Journal of Materials and Environmental Science
ISSN : 2028-2508
e-ISSN : 2737-890X
CODEN : JMESCN

J. Mater. Environ. Sci., 2023, Volume 14, Issue 10, Page 1307-1322

http://www.jmaterenvironsci.com

Castor, Jatropha, Corn and Tobacco Oils, and their Blends as Environmentally Friendly Alternatives to Mineral Oil Based Transformer Oil – A Review

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Received *25 Aug 2023,*
Revised *15 Oct 2023,*
Accepted *18 Oct 2023*

Keywords:
- ✓ *environmentally friendly;*
- ✓ *vegetable oil;*
- ✓ *transformer oil;*
- ✓ *dielectric strength;*
- ✓ *ASTM D6871-03 standard*

Citation*: Ajani, E. A., Bala, K. C., Lawal, S. A., Tsado, J. (2023) Castor, Jatropha, Corn and Tobacco Oils, and their Blends as Environmentally Friendly Alternatives to Mineral Oil Based Transformer Oil – A Review, J. Mater. Environ. Sci., 14(10), 1307-1322*

Abstract: Mineral oil is the most commonly used transformer oil. It is non-biodegradable and environmentally benign, prompting new researches into finding suitable alternatives. This paper reviewed current researches on the development of environmentally friendly alternatives to mineral oil from vegetable oils such as castor, jatropha, corn and tobacco oils to identify the research gaps. The highest value reported for dielectric strength for castor oil was 43 kV, 55 kV for jatropha oil and 98.3 kV for corn oil. These values satisfy the ASTM D6871-03 standard. There is no report for the dielectric strength of tobacco oil, hence the need to investigate its dielectric properties. Castor oil is highly viscous, with viscosities as high as 272.65 cSt. However, after refining, viscosities as low as 7.01 cSt were reported. For the four vegetable oils reviewed, the refining methods adopted by researchers effectively modified the viscosity, specific gravity, dielectric strength and acid number. However, there is need for further investigation to develop more efficient refining methods for reducing the acid number of castor oil and tobacco oil to acceptable limits. Tobacco oil was reported to record very low pour point of -15 ºC, which is good for transformer oils, especially those operated in temperate regions. Corn oil and jatropha oil responded well to refining processes adopted and showed great potentials as alternatives to mineral oil. More researches are required to develop more efficient methods for improving the physiochemical and dielectric properties of castor oil and tobacco oil to satisfy the ASTM standard.

1. Introduction

A transformer transforms electrical energy from one voltage level to another (Adekoya and Adejumobi, 2017, Adly, 2021, Giri and Tesche, 2021). It is one of the essential components of the electrical power network since its first development in 1885 (Patel *et al.,* 2021, Moosasait and Siluvairaj, 2021, Syafruddin *et al.,* 2021). A lot of heat is generated in its core and windings during operation (Onah, 2011); hence, a cooling system is incorporated into its design to help dissipate heat buildup, to avoid failure (Negi and Maithani, 2021). In oil-cooled systems, the core and windings are immersed in transformer oil, which acts as coolant, insulator and protects the core and windings from oxidation and the cellulose insulation paper from direct contact with atmospheric oxygen (Martins, 2010).

There are several types of transformer oils, including mineral oil, askarels, silicone liquid, synthetic ester oil, natural ester oil and nanofluids (Rafiq *et al.,* 2015, Bhatt and Bhatt, 2019, Reddy, 2019, Wang *et al.,* 2020), but the most commonly used is mineral oil, which is non-biodegradable, environmentally benign, with low flash point and fire point (Rouabeh *et al.,* 2019). Transformers are the highest source of polychlorinated biphenyls (PCBs) contamination to the environment. Askarel oil filled transformers, contain 40 to 60% PCBs, one of the highest ranking group of global environmental contaminants of concern, included in the first twelve compounds on the list of Persistent Organic Pollutants (POPs), declared by the Stockholm Convention on POPs in 2001 (Aganbi *et al.,* 2019). PCB contamination has adverse effect on the environment and human health (Saeedi *et al.,* 2017).

These challenges with mineral oil, including environmental concerns and expensive disposal of used oil gave rise to the need for researches into the development of new environmentally friendly vegetable oil based transformer oils (Silva and Folha, 2020, Ahmed *et al.,* 2023). Vegetable oil based transformer oils are biodegradable, they have better health and environmental profiles, transformer oil-spill management solutions are easy and used-oil disposal are cheaper (Módenes *et al.,* 2018, Schinteie *et al.,* 2019).

Vegetable oils are produced from plant oilseeds such as jatropha, neem seed, soybean, groundnut, canola, sunflower, castor, cottonseed and mahogany seed (Mokhtari *et al.,* 2014, Balachandran *et al.,* 2017, Yusuf *et al.,* 2020, Isamotu and Sanusi, 2020, Ahamed *et al.,* 2021, Das *et al.,* 2021, Abutu *et al.,* 2023). Compared with the other types of insulating liquids, vegetable oils have significantly higher flash points, higher fire points, hence they are classified as less-flammable, which reduces the risk of fire-outbreaks during transformer operation (Wang *et al.,* 2019, Rafiq *et al.,* 2020, Bilgin *et al.,* 2021, Das, 2023). They have the best biodegradability index (Ayoub *et al.,* 2021, Roslan *et al.,* 2021), hence they are classified as suitable for use in environmentally sensitive areas, such as watercourses (Salih and Salimon, 2021). The challenges with the use of vegetable oils as transformer oil includes their high level of free fatty acid content and oxidation instability (Yahaya *et al.,* 2020). In addition, contaminants such as moisture, sediments and conducting particles reduce the dielectric strength of oils. Clean dry oil has an inherently high dielectric strength (Yusoff *et al.,* 2018, Ab-Ghani *et al.,* 2020, Ranga *et al.,* 2020, Rafiq *et al.,* 2021). Moisture accelerates the deterioration of both the insulating oil and the cellulose paper insulation (Boudraa *et al.,* 2021). High level of free fatty acids increases oxidation and reduces oxidation-stability. Oil oxidation products are hydrophilic and lower the interfacial tension of the oil (Kim *et al.,* 2019, Soares *et al.,* 2021). Unrefined vegetable oils usually have high pour points (Oliveira *et al.,* 2018, Oyelaran *et al.,* 2020). High pour point is not suitable for transformer oils operating in cold climates because, if the ambient temperature falls below the pour point, wax precipitates in the oil and the oil loses its flow characteristics, causing the wax to block the filters and oil supply lines, leading to transformer failure (Hao *et al.,* 2019).

Researchers have developed biodegradable vegetable oils for industrial engineering applications including dielectric oils (Patel *et al.,* 2016, Heikal *et al.,* 2017, Lv *et al.,* 2017, Rafiq *et al.,* 2019, Raof *et al.,* 2019, Udoh *et al.,* 2020). Researches in the area of dielectric coolants are focusing on alternative environmentally friendly, vegetable oil-based transformer oils (Onuh *et al.,* 2017, Nayager, 2018, Cecilia *et al.,* 2020). There are several vegetable oils with suitable dielectric and physiochemical properties that can be adapted for the development of bio-transformer oils, which are yet to be studied adequately. This includes: neem seed oil, jatropha oil, tobacco oil, tigernut oil, sesame oil, castor oil, olive oil, moringa oil, to mention a few.

