Industrial Crops & Products 215 (2024) 118674

Contents lists available at ScienceDirect

Industrial Crops & Products

journal homepage: www.elsevier.com/locate/indcrop

# Canola oil: A renewable and sustainable green dielectric liquid for transformer insulation

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ARTICLE INFO

*Keywords:*
Transformers
Vegetable insulating liquids
Canola oil
Global warming potential

ABSTRACT

In the last decades, vegetable-based insulating liquids, derived from plant seeds, have emerged as an environmentally friendly alternative to traditional petroleum-based mineral insulating oils. These vegetable oils exhibit excellent characteristics for high-voltage insulation, including remarkable high-temperature stability, as evident in their flash and fire points. Furthermore, their high water absorption capacity may serve to safeguard the integrity of paper insulation within transformers. However, their practical application is limited to sealed transformers due to their susceptibility to oxidation. Additionally, using these oils in regions with low temperatures presents challenges because of their poor flow properties under cold conditions. Canola oil, derived from canola seeds, offers a balanced set of properties, particularly concerning pour point and oxidation stability, attributable to its unique fatty acid composition. This study reviews deeply into the potential, prospects, and possible enhancements that can be applied to canola oil. Significant tutorial elements as well as some analyses are included. The aim is to reveal the deep attributes of canola oil as a suitable insulating liquid for both free-breathing and hermetically sealed transformers, while also ensuring it serves as an efficient cooling medium for transformers operating in extremely cold environments. Of the many properties examined, this review pays particular attention to oxidation stability and the flow characteristics of the oil.

## 1. Introduction

The term ‘Canola’ is a fusion of ‘Can’ and ‘Ola’ where ‘Can’ represents Canada, and ‘Ola’ signifies oil (Hanif, 2020). Canola seeds are a relatively recent introduction with their origins in Canada. These seeds are derived from various cultivars of rapeseed, including *Brassica napus* and *Brassica rapa,* and they contain less than 2% erucic acid (Daun et al., 2015). This oilseed was made in Canada by two agricultural scientists, Keith Downey, and Baldur Rosmund Stefansson, at the University of Manitoba in 1974 (Stefansson, 2009, Parvin, 2021, Barthet, 2015, Ghazani and Marangoni, 2013). Canola seed is usually planted in the spring, and it takes three to four months before the harvest (Murthy and Kotebavi, 2019). Fig. 1 shows canola plants and the harvested dried canola seeds. Like other seeds, the oil in the seed is extracted through a mechanical press and chemical extraction. The oil yield of the seed is high relative to other seeds as it contains 43–48 percent yield (Barthet, 2015, Gaber et al., 2018). Several methods like solvent extraction, hot press, cold press, and many more have been optimized for the extraction of canola oil and it was observed that the hot-pressed method is one of the best methods for the extraction of canola oil (Ghazani et al., 2014). A simple method of canola oil extraction and purification is presented in Fig. 2. Canola plant has drawn more attention and has become the major oilseed crop in the world (Yantai et al., 2016, Khadem et al., 2023). Due to its unique qualities, it has found many applications in both industrial and domestic uses (Thiyam-Holländer et al., 2012). The oil extracted from this seed is among the healthiest oils with a low percentage of saturated fatty acid. In addition, it has contributed immensely to the economic growth of the world. In the last 21 years, canola oil has been mainly extracted in Canada from modified Brassica napus and the low percentage of erucic acid causes a high percentage of oleic acid in the oil (60%) (Ghazani and Marangoni, 2013). The fatty acid composition of canola oil, palm kernel oil, jatropha oil, coconut oil, soybean oil, and

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https://doi.org/10.1016/j.indcrop.2024.118674
Received 31 December 2023; Received in revised form 18 March 2024; Accepted 30 April 2024

**Fig. 1.** Canola plants and seeds (Growers, 2023).

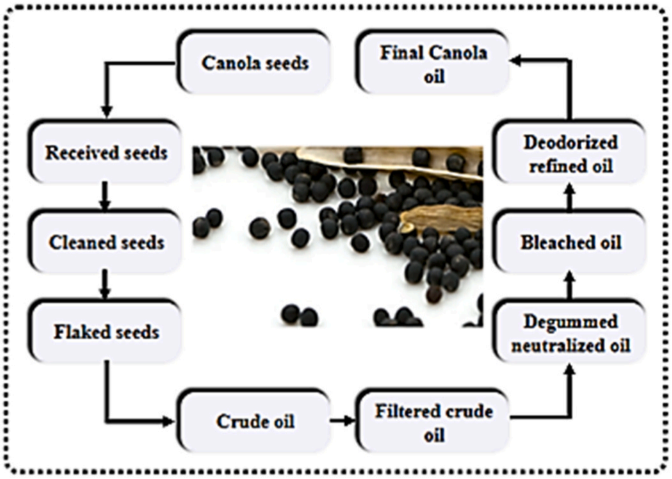


**Fig. 2.** Canola oil extraction and purification process.

rapeseed oil can be seen in Table 1(Ghazani and Marangoni, 2013, Farahmandfar et al., 2015). In recent times, canola oilseed has been ranked the third most important oilseed in the world after Soybeans and Palm, and the third source of oil around the globe (Loganes et al., 2016). According to FAOSTAT (Food and Agriculture Organization Corporate Statistical Database) in 2019, it was reported that the total production of canola seed oil in the world was 24 million tonnes with which Canada took the largest share (Demchuk, 2019). In 2019, the report also shows that the total land area used for rapeseed plantation was 35 million hectares and Canada have the highest percentage. In terms of production, Canada has the largest production yield which amounts to 28% of the world's production (Demchuk, 2019). The charts in Figs. 3–5 shows the leading countries in terms of canola plantation, production, and their geographical location respectively (Demchuk, 2019). In general, the primary source of energy has traditionally been the combustion of conventional fossil fuels, a process that releases carbon and has adverse effects on the environment (Fofana, 2013, Sen and Ganguly, 2017). Furthermore, the spillage of hydrocarbon liquids into the environment has detrimental impacts on both aquatic and terrestrial ecosystems (Enujiugha and Nwanna, 2004). The Paris Agreement, endorsed by numerous countries, aims to decrease greenhouse gas emissions, which has spurred extensive research into green energy systems (Jackson et al., 2018). Over the years, there has been a growing demand for sustainable, renewable, and environmentally friendly sources of energy. Biofuels have received significant attention, with vegetable oil being one of the primary sources (Abdelmalik, 2012). The potential of various vegetable oils, such as Jatropha oil, Palm oil, Cottonseed oil, neem oil, and more, has been extensively investigated as alternative oils. The results indicate that they have the potential to serve as replacements for conventional fossil fuels. Vegetable oils offer environmental benefits due to their biodegradability and favorable emission profiles (Aransiola et al., 2012, Rao et al., 2019, Oparanti et al., 2021a, Oparanti et al., 2021b, Oparanti et al., 2023a). The biological oxygen demand of vegetable oil is high which is a good indication of high biodegradability (Rao et al., 2019). Numerous researchers have explored the utilization of vegetable oil as a fuel in diesel engines and as a dielectric insulating oil in high-voltage equipment, particularly transformers (Hamid et al., 2022, Mohamad et al., 2022, Ab Ghani et al., 2017b). Based on comprehensive research conducted in previous years, the findings indicate that vegetable oil exhibits the potential to serve as a substitute

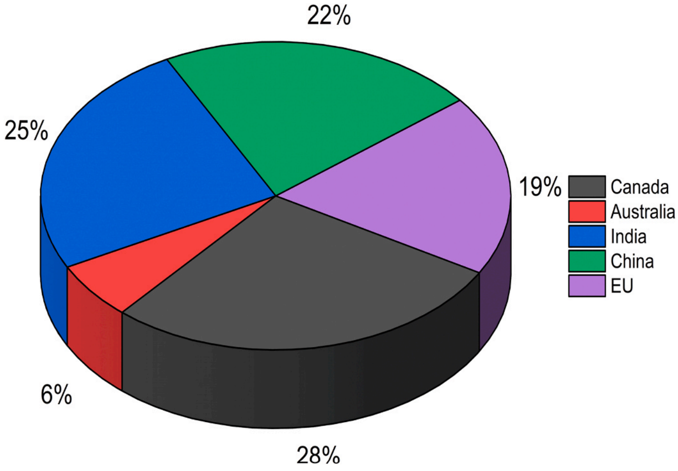


**Fig. 3.** Leading countries in terms of canola cultivation.

**Table 1**
Major fatty acid composition of Canola oil.

| Fatty acid | Canola | Palm kernel oil | Jatropha | Coconut oil | Soybean oil | Rapeseed oil |
|---|---|---|---|---|---|---|
| Caprylic acid C8:0 | - | 3.3 | - | 9.16 | - | - |
| Capric acid C10:0 | - | 3.4 | - | 6.43 | - | - |
| Lauric acid C12:0 | - | 48.2 | - | 45.56 | - | - |
| Myristic C14:0 | 0.07 | 16.2 | 0.1 | 16.65 | 0.08 | - |
| Palmitic C16:0 | 4.29 | 8.4 | 14.2 | 8.21 | 14.04 | 7 |
| Stearic C18:0 | 2.4 | 2.5 | 7.0 | 3.4 | 4.07 | 2 |
| Arachidic C20:0 | 0.8 | - | - | - | - | - |
| Palmitoleic C16:1 | 0.29 | - | - | - | 0.09 | - |
| Oleic C18:1 | 64.40 | 15.4 | 44.7 | 6.27 | 23.27 | 56 |
| Erucic C22:1 | 0.5 | - | - | - | - | - |
| Linoleic C18:2 | 17.40 | 2.3 | 32.8 | 1.39 | 52.18 | 22 |
| Linolenic C18:3 | 9.60 | - | - | - | 5.63 | 10 |

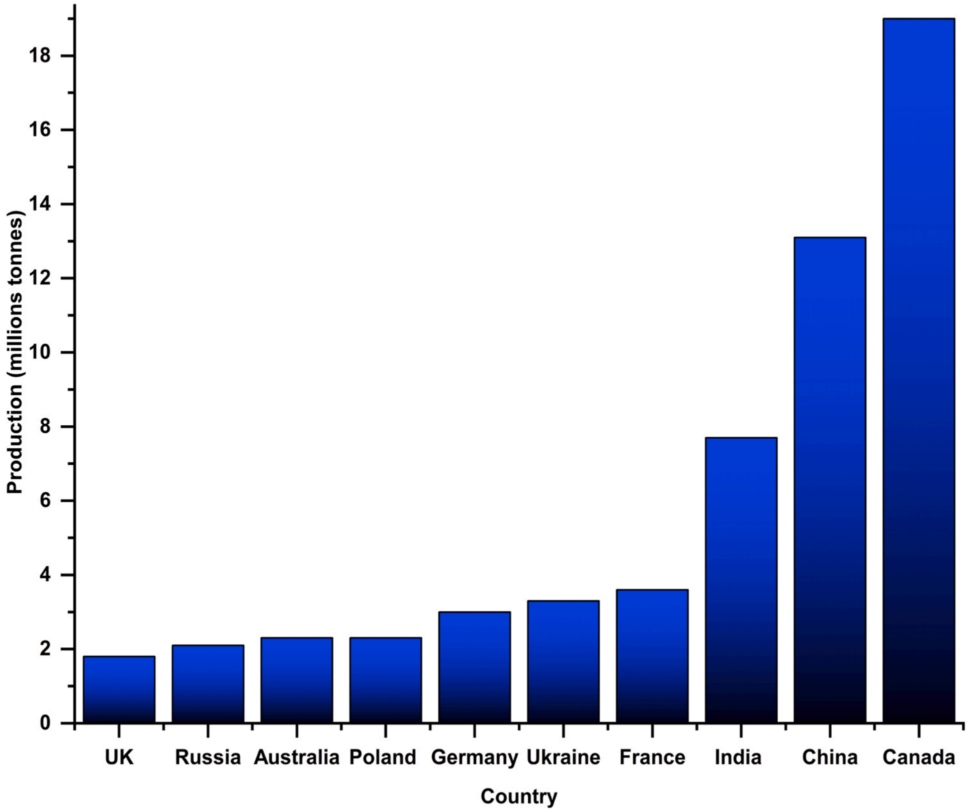


**Fig. 4.** Leading countries in terms of canola production.

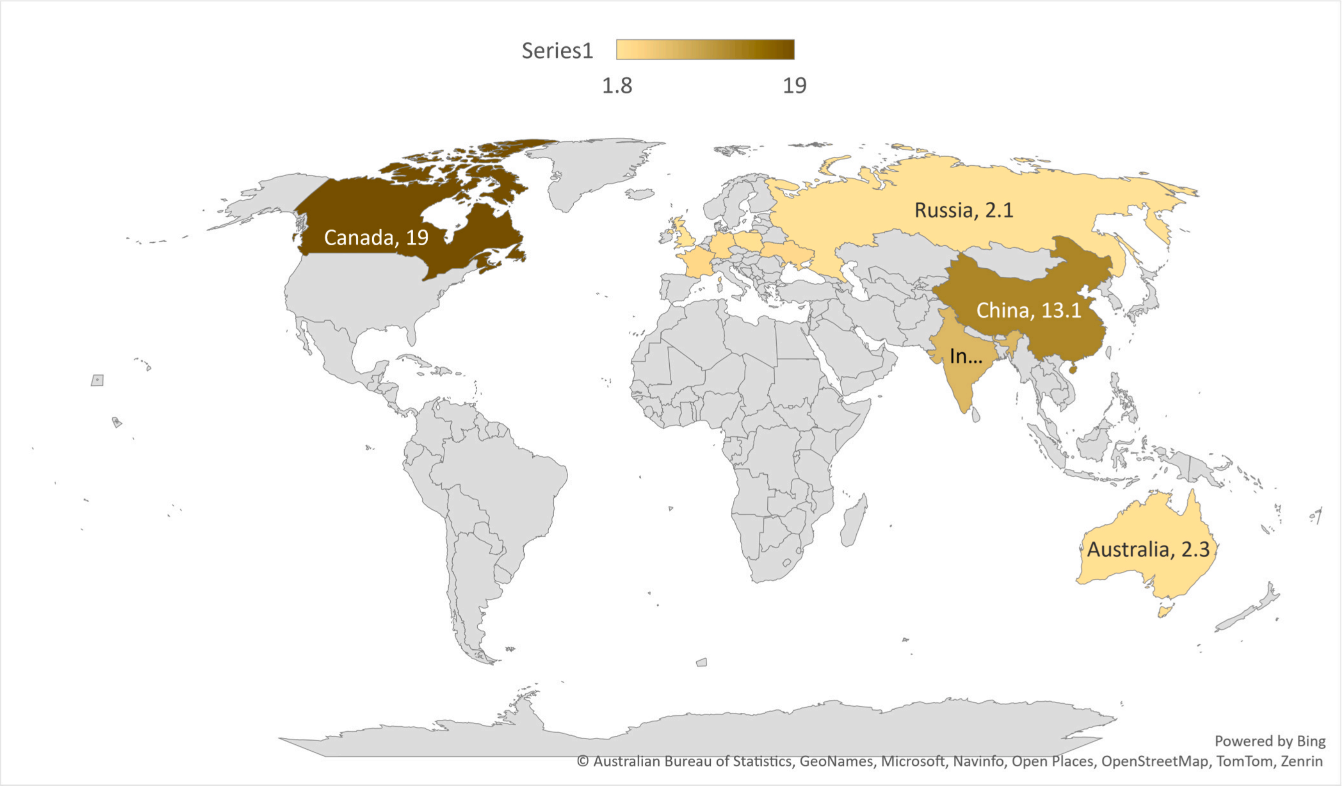


**Fig. 5.** The geographical location showing leading countries in terms of canola production.

for mineral oils commonly used in transformers (Das et al., 2021, Das et al., 2022, Das, 2022). Vegetable oils possess favorable characteristics such as high breakdown strength, elevated flash point and fire point, a suitable dielectric constant, and excellent moisture tolerance (Abdelmalik, 2012, Gnanasekaran and Chavidi, 2018, Das et al., 2023, Das, 2023b, Das, 2023c). The abundance of canola oil cannot be overemphasized, and it is currently finding several applications in high-voltage engineering due to its properties. Table 2 compares the physical properties of canola oil, other vegetable oils, and mineral-insulating oil (Przybylski et al., 2005b, Deoi and De Sousa Malafaiaii, 2021, Alaba et al., 2023, Das et al., 2021, Beltrán et al., 2017). In a prior investigation conducted by Hamid et al., various vegetable oils (including rice bran oil, palm oil, corn oil, sunflower oil, and canola oil) were examined as potential insulating liquids. The study identified canola oil as a highly promising alternative insulating oil, primarily attributed to its excellent insulating properties. The optimization of various properties across all the oils showed that canola oil outperformed the other four oils, particularly excelling in terms of low dissipation factor, high resistivity, and impressive breakdown strength (Hamid et al., 2016). There are some canola-based insulating liquids with excellent insulating properties having a pour point of −31°C and are stated to be useful both in indoor and outdoor free-breathing transformers. However, the oxidation stability assessment is limited to 48 hours, making it challenging to predict the long-term evolutionary performance of this oil. Additionally, in regions with extremely low temperatures, less than −31°C, the flow properties of the oil significantly diminish, leading to potential clogging issues in transformers. Enhancing the properties of canola oil remains of utmost importance, notwithstanding its inherent qualities.

