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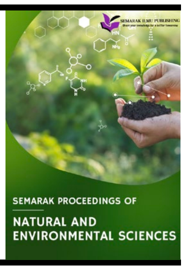

Palm Oil as a Transformer Insulating Fluid: A Review

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ABSTRACT

Traditionally, mineral oil has dominated the industry due to its reliable dielectric properties and effective thermal conductivity. However, the increasing environmental concerns surrounding the use of non-renewable and ecologically hazardous mineral oil have initiated research into alternative, sustainable insulating fluids. Palm oil has emerged as a potential candidate due to its biodegradable nature and renewable source. This paper provides a comprehensive review of palm oil's suitability as a transformer insulating fluid, comparing its dielectric properties, thermal stability, and environmental benefits to those of mineral oil. Besides, palm oil exhibits promising characteristics, including a breakdown voltage of up to 60 kV, superior moisture tolerance, and a higher relative permittivity, making it suitable for high-voltage applications. However, challenges remain, particularly regarding oxidation stability and viscosity, which require further refinement for broader adoption. The study emphasizes the potential of palm oil to align with global sustainability goals while addressing the technical requirements of transformers.

Keywords: *Transformer insulation; palm oil; dielectric strength; breakdown voltage; natural esters*

1. Introduction

The utilization of insulating oils in transformers is a critical aspect of electrical engineering, as these oils serve dual purposes: they provide electrical insulation and facilitate cooling within the transformer system. Traditionally, mineral oil has been the predominant choice for transformer insulation due to its dielectric properties and effective thermal conductivity. Mineral oil has been extensively studied and is known for its excellent dielectric strength and cooling characteristics, which have made it a staple in transformer technology for over a century [1]. The dielectric strength of mineral oil is significantly high, which minimizes the risk of electrical discharges and enhances the overall reliability of transformer operations. However, the environmental concerns associated with mineral oil, including its non-renewable nature and potential ecological hazards in case of spills, have prompted researchers to investigate alternative insulating fluids.

Considering the increasing environmental concerns associated with traditional mineral oils, there has been a marked increase in the exploration of sustainable and eco-friendly alternatives. Among these alternatives, natural ester-based oils, particularly those sourced from renewable vegetable materials, are gaining traction as viable substitutes. Specifically, palm oil (Elaeis guineensis) is being

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investigated due to its favourable environmental profiles and promising insulating characteristics. Palm oil, which is predominantly produced in tropical regions such as Southeast Asia, has shown considerable potential as an insulating fluid. It is characterized by high biodegradability, lower toxicity, and adequate electrical and thermal properties, making it a strong candidate for transformer applications [2-4].

Research indicates that palm oil exhibit dielectric properties suitable for transformer insulation, with the added advantage of being biodegradable and derived from renewable resources [5,6]. These oils demonstrate superior moisture tolerance compared to mineral oil, which is crucial for maintaining the integrity of transformer insulation over time [7,8]. However, challenges remain regarding their long-term performance, particularly concerning oxidation stability and their ability to withstand high electrical and thermal stresses. Addressing these challenges through continued research and technological advancements is vital for the broader adoption of vegetable-based insulating oils in transformers [9,10].

Palm oil is gaining attention as potential alternatives to mineral oil for transformer insulation due to their favourable electrical and dielectric properties, thermal stability, and environmental benefits. However, their adoption also presents certain challenges that must be addressed through ongoing research and technological advancements. Hence, this paper aims to provide a comprehensive review on the comparison of palm oil as alternative insulating fluids for transformers. By examining these oils in the context of transformer insulation, this study seeks to contribute to ongoing efforts to develop sustainable, high-performance insulating fluids that align with global environmental and energy efficiency goals [11-13].

