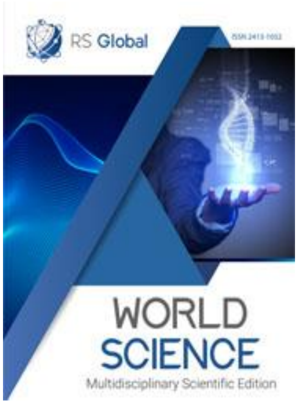

World Science

e-ISSN: 2414-6404

Scholarly Publisher
RS Global Sp. z O.O.
ISNI: 0000 0004 8495 2390

Dolna 17, Warsaw,
Poland 00-773
+48 226 0 227 03
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ARTICLE TITLE	MODERN SUBSTITUTES FOR NATURAL CASTOR OIL AS A DIELECTRIC FLUID
ARTICLE INFO	Mirjafarova Mehriban Masud, Maya Abdullayeva Yadigar. (2025) Modern Substitutes for Natural Castor Oil as A Dielectric Fluid. *World Science*. 2(88). doi: 10.31435/ws.2(88).2025.3282
DOI	https://doi.org/10.31435/ws.2(88).2025.3282
RECEIVED	06 April 2025
ACCEPTED	10 June 2025
PUBLISHED	30 June 2025
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MODERN SUBSTITUTES FOR NATURAL CASTOR OIL AS A DIELECTRIC FLUID

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ABSTRACT

Synthetic esters have become increasingly popular over the past decades, which is reflected in the steady growth in the number of installations filled with these liquids. Interest in them is due to both fundamental research aimed at studying breakdown mechanisms and applied aspects of their operation. However, the use of synthetic esters in high-voltage equipment is associated with a number of technical challenges, which requires a deeper understanding of their behavior under various operating conditions. The purpose of this review is to summarize the latest achievements in the study of synthetic esters as dielectrics as a replacement for castor oil, which are most significant for further development and optimization of dielectrics. In particular, the following are considered: electrophysical characteristics of all oils, as well as synthetic esters, their behavior.

KEYWORDS

Ester, Castor Oils. Dielectric Fluid, Dielectric Strength

CITATION

Mirjafarova Mehriban Masud, Maya Abdullayeva Yadigar. (2025) Modern Substitutes for Natural Castor Oil as A Dielectric Fluid. *World Science*. 2(88). doi: 10.31435/ws.2(88).2025.3282

Introduction.

The limited availability of natural castor oil creates an urgent need for synthetic substitutes that match its properties and, in some respects, even surpass them.

Castor oil is widely used as a dielectric fluid due to its high dielectric strength, biodegradability, and thermal stability. However, its limited availability and environmental concerns have stimulated interest in biological alternatives. The study [1] investigates the dielectric properties of oils derived from soybean, sunflower, and rapeseed, both in their natural and chemically modified forms.

The development described in [2] focuses on acylated derivatives of metathesized castor oil products, aiming to create base components for lubricants with high viscosity indices, low pour points, and excellent anti-wear properties. Castor oil, containing 89% ricinoleic acid, was subjected to metathesis in the presence of a second-generation Grubbs catalyst (0.025 mmol), followed by epoxidation and hydroxylation using the dihydroxylation method, achieving a yield of 93%. The hydroxylated derivatives were acylated using acetic, propionic, butyric, and hexanoic anhydrides, yielding 85–90%. The acylated base oils, being highly branched and of high molecular weight, exhibited very low pour points (ranging from −30 to −40 °C) and a wide viscosity range from 45.5 cSt to 60.0 cSt at 40 °C, high viscosity indices (165–191), excellent anti-wear properties (0.52–0.69 mm), good thermal and oxidative stability, along with high load-carrying capacity (165–

184 kg), making them suitable for multigrade industrial applications. These base oils can be used with minimal additive requirements during formulation [2].

Castor oil is a natural polyol and is widely used in various fields. Although it is a renewable bioproduct, its production is geographically limited to tropical regions, leading to fluctuations in supply and price stability.