In the following section a comprehensive examination of canola oil, focusing on its essential physical, chemical, and electrical properties. This examination is crucial for gaining a thorough understanding of canola oil's suitability as an insulating liquid in transformers. Moreover, various potential strategies for enhancing canola oil's properties are explored within the scope of this work. By providing this information, researchers are equipped with valuable insights and guidance on how to enhance the properties of vegetable oils, specifically canola oil, for their application in cold regions and free-breathing transformers. It is worth noting that using canola oil as a high-voltage insulator will not create competition with its use as a food product, as it is abundantly available. Instead, it has the potential to contribute to the economic development of the producing nation.

## 2. Key parameters for good insulating oil

The structure of canola oil seen in Fig. 6 has three fatty acids (triglycerides) and glycerol (Sitorus et al., 2016). Fatty acids in vegetable oils vary due to their carbon chain length and the number of double bonds present (Srivastava and Prasad, 2000). As seen in Table 1, the unsaturated fatty acid dominates the fatty acid composition of canola oil. It is important to know that some properties vary from saturated to unsaturated fatty acids, for example, pour point and oxidation stability. In this section, some specific properties of canola oil, which make it a good insulating oil in the transformer will be discussed.

**Table 2**
Physical properties of vegetable oils and mineral oil.

| Parameter | Canola oil | Palm kernel oil | Neem oil | Mineral oil | Jatropha |
|---|---|---|---|---|---|
| Kinematic Viscosity at 40 °C, $mm^2/sec$ | 35.14 | 35.36 | 28.73 | 12 | 10.45 |
| Relative Density (g/$cm^3$, 20 °C) | 0.914–0.917 | 0.91 | 0.90 | 0.88 | 0.90 |
| Flash point, open cup (°C) | 275–300 | 227 | 268–308 | 148 | 260 |
| Pour point (°C) | -24 | 21 | -6 | -50 | -12 |
| Specific heat (J/g, 20 °C) | 1.910 – 1.916 | 0.8940 | 1.75 | 1.860 | 0.9 |

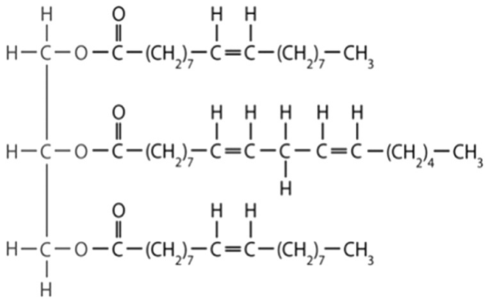


**Fig. 6.** Structure of crude canola oil.

### 2.1. *The behavior of canola oil at high temperature*

In a working transformer, whenever the insulating oil is subjected to high temperature, the molecules of the oil get excited and start losing from the liquid's body when the threshold is reached. The escaped molecules turn to vapor and ignite when they encounter flames. The minimum temperature at which the oil gives out the vapor for ignition is termed flashpoint (Phoon et al., 2015). In high voltage insulation, an insulating oil with a very high flash point is required to prevent fire outbreaks when the transformer is energized, especially those transformers used near houses and indoor purposes (Radhika et al., 2014).

In addition, transformer breakdowns and explosions are detrimental to socio-economic development as they lead to power supply interruption and a high cost of replacement if need be. The flashpoint of insulating liquids is measured according to the ASTM standard D92/D93 (Poor and Sadrameli, 2017, Abdelkhalik et al., 2018, Aljaman et al., 2022, Eriskin et al., 2017, Ge et al., 2017). In comparison to mineral oils and synthetic esters, vegetable-based insulating oils exhibit superior high-temperature performance. This is one of the key factors that distinguishes them from mineral oils and synthetic esters. The reason for the high flash point could be attributed to the high correlation between the flash point and viscosity of vegetable oils as shown in Fig. 7 (Demirbas, 2008). The activation energy required to displace oil molecules is relatively high. However, it has been observed that when vegetable oils are modified into biodiesel, the viscosity of the oil is reduced, resulting

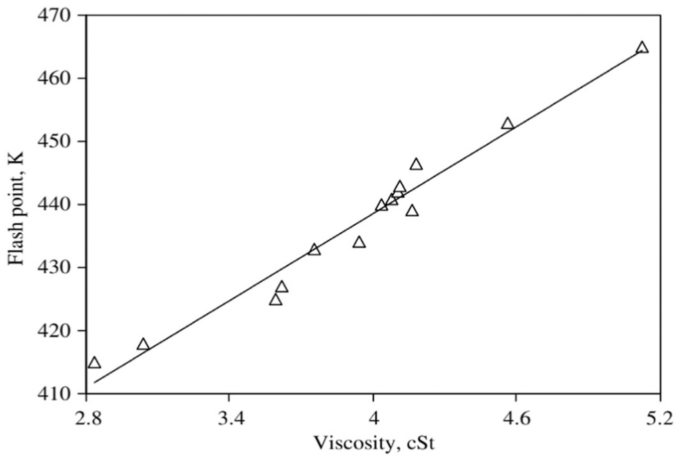


**Fig. 7.** Flash point Viscosity correlation (Demirbas, 2008).

in a lower flash point and altered fire properties. It's worth noting that the flash point is also influenced by the carbon chain length, with longer carbon chains generally leading to higher flash points (Raof et al., 2019b).

The flashpoint of canola oil, as determined by various researchers and presented in Table 3 meets the requirements specified for new natural ester insulating oils (IEEE C57.147) (Group, 2008). This indicates that the flashpoint of canola oil is well within the acceptable range for use as insulating oil in transformers and qualifies it as a K-class insulating oil (Sitorus et al., 2016, Rao et al., 2021). Table 4 compares the flash point and the fire point of several insulating liquids; mineral and vegetable-based oil (Raymon et al., 2013, Mehta et al., 2016b). The commercial canola-based insulating liquid has an outstanding fire safety performance compared with others. This saved the industry from investing in insurance and the cost of firewalls. Despite the fire safety attribute of canola oil, this property can still be enhanced by the addition of different nanoparticles. The introduction of nanoparticles into the base oil can impede the vapor generation process, thereby leading to an increase in the flash point (Baruah et al., 2019, Oparanti et al., 2021a).

### 2.2. *The behavior of canola oil in cold regions*

In colder environments, the cold flow characteristics of insulating liquid within transformers are crucial. As temperatures drop below zero, the viscosity of the insulating oil decreases, impacting its distribution within the transformer. This variation can influence both the dissipation of heat and the efficiency of the electrical insulation system. Within the industry, the pour point is an important oil property that signifies the gel temperature of crude oil, denoting the precise temperature at which a liquid ceases to flow or transforms into a semi-solid state (Li et al., 2015). In electrical devices where oil serves as both a cooling and insulating agent, it is essential for the oil to maintain flow even under extremely cold conditions. In situations where a transformer is not operational and experiences severely cold weather, the insulating oil with a relatively high pour point temperature solidifies. When the transformer is reactivated, the wax formed by the insulating oil may not dissolve immediately, impacting the cooling and insulation, potentially leading to hotspots and system breakdown. Cold starting a transformer with solidified insulating oil can also affect mechanical components such as the tap changer and oil pump. The pour point of insulating oil can be determined according to ASTM D97 (Sitorus et al., 2016, Rao et al., 2021, Committee, 2016). Several reports existing in the literature reveal that the pour point of natural ester is higher than mineral oil and it may affect their application in a sub-zero region (Rao et al., 2019, Rao et al., 2021). The pour point of natural ester varies from saturated to unsaturated. According to the report by Rao et al., the major factors that influence the pour point of natural ester are the types of branching that exist in the oil, the length of the fatty acid chain, and the level of unsaturation. The natural esters with dominating saturated fatty acids have high pour points due to the presence of short-chain fatty acids. In this type of oil, crystal formation is easy because the molecules of the oil are uniformly arranged and can be easily packed when subjected to low temperatures (Abdelmalik et al., 2018). Conversely, unsaturated fatty acids are long-chain fatty acids with the existence of bends and kinks due to the unsaturated carbon-carbon double bonds which prevent easy crystallization of the oil molecules when subjected to low temperature (Abdelmalik et al., 2018, Gunstone et al., 2007). From Table 1, more than 90% of canola oil fatty acids are unsaturated, which gives the oil an edge over the saturated natural ester when considering the pour point. The crystallization of vegetable-based insulating liquid is influenced by its unsaturation. Higher unsaturation leads to better pour point properties, although this considerably impacts the oil's oxidation stability. Canola oil's high percentage of monounsaturated fatty acids, which are relatively stable against oxidation, positions it favorably compared with oils rich in polyunsaturated fatty acids.

**Table 3**
Flash point of canola oil.

| Previous studies | Method | Flashpoint value (°C) |
|---|---|---|
| (Murthy and Kotebavi, 2019) | Open cup | 280 |
| (Przybylski et al., 2005b) | Open cup | 275–290 |
| (Deoi and De Sousa Malafaiaii, 2021) | Open cup | 300 |
| (Buda-Ortins, 2011) | - | ≥300 |

**Table 4**
Flash and fire point of mineral oil and other natural ester oils.

| Oil type | Mineral oil | Sunflower oil | Canola oil | Rice bran oil | Soya bean oil | Corn oil |
|---|---|---|---|---|---|---|
| Flash point | ≥ 145 | 260 | > 315 | 260 | 310 | 300 |
| Fire point | > 170 | 270 | > 350 | 280 | 320 | 310 |

In addition, previous studies reported that the pour point of canola oil is −24°C, which is lower than the specification for new natural ester insulating oil (Przybylski et al., 2005a, Deo and De Sousa Malafaia, 2021, Sitorus et al., 2016). Fig. 8 compares the pour point of different vegetable-based oils mineral oil and canola oil. It is important to know that the temperature at which the formation of waxes is experienced due to low temperatures in canola oil can also change. This is attributed to the planting time of the seed, it was reported that oil extracted from seeds grown in dry conditions has a higher pour point temperature relative to the ones grown in wet conditions. This change can be related to the response from dry stress conditions which eventually produces an oil with high saturated fatty acids (Przybylski et al., 1993).

The specific pour point requirement by IEC 62770, IEEE C57.147 and ASTM 6871 is ≤ −10 which makes canola oil a suitable insulating fluid in a relatively cold region (Rafiq et al., 2020, Yang et al., 2022, Mehta et al., 2016b). However, in countries with extreme weather conditions, especially in Canada and Russia where the temperature drops below −30°C, the application of canola oil for insulation might be questionable. Research findings indicate that natural esters, when solidified, tend to have a low probability of developing cavities in between, suggesting that transformers filled with natural esters could be cold-launched without special precautions, even in temperatures as low as −30°C (Moore et al., 2014, Mehta et al., 2016b, Rycroft, 2014). On the contrary, wax formation in the transformer can impede its cooling ability at low temperatures. Moreover, the presence of ice in the transformer tank could result in breakdown or serve as a conductive path. Therefore, minimizing the pour point of canola oil to the lowest workable temperature is essential to prevent thermal breakdown and some unforeseen breakdown of the equipment. The pour point of vegetable-based insulating liquids can be enhanced through the addition of pour point depressant winterization and ultrasonic treatment (Lawate et al., 1999, Dunn et al., 1996).

#### 2.2.1. *Winterization*

The winterization technique significantly enhances the cold flow characteristics of vegetable oil, employing a streamlined procedure depicted in Fig. 9. The process begins by placing the vegetable oil in a designated winterization tank or a low-temperature chamber, chilling it slightly below both its cloud point and pour point temperatures (Kumar and Sharma, 2018). This controlled temperature prompts the crystallization of oil molecules causing waxes to segregate from the liquid oil. Filtration is employed to separate these waxes from the oil. Occasionally, ethanol or a solvent is introduced to the filtered oil to further dissolve residual waxes and impurities. This process may entail repeating the crystallization and filtration steps to eliminate dissolved waxes, ensuring the removal of the solvent through

evaporation from the filtrate. The crystallization of vegetable-based liquids during the winterization process is not solely influenced by

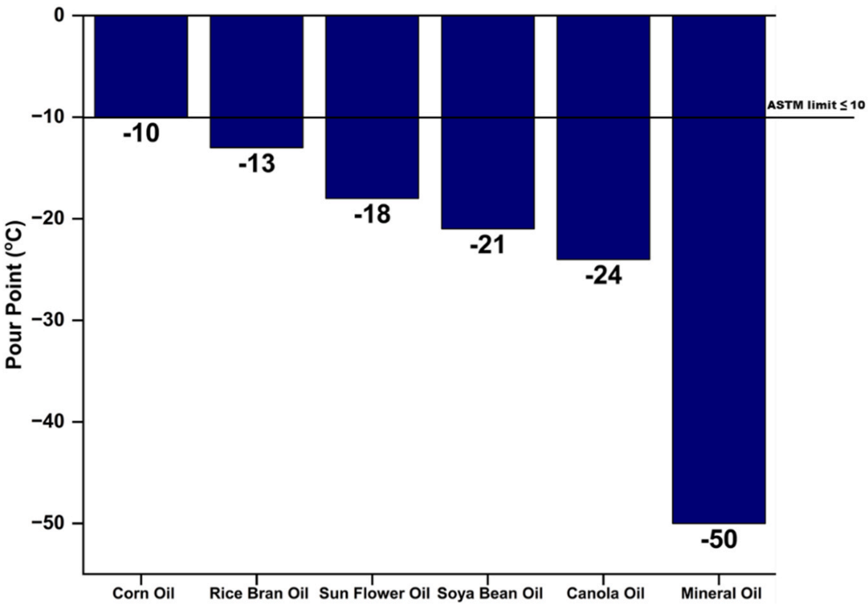


**Fig. 8.** Pour point of different vegetable-based insulating oils and mineral oil (Mohammed et al., 2021, Rani et al., 2015, Das et al., 2020, Deo and De Sousa Malafaia, 2021).