These vegetable oils, in their crude and unrefined form usually do not fully satisfy the standard specifications and requirement for transformer oils, hence some refining methods are usually adopted to improve their physical, chemical and dielectric properties, so as to satisfy the standard specifications. The usual strategy for the development of vegetable oils into transformer oils is by selecting a base vegetable oil, characterising it to identify the deficiencies in its critical parameters and using refining methods such as degumming, neutralisation, bleaching, deodorisation, filtering and drying to improve some parameters before treating it with additives to enhance those parameters that are still lacking. A few others researchers have used the strategy of blending other vegetable oils which have better properties to the base oil to improve its parameters. Blending of different vegetable oils have been reported to modify the chemical composition of oils, which in turn modified the physical and electrical properties of the oils (Wahyudi *et al.,* 2018).

This paper reviewed current researches on the development of environmentally friendly alternatives to mineral oil based transformer oil from vegetable oils such as castor oil, jatropha oil, corn oil and tobacco oil.

2. Transformer Oils

Transformer oils serves as coolants and insulators for the core, windings and the cellulose insulation paper (Hasan, 2017, Daware, 2021). Currently, millions of litres of transformer oils are required for the operation and maintenance of the large number of power transformers within the electrical networks around the world, with a market size valued at $27.7 billion in 2019, and is expected to reach $50.8 billion by 2027 (Martin-Ramos *et al.,* 2008, Ribbenfjärd, 2010, Pratik and Eswara, 2020).

2.1 Types of transformers requiring transformer oils

It is not all types of transformer that require the use of transformer oils. There are different types of transformer used in various applications (Banović and Sanchez, 2014). Considering the type of cooling system employed, transformers are classified as oil-cooled, water-cooled or air-cooled (Rakhonde and Tekade, 2014). Oil cooled transformers are the ones that use transformer oils to dissipate the heat generated within the transformer core and windings (Amoiralis *et al.,* 2012).

2.2 Types of transformer oils

Based on the type of base oil used, there are four major classes of transformer oil: mineral oils, askarels, esters and nano-fluids (Wanatasanappan *et al.,* 2022, Hussain *et al.,* 2022, Suhaimi *et al.,* 2022).

2.3 Historic evolution of vegetable oil as transformer oil

The global oil crisis of the 1970s forced the initial search for alternatives, leading to the growing desire for environment-friendly, safe, reliable and clean energy solutions (Gnanasekaran and Chavidi, 2018a & 2018b, Mahanta, 2020). Extensive research into the development of vegetable oil based transformer oil began after 1990 (Jacob *et al.,* 2020). The first commercial vegetable oil based transformer oil product was BIOTEMPs, patented in September 1999, followed by Envirotemp FR3s in March 2000. Transformer oil standard specifications are covered by the American Standard Test Measurements (ASTM). The ASTM D3487 standard was developed for mineral oil-based transformer oils (Nijssen-Wester, 2021). In the year 2003, ASTM developed a specific code for vegetable oil based transformer oils to cater for the unique properties which vegetable oils possess, which are different from mineral oils.

2.4 Electrical properties of vegetable oil-based transformer oils

Table 1 presents the ASTM D6871-03 standard, which specifies the acceptable limits for the physical, electrical and chemical properties of vegetable oil-based transformer oils (ASTM, 2003).

Table 1. ASTM D6871-03 standard specification for natural ester (vegetable oil) fluids used in electrical apparatus

Property	Limit	ASTM Test Method
Physical		
Colour, max	1.0	D 1500
Fire point, min, °C	300	D 92
Flash point, min, °C	275	D 92
Pour point, max, °C	-10	D 97
Relative density (specific gravity), 15 °C/15 °C, max	0.96	D 1298
Viscosity, max, cSt at:		D 445 or D 88
100 °C (212 °F)	15	
40 °C (104 °F)	50	
0 °C (32 °F)	500	
Visual Examination	Bright and Clear	D 1524
Electrical		
Dielectric breakdown voltage, impulse conditions:		
Disk electrodes, min, kV	30	D 877
VDE electrodes, min, kV, at:		D 1816
1 mm (0.04 in.) gap	20	
2 mm (0.08 in.) gap	35	
Dielectric breakdown voltage, impulse conditions: 25 °C, min, kV, needle negative to sphere grounded 1 in. (25.4 mm) gap	130	D 3300
Dissipation factor (or power factor) at 60 Hz, max, %		D 924
25 °C	0.20	
100 °C	4.0	
Gassing tendency, max, µL/min	0	D 2300
Chemical		
Corrosive sulphur	Not corrosive	D 1275
Neutralisation number, total acid number, max, mg KOH g^{-1} oil	0.06	D 974
PCB content, ppm	Not detectable	D 4059
Water, max, mg/kg	200	D 1533[A]

The properties of these oils affect the performance of the transformer oil as a lubricant and insulator. The dielectric strength of transformer oil is also known as the breakdown voltage (BDV). BDV is measured by observing at what voltage, sparking starts between two electrodes immersed in the oil, separated by a specific gap (Ali *et al.,* 2021). A low value of BDV indicates the presence of moisture and conducting substances in the oil. Dry and clean oil gives BDV results better than oil with moisture content and other conducting impurities. Suhaimi *et al.* (2020) reported that oil impurities had a significant effect on dielectric strength, as the concentration of impurity increased, the dielectric strength of the transformer oil reduced. Minimum breakdown voltage or dielectric strength of transformer oil, at which this oil can safely be used in a transformer, is considered as 35 kV (Alharthi *et al.,* 2018).

3. Vegetable Oils and their Blends as Transformer Oils

3.1 Castor oil as transformer oil

Egbuna *et al.* (2016) studied the development of bio-transformer oil from castor seed as an alternative to mineral oil. For the refined castor oil, they reported a dielectric strength of 23 kV, specific gravity of 0.9283, pour point of -9 °C, viscosity 7.01 cSt, flash point 253 °C and an acid number of 13.184 mg KOH g^{-1} oil. Compared with the ASTM D6871-03 standard, the dielectric strength and flash point of the refined castor oils did not satisfy the minimum requirement of 35 kV and 275 °C respectively. Similarly, the pour points and acid numbers did not satisfy the maximum limit of -10 °C and 0.06 mg KOH g^{-1} oil, respectively. The viscosity and specific gravity, satisfied the maximum limit of 50 cSt and 0.96 respectively.

Aliyu and Tijjani (2017) reported a dielectric strength of 41.01 kV, pour point of 1.15 °C, flash point of 132 °C, specific gravity of 0.85, viscosity 18.1 cSt and acid number of 2.12 mg KOH g^{-1} oil for castor oil. The dielectric strength, specific gravity and viscosity of the degummed, epoxidated and transesterified castor oil satisfied the ASTM standards. However, the pour point, flash point and acid number did not satisfy the ASTM standard. Abdulmumin *et al.* (2017) reported a dielectric strength of 24.32 kV, relative density of 0.85, pour point of 1.15 °C, viscosity of 8.1 cSt, flash point of 132 °C, acid number of 2.12 mg KOH g^{-1} oil. The dielectric strength, acid number, pour point and flash point did not satisfy the ASTM standards. However, the relative density and viscosity satisfied the ASTM standards.

Brahmin *et al.* (2018) reported a breakdown voltage of 31 kV, a flash point of 229 °C, and a fire point of 240 °C. The breakdown voltage, flash point and fire point of castor oil from their research did not satisfy the ASTM standards. Hari and Allwyn (2018) reported a dielectric strength of 26 kV for castor oil and 32 kV for the castor based nanofluid. The treatment of castor oil with Al_2O_3 nanoparticles improved the dielectric strength by 23 %, which is close to the 35 kV minimum standard limit as prescribed in the ASTM D6871-03 standards. Treatment of castor oil with Al_2O_3 nanoparticles, however, had a negative impact on the acid number, as the acid number increased from 0.1 mg KOH g^{-1} for the pure castor oil to 0.2 mg KOH g^{-1} for the castor oil based nanofluid.