The potential for producing castor oil alternatives from camelina oil - cultivated as an industrial crop in temperate regions - has been investigated, along with its subsequent use in polyurethane formulations. Castor oil substitute polyols were synthesized from camelina oil through controlled epoxidation using in situ generated performic acid, followed by hydroxylation via acid-catalyzed epoxide ring-opening with alcohol. The viscosity and hydroxyl functionality of the camelina oil-based polyol were targeted to match those of castor oil, as these parameters determine the performance of such polyols as substitutes. In polyurethane applications, it was found that although camelina oil polyols exhibited lower reactivity toward isocyanates, the reactivity could be easily adjusted to match that of castor oil by adding a small amount of conventional catalysts [3].

Overall, camelina oil-based polyols can be synthesized (Fig. 1) with a range of viscosities and hydroxyl functionalities, making them suitable substitutes for castor oil in polyurethane applications. The ability to tailor these parameters offers a significant advantage over castor oil.

Ideally, a vegetable oil primarily containing linoleic acid should yield a hydroxyl number/viscosity balance similar to that of castor oil. However, selective epoxidation of linoleic acid is not feasible, and it is practically impossible to prevent the formation of hydroxyl group isomers during hydroxylation in order to obtain a polyol that is structurally closer to castor oil at the molecular level.

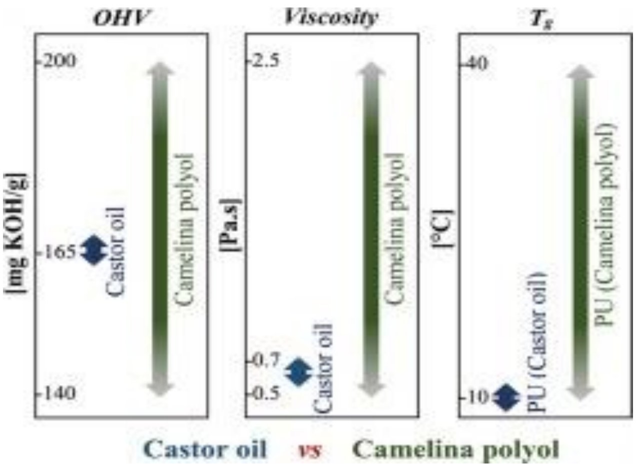

Fig. 1. *Schematic of the production of a castor oil substitute polyol using camelina oil.*

However, any vegetable oil with a high content of unsaturated compounds, preferably linoleic acid (C18:2), is suitable for this purpose. Vegetable oils with a higher unsaturated compound content and a lower content of saturated fatty acids, such as hemp oil (C18:2 54–56%, C18:3 24–26%), soybean oil (C18:2 43–55%, C18:3 5–11%), and flaxseed oil (C18:2 17–25%, C18:3 35–60%), may serve as alternative candidates for the production of castor oil substitute polyols.

The study [4] focuses on the investigation of polyols based on field mustard oil as an alternative to castor oil. It has been shown that these oils exhibit high thermal stability, making them promising as biodegradable dielectrics. Similar information is provided in work [5], which discusses the environmental aspects of using vegetable oils.The study [4] focuses on the investigation of polyols based on field mustard oil as an alternative to castor oil. It has been shown that these oils exhibit high thermal stability, making them promising as biodegradable dielectrics. Similar information is provided in work [5], which discusses the environmental aspects of using vegetable oils. It is evident that a polyol matching the overall hydroxyl functionality, viscosity, and reactivity for polyurethane applications can be obtained [4].

The results show that soybean oil also possesses dielectric strength and thermal stability comparable to castor oil, making it a promising alternative. The obtained results highlight the potential of bio-based oils to replace castor oil in dielectric applications while promoting sustainable development.

Oils derived from algae [6] are becoming a sustainable alternative to traditional dielectric fluids, such as castor oil. The dielectric properties of oils extracted from microalgae are emphasized, focusing on their fatty acid composition and thermal stability. Algal oils demonstrate superior dielectric strength, biodegradability, and low toxicity, making them suitable for environmentally sensitive applications.