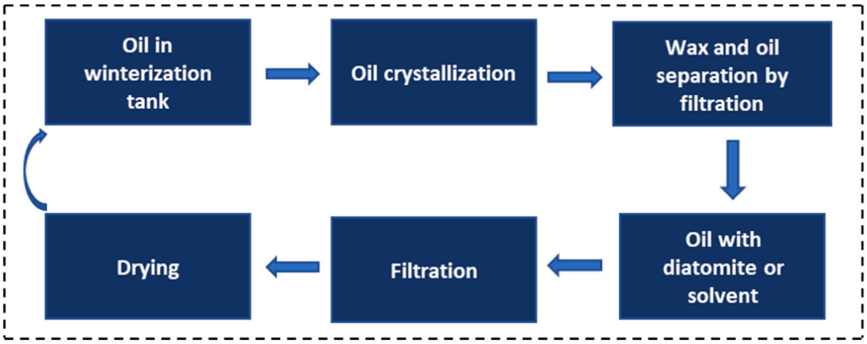


**Fig. 9.** A simple winterization process.

temperature; it is also impacted by the cooling speed of the system. Rapid cooling results in smaller crystals that tend to link together, creating a semi-solid phase that traps some liquid within. This complicates the separation of crystals from the unsolidified liquid. On the other hand, slower cooling produces more evenly formed, quasi-spherical crystals without significant interlinking. These crystals are easily separable from the liquid through a simple filtration process. For a visual representation of this differentiation in the winterization process under rapid and slow cooling rates, refer to micrograph images in reference (Zhong et al., 2016). Nucleating material like diatomite can also be added to the liquid to increase the crystallization rate of the liquid. Furthermore, it is essential to perform repeated cooling and filtration until no crystallization is experienced at the set temperature.

In the process of winterization, due to the fatty acids composition of the oil, the oil crystallizes at different temperatures in which the saturated fatty acids crystallize first (Vijayan et al., 2018). Separating these fatty acids through crystallization and filtration can impact the oxidation stability of the oil. It is then crucial to consider the oil's oxidation stability when separating fatty acids with varying melting points to ensure the preservation of its overall stability (Rafiq et al., 2020).

**Table 5**
Pour point depressants and their effects.

| S/n | Depressants | Remarks | |
|---|---|---|---|
| | | Acidity | Dielectric Loss |
| 1 | Polyacrylate | No significant effect on the acidity of the base liquid | Increases the dielectric loss of the base liquid |
| 2 | Hexylnaphthalene | Slightly increases the acidity of the base liquid | Slightly increases the dielectric loss of the base liquid |
| 3 | Polymethacrylate | No significant effect on the acidity of the base liquid | No effect on the dielectric loss of the base liquid |
| 4 | Poly alpha olefin | Increases the acidity of the base liquid | Slightly increases the dielectric loss of the base liquid |
| 5 | Poly alkyl methacrylate copolymer | - | - |
| 6 | Ethylene-vinyl acetate copolymer | - | - |

### 2.2.2. Pour point depressant

The application of pour point depressants has emerged as a significant approach to lowering the crystallization temperature of natural esters. These depressants work by inhibiting the three-dimensional formation of wax crystals within the oil. Table 5 summarizes the noteworthy depressants explored in literature for enhancing the pour point of natural esters, along with their impact on acidity and dielectric loss (Yang et al., 2022, Xue et al., 2017, Moosasait and Siluvairaj, 2021). Copolymeric additives, originating from two or more monomers, function as depressants in low-temperature settings (Mohammed et al., 2021). These substances are primarily utilized to improve petroleum-based lubricant and natural ester characteristics (Vinogradov et al., 2021). However, their effect on reducing the pour point of the base liquid is less significant compared with other depressants, such as polymethyl methacrylate. PMMA has been reported to lower the pour point of the natural ester by 10°C without causing changes in the acid value or dielectric loss of the base liquid, as outlined in reference (Yang et al., 2022). It is worth noting that further chemical modifications on these depressants remain crucial. Such modifications hold the potential to effectively reduce the pour point of natural esters to levels suitable for extremely low-temperature utilities.

### 2.2.3. *Ultrasonic treatment*

The ultrasonic treatment process serves as a means to lower the pour point temperature of vegetable-based insulating liquids. This technique employs an ultrasonic generator to transmit ultrasonic acoustic waves into a water bath where the sample is positioned. Fig. 10 illustrates the setup, enabling control over exposure time and sample temperature via an attached module on the ultrasonic generator. The core principle behind this method lies in the molecular vibration induced by the passage of waves through the medium. This vibration subjects the oil molecules to cycles of compression and stretching, thereby releasing energy and disrupting the molecular bonds among the oil molecules. Consequently, this molecular agitation causes a shift in the original molecular position, potentially altering the molecular attachments (Huang et al., 2018). This alteration impacts the crystallization process of fatty acids, potentially contributing to the reduction in the pour point of natural esters. The impact of the ultrasonic treatment process on the pour point of various natural esters was explored in reference (Moosasait and Siluvairaj, 2021). It was noted that an increase in exposure time led to a significant reduction in the pour point of all the natural esters studied. Investigating the correlation between the power and frequency of the ultrasonic wave on the base oil is an important area to investigate (Hamidi et al., 2012).

## 2.3. *Canola oil in transformer cooling*

Viscosity is the degree of resistance of a fluid to flow. The viscosity of a liquid can be influenced by several factors like temperature and molecular weight. An in-service transformer generates heat due to two major losses which are losses from the magnetic circuit and one from the windings of the transformer (Kulkarni and Khaparde, 2004). The insulating liquids help in the dissipation of heat generated during the operation and reduce the temperature of the transformer to a minimum degree (Mohamad et al., 2017). This contributes to increasing the life span of a transformer as it prevents the rapid aging of transformer components and thermal breakdown. The heat transfer efficiency of insulating oil is dependent on the viscosity, and this can be seen in Eq. 1. R is the Reynolds number, $\mu$ is the dynamic viscosity, $w$ is the oil velocity and $d$ is the diameter of the channel. Reynolds number is a liquid parameter that is inversely proportional to the dynamic viscosity. It can be used to determine the heat property of insulating oil. A good cooling liquid should have high Reynolds number which invariably means, the viscosity of the liquid should be low.

$$R = \frac{w.d}{\mu} \tag{1}$$

The viscosity of insulating oil is measured according to ASTM D445 (Rajab et al., 2019, Senthilkumar et al., 2021, Makaa et al., 2019). Deol et al. reported the kinematic viscosity of canola oil to be 35.14 $mm^2/s$ at 40°C which is almost four times the viscosity of mineral insulating oil (Deo and De Sousa Malafaia, 2021, Rafiq et al., 2020). Also, the viscosity of canola oil was reported by Przybylski et al., the viscosity was reported to be 78.2 $mm^2/s$ at 20°C (Przybylski et al., 2005a). The recommended viscosity value by IEEE C57.147 is $\leq 50\ mm^2/s$ at 40°C which indicates that canola oil falls within the required range (Sitorus et al., 2016). Table 6 presents a comparative analysis between some selected natural esters and mineral oils. The viscosity of natural ester is notably impacted by its molecular structure. Primarily, longer fatty acids in the oil tend to elevate viscosity due to increased molecular interaction. Furthermore, the level of unsaturation in the oil is inversely related to its viscosity, indicating that higher proportions of unsaturated fatty acids are linked to lower viscosity values (Boyde, 2020, Raof et al., 2019b). Additionally, the molecular configuration of unsaturated fatty acids significantly impacts viscosity, as oils with a trans configuration exhibit higher viscosity compared with those with a cis configuration (Rao et al., 2021). All the natural esters showcased higher viscosity in comparison to mineral oil. While the viscosity values of the natural esters align within the recommended range, improving their cooling capabilities remains a significant consideration to extend the transformer's lifespan. Notably, the viscosity of canola oil is high and Eq. 1 suggests that its functionality cannot be equated to mineral oil, emphasizing the necessity to lower the viscosity of canola oil to enhance its cooling efficiency.

### 2.3.1. *Viscosity enhancement*

Enhancing the viscosity of natural esters utilized in transformer insulation is an area of research that has received relatively less focus in the available literature. As previously mentioned, this property significantly impacts the thermal efficiency of the transformer oil during the cooling process. Several researchers have attempted to enhance the viscosity of vegetable-based insulating liquids through the transesterification process (Yu et al., 2017). However, this procedure has been found to have negative effects on certain oil properties, including flash points, fire points, dielectric loss, and oil conductivity (Abdelmalik, 2012). These detrimental effects are likely due to the presence of dissociated materials during the chemical process, with further details available in the reference (Abdelmalik, 2012). Furthermore, the transesterification process used in biodiesel production has made the

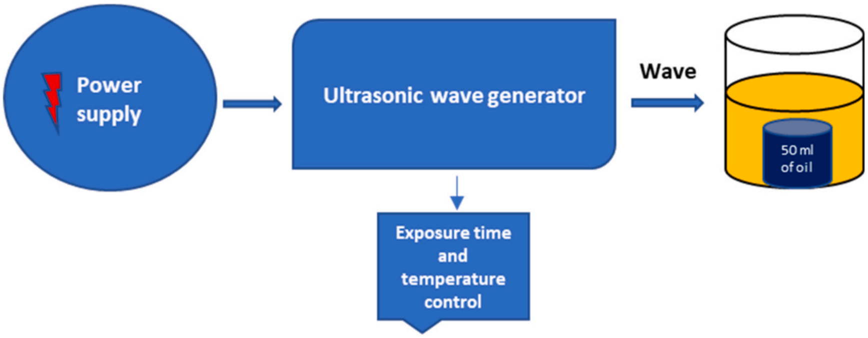


**Fig. 10.** Ultrasonication process setup.

**Table 6**
Viscosity of some natural esters and mineral oil.

| Oil type | Mineral oil | Natural ester | Canola oil | Rice bran oil | Soya bean oil | Corn oil |
|---|---|---|---|---|---|---|
| Viscosity mm$^2$/s (40°C) | ≤ 12 (Mehta et al., 2016a) | ≤ 50 (Mehta et al., 2016a) | 35.14 (Deo and De Sousa Malafaia, 2021) | 42.075 (Acharya et al., 2010) | 28.974 (Deepa et al.,) | 56 (Kumar et al., 2016a) |

biodiesel itself costlier compared with mineral-based materials, resulting in cost discrepancies (Leung and Guo, 2006).

### 2.3.2. A. Viscosity enhancement through natural additives

Improving the viscosity of natural esters can be achieved by incorporating natural additives, yet several factors significantly affect the solubility of these additives. The base oil's polarity is a critical determinant governing the uniform solubility of additives within it. Oils with short and straight fatty acids possess strong polarity, whereas those with long-chain and unsaturated fatty acids exhibit weak polarity (Widodo et al., 2021). Enhanced polarity in oils attracts potent additives, indicating that they are readily absorbed by shorter and straight fatty acids. It's important to note that some additives can generate a low-intensity magnetic field, supporting electron spin within fatty acid molecules, and resulting in increased mobility. This phenomenon leads to molecular relaxation and an increase in molecular distance. Consequently, momentum transfer between molecules is reduced, thereby weakening the London force. Conversely, a stronger magnetic field enhances the London force (Fang et al., 2019). The efficacy of plant extracts derived from *Areca catechu* is detailed in reference (Widodo et al., 2021), where the extract's molecular composition includes the presence of the epicatechin aromatic ring. The structural representation of this compound is presented in Fig. 11 and this compound is recognized for generating a low-intensity magnetic field due to phi electron resonance (Ajami et al., 2003). Epicatechin's low magnetic field affects the electron spin in fatty acid molecules, thereby diminishing the momentum transfer between molecules and reducing the London force (Widodo et al., 2021, Cao et al., 2009). Viscosity, a physical property, is directly influenced by polarity and the London force (Idrees et al., 2019). Thus, the reduction of viscosity is prominent in vegetable-based insulating fluids with a high percentage of saturated fatty acids when additives capable of generating low magnetic fields are introduced. Conversely, viscosity reduction is less significant in fatty acids with a high percentage of unsaturated fatty acids. This is because unsaturated fatty acids can disrupt the local magnetic field induction on electron spin. This observation is substantiated by the findings from (Widodo et al., 2021), where the viscosities of coconut oil, refined corn oil, and refined palm oil decreased by 28.80%, 16.99%, and 15.44% respectively, as illustrated in Fig. 12.

Benzyl benzoate, a transparent aromatic compound, serves as a key element in reducing the viscosity of natural esters (Del Olmo et al., 2017). It is obtained from plant species within the Polyalthia genus and can be synthesized through the chemical process of transesterification involving methyl benzoate and benzyl alcohol. One of its notable characteristics is its ability to enhance the dielectric breakdown strength of natural esters (Moosasait et al., 2021). A study in reference (Moosasait et al., 2021) observed the impact of varying concentrations of benzyl benzoate on both edible and non-edible natural esters. The results depicted in Fig. 13 demonstrate that consistent loading of benzyl benzoate led to decreased viscosity in all six distinct natural esters. The reduction in viscosity can be attributed to the hydrolysis of benzyl benzoate, which generates benzyl alcohol. This low-viscosity benzyl alcohol solvent reacts with the natural ester, causing a dilution that effectively reduces the base oils' viscosity (Moosasait et al., 2021, Haynes, 2014).

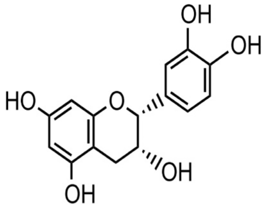


**Fig. 11.** Structural representation of epicatechin (Borges et al., 2018, Qu et al., 2021).

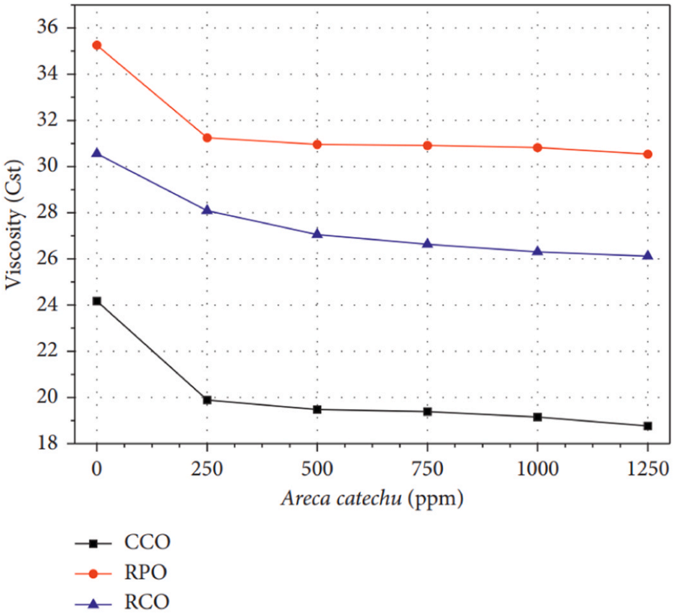


**Fig. 12.** Effect of *Areca catechu* plant extract on coconut oil, refined corn oil, and refined palm oil (Widodo et al., 2021).

The viscosity of the oil can also be modified using the ultrasonication process. Exposing natural ester to ultrasonic waves could cause some displacement in the oil molecule due to compression and stretching because of vibration. At the point when the stretching limit is exceeded, the molecule of the oil loses its bond creating a cavity that could generate heat and reduce the viscosity of the oil. The schematic illustration of the effect of ultrasonic waves can be found in Fig. 10 (Bakrutheen et al., 2018).