Nkouetcha *et al.* (2019) reported a relative density of 0.965 for the crude castor and 0.956 for the purified castor oil. They also reported an acid number of 2.03 and 0.1 mg KOH g^{-1} oil, for the crude and refined castor oil respectively, which are both higher than the maximum standard limit. They reported an improvement in the value of viscosity of the crude castor oil from 272.65 cSt to 18.42 cSt for the purified castor oil, which falls within the acceptable limits.

3.2 Castor oil blended with other vegetable oils as transformer oil

Kumara *et al.* (2017) characterised castor, sesame and coconut oils and their blends. They observed that the physical, chemical and electrical properties of the oil blends changed with respect to the ratio of the mixtures. After blending coconut oil with castor oil in ratio 1:1, they observed that the breakdown voltage of castor oil was reduced from 23.4 to 10.1 kV, viscosity improved from 265 to 156 cSt, acid number improved from 5.6 to 3.2 mg KOH g^{-1} oil. For the castor-sesame oil blend, at ratio 1:1, the breakdown voltage of castor oil was reduced from 23.4 to 11.6 kV, viscosity improved from 265 to 147 cSt, acid number of castor oil improved from 5.6 to 5.1 mg KOH g^{-1} oil. For the castor-coconut-sesame oil blend, in ratio 1:1:1, the breakdown voltage of castor oil was reduced from 23.4 to 6.6 kV, viscosity improved from 265 to 95 cSt, acid number of castor oil improved from 5.6 to 3.9 mg KOH g^{-1} oil. They concluded that the physical, chemical and electrical properties of oils can be changed or improved by blending them with appropriate oil(s), in the appropriate ratios.

Sakharwade *et al.* (2017) blended castor oil and mahua oil in three different ratios. They reported that blending mahua oil with castor oil improved the viscosity, density and pour point but negatively affected the dielectric strength and flash point.

Okafor and Okafor (2018) investigated the effect of blending castor and neem seed oils. They observed that as the percentage content of neem oil increased, the viscosity of the blended oils also improved, while the dielectric strength reduced. They recorded an optimum flash point of 168 ºC at 50:50 blend ratio, the optimum oil density of 0.8219 gcm^{-1} at 40 % neem content, and the optimum acid value of 0.1405 $mgKOHg^{-1}$ oil when the percentage content of neem oil in the blend was at 40 and 50 %.

3.3 Jatropha oil as transformer oil

Goyal *et al.* (2012 & 2013) reported a viscosity of 50 cSt, density of 0.93 gcm^{-3}, and flash point of 241ºC for crude jatropha curcas oil. Garba *et al.* (2013) characterized refined jatropha oil and reported a dielectric strength of 22 kV, a specific gravity of 0.8480, an acid value of 0.1428 mg KOH g^{-1} oil, a viscosity of 82 cSt, a flash point of 150 °C, saponification value of 155 mg KOH g^{-1} oil, a peroxide value of 7.20 meq g^{-1} oil, iodine value of 51.27 g $100g^{-1}$ oil, a free fatty acid value of 0.0718 mg KOH g^{-1} oil, a density of 0.725 gcm^{-3}, a boiling point of 124 °C, a cloud point of 14 °C and a pH value of 5.15. They concluded that since the parameters of the degummed jatropha oil had a reasonable agreement with the ASTM D3487 standards for mineral oil based transformer oils, refined jatropha curcas seed oil could be a good alternative to mineral oil.

Olutoye (2015) characterized crude jatropha oil and reported an acid value of 14.47 mg KOH g^{-1} oil. Evangelista *et al.* (2017) investigated the development of transformer oil from jatropha curcas oil. They reported that degumming refining process reduced the acid number of the crude jatropha oil from 6.8 to 5.8 mg KOH g-1 oil. Alkali neutralization reduced the acid number from 5.8 to 0.23 mg KOH g^{-1} oil. Dry neutralization of the degummed jatropha oil reduced the acid value from 5.8 to 0.5 mg KOH g^{-1} oil at a concentration of (0.5 g/g oil) impregnated in NaOH-water solution (2.0 g/g solid). Clarification of the dry-neutralized oil reduced the acid value from 0.5 to 0.04 mg KOH g^{-1} oil, which satisfies the ASTM D6871-03 standard.

Aliyu and Tijjani (2017) treated and characterized jatropha oil. They reported a dielectric strength of 43 kV, pour point of 4 ºC, flash point of 146 ºC, specific gravity of 0.83, viscosity of 16.5 cSt and acid number of 3.45 mg KOH g^{-1} oil, for degummed, epoxidated and transesterified jatropha oil. The dielectric strength, specific gravity and viscosity satisfied the ASTM standards. However, the pour point, flash point and acid number did not satisfy the ASTM standards. They concluded that with its high dielectric strength, jatropha oil has a great potential for being developed as a bio-transformer oil for both high and low voltage transformers with further refinements of the oil.

Abdulmumin *et al.* (2017) investigated the physicochemical properties of jatropha, moringa, castor, cotton and shea. For the purified jatropha oil, they reported a dielectric strength of 25.18 kV, relative density of 0.83, pour point of 4 ºC, viscosity of 6.5 cSt, flash point of 146 ºC, and acid number of 3.45 mg KOH g^{-1} oil. The dielectric strength, acid number, pour point and flash point did not satisfy the ASTM standards. However, the relative density and viscosity satisfied the ASTM standards. They concluded that jatropha oil could serve as a transformer oil if it were better refined, which is in agreement with the conclusion of Abdelmalik *et al.* (2018).

Wu and Zhang (2020) used winterization/dewaxing, alkali refining, washing with deionized water, deodorizing and bleaching processes to refine jatropha oil. After this, they treated it with 4 % (w/w of oil) Al_2O_3 powder, stirred at 50 ºC for one hour, after which it was centrifuged at 6500 rpm for 10 minutes and the supernatant oil was decanted. They reported that the refined jatropha oil satisfied all the standard requirements for vegetable insulating oils, as specified in the ASTM D6871-17 standards.

3.4 Jatropha oil blended with other vegetable oils as transformer oil

Wahyudi *et al.* (2018) investigated the effect of blending jatropha oil with coconut oil. They reported that the dominant fatty acid in the jatropha oil sample, with 80.66% content, was cis-8,11,14 eicosatrienoic acid (with the three double bonds at positions 8, 11 and 14) as presented in **Figure 1**. They observed that heating and stirring the jatropha oil at 90 °C changed the positions of the double bonds to 11, 14 and 17 to form Cis-11,14,17 eicosatrienoic acid (as presented in **Figure 2**), which was the dominant fatty acid at 87.19 %. Thus, ordinary heating the jatropha oil to 90 °C did not break the long carbon chain, it only changed the position of the double bonds.

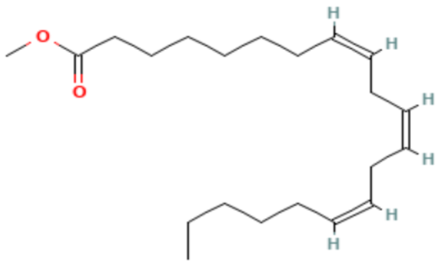

Figure 1. cis-8,11,14 eicosatrienoic acid (C20:3)

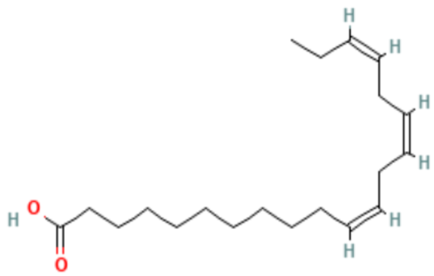

Figure 2. cis-11,14,17 eicosatrienoic acid (C 20:3)

They observed that the combined effect of heating and mixing jatropha oil with 10 % v/v coconut oil led to the complete breakdown of the cis-11,14,17 eicosatrienoic acid (C 20:3) to form several other shorter carbon chain fatty acids (as presented in **Figure 3**), with linolelaidic acid (C 18:2) being the dominant, at 43.17 %, followed by lauric acid (C 12:0) at 21.57 %.
This chemical change from the breakdown of long chain fatty acid to short chain fatty acids also brought about changes in the physical properties of the oil blends, including viscosity and density. At 90:10 ratio, viscosity reduced by about 27.59 % while mixing with 80:20 ratio decreased the viscosity by 47.41%.

