247,248] with spherical electrodes and defined gap spacing, whereas more research works are now performed in non-homogeneous fields to identify streamer discharge patterns [249] under varying gap distances, tip radii and voltage waveforms. EFs more viscous than MO must be given a longer relaxation time before undergoing experimental tests and between subsequent breakdown intervals, thus providing sufficient time for gas bubble dispersion [63]. The BDV is affected by multiple parameters, similarly to the PDIV. There are many influencing elements and an integrated mechanism that make the BDV stochastic in nature. The BDV of insulating fluids under AC voltage is lower than that under DC voltages due to the higher dV/dt in the applied AC waveform. Further, the BDV is polarity-dependent, with increased voltage noticed under $-DC$ voltage compared to $+DC$ voltage. During the transformer operation, solid particles from either the copper winding or pressboard insulation can diffuse into the insulating fluid, and these solid impurities are aligned with the impact of external field conditions, creating electrode gaps and initiating the breakdown process [250]. Cheng et al. [251] studied the dispersion of cellulosic fibres and copper particles in both MO and NE under DC voltages, observing a change in particle alignment along the electrode for both fluids. The particles in MO bridge the gap at an earlier stage, whereas the particles in EF get attached to electrode edges, causing early breakdown in MO. It was also inferred that particle alignment in an insulating fluid depends on parameters (viscous drag force, interaction between the particles, buoyancy force, dielectrophoretic force) that can influence the breakdown mechanism. Similar conclusions were made under non-uniform field conditions for both MO and NE [252].

The molecular structure of different EFs used for insulation influences the breakdown strength [253]; MIDEL 1215, having relatively high unsaturated fatty acid content, exhibits a lower AC BDV than coconut oil, with more saturated fatty acids. The lower ionization potential of MIDEL 1215 has led to premature breakdown compared to coconut oil. Beroual et al. [254] studied the use of *Jatropha curcas* methyl ester oil (JMEO) for AC and DC breakdown under uniform field configurations. JMEO had a higher BDV than MO, and the mixed fluid (80% JMEO + 20% MO) had a higher BDV than the individual fluids. DC voltage investigations of NEs (olive oil, rapeseed oil) for BDV showed an improved voltage for SE and MO [255]. Compared to JMEO, a mixture of olive oil (80%) and MO (20%) was found to be optimal for transformer applications. On the other hand, an increase in the non-homogeneity of field configurations results in a marginal reduction in the BDV of NE at lower gap spacing (10 mm) compared to MO, where a change is noticed at longer gap spacings (25 mm) [256]. Despite similar field distributions, the protection risk associated with NE is reduced by around 30% under AC voltages due to its lower dielectric strength at longer gap distances [257]. The propagation of streamers in the liquid (velocity, tip radius, polarity) plays a major role in the breakdown mechanism, where both EFs had a higher streamer inception voltage compared to MO [258]. Antioxidants are used with NE to improve oxidation stability, and Raymon et al. [199] used different antioxidants (citric

acid, BHT, BHA, Propyl gallate) with vegetable oils (soyabean, sunflower, corn and rice bran), improving their BDV by more than 50%. Also, the addition of electronic scavenger additives (carbon tetrachloride (CCl_4) and iodomethane (CH_3I)) improved the BDV of NE by 15% with CCl_4 and only 2% in the case of CH_3I [259]. This improvement in the BDV of NE was found to be higher than its impact with different nanoparticles. The BDV of PFAE under different electrode configurations and gap spacings to observe its electric field distributions showed that PFAE also provided better insulation than other EFs under ageing conditions, suggesting it to be a suitable insulating fluid for power transformer applications [91,172]. The thermal ageing of EFs (palm oil, FR3) and MO at 160 °C in the presence of pressboard insulation indicated better BDVs for palm oil and MO compared to FR3 [260]. The formation of low-molecular-weight acids and the percentage of water diffusion in FR3 were found to reduce its breakdown strength with thermal ageing. SEs with low pour points have been compared with MO for thermal ageing performance and were tested for BDV [261] with three different needle tip radii (0.93 μm , 5.46 μm , 10.75 μm). It was concluded that BDV was higher with a larger tip radius, and its magnitude was higher for SE compared to MO.