Furthermore, the scalability of algae cultivation ensures reliable and renewable supplies. Algae-based oils are a viable and eco-friendly substitute for castor oil in dielectric applications, aligning with global sustainable development goals. Algae are an efficient biological factory capable of absorbing carbon waste and converting it into a high-density liquid energy form (natural oil). Algae consist of carbohydrates, proteins, and natural oils. Algae can produce up to 60% (or more) of their weight in the form of natural oil, such as triglycerides. A 'triglyceride' is a glycerol backbone bound to three fatty acid molecules. Unrestrictive procedures suitable for extracting triglycerides from algae include expeller/pressing, solvent extraction, supercritical fluid extraction, enzymatic extraction, osmotic shock, electromechanical extraction, and any combination of the above.

The dielectric fluid includes algae oil, which contains a natural antioxidant from algae. The algae oil in this dielectric fluid includes the antioxidant. The antioxidant inhibits the oxidation of triglycerides. The antioxidant is a natural antioxidant produced by algae. 'Natural antioxidant from algae' refers to an antioxidant produced by algae. Non-limiting examples of natural antioxidants from algae include astaxanthin and beta-carotene [6].

Dielectric properties of green algae and the evaluation of their emissivity at different moisture contents at a frequency of 5 GHz. These parameters are important for the interpretation and application of microwave remote sensing for monitoring aquatic vegetation, especially algal blooms and algae growth in water. This study is also useful for designing active and passive microwave sensors for dielectric properties of aquatic vegetation, providing fundamental information for remote sensing devices [7].

To overcome the limitations of castor oil as a dielectric fluid, the use of dielectric fluids enhanced with nanofluids is being studied. Dispersion of nanoparticles, such as titanium dioxide or silica, in bio-based oils significantly improves the dielectric and thermal properties of base fluids. Nanofluids exhibit higher dielectric strength, better heat dissipation, and enhanced stability under high voltage conditions compared to castor oil. Dielectric fluids enhanced with nanofluids represent a promising alternative to castor oil, especially in advanced electrical and electronic applications[8].

Exploring the potential of chemically modified vegetable oils, such as epoxidized linseed oil and acrylated palm oil, as substitutes for castor oil in dielectric applications. These modifications enhance the dielectric strength, thermal stability, and oxidative resistance of the oils. These modified oils perform comparably to or better than castor oil in terms of dielectric properties and aging characteristics. The study highlights the potential of using modified vegetable oils as eco-friendly and highly efficient dielectric fluids, reducing dependence on castor oil [9].

Comparing the dielectric properties of two medicinal oils: castor oil and wheat germ oil, as well as their binary mixtures at different temperatures and frequencies. Dielectric parameters and temperature maintenance of pure oils and their binary mixtures were measured using a gain/phase impedance analyzer and a temperature regulator. The dielectric permittivity and dielectric losses of pure castor oil, wheat germ oil, and their binary mixtures were studied [5, 10].

A dielectric fluid containing oil and one or more compounds selected from the group consisting of phosphite compounds. The addition of one or more compounds selected from the group consisting of phosphite compounds to dielectric fluids containing oil provides a stabilizing effect that reduces, inhibits, or prevents the formation of foreign gases in the dielectric fluid during normal use [11] .

Synthetic esters have attracted attention as potential substitutes for castor oil in dielectric applications due to their tunable properties and excellent performance under extreme conditions. This study evaluates the dielectric properties, thermal stability, and environmental impact of synthetic esters, such as pentaerythritol esters and trimethylolpropane esters. The study shows that synthetic esters have higher oxidative stability and smaller viscosity fluctuations compared to castor oil, making them suitable for high-voltage applications. The results indicate that synthetic esters can effectively replace castor oil, providing enhanced reliability and reduced environmental impact.