3.5 Corn oil as transformer oil

Taslak *et al.* (2015) investigated the suitability of corn oil as an alternative to mineral oil based transformer oil. They reported a dielectric strength of 52.73 kV for corn oil, which satisfies the ASTM standard and was observed to be higher than the 51.60 kV recorded for APAR 60UX mineral oil based transformer oil sample that it was compared with. Kumar *et al.* (2016) investigated the suitability of commercially available refined corn oil and rice bran oil as alternatives to mineral oil based transformer oil. They reported a dielectric strength of 37.8 kV for corn oil, flash point of 258 °C, fire point of 272 °C, viscosity of 75 cSt and acid value of 0.0297 mg KOH g^{-1} oil. They compared the parameters of corn oil with mineral based transformer oil and reported that the dielectric strength, flash point, fire point of corn oil was better than those of the mineral oil. Acid values of both corn oil and mineral oil were about the same. The viscosity of mineral oil was lower and better than that of corn oil.

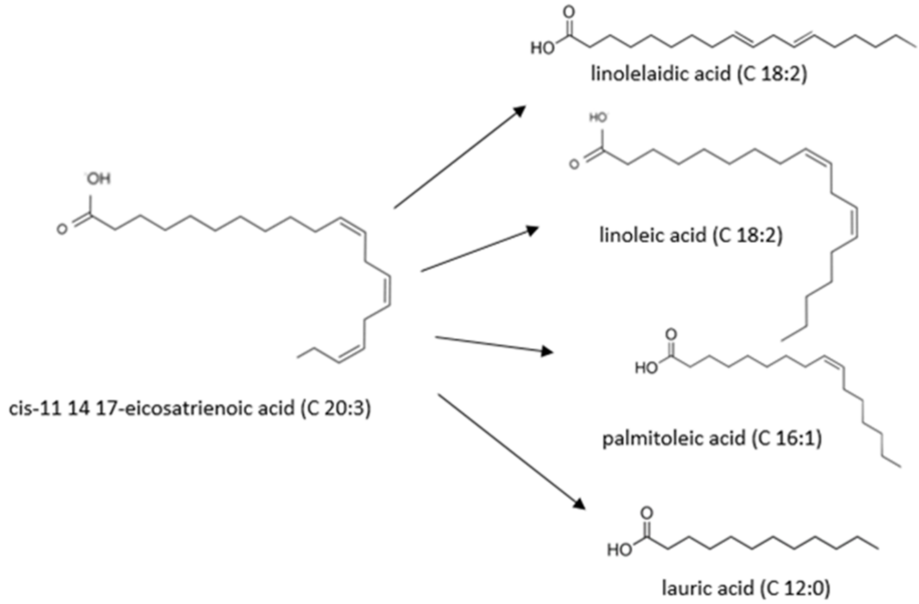

Figure 3. Breakdown of long chain fatty acid to short chain fatty acids

Hamid *et al.* (2016) reported a breakdown voltage of 35.6 kV for the fresh corn oil and 98.3 kV for the filtered and dried corn oil. Filtering and drying thus improved the dielectric strength of corn oil by 176 %. Feroz *et al.* (2018) compared the dielectric strength of synthetic ester, corn oil, olive oil, castor oil and mineral oil. They reported a dielectric strength of 51.5 kV for corn oil, 48.7 kV for castor oil, 45.8 kV for olive oil, 33.7 kV for mineral oil and 20.9 kV for synthetic ester oil. They concluded that the natural ester oils, especially corn oil has better dielectric strength than mineral oil and synthetic ester oil and thus would be better alternatives to mineral oil based transformer oil.

3.6 Corn oil blended with other vegetable oils as transformer oil

Manjang *et al.* (2019) studied the effect of blending corn oil with mineral oil based transformer oil. They observed that the dielectric strength of mineral oil was improved from 26.05 kV to 30.66 kV (at 20 % corn oil) and also reported that as the percentage of corn oil in the mixture increased, the specific gravity and viscosity of the blend also increased.

3.7 Physiochemical properties of tobacco seed oil

The seed of tobacco (Nicotiana tobacum L.), is an agricultural waste from the tobacco leaf manufacturing industry (Samuel *et al.,* 2021). The endosperm of tobacco seed comprises of oil-filled cells within thin walls, containing more than 30 % seed oil after extraction (Rajan *et al.,* 2021). Nirmal-Kumar and Sarathbabu (2014) extracted tobacco seed oil by cold press method and filtered it using serigraphy papers (A1, A2). They characterized the oil and reported a specific gravity of 0.917, viscosity of 48.4 cSt, flash point of 185 °C and fire point of 192 °C. Chiririwa *et al.* (2014) reported that the oil yields from three different varieties of tobacco seeds used in their study ranged from

34.17 - 36.55 %. They also reported a density 0.926 gm^{-3}, a viscosity of 94.3 cSt, an iodine value of 133.71 g 100 g^{-1} oil and a saponification values of 189.48 mg KOH g^{-1} oil. Ashirov *et al.* (2020) reported a 36.75 % oil yield for tobacco oil, a very low pour point of -15 ºC, specific gravity of 0.9279, and a viscosity of 0.744 cSt, which satisfied the ASTM D6871 standard. Hariram and Gowtham. (2016) reported a relative density 0.886, viscosity of 3.7 cSt, flash of 172 ºC and fire point of 182 ºC, for refined tobacco seed oil. They reported a density of 0.888 gcm^{-3}, viscosity of 3.5 cSt, acid value of 0.45 mg KOH g^{-1} oil and a flash point of 212 ºC for a two-stage transesterified tobacco oil. The electrical properties of tobacco seed oil was not investigated by any of the related research work reviewed.

4. Research Gaps

Castor oil is highly viscous, recording viscosities as high as 272.65 cSt. However, for refined castor oil, the lowest value of 7.01 cSt was reported for viscosity, 0.85 for specific gravity, and 48.7 kV as the highest value reported for dielectric strength. These all satisfy the ASTM standard. The lowest acid number reported was 0.1 mg KOH g^{-1} oil, lowest pour point of -9 ºC, and highest flash point of 253 ºC. These values do not satisfy the ASTM standard. It can therefore be concluded that with proper treatment and refining method, the dielectric strength, specific gravity and viscosity of castor oil could be improved to the ASTM acceptable limit. Researchers intending to develop castor oil bio-transformer however need to focus more on developing efficient treatment methods to improve the acid number, pour point, flash and fire points to the acceptable limits.

For refined jatropha oil, the highest value reported for dielectric strength is 43 kV, the lowest viscosity is 6.5 cSt, specific gravity of 0.83, and acid value of 0.04 mg KOH g^{-1} oil. These values satisfy the ASTM standard, meaning that with proper treatment and refining methods, these properties could be modified to meet the ASTM standard. However, the highest flash point of 150 °C and lowest pour point of 4 ºC were reported, which do not satisfy the ASTM standard. This means that researchers interested in developing jatropha oil bio-transformer would need to focus more of their work on developing refining methodologies for improving flash point, fire point and pour point of the crude jatropha oil. Jatropha oil exhibits great potential as an alternative to mineral oil based transformer oil.