The EF should also be tested for transient overvoltage before its application to transformers, with IEC 60060-2 [262] providing the necessary guidelines on the testing procedures. During this analysis, the pre-breakdown phenomenon of the EF should be well understood, where streamer characteristics (electrode configurations, stopping length, light emission, streamer shape) are emphasized [263,264]. Sitorus et al. [265] investigated vegetable oil extracted from *Jatropha curcas* seeds for its breakdown characteristics under lightning impulse and inferred that its pre-breakdown parameters were similar to those of MO. Similarly, refined palm oil was compared with MO under both polarities of impulse voltages [266]. Under positive polarity, palm oil exhibited a higher LI BDV than MO with increased streamer stopping length, whereas under negative polarity, the LI BDV of MO exceeded that of palm oil by around 60.5%. The natural EF tested with a wide range of gap spacings (3 mm to 55 mm) and insulation interfaces for LI showed better characteristics, resembling the behaviour of MO [267]. Liu et al. [268] analyzed the pressboard interface and measured the LI BDV of both SE and NE under a non-homogeneous (point–plane) configuration with an electrode distance of 75 mm. The NE had a negligible influence on acceleration voltage with the pressboard interface under positive polarity, and at larger gap spacings, streamer velocities were accelerated for both NE and MO under negative polarity. To conclude, the pressboard interface with EF results in lower LI BDV compared with MO for a fixed gap distance. Palm oil and coconut oil tested for LI [269] under small gap distances (2 mm, 3.8 mm, 6 mm) with non-uniform field configurations (needle–sphere) exhibited a negligible difference in their BDVs under positive polarity but showed an 11% increase compared to MO. But under negative polarity, both the EFs had an LI BDV that was 22.5% lower than that of MO. The molecular structure of EFs can influence the LI BDV [270], as the dissociation of ions in EFs happens more easily than in MO, with space charge influencing the electric field distributions under different gap spacings. This could have been the reason for the lower negative LI BDV of NE compared to that of MO. Reffas et al. [271] noticed a change in the streamer behaviour of EFs and MO, reporting greater luminosity in negative streamers compared to positive streamers. The streamer branching for MO always starts at the streamer ending point, whereas for NE and SE fluids, the branching starts at electrode points. Further, streamers were found to be higher under positive polarity than under negative polarity, and research confirmed that olive oil and MO had similar streamer characteristics with impulse voltages. The investigation of the LI BDV of EFs with MO under a quasi-uniform field showed no polarity effect with different testing methodologies under varying gap spacings. The SI BDVs of both EFs and

MO were lower than LI BDVs [272]. NEs with varying viscosities ($8 \text{ mm}^2/\text{s}$, $4.6 \text{ mm}^2/\text{s}$) showed a significant difference only in the case of positive polarity, with no change noticed under negative polarity [273]. Also, the NE with low viscosity exhibited a higher light intensity than the more viscous fluid due to greater ionization. Williamson et al. [274] measured the effect of variation in the relative humidity on the LI BDV of EFs and MO. The authors reported that NE fluid showed a higher LI BDV than SE and MO, with no significant change noticed when varying the humidity of insulating fluids on the LI BDV. There has been much literature on impulse voltage testing of EFs for their application to power transformers, but more test data on switching impulse (SI) voltages are required for biodegradable fluids. Per ASTM D1816, the breakdown voltage of algal oil is around 35 kV [29], but the breakdown mechanism of biofuels from different algal species must be investigated under different voltage profiles (AC, DC, LI, SI) and field configurations in laboratory conditions to observe their dielectric withstand strength. Once this is done, then insulation engineers can relate their response to existing standards on ester fluids and mineral oil for proper operation in power transformer networks.