### 2.3.3. B. Mixing natural ester with low viscous liquids

Combining natural esters with low-viscosity liquids, such as mineral oil, presents a systematic approach to decreasing the viscosity of natural esters. Natural esters exhibit good miscibility with various organic compounds, including hydrocarbons and ethers, regardless of the proportions. Elevating the temperature enhances the miscibility by accelerating the kinetics of the oil molecules (Board, 2013). Mineral oil, a longstanding insulating liquid in the industry, possesses low viscosity. When mixed with natural esters like canola oil, it contributes to a reduction in the viscosity of the natural ester. The impact of incorporating mineral oil into olive oil and coconut oil was examined in (Madavan et al., 2022), revealing a decrease in viscosity for both natural esters as the proportion of mineral oil increased. Similarly, (Radha et al., 2016), investigated the effect of mineral oil on olive oil and rapeseed oil, resulting in a significant reduction in viscosity.

It is crucial to note that blending canola oil with mineral oil may influence other essential properties of natural esters, including flash

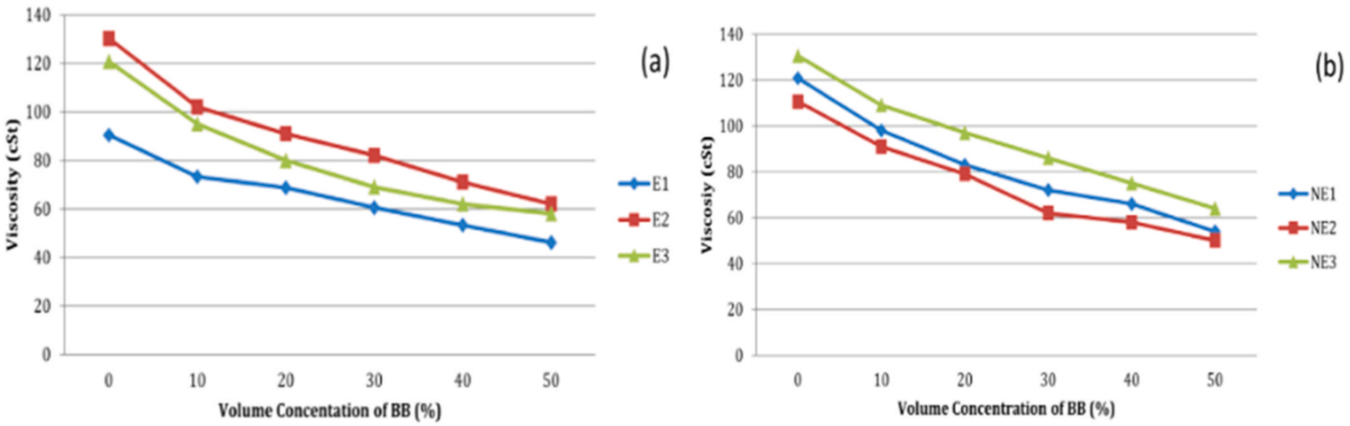


**Fig. 13.** Effect of benzyl benzoate on the viscosity of (a) edible and (b) non-edible natural ester.

point, fire safety, biodegradability, and environmental friendliness. Another approach involves mixing two or more natural esters with different viscosity values to achieve a low-viscosity liquid. In (Chen et al., 2022), the report explored blending rapeseed oil with palm fatty acid ester, resulting in a 51.3% reduction in kinematic viscosity when the mixing ratio was 80% rapeseed oil and 20% PFAE. Similarly, reference (Ghislain et al., 2022) utilized a simplex lattice design to blend methyl ester from palm kernel oil with refined palm kernel oil, successfully reducing viscosity without compromising fire safety and dielectric properties. The optimum composition for the desired response was found to be 32.22% methyl ester palm kernel oil and 67.78% refined palm kernel oil. Both the mixing of mineral oil with natural esters and the blending of different natural esters, lead to reduced viscosity, attributed to the dilution process.

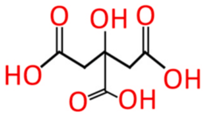
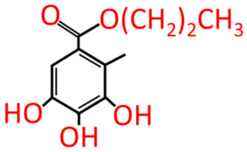
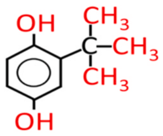
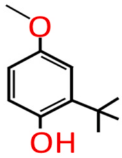
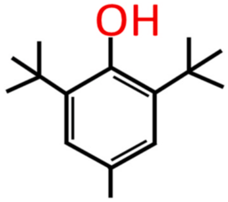
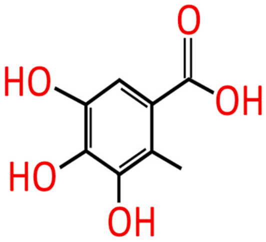
### 2.4. *Oxidation stability of canola oil in high voltage transformer*

The oxidation stability of insulating oil signifies its resistance to oxidation, a crucial chemical property to assess before using it in transformer insulation. Given that insulating oil operates in high-temperature conditions where heat catalyzes oxidation (Xu et al., 2014), evaluating its oxidative stability becomes important. The lifespan of a transformer relies significantly on the effectiveness of its cooling and dielectric systems. Oxidation of insulating oil significantly impacts both these systems. Various factors like operational temperature, dissolved oxygen, moisture, arcing, and metal impurities catalyze oil oxidation. This process results in the formation of oxidation byproducts including alcohols, peroxides, aldehydes, ketones, and acids within the system. These byproducts adversely affect the oil's cooling and dielectric performance(Zhou et al., 2012). The byproducts of oxidation can expedite the aging process of both the oil and the cellulose insulation within the system. The aging impacts the cooling and dielectric properties of the oil and directly influences the mechanical and dielectric strength of the paper insulation materials. Among the outstanding oxidation assessment process used for assessing insulating oils are ASTM D2440 and ASTM D2112. The assessments are done by measuring the acid value and oxidation induction time respectively. Reports indicate that mineral-based insulating oils demonstrate greater oxidation resistance compared with vegetable oils (Abdelmalik et al., 2011a, Abdelmalik, 2014, Abdelmalik et al., 2011b, Xu et al., 2014, Oommen, 2002, Stockton et al., 2008). Furthermore, vegetable oils rich in saturated fatty acids exhibit higher oxidation stability compared with those with higher levels of unsaturated fatty acids (Abdelmalik, 2014). Consequently, the susceptibility of vegetable oils to oxidation increases with a higher degree of unsaturation, particularly as the composition shifts from monounsaturated to polyunsaturated fats (Oparanti et al., 2023b, Abdelmalik, 2014).

As plants absorb nutrients from the soil, certain elements such as iron and copper become part of the oil's composition, influencing its oxidation stability. However, when the levels of these elements drop below 0.1 mg/kg for iron and 0.02 mg/kg for copper, their impact on the oil's oxidative stability becomes insignificant (Warner and Eskin, 1995). Moreover, the elements present in the oil contribute to its coloration. Thus, a straightforward approach to improving the oxidation stability of natural esters involves decolorizing the oil. This process can be accomplished using bleaching clay, and the optimal percentage concentration of clay required for both prooxidant removal and element extraction from the oil was determined in reference (Abdelmalik, 2012), this helps to remove trace elements that can enhance the oxidation of the oil. The choice of canola oil as an insulating oil finds justification in its notably low melting and pour points. Additionally, compared with various oils rich in unsaturated fatty acids, canola oil stands out due to its elevated proportion of monounsaturated fatty acids, such as oleic acid. In contrast to oils like Jatropha and Soybean, which contain higher levels of polyunsaturated fatty acids prone to oxidation, canola oil presents a more stable option. The evaluation made by (Viertel et al., 2011, Hamid et al., 2016) indicates that oils with high levels of monounsaturated fatty acids are relatively stable to oxidation. This stability correlates to the carbon chain length of the fatty acids. In addition, canola oil also has vitamin E and 2,6-Dimethoxy-4-vinylphenol (Canolol) in its chemical content which are good antioxidants and radical scavengers respectively. Despite these advantages, the inherent unsaturation of canola oil renders it susceptible to oxidation when exposed to stressors, contaminants, or atmospheric oxygen (Zhou et al., 2012). Addressing this technical concern regarding oxidation stability is crucial, especially in free-breathing transformers, to enhance the reliability and efficiency of natural-based insulating systems.

Literature has extensively explored methods to enhance the oxidation resistance of natural ester-insulating liquids, often by integrating oxidation inhibitors and radical scavengers. These additives work to scavenge and counteract free radicals triggered by light exposure, increased temperatures, or metal ion particles. Table 7 consolidates a range of antioxidants used in recent studies, along with their reported impact on oil properties. It is crucial to assess the compatibility of these antioxidants with natural esters before subjecting the mixture to accelerated thermal aging or oxidation tests in the laboratory. Such evaluations aid both industry and academia in selecting highly effective antioxidants for enhancing oxidation in natural esters. Furthermore, considering the potential dissociation of certain chemical materials at high electric fields, understanding the electric and thermal stability of these antioxidants in the oils holds significant importance.

**Table 7**
Recent antioxidants used in natural ester oxidation stability enhancement.

| S/n | Antioxidants | Base sample | Markers | Remarks | Structures |
|---|---|---|---|---|---|
| 1 | Oil soluble Polysesquioxane (POSS) | FR3 | Activation energy | The inclusion of POSS enhances the oxidation stability of the base liquid (Wang et al., 2021). | - |
| 2 | Citric Acid (CA) | Rapeseed oil | Dielectric parameters | No significant effect on tan$\delta$ value (Totzauer et al., 2017) |  |
| 3 | Propyl Gallate (PG) | Rapeseed oil | Dielectric parameters | Increases the value of tan$\delta$ above the required value by IEC at 90°C (Totzauer et al., 2017) |  |
| 4 | Tert – Butylhydroquinone (TBHQ) | Rapeseed oil | Dielectric parameters | No significant effect on tan$\delta$ value(Totzauer et al., 2017) |  |
| 5 | Butylated Hydroxyanisole | Rapeseed oil | Dielectric parameters | No significant effect on tan$\delta$ value (Totzauer et al., 2017) |  |
| 6 | Butylated Hydroxyl toluene | Natural esters | Breakdown and flash point | Slightly enhances the flash point and the breakdown voltage of the base liquid with optimum performance at 0.75% volume fraction loading (Kumar et al., 2016b). |  |
| 7 | Gallic Acid | Natural esters | Breakdown and flash point | Slightly enhances the flash point and the breakdown voltage of the base liquid with optimum performance at 0.5% volume fraction loading (Kumar et al., 2016b). |  |

### 2.5. Canola compatibility with cellulose paper

The aging of insulating materials, while an inevitable process, stands as a critical factor requiring consideration. When integrating a new insulating liquid, assessing its compatibility with the insulating paper becomes crucial. Unlike oil, which can be replaced upon degradation, insulating paper lacks this flexibility. Fig. 14 outlines a step-by-step laboratory impregnation method of oil with paper, emphasizing the significant impact of paper quality on the transformer's lifespan. As paper insulating materials comprise polysaccharides, they are directly susceptible to moisture within the insulation system. The integrity of the paper is gauged by quantifying the number of monomers within the polymer chain. This assessment termed the degree of polymerization, diminishes as polymer chain scissions occur (Adekunle et al., 2023). ASTM D4243 offers a method to determine the degree of polymerization (D, 2009). The chart presented in Fig. 15 gives a simple description of the degree of polymerization assessment. Eq. (2) aids in calculating the average degree of polymerization of the test solution, providing insight into the paper's structural integrity. Paper impregnated with natural esters demonstrates greater thermal stress endurance compared with paper impregnated with mineral oil. Additionally, natural ester impregnated paper contains less moisture than its mineral oil impregnated counterpart, effectively decelerating the paper degradation rate (Sayed et al., 2019). Accelerated thermal aging has revealed that the life expectancy of cellulose in natural ester is five times that of mineral oil-impregnated cellulose and seven times more in thermally upgraded cellulose paper (Transformers, 2013).

Canola oil, categorized as a natural ester liquid and possessing comparatively superior oxidation stability among other natural esters, emerges as a strong candidate for replacing mineral oil in terms of cellulose paper preservation. Since moisture, as part of the oxidation process, harms cellulose, choosing a natural ester with good oxidation stability holds significant importance in mitigating this degradation.

$$DP^{\propto} = \frac{\eta}{K} \tag{2}$$

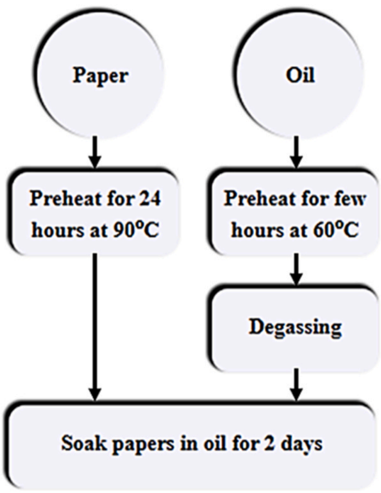


**Fig. 14.** Paper impregnation.

Where $\eta$ is the intrinsic viscosity, K is a constant and $\alpha$ is 1(Sayed et al., 2019).

### 2.6. Dielectric properties of canola insulating oil

The remarkable dielectric properties of vegetable oils offer a compelling case for replacing mineral oil in transformer insulation. These oils, owing to their polar nature, exhibit increased dielectric constants under electric fields, surpassing those of mineral oil as seen in Table 8 (Rao et al., 2021, Souček et al., 2015, Das, 2023a, Raj et al., 2020, Šegatin et al., 2020). The elevated dielectric constant of natural esters enhances voltage regulation by effectively dispersing electrical stress within the insulation system, relieving strain on solid insulating materials. However, this polarity can also pose challenges; the higher polarity associated with vegetable oils may escalate dielectric losses, contributing to the elevated loss observed in natural esters compared with mineral oil (Shah and Tahir, 2011). Natural esters, in addition, often face issues with ionization resistance and resistivity. It is worth noting that dielectric properties vary slightly among vegetable oils, especially concerning breakdown strength, potentially due to differences in their fatty acid compositions. Variations in fatty acid chains, from short chains to long chains, likely impact the ionization rate in these oils. For instance, a study reported in (Hamid et al., 2016) compared different oils with different fatty acid compositions.