The highest value reported for dielectric strength of treated corn oil is 98.3 kV, a 176 % improvement from 35.6 kV for the fresh corn oil, as a result of filtration and drying refining processes. A high flash point of 258 ºC and fire point of 272 ºC were also reported for corn oil. The lowest acid value of 0.0297 mg KOH g^{-1} oil was reported for treated corn oil, which value satisfies the ASTM standard. The minimum viscosity of 75 cSt was recorded for treated corn oil, which does not satisfy the ASTM standard. Corn oil thus shows a great potential as an alternative to mineral oil based transformer oil. For tobacco oil, there is no reported value for its dielectric strength. A very low pour point of -15 ºC, low viscosity of 0.744 cSt, and relative density of 0.886 were reported for tobacco oil, which all satisfy the ASTM standard. The lowest acid value of 0.45 mg KOH g^{-1} oil and the highest flash point of 220 ºC and the fire point 230 ºC were reported for fresh tobacco oil. These values do not satisfy the ASTM standard. There is need for more research on tobacco oil as an alternative to mineral oil based transformer oil.

5. Conclusion

Several researchers have developed environmentally friendly transformer oils from different vegetable oils as alternative to mineral oil based transformer oils. However, there are still several vegetable oils yet to be researched and the need for more studies on developing more efficient refining methods for the vegetable oils.

Acknowledgement: The technical inputs of Mr. Isaac Okorie and other staff of the Centre for Genetic Engineering and Biotechnology Laboratory, Bosso Campus, Federal University of Technology, Minna, Niger State are acknowledged.

Disclosure statement: *Conflict of Interest:* The authors declare that there are no conflicts of interest.
Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

References

Abdelmalik, A. A., Abolaji, P. A., Sadiq, H. A. (2018) Assessment of Jatropha oil as insulating fluid for power transformers, *Journal of Physical Science*, 29(1), 1–16. https://doi.org/10.21315/jps2018.29.1.1

Abdulmumin, S., Nana, B. I., Izom, I. I., Mamuda, A., Muhammad, A., Abbas, A. M. (2017) Determination of physicochemical properties of electric transformer oil extracted from selected plant seeds in Nigeria, *International Research Journal of Engineering and Technology*, 4(1), 760–767.

Ab-Ghani, S., Bakar, N. A., Chairul, I. S., Khiar, M. S. A., Ab-Aziz, N. H. (2020) Effects of moisture content and temperature on the dielectric strength of transformer insulating oil, *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 63(1), 107–116.

Abutu J., Elachi E. E., Tanko B., Akene P., Musa K., Lawal S. A. (2023) Development of Cutting Fluid from Mahogany Seed oil and Neem leaves for the Turning of AISI 304 Austenitic Stainless Steel, *J. Mater. Environ. Sci.,* 14(8), 878-889.

Adekoya, D. O., Adejumobi, I. A. (2017) Analysis of acidic properties of distribution transformer oil insulation: case study of Jericho (Nigeria) distribution network, *Nigerian Journal of Technology (NIJOTECH)*, 36(2), 563-570.

Adly, A.A. (2021) Computer-aided transformer design capacity building, *Transformers Magazine*, 8(1), 72-77.

Aganbi, E., Iwegbue, C. M. A., Martincigh, B. S. (2019) Concentrations and risks of polychlorinated biphenyls (PCBs) in transformer oils and the environment of a power plant in the Niger Delta, Nigeria, *Toxicology Reports*, 6(1), 933–939. https://doi.org/10.1016/j.toxrep.2019.08.008

Ahamed, S. A., Riyaz, S. M., Mahadevan, A., Hathim, J. M., Bakrutheen, M., Iruthayarajan, M. W. (2021) Impact of moisture on AC breakdown voltage of crude, refined and transesterified groundnut oil-based liquid insulations, *Arabian Journal for Science and Engineering*, 2(1), 1–8. https://doi.org/10.1007/s13369-021-05543-5

Ahmed, U. O., Mohammed, Y.S., Audu, N. (2023) Potential characterization of bush mango oil for application in transformer insulation, *Asian Journal of Engineering and Applied Technology*, 12(1), 51-54.

Alharthi, M. M., Ghoneim, S. S. M., Taha, I. B. M. (2018) Breakdown Voltage of the Transformer Oils under Certain Conditions, *International Journal of Applied Engineering Research*, 13(1), 3810–3815.

Ali, M., Deenesh, N. K., Kadir, G., Hasnan, K., Nayan, N. (2021) Effect of purification process on the thermal conductivity and breakdown voltage of inhibited, isoparaffinic transformer oil used in electric train, *Journal of Physics: Conference Series,* 1878(1), 1–9. https://doi.org/10.1088/1742-6596/1878/1/012009

Aliyu, A. O., Tijjani, A. (2017) Transesterification and epoxidation of oil extracts from selected plants for use as bio-transformer oil, *International Research Journal of Pure & Applied Chemistry*, 14(1), 1–7. https://doi.org/10.9734/IRJPAC/2017/33506

American Society for Testing and Materials (2003) D6871-03 Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus, ASTM International, Pennsylvania, USA.

Amoiralis, E. I., Tsili, M. A., Kladas, A. G., Souflaris, A. T. (2012) Distribution transformer cooling system