4.10. Reclamation and Recycling

The reclamation of service-aged insulating fluids is the process of removing the contaminants and degraded products for the reuse of the fluids in transformers. There are two methods of reclamation: one method is reclamation through percolation, and the other method is reclamation through contact [275]. The former technique involves the collection of service-aged fluid from the bottom of electrical equipment, which is then heated and passed through different adsorbents or layers of filters and then finally delivered back to the top of the electrical equipment. The latter techniques involve reclamation of oil using a suitable container with a specific adsorbent, which is possible only in laboratory applications and not in real-time electrical equipment or industrial applications. Nevertheless, this method is useful for recycling waste oils for other applications. There are numerous recycling techniques for restoring the insulating properties of transformer fluids for reuse, as well as other methods to turn them into value-added products or to lessen the detrimental effects of waste transformer oil on the environment and other living things. IEEE Std. C57.637 [276] and IEEE C57.147 [63] are the main standards used for reclamation of mineral oil and ester fluids respectively. Saffidine et al. performed the reclamation of transformer oil using four different adsorbents (activated carbon (ACH), silica gel (SG), magnesium oxide (MG) and activated bentonite (AB)) and concluded that 1% ACH, 6% SG, 1% MG and 1% AB led to better enhancement of permittivity, colour, dissipation factor and acid number [277]. Duraisamy et al. [278] investigated the performance of polyaniline (PANI)-coated Kappa Cotton (KPC) and activated clay–biopolymer, bentonite (aB) composite and chitosan (CTN), to recover the aged transformer oil. The natural compounds from each of these adsorbents eliminate the polar and non-polar contaminants. Sepiolite as an adsorbent for thermally aged ester fluid showed better adsorption capability, with partial recovery of fluid properties, which was confirmed using UV-Vis spectroscopy and NMR analysis [279]. Amalanathan et al. [280] studied the influence of surface-modified bentonite as an adsorbent with thermally aged ester fluid and observed better inception and breakdown voltages, along with the removal of solid impurities, confirmed through FTIR. In addition, this adsorbent reduced streaming electrification of aged ester fluids at the pressboard interface, indicating its better adsorption to ionic impurities. Thus, by using the suggested reclamation procedure, a specific strategy will lessen the risk associated with incineration, potentially making it a cost-effective and environmentally beneficial choice.

4.11. Costs and Environmental Footprint

Algal oil is presently considerably more costly and typically has a greater energy and resource footprint compared to modern vegetable ester oils derived from crops such as soybean, rapeseed, or canola; however, it may provide benefits in land utilization and long-term scalability under optimal conditions [30,281–283].

4.11.1. Cost Comparison

Even under ideal scenarios using improved solvents and processes, techno-economic assessments for algal lipids and biodiesel estimate minimal product costs, in the range of approximately 8–10 USD per gallon of biodiesel, which is still about 3–4X the price of fossil diesel. According to earlier NREL work on microalgae lipids, the modelled baseline costs for algal oil are more than \$200 USD per barrel. Aggressive “best-case” R&D scenarios could lower costs below those of conventional crude oil, but they would require significant, as yet unrealized, gains in productivity and process efficiency. Large-scale commercial production of vegetable oils for advanced esters, such as canola, soybean, and rapeseed, is the exception. LCAs and TEAs treat these oils as relatively mature, cost-competitive feedstocks for biodiesel and natural ester fluids, with production economics driven more by commodity oil prices and agricultural yields than by intricate downstream processing.

4.11.2. Environmental Footprint Comparison

LCAs of microalgal biofuel systems reveal that, unless very high productivities, efficient nutrient recycling, and low-impact energy sources are assumed, current algal oil routes can have high energy use, greenhouse-gas emissions, and water demand, primarily due to cultivation (nutrients, mixing/aeration), harvesting/dewatering, and so on [284]. Even when alternative, “greener” solvents are utilized, detailed assessments show that solvent-based lipid extraction and cell disruption stages are significant contributors to energy intensity and environmental impacts in algal biodiesel synthesis. Although there are environmental hotspots in farming (fertilizers, pesticides, field emissions) and land use, vegetable oil-based esters usually demonstrate clear greenhouse-gas benefits over fossil fuels. LCAs for the rapeseed, sunflower, and soybean pathways show that the main impacts, including toxicity, eutrophication, and fossil energy use, are caused by seed production and drying/extraction [285,286]. Since microalgae can theoretically be grown on non-arable sites and with non-potable water, they do not require arable land. As a result, LCAs frequently highlight less rivalry with food production and, if extremely high areal productivities are attained, possibly lower land-use impacts per unit of oil. Although these are future-looking, not existing, industrial realities, scenario evaluations suggest that algal systems might approach or surpass crop-based oils in GHG performance with significant improvements in biomass productivity, lipid content, and nutrient/energy recycling. Algal oil is still more expensive and has a larger environmental impact than mature vegetable ester feedstocks today, mostly due to its energy- and nutrient-intensive production and intricate downstream processing. Although they present issues with land use and expensive farming inputs, advanced vegetable ester oils used for transformer fluids have the advantages of simpler processing and well-established agricultural supply networks, which improve their current cost and environmental performance.