This study suggested that oils with higher levels of long-chain fatty acids tend to exhibit superior dielectric strength. The experimental findings emphasize canola oil’s exceptional performance in terms of dielectric loss, resistivity against temperature fluctuations, and relatively robust breakdown voltage. Canola oil’s optimized performance positions it favorably as an insulating oil compared with other vegetable oils. Additionally, the presence of antioxidant and radical scavenger components such as vitamin E and 2,6-dimethoxy-4-vinylphenol

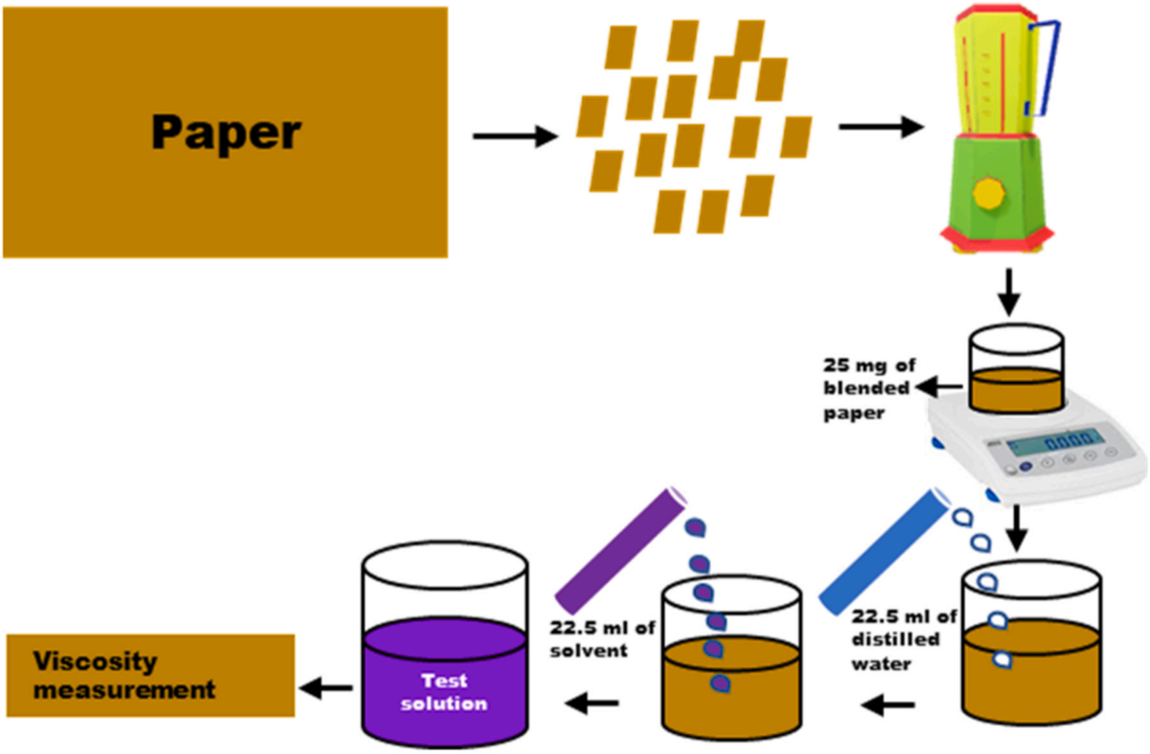


**Fig. 15.** Degree of polymerization preparation stages.

**Table 8**
Electrical properties of some vegetable oils and mineral oil.

| Oil types<br>Properties | Mineral oil | Canola oil | Coconut oil | Palm oil | Rapeseed oil | Jatropha | Corn oil |
|---|---|---|---|---|---|---|---|
| AC Breakdown voltage (2.5 mm) kV | 59.86 | 61.54 | 60 | 81 | 73 | 73 | 57 |
| Dielectric loss (90 °C) | 0.005 | 0.01667 | 0.09 | - | 0.0047 | 0.145 | 0.07 |
| Dielectric constant | 2.1 | 3.4 | 3.3 | 3.13 | 3.12 | 3.2 | 2.73 |

(canolol) in canola oil's chemical makeup further augments its dielectric properties. The analysis of dielectric properties conducted on canola oil and mineral oil in (Souček et al., 2015) indicates a higher dielectric strength of canola oil compared with mineral oil. Canola oil exhibits a breakdown voltage of 61.54 kV, while mineral oil has a breakdown voltage of 59.86 kV. The dielectric loss of canola oil is reported to be greater than that of mineral oil, potentially due to the polar nature of canola oil. However, despite this higher dielectric loss, the reported value of 0.01667 remains below the threshold recommended by IEC 60247. It is important to know that the rate of ionization in oils is linked to their molecular structure. Oils abundant in long-chain fatty acids typically exhibit elongated carbon chains compared with those with shorter chains. This extended molecular configuration, characterized by a higher number of carbon atoms, offers additional sites prone to ionization. Consequently, this property may contribute to higher dielectric strength in such oils when subjected to electrical stress. Hence, the choice of fatty carbon chain length could also be a crucial condition to be put into consideration when selecting natural ester-insulating materials.

## 3. Global warming potential (GWP) and greenhouse gas (GHG) intensity

Exploring the technical attributes of canola oil as an insulating liquid is important. Equally important is looking into the impact of canola cultivation on greenhouse gas emissions, given the pressing concern of global warming. Agricultural practices have been identified as major contributors to anthropogenic greenhouse gases, with statistics indicating significant percentages: up to 84% for nitrous oxides and 52% for methane emissions globally. Studies have established a clear link between cultivation methods and their potential to contribute to global warming (Kamran et al., 2023, Ouyang et al., 2013). However, curbing cultivation worldwide poses challenges due to rapid population growth and economic advancement. Forecasts suggest a staggering 100% increase in global crop production by 2050 to meet the escalating demands for human and livestock sustenance (Zhang et al., 2016). Agricultural activities, crucial for meeting these demands, also generate greenhouse gases such as carbon dioxide, primarily from manufacturing, crop fertilizer application, fuel usage in machinery, and notably, irrigation systems. Methane emissions result from biomass burning, manure management, and rice cultivation. Additionally, the use of nitrogen-based fertilizers significantly contributes to the greenhouse gas potential by generating nitrous oxide during microbial activities.

Interest in using natural esters for industrial purposes, particularly in transformer insulation, has rapidly increased. However, these liquids are derived from plants that require precise cultivation for optimal yield. Derived from sources like sunflower, corn seed, rapeseed, canola, and palm seed, these materials necessitate significant cultivation efforts, directly contributing to greenhouse gas emissions. To counter this, directing attention to plants with outstanding insulating properties becomes crucial, as certain plant cultivations have minimal environmental impact. Moreover, industrial cultivation of oilseeds could potentially compete for land initially designated for food crops, encroaching upon essential food production spaces. Therefore, focusing on oils with superior transformer insulation capabilities could mitigate the potential rise in greenhouse gas emissions linked to diverse agricultural activities. As previously highlighted, canola oil stands out for its exceptional properties, making it a prime candidate for increased production. By prioritizing the production of oils renowned for their transformer insulation prowess, we can circumvent an escalation in greenhouse gas emissions emanating from extensive agricultural practices. This strategic shift not only addresses environmental concerns but also minimizes the strain on land designated for essential food crop production.

### 3.1. *Advantages of Canola Cultivation for the Ecosystem*

Canola cultivation is an amazing crop production that poses a less negative impact on the environment. Due to the high percentage yield of oil quantity from canola relative to other plants, a large quantity of oil can be obtained from minimal crop production, which minimizes land usage, reduces farm mechanical activities, and reduces biomass burning. Several key reasons underscore the significance of cultivating canola, with a few highlighted below:

i. *Low environmental impact:* The cultivation of canola results in lower greenhouse gas emissions. This is primarily due to reduced fertilizer usage in growing the canola plants, leading to a decrease in emitted nitrous oxides (Growers, 2023). Additionally, canola cultivation encourages effective land management practices that allow for versatile land use without compromising soil quality. It aids in revitalizing essential soil nutrients, reducing the reliance on fertilizers for subsequent crops. This approach not only minimizes environmental impact but also promotes sustainable agriculture by preserving soil health.
ii. *Carbon Sequestration:* Removing carbon from the atmosphere stands as a viable method for decreasing greenhouse gas levels. Canola plants possess the capacity to absorb carbon from the atmosphere, thus aiding in diminishing the overall carbon footprint. The impressive yield potential and expansive root system of canola contribute significantly to its role as a facilitator in reducing greenhouse gases. For example, the Canadian farmers due to responsible farming practices sequester 11 million of GHGs yearly (Growers, 2023).
iii. *Promotion of Sustainable Agriculture:* Crop rotation, a practice promoted by canola cultivation, stands as a factor that promotes sustainable farming. This method contributes to decreased pesticide usage, supports soil conservation efforts, and consequently mitigates emissions (Rehman et al., 2022).

### 3.2. *Eco-toxicity of canola oil*

After observing the advantages of canola cultivation on the ecosystem, it becomes imperative to also understand the eco-toxicity of the oil. Eco-toxicity denotes the potential of a substance to harm ecosystems, encompassing animals, plants, microorganisms, water, air, and soil. This harm can manifest as acute or chronic toxicity (Khadem et al., 2023). Studies indicate that prolonged exposure to discarded mineral oil may result in cancer, skin ailments, and allergic reactions (Khadem et al., 2023). The biodegradability, or persistence, of insulating liquids determines how long they persist in the ecosystem before degradation. Mineral oil typically takes 1–10 years to decompose, while vegetable oils like canola oil degrade within 4–48 weeks, indicating relatively lower persistence. The high biological oxygen demand of natural esters placed them as a readily degradable insulating liquid which canola oil is also inclusive (Rao et al., 2019).

Similar to other vegetable oils, canola oil exhibits comparable toxicological profiles and possesses high biodegradability. Consequently, it is anticipated to pose no significant health risks when exposed to humans and their surroundings. Moreover, its environmental impact is expected to be minimal due to its high biodegradability. Canola oil is not classified as carcinogenic, nor does it exhibit reproductive, developmental, or nervous system toxicity. However, it may cause minimal irritation to the eyes and mild irritation to the skin.

### 3.3. *Canola oil in water*

Canola oil readily undergoes decomposition by microorganisms such as bacteria, indicating that it does not persist in water bodies and consequently has fewer impacts on aquatic animals. An acute toxicity study of canola oil reported no adverse effects, as documented in (Fingas, 2014). Reports by (Das et al., 2022) and (Anand and Chhibber, 2006) highlight that vegetable oils exhibit very low German Wassergefahrdungklasse (WGK) and Water Endangering Number (WEN), indicating their non-hazardous nature to water. Nonetheless, it is essential to minimize the spillage of canola oil into water bodies, as research suggests that such spills could lead to oxygen depletion and asphyxiation in confined or shallow areas during degradation, consequently resulting in the death of aquatic organisms (Fingas, 2014).

### 3.4. Canola oil in the soil

Due to the high degradability of vegetable oil, its presence in soil has a short lifespan, which typically results in minimal impact on soil topology. The biocatalysts present in soil play a crucial role in breaking down natural esters into fatty acids, subsequently metabolizing them with the aid of biocatalysts, ultimately eliminating carbon. However, the effect of vegetable oils like canola oil on soil properties may vary depending on factors such as the concentration of spilled oil, soil type, and climatic conditions. It is important to note that during the degradation of canola oil, both the spilled oil and its degraded byproducts may initially exhibit toxicity to organisms, but this toxicity diminishes rapidly over time due to canola oil's biodegradability, thereby reducing its environmental concentration (Tamothran et al., 2022).

### 3.5. Canola in the air

The introduction of canola oil into the atmospheric environment typically poses fewer ecological risks compared to other insulating liquids like mineral oil and silicone oils. This is primarily attributed to canola oil's biodegradability and lower toxicity levels. However, it is crucial to acknowledge that secondary actions such as frying, combustion, and microbial breakdown of the oil can result in transient pollution, especially in localized regions or specific scenarios. These secondary processes may release pollutants into the air, potentially impacting air quality. Hence, despite the environmental benefits of canola oil compared to other insulating liquids, careful management and consideration of its potential impacts are essential to mitigate pollution risks.

## 4. Useful life, Recyclability, and Regeneration of natural esters

### 4.1. Useful life

Natural esters have found significant utility in transformer applications, particularly in low and medium-voltage duty transformers. Their exceptional miscibility makes them ideal for replacement and retrofilling (Rao et al., 2019, Chronis et al., 2021). When employed as insulating liquids, natural esters produce fewer dissolved gases during thermal and electrical faults compared with mineral oil. This difference indicates superior performance, suggesting that natural esters can extend the lifespan of transformers in contrast to mineral oil (Chronis et al., 2021). Moreover, the hydrophilic properties of natural esters contribute to keeping the insulating paper dry, thereby enhancing the overall longevity of the transformer (Yang et al., 2010). In unforeseen or challenging situations, it is highly advantageous for insulating materials to possess a high safety margin, capable of withstanding stresses beyond standard levels. This extra reserve capacity serves as a shield against damage, enabling the insulating material to endure sudden increases in factors such as temperature, electrical stress, and related elements without compromising its integrity. Highlighting the importance of this extra capacity cannot be emphasized enough, as it significantly fortifies the resilience and reliability of insulating systems. Fig. 16 compares the additional reserve capacity of mineral oil and natural ester insulating liquids given that the additional reserve capacity is described as in Eq. 3. Natural esters exhibit a notably higher margin of additional and overload capacity compared with mineral oil. Moreover, they showcase a substantial margin of rated life due to their lower rate of paper degradation and fewer instances of dielectric failure. Essentially, this implies that employing natural esters in transformer insulation enhances the

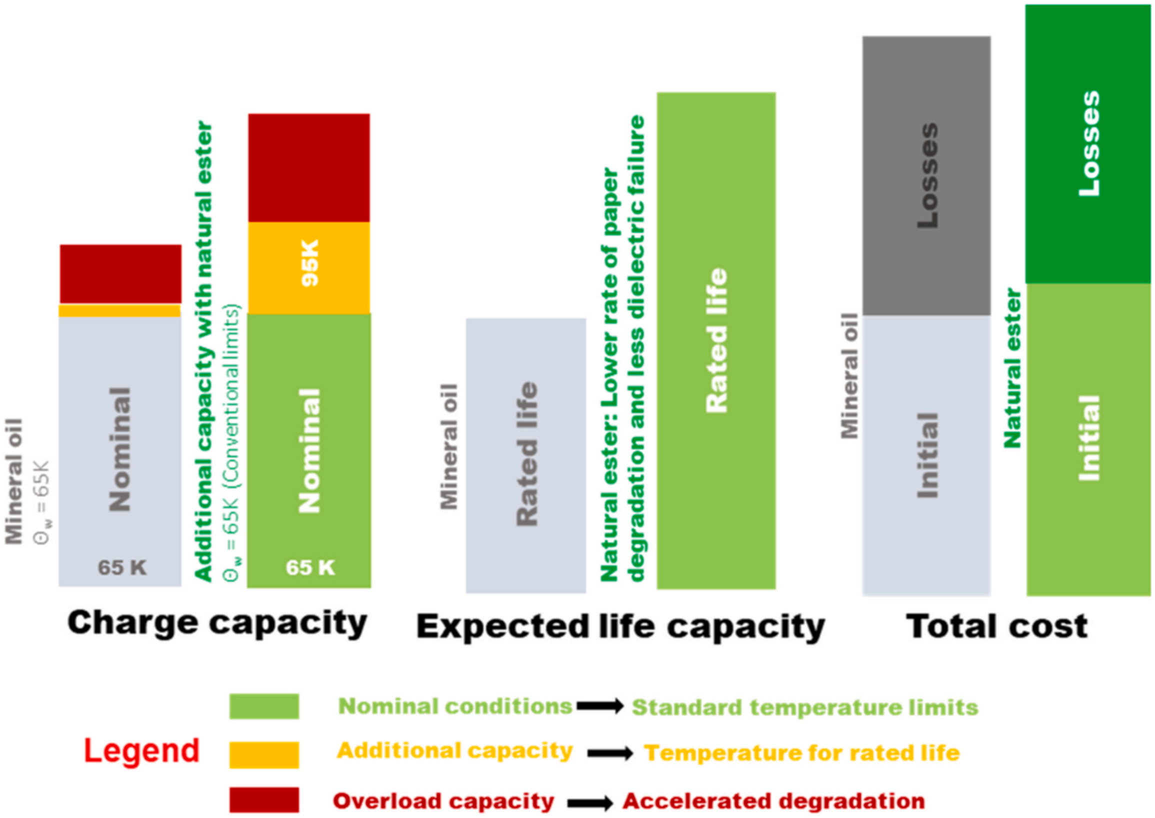


**Fig. 16.** Natural ester and mineral oil reserve capacity.

network's resilience, reliability, and transformer useful life. Therefore, using canola oil as an insulating liquid in transformer applications not only enhances network reliability but also extends the transformer's useful life compared with mineral oil. It is important to emphasize that a high additional capacity and an extended rated life lead to reduced life cycle costs and postponed asset replacement (Bingenheimer and Franchini, 2011).

$$\theta_w = 65K \quad \times nominal\ life\ at 95K \tag{3}$$

However, the oxidation instability inherent in natural esters might impact their potential, especially when utilized in free-breathing transformers. As highlighted in Section 2.4, canola oil exhibits notable oxidation stability relative to other vegetable-based insulating oils due to its high percentage of monounsaturated fatty acids and unique composition. Consequently, investigating deeper into the properties of canola oil becomes crucial, presenting a promising avenue for potentially replacing mineral oil entirely in transformer applications.