improvement by innovative tank panel geometries, *IEEE Transactions on Dielectrics and Electrical Insulation*, 19(1), 1021–1028. https://doi.org/10.1109/TDEI.2012.6215108
Ashirov, M. Z., Datkhayev, U. M., Myrzakozha, D. A., Sato, H., Zhakipbekov, K. S., Rakhymbayev, N. A., Sadykov, B. N. (2020) Study of cold-pressed tobacco seed oil properties by gas chromatography method, *Hindawi: The Scientific World Journal*, 1(1), 1–5. https://doi.org/10.1155/2020/8852724
Ayoub, M., Yusoff, M. H. M., Nazir, M. H., Zahid, I., Ameen, M., Sher, F., Floresyona, D., Budi, N. E. (2021) A comprehensive review on oil extraction and biodiesel production technologies, *Sustainability*, 13(1), 1–28. https://doi.org/10.3390/su13020788
Balachandran, T.G., Sendilvelan, S., Bhaskar, K. (2017) A Comparative Evaluation of Usage of Methyl Esters of Jatropha and Fish Oil for Environmental Protection. *J. Mater. Environ. Sci.,* 8 (7), 2564 – 2571.
Banović, M., Sanchez, J. (2014) Classification of transformers family, *Transformers Magazine*, 1(1), 24–31.
Bhatt, M. A., Bhatt, P. J. (2019) A review on electrical characteristics of nanofluid based transformer oil, *Indian Journal of Science and Technology*, 12(1), 1–20. https://doi.org/10.17485/ijst/2019/v12i27/142960
Bilgin, N., Balci, C., Aslanbas, A. (2021) Case studies leading to the management of tunnel fire risks during TBM drives in an old coalfield, *Tunneling and Underground Space Technology*, 112(1), 103902. https://doi.org/10.1016/j.tust.2021.103902
Boudraa, S., Mokhnache, L., Fofana, I., Benabed, F. (2021) Study of spectral response of transformer oil under low electrical discharge and thermal stress, *18th International Multi-Conference on Systems, Signals & Devices*, Monastir, Tunisia, 712-718. https://doi.org/10.1109/SSD52085.2021.9429501
Brahmin, A., Neema, D.D., Brahmin, K. (2018) Suitability analysis of vegetable oils for high voltage applications, *International Journal of Engineering Technology Science and Research,* 5(1), 200–204.
Cecilia, J. A., Ballesteros-Plata, D., Alves-Saboya, R. M., Tavares de Luna, F. M., Cavalcante, C. L., Rodríguez-Castellón, E. (2020) An overview of the biolubricant production process: challenges and future perspectives, *Processes*, 8(1), 1–24. https://doi.org/10.3390/pr8030257
Chiririwa, H., Hapanyengwi, A., Muzenda, E. (2014) Tobacco seed oil as an economically viable alternative for the tobacco industry, *Int'l Conf. on Chemical Engineering & Advanced Computational Technologies*.
Das, A. K., Chavan, A. S., Shill, D. C., Chatterjee, S. (2021) Jatropha Curcas oil for distribution transformer – A comparative review, *Sustainable Energy Technologies and Assessments*, 46, 1–5. https://doi.org/10.1016/j.seta.2021.101259
Das, A. K. (2023) Analysis of AC breakdown strength of vegetable oils and effect of mineral oil, *Elsevier Electric Power Systems Research,* 214(A), 1-11.
Daware, K. (2021) Electrical Transformer - Basic construction, working and types, *Electricaleasy*. www.electricaleasy.com/2014/03/electrical-transformer-basic.html Accessed on August 16, 2023.
Egbuna, S. O., Ude, O. C., Ude, C. N. (2016) Castor seed bio-transformer oil as an alternative to conventional transformer oil, *International Journal of Engineering & Research Technology*, 5(1), 97–104.
Evangelista, J. M. G., Coelho, F. E. B., Carvalho, J. A. O., Araújo, E. M. R., Miranda, T. L. S., Salum, A. (2017) Development of a new bio-based insulating fluid from jatropha curcas oil for power transformers, *Advances in Chemical Engineering and Science*, 7(1), 235–255. https://doi.org/10.4236/aces.2017.72018
Feroz, S., Tunio, M. A., Tunio, N. A., Ali, Z. (2018) Characteristics of vegetable oils as liquid insulation for transformer: an experimental study, *International Journal of Computer Science and Network Security*, 18(1), 1–4.
Garba, Z. N., Gimba, C. E., Emmanuel, P. (2013) Production and characterisation of biobased transformer oil from jatropha curcas seed, *Journal of Physical Science*, 24(1), 49-61.
Giri, D. V., Tesche, F. M. (2021) Review of Electrical-Power Transformer Responses to Fast Transients, *United States National Committee of URSI National Radio Science Meeting*, pp. 10–11. https://doi.org/10.23919/USNC-URSINRSM51531.2021.9336502.

Gnanasekaran, D., Chavidi, V. P. (2018) Properties of vegetable fluids: a green insulator for power Sector, in: Vegetable Oil based Bio-lubricants and Transformer Fluids, *Springer*, 125-155. https://doi.org/10.1007/978-981-10-4870-8_7

Gnanasekaran, D., Chavidi, V.P. (2018) Vegetable Oil: An Eco-friendly Liquid Insulator, in: Vegetable Oil based Bio-lubricants and Transformer Fluids, *Springer*, 101-124. https://doi.org/10.1007/978-981-10-4870-8

Goyal, P., Sharma, M.P., Jain, S. (2012) How green the Jatropha curcas Biodiesel remains when contaminated with Kerosene? *J. Mater. Environ. Sci.*, 3(6), 1093-1100.

Goyal, P., Sharma, M.P., Jain, S. (2013) Optimization of transesterification of Jatropha Curcas Oil to Biodiesel using Response Surface Methodology and its Adulteration with Kerosene. *J. Mater. Environ. Sci.,* 4 (2), 277-284

Hamid, M. H. A., Ishak, M. T., Din, M. F. M., Suhaimi, N. S., Katim, N.I.A. (2016) Dielectric properties of natural ester oils used for transformer application under temperature variation, *IEEE International Conference on Power and Energy*, pp. 54-57. https://doi.org/10.1109/PECON.2016.7951472

Hao, Y., Yu, N., Qi, G., Qin, J., and Zhang, R. (2019) Study on the influence of antioxidants on transformer oil related indicators, *IOP Conference Series: Earth & Environmental Science*, 223(1), 12-32. https://doi.org/10.1088/1755-1315/223/1/012032

Hari, P. T., Allwyn, C. A. A. (2018) Development of eco-friendly oils for transformers and examination of its dielectric properties for enhancing environmental safety, *Researchgate*, Sivakasi, India, November, 2018, https://erp.mepcoeng.ac.in/images/Employee/Conference/Paper1248.pdf Accessed on Aug 16, 2023

Hariram, V., Gowtham R. A. (2016) Extraction of tobacco (Nicotiana tabacum L.) seed oil and biodiesel preparation through two-stage transesterification, *Research Journal of Pharmaceutical, Biological and Chemical Sciences*, 7(1), 978–983.

Hasan, M. I. (2017) Improving the cooling performance of electrical distribution transformer using transformer oil–Based MEPCM suspension, *Engineering Science and Technology, an International Journal*, 20(1), 502–510. https://doi.org/10.1016/j.jestch.2016.12.003

Heikal, E. K., Elmelawy, M. S., Khalil, S. A., Elbasuny, N. M. (2017) Manufacturing of environment friendly biolubricants from vegetable oils, *Egyptian Journal of Petroleum*, 26(1), 53-59. https://doi.org/10.1016/J.EJPE.2016.03.003

Hussain, M., Mir, F.A., Ansari, M.A. (2022) Nanofluid transformer oil for cooling and insulating applications: A brief review, *Applied Surface Science Advances*, 8(1), 1-12.

Isamotu, O., Sanusi, S. (2020) Performance Evaluation of Biodiesel Sourced from Groundnut Oil for an I.C. Engine, *J. Mater. Environ. Sci.*, 11(7), 1163-1172.

Jacob, J., Preetha, P., Krishnan, S. T. (2020) Review on natural ester and nanofluids as an environmental friendly alternative to transformer mineral oil, *IET Nanodielectrics, Journals of the Institute of Engineering and Technology*, 3(1), 33–43. https://doi.org/10.1049/iet-nde.2019.0038

Kim, M., Haroun, M., Rahman, M. M., Kobaisi, M. A. (2019) Hybrid nano acid fluid pulsed with electrokinetic to stimulate tight carbonate reservoirs: A novel EOR/IOR method, *SPE/IATMI Asia Pacific Oil & Gas Conference and Exhibition*, Bali, Indonesia, October 29–31, 2019. https://doi.org/10.2118/196317-MS

Kumar, S.S., Iruthayarajana, M. W., Bakrutheen, M. (2016) Investigations on the suitability of rice bran oil and corn oil as alternative insulating liquids for transformers, *Institute of Electrical Engineers of Japan, Transactions on Electrical and Electronic Engineering*, 11(1), 10–14. https://doi.org/10.1002/tee.22182

Kumara, J. R. S. S., Fernando, M. A. R. M., Kalpage, C. S. (2017) Comparison of coconut/sesame/castor oils and their blends for transformer insulation, *IEEE International Conference on Industrial and Information Systems,* pp 1-6. https://doi.org/10.1109/ICIINFS.2017.8300410