Dielectric fluids containing a mixture of polyol esters, obtained from the reaction of a) a polyol containing pentaerythritol, trimethylolpropane, neopentyl glycol, or combinations thereof, and b) a mixture of fatty acid esters derived from high-oleic soybean oil, containing fatty acid fragments where the high-oleic soybean oil has a C18:1 content of more than 65% fatty acid fragments in the oil and a combined C18:2 and C18:3 content of less than 20% fatty acid fragments in the oil, are proposed. Also provided are electrical devices containing the dielectric fluids and methods for preparing polyol ester mixtures. [11]

The dielectric properties of a 20% synthetic ester oil mixed with mineral oil were studied for its potential application as an insulator in transformers. The corona inception voltage of the mixed oil under alternating and direct current voltage was measured using the ultra-high frequency (UHF) method. A statistical study of the breakdown voltage of the mixed oil under alternating, direct, and standard lightning impulse voltages was conducted to generate a database that will be useful for transformer insulation design. Additionally, the mixture underwent continuous breakdown studies under alternating voltage with lightning impulse voltage at regular intervals and was characterized by measuring interfacial tension, flash point, ionic mobility, as well as UV-visible spectroscopy and frequency-domain spectroscopy to understand the chemical stability of the fluid. The study results showed that the mixture remained stable even after several breakdowns. Ionic mobility and polarization current increased, indicating higher losses in the oil. Analysis of the UHF signal energy and partial discharge analysis with phase resolution revealed a decrease in discharge activity with the mixed oils. [3, 12]

Analysis [6, 11, 13] shows that significant attention is being given to the development of new dielectric compositions. In particular, patent [6] describes a technology for improving heat dissipation in transformers using nanofluids, while patent [13] discusses compositions based on synthetic esters to enhance oxidation resistance.

The main functions of dielectric oils are thermal and electrical insulation, as well as cooling of transformer metal components through the process of convection.

Dielectric oils are capable of dissipating heat generated by the resistance of metal conductors and windings and transferring it away. Therefore, they must have high dielectric strength, thermal conductivity, and chemical stability. Additionally, they should possess good antioxidant properties, as they need to maintain their characteristics over a long period of time.

Characteristics of dielectric oil:

• High dielectric strength: the ability of the oil to withstand the voltage between transformer windings, preventing the formation of arcs and electrical discharges.

• Low viscosity: low viscosity facilitates the circulation of the oil and, as a result, helps dissipate heat through convection.

• Material compatibility: Dielectric oil is compatible with all materials used in the manufacture of electrical equipment, minimizing the likelihood of corrosion or damage to internal components.

• High flash point: Dielectric oils must have a high flash point (above 135ºC) to enhance safety in installations where there is a risk of explosion. Oils with a combustion temperature above 300ºC are considered to be of increased safety, mandatory for use in critical facilities such as hospitals, schools, etc.

• Biodegradability: More modern formulas focus on this property, reducing environmental impact in case of leaks or spills. Additionally, biodegradable dielectric fluids from Repsol ensure zero ecotoxicity in both aquatic and terrestrial systems.

• Interfacial tension: Indicates the presence of polar compounds due to the deterioration of the dielectric oil or cellulose insulating material. This is an indirect measure of the deterioration of the paper/oil system, which can be useful when making changes or taking actions to ensure the proper operation of the transformer.

It should be noted that dielectric oil plays a multifaceted role in the efficient and safe operation of electrical equipment, optimizing the performance and longevity of devices [14]. Studies on the dielectric properties of mixtures of mineral oil and synthetic esters [3,15, 23] confirm that such mixtures can improve insulation characteristics and extend the service life of equipment.

Conclusions.

Dielectric fluids play a crucial role in various electrical and power engineering applications, providing insulation, cooling, and equipment protection. In recent years, significant attention has been given to eco-friendly and highly efficient alternatives to traditional mineral oils. In recent years, significant attention has been given to eco-friendly and highly efficient alternatives to traditional mineral oils. This review discusses the latest research and patents related to dielectric fluids, including nanofluids and synthetic complex esters. The analysis shows that nanofluids possess enhanced thermal conductivity and dielectric permittivity, making them promising for use in transformers and other high-voltage systems.

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