5. The Next Frontier in Algal Research

Algal oils are currently being researched across a wide range of applications, and based on the findings of the following studies, they could soon be considered sustainable biofuels in the power sector.

- The selection of suitable algal species for the extraction of biofuel is necessary, and their properties should comply with the nominal standards developed for transformers.
- The tangential electrical stress exhibited by algal oils in combination with insulating pressboard/paper insulation illustrates their feasibility with the surrounding dielectric medium inside power transformers.
- Fault mechanisms such as protrusions in windings, particle defects, and surface discharge should be investigated for algal oils in laboratory conditions before their application to real-time power transformers.
- The evolution of gases under fault conditions, such as partial discharge, thermal faults and arcing, should be compared between algal and second-generation biofuels.
- Based on the various observations of algal oils, a separate IEEE/IEC standard should be developed for their precautionary and safe application in power transformers.

6. Future Perspectives and Conclusions

Comprehensive information on the biodegradable ester fluids and algal oils was used to draw the following conclusions:

- The precautionary measures followed for second-generation feedstock in transformers should be tested and validated for third-generation feedstock. Considering biodegradability and susceptibility to environmental conditions, the fatty acid composition and lipid content of biofuels from different algal species should be examined to determine a suitable composition and exact composition of an insulating fluid for power transformers.
- Some of the algal bio-oils extracted from different algal species have viscous properties similar to those of oils from vegetable and plant crops. This suggests that algal oils can be used in transformers designed for biodegradable ester fluids, providing a similar heat transfer mechanism between the windings involved in the pressboard stacks. The electrostatic charge separation at the fluid/pressboard interfaces is also a function of viscosity and conductivity, and more investigations on algal oils are required to compare them with oils from second-generation feedstock.
- The flash point and fire point of algal oils are suitable for diesel engine applications, but for their use in power transformers, the limit depends on the algal species, and the maximum value is closer to that of conventional mineral oil. Thus, algal oils could be considered to be under thermal class K, which is lower than thermal class O of second-generation feedstocks. These properties should be considered by insulation engineers before implementing algal-oil-based transformers near load centres.
- Extensive research is needed to determine how the dielectric properties of algal oils, such as permittivity and the dissipation factor, might affect the lifetime of cellulose insulation and fluids inside transformers. Further, the partial discharge and breakdown voltage of the insulating fluid depend on the chemical constituents and stability, which should be researched in algal oils. For the establishment of an IEC or IEEE standard, it is necessary to comprehend how algal oils limit electron avalanche in contrast to second-generation oils. Further, more data are still required on the effects of nominal voltage profiles (AC, DC and +DC), harmonic voltage profiles and transients (impulse voltages and switching surges) on the partial discharge mechanism and breakdown in algal oils under different simulated faulty conditions.
- The oxidation stability of algal oils was found to be higher for species containing DHA, which complies with power transformer standards, and more studies in laboratory conditions could explore their use in either air-forced or sealed-type power transformer units. Accelerated thermal ageing is another important aspect to be understood for algal oils, which can provide information on their degradation mechanism and lifetime inside transformers. The versatility of algal biofuels, pressboard insulation, and design

modifications may open the door for green fluid to enter the energy sector, even though their distinct qualities may correspond with feedstocks of the second generation.

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