Lv, Y., Rafiq, M., Li, C., Shan, B. (2017) Study of dielectric breakdown performance of transformer oil based

magnetic nanofluids, *Energies*, 10(1), 1–21. https://doi.org/10.3390/en10071025
Mahanta, D. K. (2020) Green Transformer Oil: A Review, *IEEE*, 1-6. https://doi.org/10.1109/EEEIC/ICPSEurope49358.2020.9160654
Manjang, S., Kitta, I., Ikhlas, A. (2019) Voltage breakdown characteristics of transformer mineral oil with varies the composition of corn oil, *2nd International Conference on High Voltage Engineering and Power Systems (ICHVEPS)*, Denpasar, Indonesia, 2019, 1-4. https://doi.org/10.1109/ICHVEPS47643.2019.9011119
Martin-Ramos, J. A., Pernia, A. M., Diaz, J., Nuno, F., Martinez, J. A. (2008) Power supply for a high-voltage application, *IEEE Transactions on Power Electronics*, 23(1), 1608–1619. https://doi.org/10.1109/TPEL.2008.925153
Martins, M. A. G. (2010) Vegetable oils, an alternative to mineral oil to power transformers experimental study of paper aging in vegetable oil versus mineral oil, *IEEE Insulation Magazine*, 26(1), 7–13. https://doi.org/10.1109/MEI.2010.5599974
Módenes, A. N., Sanderson, K., Trigueros, D. E. G., Schuelter, A. R., Espinoza-Quinones, F. R., Neves, C. V., Zanao Jr., L. A., Kroumov, A. D. (2018) Insights on the criteria of selection of vegetable and mineral dielectric fluids used in power transformers on the basis of their biodegradability and toxicity assessments, *Chemosphere*, 199(1), 312–319. https://doi.org/10.1016/j.chemosphere.2018.02.033
Mokhtari, O., Hamdani, I., Chetouani, A., Lahrach, A., El-Halouani, H., Aouniti, A., Berrabah, M. (2014) Inhibition of Steel Corrosion in 1M HCl by Jatropha Curcas oil, *J. Mater. Environ. Sci.*, 5(1), 277-284.
Moosasait, B., Siluvairaj, W. I. M. (2021) Impact of ultrasonic treatment process on pour point of vegetable oils based liquid insulation", *Ultrasonics Sonochemistry*, 71(1), 1–8. https://doi.org/10.1016/j.ultsonch.2020.105380
Nayager, S. (2018) Transformer design considerations utilising natural ester oils, KwaZulu-Natal, South Africa, March 12, 2018, pp. 1-93. Retrieved from https://researchspace.ukzn.ac.za/xmlui/handle/10413/16178
Negi, J., Maithani, G. (2021) Power transformer condition assessment through insulating oil testing, in: K.K.Singh Mer, V.B. Semwal, V. Bijalwan, R.G. Crespo (Eds.), *Proceedings of Integrated Intelligence Enable Networks and Computing, Algorithms for Intelligent Systems. Springer Nature*, Switzerland, pp. 161-170. https://doi.org/10.1007/978-981-33-6307-6_17
Nijssen-Wester, C. M. (2021) Results of proficiency test transformer oil (fresh), Institute for *Interlaboratory Studies,* Spijkenisse, The Netherlands, February 2021, pp 1-39.
Nirmal-Kumar, R., Sarathbabu, R. T. (2014) Performance and emissions analysis using diesel and TSOME blends, *International Journal of Modern Engineering Research*, 4(1), 69-80.
Nkouetcha, E. T., Mengounou, G. M., Imano, A. M. (2019) Elaboration and performance analysis of a bio-based insulating liquid from castor oil for power transformers, *Open Access Library Journal*, 6, 1-16. https://doi.org/10.4236/oalib.1105404
Okafor, K. O., Okafor, J. O. (2018) Production and characterization of electrical transformer insulating fluid from blending Castor and Neem seed oils, *IOP Conference Series: Earth and Environmental Science*, 173(1), 1–10. https://doi.org/10.1088/1755-1315/173/1/012004
Oliveira, L. M. S. L., Nunes, R. C. P., Ribeiro, Y. L. L., Coutinho, D. M., Azevedo, D. A., Dias, J. C. M., Lucas, E. F. (2018) Wax behavior in crude oils by pour point analyses, *Journal of the Brazilian Chemical Society*, 29(1), 2158–2168. https://doi.org/10.21577/0103-5053.20180092
Olutoye, M.A. (2015) Transesterification of Crude Jatropha Curcas Linnaeus Oil catalyzed by waste marble derived solid catalyst, *Nigerian Journal of Technology (NIJOTECH)*, 34(1), 119 – 126.
Onah, A. J. (2011) Modern devices/techniques in the protection of transformers", *Nigerian Journal of Technology (NIJOTECH)*, 30(3), 103-110.
Onuh, C. Y., Dosunmu, A., Anawe, P. A. L., Efeovbokhan, V. E., Adebisi, A. A. (2017) Transesterification of non-edible vegetable oil for lubricant applications in water-based mud: a review, *International*

Journal of Applied Engineering Research, 12(1), 7397–7401. Corpus ID: 27072159. Retrieved from http://www.ripublication.com/ijaer17/ijaerv12n18_42.pdf

Oyelaran, O. A., Bolaji, B. O., Samuel, O. D. (2020) Assessment of calabash seed oil as biobased insulating fluid for power transformers, *Journal of Chemical Technology and Metallurgy*, 55(1), 307-313.

Patel, R., Brahmin, A., and Kaur, S. (2021) A review on utilization of vegetable oils as transformer oils, *International Research Journal of Engineering and Technology*, 8(1), 2598–2601.

Patel, V. R., Dumancas, G. G., Viswanath, L. C. K., Maples, R., Subong, B. J. J. (2016) Castor oil: properties, uses, and optimization of processing parameters in commercial production, *Lipid Insights*, 9(1), 1–12. https://doi.org/10.4137/LPI.S40233.

Pratik, M. and Eswara, P. (2020) Power Transformer Market: Global Opportunity Analysis and Industry Forecast, 2020–2027, *Allied Market Research*, pp. 1-165.

Rafiq, M., Lv, Y. Z., Zhou, Y., Ma, K. B., Wang, W., Li, C. R., Wang, Q. (2015) Use of vegetable oils as transformer oils – a review, *Renewable and Sustainable Energy Reviews*, 52(1), 308–324. https://doi.org/10.1016/j.rser.2015.07.032

Rafiq, M., Chengrong, L., Lv, Y. (2019) Effect of Al_2O_3 nanorods on dielectric strength of aged transformer oil/paper insulation system, *Journal of Molecular Liquids*, 284(1), 700–708. https://doi.org/10.1016/j.molliq.2019.04.041

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(1), 1–10. https://doi.org/10.3390/molecules25173901

Rafiq, M., Shafique, M., Anam, A., Ateeq, M. (2021) Transformer oil-based nanofluid: The application of nanomaterials on thermal, electrical and physicochemical properties of liquid insulation - A review, *Ain Shams Engineering Journal*, 12(1), 555-576. https://doi.org/10.1016/j.asej.2020.08.010

Rajan, A. G., Sivasubramanian, M., Gowthaman, S., Ramkumar, P. (2021) Investigation of physical and chemical properties of tobacco seed oil fatty acid methyl ester for biodiesel production, *Materialstoday*, 46(1), 7670–7675. https://doi.org/10.1016/j.matpr.2021.02.081

Rakhonde, B. S., Tekade, N. A. (2014) Microcontroller based transformer cooling control system, *IOSR Journal of Electrical and Electronics Engineering*, 1(1), 1–5.