### 4.2. Recyclability and regeneration

The process of reclaiming insulating oil is known to be cost-effective, as the price of the reclaimed oil falls below that of newly produced oil (Wilhelm et al., 2013). According to the IEEE guide, the elimination of degradation products in natural esters can be achieved using fuller earth (Group, 2008). However, during the reclamation process, certain additives, such as antioxidants, which were initially included during the new oil's synthesis, might also be removed. Therefore, it is crucial to reintroduce these additives after the reclamation process. The process of oil reclamation can be seen in Fig. 17.

Regenerating natural esters presents a considerable challenge, with little literature addressing this process. The lack of enough information suggests that regenerating natural esters might be an exceedingly challenging, if not nearly impossible, task. Although some literature reported that natural ester can be rejuvenated and reused (Trnka et al., 2011, Mcshane, 2002), this may be achievable only if the viscosity of the oil has not increased beyond a certain percentage. This is because when vegetable oil undergoes oxidation, it does not form sludge as mineral oil does. This distinction arises from the ability of the oxidation products and varnishes to readily dissolve in vegetable-based liquid. In contrast, oxidation products do not dissolve in mineral oil due to its non-polar nature (Raof et al., 2019a). The dissolved oxidation products in natural esters become an intrinsic part of the oil, forming a homogenous mixture and may be highly inseparable. As the oil ages, thermal polymerization of the oil progresses with time, and the viscosity of the oil increases till a gel-like material is formed (Rao and Fofana, 2021, Rao et al., 2022, Abdelmalik et al., 2018, Abdelmalik, 2012). This inherent nature of natural esters poses a challenge when attempting to regenerate them after prolonged use in transformer insulation. Essentially, the viscosity of natural esters in service significantly impacts the regeneration process. The findings from (Wilhelm et al., 2013) show that utilizing adsorbents in the reclamation of natural esters does not significantly improve oil viscosity due to the adsorbent's incapacity to eliminate polar and polymeric substances from the oil. The report concludes that aged natural ester, exhibiting a viscosity 35% higher than the recommended value by IEEE, is not reclaimable. Hence, considering the percentage increase in oil viscosity from the initial energization day is crucial when planning for the regeneration of used natural esters. Adopting suitable and low cost recycling processes for used natural esters, such as their conversion into lubricants, soap, or biodiesel, proves highly beneficial (Bingenheimer and Franchini, 2011, Rafiq et al., 2020,

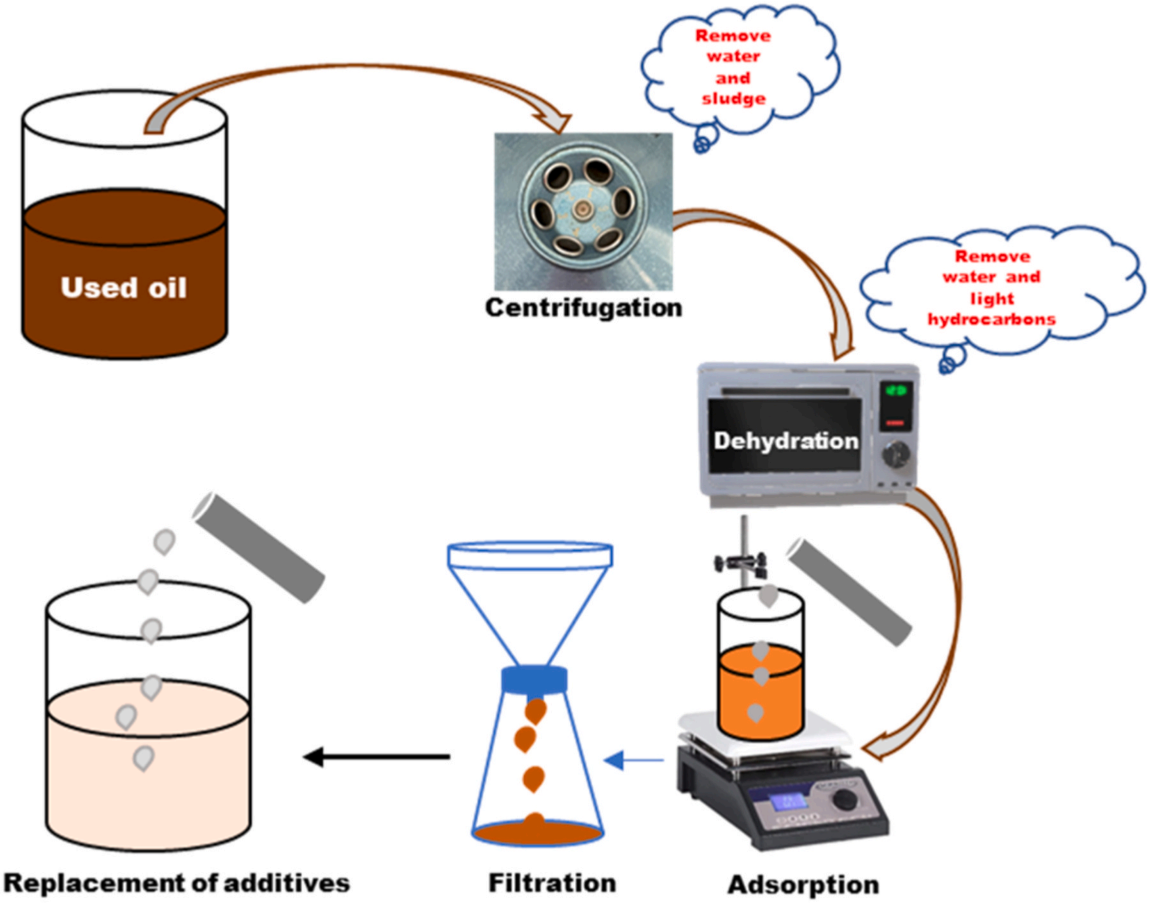


**Fig. 17.** Oil reclamation process.

Pompili et al., 2018). These prevent wastage, pollution and also provide a valuable approach towards sustainability.

## 5. Discussion

The use of natural esters in transformer insulation is an expanding field of study, particularly in extra-high-voltage applications. These liquids serve as compelling substitutes for mineral oil owing to their exceptional characteristics and environmental compliance. Similar to mineral oil, established standards like IEC 62770 and ASTM 6871 provide guidelines for the use of natural esters in transformers and electrical appliances (Iec, 2013). Moreover, IEEE STD C57.147 offers direction for accepting and maintaining natural esters in transformers (Group, 2008), ensuring their proper application in electrical equipment. Notably, the fire safety attributes of natural esters significantly contribute to the safety of transformers placed near sensitive infrastructures like schools, hospitals, and markets. The potential of canola oil in this field is striking. With a reported flash point exceeding 300°C, canola oil falls among less flammable liquids, making it a secure choice as insulation for high-voltage equipment. Its use ensures the safety of both the equipment and its surrounding environment. However, the high viscosity of natural esters, nearly three times that of mineral oil, poses challenges. This viscosity disparity affects liquid flow rates, leading to significant temperature discrepancies within transformers and necessitating high-rating pumps for forced-directed flow cooling systems. While reducing the viscosity of natural esters including canola oil has been discussed, it might impact essential material qualities like dielectric loss, breakdown strength, and flash point. Decreasing viscosity weakens molecular bonds and the forces holding the oil together, potentially facilitating easier dissociation of oil molecules at high temperatures. This may affect the oil's flash point and create pathways for streamers to propagate, impacting its insulating qualities. When low-viscosity liquids are mixed with canola-based insulating liquids, the overall viscosity decreases. However, it is crucial to consider the inverse relationship between charge mobility and viscosity according to Stoke's relation (Abdelmalik, 2012). Therefore, evaluating the dielectric properties of such mixed liquids becomes crucial for assessing their suitability for electrical applications.

Canola insulating oil demonstrates satisfactory cold flow properties, meeting standard requirements outlined by ASTM, IEEE, and IEC. No special measures are necessary for starting transformers operating on natural esters (Mehta et al., 2016b). Nevertheless, at extremely low temperatures, the increased viscosity of canola oil might affect the transformer's cooling system. Implementing a winterization process to reduce the pour point effectively addresses this issue. However, this process warrants investigation into the winterized oil's thermal stability, as it might remove fatty acids with high melting points during crystallization and filtration. Enhancing canola oil's pour point temperature through ultrasonication requires thorough research due to the molecular shift of oil molecules and its impact on dielectric properties. Comparatively, the oxidation stability of canola oil exceeds that of other vegetable liquids with highly unsaturated fatty acids but falls short of mineral oil's stability. Consequently, its application in procedures similar to mineral oil is limited. To enhance its stability against oxidation, ongoing research focuses on antioxidants for natural esters. While various antioxidants have been explored, none has emerged as the definitive choice, warranting further optimization. Antioxidants like Tert-Butylhydroquinone (TBHQ) and Butylated Hydroxyl toluene have shown no adverse effects on natural ester properties. Reports even suggest that Butylated Hydroxyl toluene can enhance the dielectric strength of the base fluid (Kumar et al., 2016b) These antioxidants function by preventing free radical formation, which could otherwise deteriorate the oil's properties. Optimizing the effects of multiple antioxidants on canola oil using statistical techniques holds substantial promise (Ab Ghani et al., 2017a). Canola oil, just like any other natural ester, exhibits commendable dielectric properties, including a robust breakdown voltage even in the presence of moisture, surpassing mineral oil (Prevost, 2006). Nonetheless, its relatively low volume resistivity compared with mineral oil requires careful consideration. Addressing these limitations involves incorporating low ionization potential additives like Dimethylaniline (DMA) and Azobenzene showing promise in enhancing streamer acceleration voltage and lightning impulse breakdown voltage of the base oil (Unge et al., 2013, Unge et al., 2014). In addition, the application of nanoparticles emerges as a promising avenue for enhancing the dielectric properties of natural ester-insulating liquids. This emerging research area systematically improves various aspects of natural esters, such as DC resistivity, streamer propagation in nonuniform fields, partial discharge inception voltage, and increased relative permittivity (Makmud et al., 2018, Karatas and Bicen, 2022).

## 6. Challenges and outlook

When compared to other green-insulating liquids, canola oil exhibits numerous outstanding characteristics. Its high concentration of monounsaturated fatty acids gives it an advantage over alternative green-insulating liquids. However, the common challenges of natural esters can not be undermined and there is room for extensive research in enhancing the quality of the natural esters for environmental benefit and the utilities. Areas requiring thorough investigation regarding the properties of canola oil include its gassing behavior, thermal behavior, and ionization characteristics. Understanding the types of gases released and their effects on electrical insulating systems during electrical faults is crucial for managing such situations effectively.

Regarding the cooling capabilities of canola oil, its viscosity plays a crucial role, which typically aligns with standard recommendations. However, in scenarios such as retrofilling or when utilities opt to replace mineral oil with canola-based insulating liquid in compliance with environmental regulations, there arises a necessity to modify cooling systems, potentially incurring financial expenses. Hence, it becomes imperative to investigate methods for reducing the viscosity of canola oil to match that of mineral oil, particularly for retrofilling purposes. Furthermore, enhancing the performance of canola oil at lower temperatures is crucial. The gelation of natural esters within transformer systems is closely linked to their oxidation stability. Therefore, research aimed at improving the oxidation stability of canola oil-based insulating liquids is essential for prolonging transformer lifespan and ensuring optimal performance.

The ionization characteristics of canola-based insulating oil are recognized as inferior to those of mineral oils, which is a challenge to its insulating properties. However, research indicates that this limitation can be addressed through the addition of certain additives with low ionization potential and low first excitation energy. Therefore, there is a need for further investigation into identifying the most suitable additives to enhance the ionization characteristics of canola oil, thus improving its overall performance as an insulating fluid.

Another important issue to address is the recyclability/regeneration/reuse in the context of circular economy and efficient use of resources in a systemic, cyclical and prospective approach.

## 7. Conclusion

Research into canola oil, a sustainable insulating liquid, has revealed its significant potential for high-voltage equipment. Incorporating canola oil in the electrical industry not only decreases greenhouse gas emissions but also extends the lifespan of transformers compared with other natural esters. Its array of qualities, from impressive fire safety features to excellent cold flow properties, establishes this oil as a standout insulating material among its natural ester alternatives. This inherent promise suggests a reliable future, potentially leading to the complete replacement of mineral oil in response to the growing demand for green energy. Nevertheless, significant challenges persist regarding canola oil, particularly concerning its oxidation stability, cold flow properties, and ionization resistance, presenting ongoing areas for research and urging further investigations. Methods previously discussed, such as incorporating additives, winterization, and ultrasonication, have demonstrated systematic pathways to enhance the base liquid's properties. However, understanding the impact of these methods on the fundamental dielectric properties of the base liquid remains crucial.

Investigating deeper into the insulating properties of canola oil holds immense significance for both the economy and the agricultural sector. Furthermore, the cultivation and production of canola present a systematic approach to encouraging environmental sustainability, contributing to a greener world, and combating global warming.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

## Acknowledgments

This work is funded by the Fonds de recherche du Québec – Nature et Technologies (FRQNT) and supported by Natural Sciences and Engineering Research Council of Canada.

## References

Ab Ghani, S., Muhamad, N.A., Noorden, Z.A., Zainuddin, H., Talib, M.A., 2017a. Oxidation stability enhancement of natural ester insulation oil: Optimizing the antioxidants mixtures by two-level factorial design. ARPN J. Eng. Appl. Sci. 12, 1694–1700.

Ab Ghani, S., Muhamad, N.A., Zainuddin, H., Noorden, Z.A., Mohamad, N., 2017b. Application of response surface methodology for optimizing the oxidative stability of natural ester oil using mixed antioxidants. IEEE Trans. Dielectr. Electr. Insul. 24, 974–983.

Abdelkhalik, A., Elsayed, H., Hassan, M., Nour, M., Shehata, A., Helmy, M., 2018. Using thermal analysis techniques for identifying the flash point temperatures of some lubricant and base oils. Egypt. J. Pet. 27, 131–136.

Abdelmalik, A.A. 2012. The feasibility of using a vegetable oil-based fluid as electrical insulating oil. University of Leicester.

Abdelmalik, A., 2014. Chemically modified palm kernel oil ester: a possible sustainable alternative insulating fluid. Sustain. Mater. Technol. 1, 42–51.

Abdelmalik, A.A., Abbott, A.P., Fothergill, J.C., Dodd, S., Harris, R., 2011b. Synthesis of a base-stock for electrical insulating fluid based on palm kernel oil. Ind. Crops Prod. 33, 532–536.

Abdelmalik, A.A., Abolaji, P.A., Sadiq, H.A., 2018. Assessment of Jatropha Oil as Insulating Fluid for Power Transformers. J. Phys. Sci. 29, 1–16.

Abdelmalik, A., Fothergill, J.C., Dodd, S.J., Abbott, A.P. & Harris, R. Effect of side chains on the dielectric properties of alkyl esters derived from palm kernel oil. 2011 IEEE international conference on dielectric liquids, 2011a. IEEE, 1-4.

Acharya, S.K., Swain, R.K. & Mohanty, M.K. 2010. The Use of Rice Bran Oil as a Fuel for a Small Horse-power Diesel Engine. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 33, 80-88.

Adekunle, A.A., Oparanti, S.O., Fofana, I., 2023. Performance assessment of cellulose paper impregnated in nanofluid for power transformer insulation application: a review. Energies 16, 2002.