Ranga, C., Kumar, A., Chandel, R. (2020) Influence of electrical and thermal ageing on the mineral insulating oil performance for power transformer applications, *Insight Non-Destructive Testing and Condition Monitoring,* 62(1), 222–231. https://doi.org/10.1784/insi.2020.62.4.222

Raof, N. A., Yunus, R., Rashid, U., Azis, N. B., Yaakub, Z. (2019) Effects of palm-based trimethylolpropane ester/mineral oil blending on dielectric properties and oxidative stability of transformer insulating liquid, *IEEE Transactions on Dielectrics & Electrical Insulation*, 26(1), 1771-1778. https://doi.org/10.1109/TDEI.2019.008128

Reddy, B. K. (2019) Latest trends in use of transformer oils, *International Journal of Engineering Trends and Technology*, 67(1), 37–39. https://doi.org/10.14445/22315381/IJETT-V67I7P207

Ribbenfjärd, D. (2010) Electromagnetic transformer modelling including the ferromagnetic core, Stockholm, Sweden, pp. 1-183. Retrieved from http://kth.diva-portal.org/smash/record.jsf?pid=diva2%3A320714&dswid=-6699

Roslan, M. H., Mohamad, N. A., Von, T. Y., Zadeh, H. M., Gomes, C. (2021) Latest developments of palm oil as a sustainable transformer fluid: a green alternative to mineral oils, *Biointerface Research in Applied Chemistry*, 11(1), 13715-13728. https://doi.org/10.33263/BRIAC115.1371513728

Rouabeh, J., M'barki, L., Hammami, A., Jallouli, I., Driss, A. (2019) Studies of different types of insulating oils and their mixtures as an alternative to mineral oil for cooling power transformers, *Heliyon*, 1(1), 1–19. https://doi.org/10.1016/j.heliyon.2019.e01159

Saeedi, R., Khakzad, S., Koolivand, A., Dobaradaran, S., Khaloo, S. S., Jorfi, S., Abtahi, M. (2017) Transformer oils as a potential source of environmental exposure to polychlorinated biphenyls (PCBs): an assessment in three central provinces of Iran, *Journal of Environmental Science and*

Pollution Research, 24(1), 19098-19103. https://doi.org/10.1007/s11356-017-9576-2

Sakharwade, A., Tiwari, J. K., Sharma, A. (2017) Suitability study and analysis of Blended Castor and Madhucaindica oil as an alternative to Traditional Transformer oil, *International Research Journal of Engineering and Technology,* 4(1), 1471–1477.

Salih, N., Salimon, J. (2021) A review on eco-friendly green biolubricants from renewable and sustainable plant oil sources*, Biointerface Research in Applied Chemistry*, 11(1), 13303-13327. https://doi.org/10.33263/BRIAC115.1330313327

Samuel, O. D., Okwu, M.O., Tartibu, L. K., Giwa, S. O., Sharifpur, M., Jagun, Z. O. O. (2021) Modelling of nicotiana tabacum l. oil biodiesel production: comparison of ANN and ANFIS, *Frontiers in Energy Research*, 8(1), 1–14. https://doi.org/10.3389/fenrg.2020.612165

Schinteie, R., Tran-Dinh, N., Vergara, T. J., Midgley, D. J. (2019) An estimation of chemical compound concentrations used in onshore gas production, a review of their degradation, and associated policy frameworks in South Australia, *Report Number: EP19349, CSIRO Energy*, North Ryde, Australia. Retrieved from https://gisera.csiro.au/wpcontent/uploads/2019/05/Water-15-Literature-Review.pdf

Silva, J., Folha, A. A. A. (2020) A Analysis of the application of insulating vegetable oil in electric power distribution transformers, *Academic Journal on Computing, Engineering and Applied Mathematics*, 1(1), 1–10. https://doi.org/10.20873/uft.2675-3588.2020.v1n3.p1-10

Soares, M. E., Araujo, A. J., Silva, F. S., Silva, M. R. A., Barbosa, N. V. (2021) Regeneration of transformer oil using a microemulsion with Triton X-100, *Brazilian Journal of Chemical Engineering*, 4(1), 1–11. https://doi.org/10.1007/s43153-021-00113-6

Suhaimi, N. S., Md Din, M. F., Abdul Rahman, A. R., Abdul Hamid, M. H., Mohamad Amin, N. A., Wan Zamri, W. F. H., Wang, J. (2020) Optimum electrical and dielectric performance of multi-walled carbon nanotubes doped disposed transformer oil, *Energies*, 13(1), 1–19. https://doi.org/10.3390/en13123181

Suhaimi, N. S., Din, M. F. M., Ishak, M. T., Rahman, A. R. A., Wang, J., Hassan, M. Z. (2022) Performance and limitation of mineral oil-based carbon nanotubes nanofluid in transformer application, *Elsevier Alexandria Engineering Journal*, 61(12), 9623-9635.

Syafruddin, H.S., Supriyadi, Maksum, P. (2021) Analysis of mixing oil (Diala B with S2-ZUI) for cooling systems used in power transformers, *Journal of Physics Conference Series*, 1811, 1–6. https://doi.org/10.1088/1742-6596/1811/1/012044

Taslak, E., Kocatepe, C., Arikan, O., Kumru, C. F. (2015) Electrical analysis of corn oil as an alternative to mineral oil in power transformers, *International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering,* 9(1), 714–718.

Udoh, A. P., Umoren, I. U., Michael, E. P. (2020) Physicochemical properties and storage stability of the raw seed oil of Huracrepitansat room temperature, *J. Mater. Environ. Sci.*, 11(1), 157-165.

Wahyudi, W., Wardana, I. N. G., Widodo, A., Wijayanti, W. (2018) Improving vegetable oil properties by transforming fatty acid chain length in jatropha oil and coconut oil blends, *Energies*, 11(1), 1–12. https://doi.org/10.3390/en11020394

Wanatasanappan, V. V., Rezman, M., Abdullah, M. Z. (2022) Thermophysical Properties of Vegetable Oil-Based Hybrid Nanofluids Containing Al_2O_3-TiO_2 Nanoparticles as Insulation Oil for Power Transformers, *Nanomaterials,* 12(3621), 1-21.

Wang, F., Wang, K., Li, J., Han, Q., Zhao, Q., Hu, K. (2019) Synthesis of Trimethylolpropane Esters as Potential Insulating Oil Base Stocks, *IEEE 20th International Conference on Dielectric Liquids*, Rome, Italy, pp. 1–4. https://doi.org/10.1109/ICDL.2019.8796514.

Wang, X., Li, C., Zhang, Y. Ding, W., Yang, M., Gao, T., Cao, H., Xu, X. F., Wang, D., Said, Z., Debnath, S., Jamil, M., Ali, H.M. (2020) Vegetable oil-based nanofluid minimum quantity lubrication turning: academic review & perspectives, *Journal of Manufacturing Processes*, 59(1), 76-97. https://doi.org/10.1016/j.jmapro.2020.09.044

Wu, J., Zhang, J. (2020) Research and development of natural vegetable insulating oil based on jatropha curcas seed oil, *Energies*, 13(1), 1–12. https://doi.org/10.3390/en13174319

Yahaya, W. M. A. W., Dandan, M. A., Samion, S., Musa, M. N. (2020) A comprehensive review on palm oil and the challenges using vegetable oil as lubricant base-stock, *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences,* 52(1), 182–197. Retrieved from https://www.akademiabaru.com/submit/index.php/arfmts/article/view/2389

Yusoff, S. F. A. Z., Mezher, M. H., Amiri, I. S., Ayyanar, N., Vigneswaran, D., Ahmad, H., Zakaria, R. (2018) Detection of moisture content in transformer oil using platinum coated on D-shaped optical fiber, *Optical Fiber Technology*, 45(1), 115–121. https://doi.org/10.1016/j.yofte.2018.07.011

Yusuf, I., Jibrin, I., Zaharaddeen, M., Adamu, M. D. (2020) Synthesis, characterization and formation of KNO_3 treated CaO-MgO composite catalysts for biodiesel production using Neem seed oil, *J. Mater. Environ. Sci.,* 11(5), 781-787.

(2023) ; http://www.jmaterenvironsci.com