Ajami, D., Oeckler, O., Simon, A., Herges, R., 2003. Synthesis of a möbius aromatic hydrocarbon. Nature 426, 819–821.

Alaba, E., Kazeem, R., Adebayo, A., Petinrin, M., Ikumapayi, O., Jen, T.-C., Akinlabi, E., 2023. Evaluation of palm kernel oil as cutting lubricant in turning AISI 1039 steel using Taguchi-grey relational analysis optimization technique. Adv. Ind. Manuf. Eng. 6, 100115.

Aljaman, B., Ahmed, U., Zahid, U., Reddy, V.M., Sarathy, S.M., Jameel, A.G.A., 2022. A comprehensive neural network model for predicting flash point of oxygenated fuels using a functional group approach. Fuel 317, 123428.

Anand, O., Chhibber, V.K., 2006. Vegetable oil derivatives: environment-friendly lubricants and fuels. J. Synth. Lubr. 23, 91–107.

Aransiola, E.F., Daramola, M.O., Ojumu, T.V., Aremu, M.O., Kolawole Layokun, S., Solomon, B.O., 2012. Nigerian Jatropha curcas oil seeds: prospect for biodiesel production in Nigeria. Int. J. Renew. Energy Res. 2, 317–325.

Bakrutheen, M., Iruthayarajan, M.W., Narayani, A., 2018. Influence of ultrasonic waves on viscosity of edible natural esters based liquid insulation. IEEE Trans. Dielectr. Electr. Insul. 25, 1628–1635.

Barthet, V. 22 March 2015. "Canola", [Online]. The Canadian Encyclopedia. Historica Canada. Available: www.thecanadianencyclopedia.ca/en/article/canola [Accessed 03 January 2023].

Baruah, N., Maharana, M., Nayak, S.K., 2019. Performance analysis of vegetable oil-based nanofluids used in transformers. IET Sci. Measurement Technol. 13, 995–1002.

Beltrán, N., Palacios, E., Blass, G., 2017. Potential of Jatropha curcas oil as a dielectric fluid for power transformers. IEEE Electr. Insul. Mag. 33, 8–15.

Bingenheimer, D., Franchini, L., Del Fiacco, E., Mak, J., Vasconcellos, V. & Rapp, K. Sustainable electrical energy using natural ester technology. CIRED 21st Intl. Conf. Electr. Distr, 2011. Citeseer, 6-9.

Board, N. 2013. *Modern Technology Of Oils, Fats & Its Derivatives: Extraction of fats and oils, Extraction of Olive Oil, Extraction of Palm Oil, Fat and oil processing, Fats and oils Based Profitable Projects, Fats and oils Based Small Scale Industries Projects, Fats and oils food production, Fats and Oils Handbook, Fats and Oils Industry Overview, Fats and oils making machine factory, Fats and oils Making Small Business Manufacturing, Fats and oils Processing Industry in India*, Asia Pacific Business Press Inc.

Borges, G., Ottaviani, J.I., Van Der Hooft, J.J., Schroeter, H., Crozier, A., 2018. Absorption, metabolism, distribution and excretion of (−)-epicatechin: a review of recent findings. Mol. Asp. Med. 61, 18–30.

Boyde, S. 2020. Esters. Synthetics, Mineral Oils, and Bio-Based Lubricants. CRC Press.

Buda-Ortins, K. 2011. Auto-ignition of cooking oils.

Cao, B.-Y., Sun, J., Chen, M., Guo, Z.-Y., 2009. Molecular momentum transport at fluid-solid interfaces in MEMS/NEMS: a review. Int. J. Mol. Sci. 10, 4638–4706.

Chen, B., Su, Z., Du, Z., Ma, M., Zhang, J., Tang, C., 2022. A new type of mixed vegetable insulating oil with better kinematic viscosity and oxidation stability. J. Mol. Liq. 360, 119512.

Chronis, I., Kalogeropoulou, S., Psomopoulos, C.S., 2021. A review on the requirements for environmentally friendly insulating oils used in high-voltage equipment under the eco design framework. Environ. Sci. Pollut. Res. 28, 33828–33836.

Committee, A. 2016. ASTM D97-16 standard test method for pour point of petroleum products. ASTM Annual Book of Standards.

D, A. 2009. Standard test method for measurement of average viscometric degree of polymerization of new and aged electrical papers and boards. ASTM International West Conshohocken, PA, USA.

Das, A.K., 2022. Statistical evaluation of the AC breakdown voltages of vegetable oil exposed to direct sunlight. Mater. Chem. Phys. 285, 126106..

Das, A.K., 2023a. Analysis of AC breakdown strength of vegetable oils and effect of mineral oil. Electr. Power Syst. Res. 214, 108920.

Das, A.K., 2023c. Investigation of electrical breakdown and heat transfer properties of coconut oil-based nanofluids. Ind. Crops Prod. 197, 116545.

Das, A.K., 2023b. Comparative analysis of AC breakdown properties of Jatropha-based ester and other insulating oils: commercial natural ester, synthetic ester, and mineral oil. Biomass-.-. Convers. Biorefin. 1–13.

Das, A.K., Chavan, A.S., Shill, D.C., Chatterjee, S., 2021. Jatropha curcas oil for distribution transformer–a comparative review. Sustain. Energy Technol. Assess. 46, 101259.

Das, A.K., Shill, D.C., Chatterjee, S., 2020. Potential of coconut oil as a dielectric liquid in distribution transformers. IEEE Electr. Insul. Mag. 36, 36–46.

Das, A.K., Shill, D.C., Chatterjee, S., 2022. Coconut oil for utility transformers–environmental safety and sustainability perspectives. Renew. Sustain. Energy Rev. 164, 112572.

Das, A.K., Shill, D.C., Chatterjee, S., 2023. Experimental investigation on breakdown performance of coconut oil for high voltage application. Electr. Power Syst. Res. 214, 108856.

Daun, J.K., Eskin, M.N. & Hickling, D. 2015. Canola: chemistry, production, processing, and utilization, Elsevier.

Deepa, S., Srinivasan, A. & Veeramanju, K. Investigation of the Dielectric Properties of Mineral Oil Blended with Soyabean Oil for Power Transformers.

Del Olmo, A., Calzada, J., Nuñez, M., 2017. Benzoic acid and its derivatives as naturally occurring compounds in foods and as additives: uses, exposure, and controversy. Crit. Rev. Food Sci. Nutr. 57, 3084–3103.

Demchuk, V.Jun. 15, 2020. “TOP 10 Rapeseed Producing Countries in 2019,” [Online]. Latifundist.com. Available: https://latifundist.com/en/rating/top-10-proizvoditelej-rapsa-v-2019-godu [Accessed].

Demirbas, A., 2008. Relationships derived from physical properties of vegetable oil and biodiesel fuels. Fuel 87, 1743–1748.

Deo, L.P. & De Sousa Malafaia, A.M. 2021. Canola oil as an alternative quenchant for the AISI 8640 steel. Revista Eletrônica em Gestão, Educação e Tecnologia Ambiental, 25, e4-e4.

Deoi, L.P. & De Sousa Malafaiaii, A.M. 2021. Canola oil as an alternative quenchant for the AISI 8640 steel. Revista Eletrônica em Gestão, Educação e Tecnologia Ambiental, 25, e4-e4.

Dunn, R., Shockley, M., Bagby, M., 1996. Improving the low-temperature properties of alternative diesel fuels: vegetable oil-derived methyl esters. J. Am. Oil Chem. ’ Soc. 73, 1719–1728.

Enujiugha, V., Nwanna, L., 2004. Aquatic oil pollution impact indicators. J. Appl. Sci. Environ. Manag. 8, 71–75.

Eriskin, E., Karahancer, S., Terzi, S., Saltan, M., 2017. Waste frying oil modified bitumen usage for sustainable hot mix asphalt pavement. Arch. Civ. Mech. Eng. 17, 863–870.

Fang, H., Ni, K., Wu, J., Li, J., Huang, L., Reible, D., 2019. The effects of hydrogen bonding on the shear viscosity of liquid water. Int. J. Sediment Res. 34, 8–13.

Farahmandfar, R., Asnaashari, M., Sayyad, R., 2015. Comparison antioxidant activity of Tarom Mahali rice bran extracted from different extraction methods and its effect on canola oil stabilization. J. Food Sci. Technol. 52, 6385–6394.

Fingas, M., 2014. Vegetable oil spills: oil properties and behavior. Handb. oil spill Sci. Technol. 79–91.

Fofana, I., 2013. 50 years in the development of insulating liquids. IEEE Electr. Insul. Mag. 29, 13–25.

Gaber, M. a F.M., Tujillo, F.J., Mansour, M.P., Juliano, P., 2018. Improving oil extraction from canola seeds by conventional and advanced methods. Food Eng. Rev. 10, 198–210.

Ge, J.C., Yoon, S.K., Choi, N.J., 2017. Using canola oil biodiesel as an alternative fuel in diesel engines: A review. Appl. Sci. 7, 881.

Ghazani, S.M., García-Llatas, G., Marangoni, A.G., 2014. Micronutrient content of cold-pressed, hot-pressed, solvent extracted and RBD canola oil: implications for nutrition and quality. Eur. J. Lipid Sci. Technol. 116, 380–387.

Ghazani, S.M., Marangoni, A.G., 2013. Minor components in canola oil and effects of refining on these constituents: a review. J. Am. Oil Chem. ' Soc. 90, 923–932.

Ghislain, M.M., Gerard, O.B., Emeric, T.N. & Adolphe, M.I. 2022. Improvement of environmental characteristics of natural monoesters for use as insulating liquid in power transformers. Environmental Technology & Innovation, 27, 102784.

Gnanasekaran, D. & Chavidi, V.P. 2018. Vegetable Oil: An Eco-friendly Liquid Insulator. Vegetable Oil based Bio-lubricants and Transformer Fluids. Springer.

Group, I.N.E.W. 2008. IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers. IEEE Std. C, 57, 147-2008.

Growers, M.C. 2023. Canolaeatwell: Carbon Reduction & Sequestration.

Gunstone, F., Alander, J., Erhan, S., Sharma, B., Mckeon, T., Lin, J., 2007. Nonfood uses of oils and fats. Lipid Handb. 3.

Hamid, M., Ishak, M., Din, M.M., Suhaimi, N. & Katim, N. Dielectric properties of natural ester oils used for transformer application under temperature variation. 2016 IEEE International Conference on Power and Energy (PECon), 2016. IEEE, 54-57.

Hamid, M., Ishak, M., Suhaimi, N., Adnan, J., Hashim, N., Ariffin, M., Katim, N., Abd Rahman, R., 2022. Electrical properties of palm oil and rice bran oil under AC stress for transformer application. Alex. Eng. J. 61, 9095–9105.

Hamidi, H., Rafati, R., Junin, R.B., Manan, M.A., 2012. A role of ultrasonic frequency and power on oil mobilization in underground petroleum reservoirs. J. Pet. Explor. Prod. Technol. 2, 29–36.

Hanif, S. 2020. Efficacy and mechanisms of bacterial biocontrol agents against Leptosphaeria maculans (Desm.) causing blackleg disease of canola (Brassica napus L.). Charles Sturt University, Australia.

Haynes, W.M. 2014. CRC handbook of chemistry and physics, CRC press.

Huang, X., Zhou, C., Suo, Q., Zhang, L., Wang, S., 2018. Experimental study on viscosity reduction for residual oil by ultrasonic. Ultrason. Sonochem. 41, 661–669.

Idrees, S.A., Mustafa, L.L., Saleem, S.S., 2019. Improvement viscosity index of lubricating engine oil using low molecular weight compounds. Sci. J. Univ. Zakho 7, 14–17.

Iec, I. 2013. 62770 Fluids for electrotechnical applications-Unused natural esters for transformers and similar electrical equipment. Geneve.

Jackson, L.P., Grinsted, A. & Jevrejeva, S. 2018. 21st Century sea-level rise in line with the Paris accord. Earth's Future, 6, 213-229.

Kamran, M., Yan, Z., Ahmad, I., Jia, Q., Ghani, M.U., Chen, X., Chang, S., Li, T., Siddique, K.H., Fahad, S., 2023. Assessment of greenhouse gases emissions, global warming potential and net ecosystem economic benefits from wheat field with reduced irrigation and nitrogen management in an arid region of China. Agric. Ecosyst. Environ. 341, 108197.

Karatas, M., Bicen, Y., 2022. Nanoparticles for next-generation transformer insulating fluids: a review. Renew. Sustain. Energy Rev. 167, 112645.

Khadem, M., Kang, W.-B., Kim, D.-E., 2023. Green Tribology: a review of biodegradable lubricants—properties, current status, and future improvement trends. Int. J. Precis. Eng. Manuf. -Green. Technol. 1–19.

Kulkarni, S.V. & Khaparde, S. 2004. Transformer engineering: design and practice. Vol. 25. Boca Raton, FL, USA: CRC.

Kumar, S.S., Iruthayarajan, M.W., Bakrutheen, M., 2016a. Investigations on the suitability of rice bran oil and corn oil as alternative insulating liquids for transformers. IEEJ Trans. Electr. Electron. Eng. 11, 10–14.

Kumar, S.S., Iruthayarajan, M.W., Bakrutheen, M., Kannan, S.G., 2016b. Effect of antioxidants on critical properties of natural esters for liquid insulations. IEEE Trans. Dielectr. Electr. Insul. 23, 2068–2078.

Kumar, M., Sharma, M., 2018. Investigating and improving the cold flow properties of waste cooking biodiesel using winterization and blending. Mater. Today.: Proc. 5, 23051–23056.

Lawate, S., Unger, R., Huang, C., 1999. Commercial additives for vegetable lubricants. Lubr. World 43–45.

Leung, D., Guo, Y., 2006. Transesterification of neat and used frying oil: optimization for biodiesel production. Fuel Process. Technol. 87, 883–890.

Li, H., Zhang, J., Song, C., Sun, G., 2015. The influence of the heating temperature on the yield stress and pour point of waxy crude oils. J. Pet. Sci. Eng. 135, 476–483.

Loganes, C., Ballali, S., Minto, C., 2016. Main properties of canola oil components: a descriptive review of current knowledge. *The Open Agriculture*. Journal 10.

Madavan, R., Saroja, S., Karthick, A., Murugesan, S., Mohanavel, V., Velmurugan, P., Al Obaid, S., Alfarraj, S., Sivakumar, S., 2022. Performance analysis of mixed vegetable oil as an alternative for transformer insulation oil. Biomass-.-. Convers. Biorefinery 1–6.

Makaa, B.M., Irungu, G.K. & Murage, D.K. Investigation of Persea americana Oil as an Alternative Transformer Insulation Oil. 2019 IEEE Electrical Insulation Conference (EIC), 2019. IEEE, 197-200.

Makmud, M.Z.H., Illias, H.A., Chee, C., Sarjadi, M.S., 2018. Influence of conductive and semi-conductive nanoparticles on the dielectric response of natural ester-based nanofluid insulation. Energies 11, 333.

Mcshane, C.P., 2002. Vegetable-oil-based dielectric coolants. IEEE Ind. Appl. Mag. 8, 34–41.

Mehta, D.M., Kundu, P., Chowdhury, A., Lakhiani, V., Jhala, A., 2016b. A review on critical evaluation of natural ester vis-a-vis mineral oil insulating liquid for use in transformers: Part 1. IEEE Trans. Dielectr. Electr. Insul. 23, 873–880.

Mehta, D.M., Kundu, P., Chowdhury, A., Lakhiani, V., Jhala, A., 2016a. A review of critical evaluation of natural ester vis-a-vis mineral oil insulating liquid for use in transformers: Part II. IEEE Trans. Dielectr. Electr. Insul. 23, 1705–1712.

Mohamad, N.A., Azis, N., Haron, A.R., Von, T.Y. & Yaakub, Z. AC Withstand Voltage of Palm Oil based CuO nanofluids with CTAB, SDS and OA. 2022 IEEE International Conference on Power and Energy (PECon), 2022. IEEE, 45-48.

Mohamad, M.S., Zainuddin, H., Ab Ghani, S., Chairul, I.S., 2017. AC breakdown voltage and viscosity of palm fatty acid ester (PFAE) oil-based nanofluids. J. Electr. Eng. Technol. 12, 2333–2341.

Mohammed, A., Dhedan, R.M., Mahmood, W.A., Musa, A., 2021. Copolymers of castor and corn oils with lauryl methacrylate as green lubricating additives. Egypt. J. Chem. 64, 4271–4276.

Moore, S.P., Wangard, W., Rapp, K.J., Woods, D.L. & Del Vecchio, R.M. 2014. Cold start of a 240-MVA generator step-up transformer filled with natural ester fluid. IEEE Transactions on Power Delivery, 30, 256-263.

Moosasait, B., Maria Siluvairaj, W.I., Eswaran, R., 2021. Experimental studies on the influence of benzyl benzoate on viscosity of vegetable oil based insulating liquids for power transformer. *IET Science*. Meas. Technol. 15, 527–534.

Moosasait, B., Siluvairaj, W.I.M., 2021. Impact of ultrasonic treatment process on pour point of vegetable oils based liquid insulation. Ultrason. Sonochem. 71, 105380.

Murthy, K.K. & Kotebavi, V.M. Study on performance and emission characteristics of CI engine fueled with canola oil-Diesel blends. AIP conference proceedings, 2019. AIP Publishing LLC, 020049.

Oommen, T., 2002. Vegetable oils for liquid-filled transformers. IEEE Electr. Insul. Mag. 18, 6–11.

Oparanti, S.O., Khaleed, A.A., Abdelmalik, A.A., 2021b. AC breakdown analysis of synthesized nanofluids for oil-filled transformer insulation. Int. J. Adv. Manuf. Technol. 117, 1395–1403.

Oparanti, S., Khaleed, A., Abdelmalik, A., 2021a. Nanofluid from palm kernel oil for high voltage insulation. Mater. Chem. Phys. 259, 123961.

Oparanti, S.O., Rao, U.M., Fofana, I., 2023a. Natural esters for green transformers: challenges and keys for improved serviceability. Energies 16, 61.

Oparanti, S.O., Yapi, K.M.L., Fofana, I. & Rao, U.M. Preliminary studies on Improving the Properties of Canola Oil by Addition of Methyl Ester from a Saturated Vegetable Oil. 2023 IEEE Electrical Insulation Conference (EIC), 2023b. IEEE, 1-4.

Ouyang, W., Qi, S., Hao, F., Wang, X., Shan, Y., Chen, S., 2013. Impact of crop patterns and cultivation on carbon sequestration and global warming potential in an agricultural freeze zone. Ecol. Model. 252, 228–237.

Parvin, A. 2021. The effect of stem diameter on the Brassica napus (type: canola) (cultivar: HYHEAR 3) fiber quality.

Phoon, L.Y., Mustaffa, A.A., Hashim, H., Mat, R., 2015. Flash point prediction of tailor-made green diesel blends using UNIFAC-based models. Chem. Eng. Trans. 45, 1153–1158.

Pompili, M., Calcara, L., Sangiovanni, S., Scatiggio, F., Mazzaro, M. & De Bartolomeo, D. Natural esters and mineral oils fire behavior. 2018 IEEE 2nd International Conference on Dielectrics (ICD), 2018. IEEE, 1-4.

Poor, H.M., Sadrameli, S., 2017. Calculation and prediction of binary mixture flash point using correlative and predictive local composition models. Fluid Phase Equilibria 440, 95–102.

Prevost. Dielectric properties of natural esters and their influence on transformer insulation system design and performance. 2005/2006 IEEE/PES Transmission and Distribution Conference and Exhibition, 2006. IEEE, 30-34.

Przybylski, R., Mag, T., Eskin, N., Mcdonald, B., 2005a. Canola oil. Baile 'S. Ind. oil Fat. Prod. 2, 61–122.

Przybylski, R., Mag, T., Eskin, N. & Mcdonald, B. 2005b. Canola oil. Bailey's industrial oil and fat products. John Wiley & Sons, Inc, 6, 61-121.

Przybylski, R., Malcolmson, L., Eskin, N., Durance-Tod, S., Mickle, J., Carr, R., 1993. Stability of low linolenic acid canola oil to accelerated storage at 60C. LWT-Food Sci. Technol. 26, 205–209.

Qu, Z., Liu, A., Li, P., Liu, C., Xiao, W., Huang, J., Liu, Z., Zhang, S., 2021. Advances in physiological functions and mechanisms of (−)-epicatechin. Crit. Rev. Food Sci. Nutr. 61, 211–233.

Radha, R., Iruthayarajan, M.W & Bakrutheen, M. Performance of natural high oleic ester based blended oil insulation for transformer. 2016 10th International Conference on Intelligent Systems and Control (ISCO), 2016. IEEE, 1-5.

Radhika, R., Iruthayarajan, M.W. & Pakianathan, P.S. Investigation of critical parameters of mixed insulating fluids. 2014 International conference on circuits, power and computing technologies [ICCPCT-2014], 2014. IEEE, 357-362.

Rafiq, M., Shafique, M., Azam, A., Ateeq, M., Khan, I.A., Hussain, A., 2020. Sustainable, renewable and environmental-friendly insulation systems for high voltages applications. Molecules 25, 3901.

Raj, R.A., Ravi, S., Yahya, A., Mosalaosi, M., 2020. An overview of potential liquid insulation in power transformer. Int. J. Energy Convers. (IRECON) 8, 126–140.

Rajab, A., Putra, F., Ramadhani, J., Silitonga, M., Kurniawan, R., Qibran, K., Latif, M. & Hamid, M. Preliminary results on the development of monoester type insulating oil from coconut oil. IOP conference series: materials science and engineering, 2019. IOP Publishing, 012035.

Rani, S., Joy, M., Nair, K.P., 2015. Evaluation of physiochemical and tribological properties of rice bran oil–biodegradable and potential base stoke for industrial lubricants. Ind. Crops Prod. 65, 328–333.

Rao, U.M., Fofana, I. & Sarathi, R. 2021. Alternative liquid dielectrics for high voltage transformer insulation systems: performance analysis and applications, John Wiley & Sons.

Rao, U.M., Fofana, I., Jaya, T., Rodriguez-Celis, E.M., Jalbert, J., Picher, P., 2019. Alternative dielectric fluids for transformer insulation system: progress, challenges, and future prospects. IEEE Access 7, 184552-184571.

Rao, U.M. & Fofana, I. Monitoring the Sol and Gel in Natural Esters under Open Beaker Thermal Aging. 2021 IEEE 5th International Conference on Condition Assessment Techniques in Electrical Systems (CATCON), 2021. IEEE, 127-131.

Rao, U.M., Fofana, I., Rozga, P., Picher, P., Sarkar, D.K., Karthikeyan, R., 2022. Influence of gelling in natural esters under open beaker accelerated thermal aging. IEEE Trans. Dielectr. Electr. Insul. 30, 413–420.

Raof, N.A., Yunus, R., Rashid, U., Azis, N., Yaakub, Z., 2019b. Effects of molecular structure on the physical, chemical, and electrical properties of ester-based transformer insulating liquids. J. Am. Oil Chem. ’ Soc. 96, 607–616.

Raof, N.A., Yunus, R., Rashid, U., Azis, N., Yaakub, Z., 2019a. Effect of molecular structure on oxidative degradation of ester based transformer oil. Tribology Int. 140, 105852.

Raymon, A., Pakianathan, P.S., Rajamani, M., Karthik, R., 2013. Enhancing the critical characteristics of natural esters with antioxidants for power transformer applications. IEEE Trans. Dielectr. Electr. Insul. 20, 899–912.

Rehman, A., Farooq, M., Lee, D.-J., Siddique, K.H., 2022. Sustainable agricultural practices for food security and ecosystem services. Environ. Sci. Pollut. Res. 29, 84076–84095.

Rycroft, M., 2014. Vegetable oil as insulating fluid for transformers. Energize 4, 37–40.

Sayed, N., Jacob, J., Sindhu, T. & Preetha, P. Compatibility analysis of paper insulation with natural ester. 2019 IEEE 4th International Conference on Condition Assessment Techniques in Electrical Systems (CATCON), 2019. IEEE, 1-5.

Šegatin, N., Pajk Žontar, T., Poklar Ulrih, N., 2020. Dielectric properties and dipole moment of edible oils subjected to ‘frying’thermal treatment. Foods 9, 900.

Sen, S., Ganguly, S., 2017. Opportunities, barriers and issues with renewable energy development–a discussion. Renew. Sustain. Energy Rev. 69, 1170–1181.

Senthilkumar, S., Karthick, A., Madavan, R., Moshi, A. a M., Bharathi, S.S., Saroja, S., Dhanalakshmi, C.S., 2021. Optimization of transformer oil blended with natural ester oils using Taguchi-based grey relational analysis. Fuel 288, 119629.

Shah, Z.H., Tahir, Q., 2011. Dielectric properties of vegetable oils. J. Sci. Res. 3, 481–492.

Sitorus, H.B., Setiabudy, R., Bismo, S., Beroual, A., 2016. Jatropha curcas methyl ester oil obtaining as vegetable insulating oil. IEEE Trans. Dielectr. Electr. Insul. 23, 2021–2028.

Souček, J., Hornak, J., Svoboda, M., Gutten, M. & Koltunowicz, T. Comparison of the electrical properties of canola oil with commercially available mineral oil. 2015 16th International Scientific Conference on Electric Power Engineering (EPE), 2015. IEEE, 634-637.

Srivastava, A., Prasad, R., 2000. Triglycerides-based diesel fuels. Renew. Sustain. Energy Rev. 4, 111–133.

Stefansson, B.R. 2009. Baldur Rosmund Stefansson. Wolf Prize In Agriculture. World Scientific.

Stockton, D.P., Bland, J.R., Mcclanahan, T., Wilson, J., Harris, D.L., Mcshane, P., 2008. Seed-oil-based coolants for transformers. IEEE Ind. Appl. Mag. 15, 68–74.

Tamothran, A.M., Bhubalan, K., Anuar, S.T., Curtis, J.M., 2022. The degradation and toxicity of commercially traded vegetable oils following spills in aquatic environment. Environ. Res. 214, 113985.

Thiyam-Holländer, U., Eskin, N.M. & Matthäus, B. 2012. Canola and rapeseed: production, processing, food quality, and nutrition, CRC Press.

Totzauer, P., Trnka, P., Mentlík, V., Hornak, J., Kadlec, P., Ulrych, J. & Pihera, J. A study of various inhibitor mixtures in natural ester oil. 2017 IEEE 19th International Conference on Dielectric Liquids (ICDL), 2017. IEEE, 1-4.

Transformers, P. 2013. Part 14: Liquid-immersed power transformers using high-temperature insulation materials. IEC Standard IEC, 60076-14.

Trnka, P., Mentlik, V. & Cerny, J. Electroinsulating fluids—New insulating mixtures. 2011 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, 2011. IEEE, 575-578.

Unge, M., Singha, S., Ingebrigtsen, S., Linhjell, D. & Lundgaard, L.E. Influence of molecular additives on positive streamer propagation in ester liquids. 2014 IEEE 18th International Conference on Dielectric Liquids (ICDL), 2014. IEEE, 1-4.

Unge, M., Singha, S., Van Dung, N., Linhjell, D., Ingebrigtsen, S., Lundgaard, L.E., 2013. Enhancements in the lightning impulse breakdown characteristics of natural ester dielectric liquids. Appl. Phys. Lett. 102.

Viertel, J., Ohlsson, K. & Singha, S. Thermal aging and degradation of thin films of natural ester dielectric liquids. 2011 IEEE International Conference on Dielectric Liquids, 2011. IEEE, 1-4.

Vijayan, S.K., Victor, M.N., Sudharsanam, A., Chinnaraj, V.K., Nagarajan, V., 2018. Winterization studies of different vegetable oil biodiesel. Bioresour. Technol. Rep. 1, 50–55.

Vinogradov, A.A., Nifant’ev, I.E., Vinogradov, A.A., Borisov, R.S. & Ivchenko, P.V. 2021. Precision rheological study of the effectiveness of polymer cold flow improvers for corn oil based biodiesel. Mendeleev Communications, 31, 709-711.

Wang, C., Sha, Z., Wang, F., Huang, Z., Jia, M. & Rozga, P. Improved Oxidation Resistance of Natural Ester Insulating Oil by Oil-soluble Polysesquioxane. 2021 6th International Conference on Nanotechnology for Instrumentation and Measurement (NanofIM), 2021. IEEE, 1-4.

Warner, K. & Eskin, N. a M. 1995. Methods to access quality and stability of oils and fat-containing foods, The American Oil Chemists Society.

Widodo, A.S., Wijayanti, W., Wardana, I., 2021. The role of areca catechu extract on decreasing viscosity of vegetable oils. Sci. World J. 2021.

Wilhelm, H., Stocco, G., Batista, S., 2013. Reclaiming of in-service natural ester-based insulating fluids. IEEE Trans. Dielectr. Electr. Insul. 20, 128–134.

Xu, Y., Qian, S., Liu, Q., Wang, Z., 2014. Oxidation stability assessment of a vegetable transformer oil under thermal aging. IEEE Trans. Dielectr. Electr. Insul. 21, 683–692.

Xue, Y., Yang, C., Xu, G., Zhao, Z., Lian, X., Sheng, H., Lin, H., 2017. The influence of polymethyl acrylate as a pour point depressant for biodiesel. Energy Sources, Part A: Recovery, Util., Environ. Eff. 39, 17–22.

Yang, L., Liao, R., Sun, C., Yin, J. & Zhu, M.. Influence of vegetable oil on the thermal aging rate of Kraft paper and its mechanism. 2010 International Conference on High Voltage Engineering and Application, 2010. IEEE, 381-384.

Yang, T., Wang, F., Yao, D., Li, J., Zheng, H., Yao, W., Lv, Z., Huang, Z., 2022. Low-temperature property improvement on green and low-carbon natural ester insulating oil. IEEE Trans. Dielectr. Electr. Insul. 29, 1459–1464.

Yantai, G., Harker, K.N., Kutcher, H.R., Gulden, R.H., Irvine, B., May, W.E., O’donovan, J.T., 2016. Canola seed yield and phenological responses to plant density. Can. J. Plant Sci. 96, 151–159.

Yu, H., Yu, P., Luo, Y., 2017. Renewable low-viscosity dielectrics based on vegetable oil methyl esters. J. Electr. Eng. Technol. 12, 820–829.

Zhang, X., Xu, X., Liu, Y., Wang, J., Xiong, Z., 2016. Global warming potential and greenhouse gas intensity in rice agriculture driven by high yields and nitrogen use efficiency. Biogeosciences 13, 2701–2714.

Zhong, H., Watanabe, M., Enomoto, H., Jin, F., Kishita, A., Aida, T.M., Smith, Jr, R.L., 2016. Winterization of vegetable oil blends for biodiesel fuels and correlation based on initial saturated fatty acid constituents. Energy Fuels 30, 4841–4847.

Zhou, Z., Kai, L., Tao, W., Xu, H., Hui, Q., Bing, F., 2012. Rapid determination of oxidation stability for transformer oils with antioxidant. IEEE Trans. Dielectr. Electr. Insul. 19, 1604–1608.