2. Palm Oil

Palm oil has emerged as a potential alternative to mineral oil for transformer insulation due to its favorable physical and chemical properties [14]. Vegetable oils like palm oil have shown promise in increasing transformer lifetime by 33% and insulation paper lifetime up to 5-8 times longer compared to conventional mineral oils. Palm oil is an attractive choice as it is readily available, cost-effective, and has a lower environmental impact compared to petroleum-based oils. Palm oil is composed of triglycerides, which are esters of three-unit fatty acids linked to the trifunctional alcohol glycerol. This molecular structure gives palm oil several desirable properties for transformer insulation, such as high flash point, low pour point, and good thermal cooling capacity [15]. In comparison, mineral oils are made up of a mixture of aromatic, paraffinic, iso-paraffinic, and naphthenic compounds, with only a portion of these compounds providing excellent insulation properties. Global palm oil production has increased significantly in recent decades, driven by growing demand for vegetable oils and biofuels. Indonesia and Malaysia are the world's largest producers, accounting for over 80% of global output [14,15]. The processing and refinement of palm oil involves several steps to extract and purify the oil from the fruit of the oil palm tree. These steps include harvesting the fresh fruit bunches, sterilization, fruit stripping, oil extraction, purification, and refining. The refining process typically involves degumming, neutralization, bleaching, and deodorization to remove impurities and produce a high-quality oil suitable for various applications, including transformer insulation.

2.1 Dielectric Properties

The dielectric strength of an insulating fluid is crucial for its performance in high-voltage applications. Studies indicate that palm oil exhibits dielectric properties that are comparable to those of traditional mineral oil, which has dominated the industry for years. Extensive studies have demonstrated that palm oil exhibits several favourable dielectric properties that make it a promising insulation material for transformers [1,16,17]. In 2024, Mustangin *et al.,* [18] figured out that palm oil has been shown to exhibit a breakdown voltage of up to 60 kV which aligns with international standards for insulating oils [19]. Additionally, the esterification process significantly enhances the electrical properties of palm oil, improving its performance in practical applications [20]. Studies also reveal that palm fatty acid ester (PFAE) demonstrates a higher relative permittivity compared to mineral oil, contributing to better cooling performance in transformer systems [21]. While palm oil presents promising dielectric properties, challenges such as moisture content and acidity levels still require further refinement to fully optimize its use in transformer applications

2.2 Thermal Stability and Cooling Efficiency

The thermal properties of palm oil are an essential consideration in its suitability as an insulating fluid for transformers. Transformers generate substantial heat during operation, and the insulating fluid's capacity to efficiently dissipate this heat is critical in preventing overheating and ensuring the transformer's long-term durability. Palm oil demonstrates favourable thermal conductivity, and a higher flash point compared to mineral oil, enhancing its safety in high-temperature environments. Additionally, while palm oil's viscosity is slightly elevated relative to mineral oil, it does not significantly compromise its cooling performance. Through modified transformer designs, the higher viscosity can be accommodated, enabling palm oil to effectively transfer heat away from the transformer windings [14,22].

2.3 Environmental Stability

The environmental sustainability of palm oil is one of its most significant advantages as a transformer insulating fluid. Being biodegradable and renewable, palm oil presents a more environmentally friendly alternative to mineral oil, which is derived from non-renewable fossil fuels. In the event of spills, palm oil decomposes more rapidly, reducing long-term environmental damage. This aligns with global trends toward greener industrial practices and the reduction of carbon footprints. Additionally, the large-scale production of palm oil in countries like Malaysia and Indonesia not only supports local economies but also lessens dependence on fossil fuel [15].

2.4 Challenges and Future Research

Despite its potential, there are several challenges associated with using palm oil as a transformer insulating fluid. The most significant issue is its susceptibility to oxidation. Natural ester oils, including palm oil, tend to oxidize over time, leading to the formation of sludge and acidic by-products, which can impair the oil’s insulating capabilities. Although palm oil contains natural antioxidants that provide some resistance to oxidation, further refinement and the incorporation of synthetic antioxidants are necessary to improve its long-term stability. Additionally, the higher viscosity of palm oil, while manageable, may pose challenges in transformers optimized for lower-viscosity fluids like mineral oil [23]. Ongoing research is focused on enhancing the oxidation stability of palm oil and refining transformer designs to accommodate its unique properties. With further advancements in formulation and system optimization, palm oil has the potential to become a widely accepted alternative to mineral oil, offering both technical and environmental advantages for transformer insulation in the future.

3. Conclusions

Palm oil presented a sustainable and environmentally friendly alternative to mineral oil for transformer insulation. Its favourable dielectric properties, biodegradability, and renewable source make it an attractive option in the context of global sustainability efforts. Palm oil has demonstrated comparable, and in some cases superior, insulating characteristics to mineral oil, particularly in terms of breakdown voltage and moisture tolerance. However, challenges related to oxidation stability and viscosity must be addressed through further research and development. The incorporation of synthetic antioxidants and improvements in transformer design are crucial steps toward optimizing palm oil for widespread industrial use. Continued advancements in this area will enable palm oil to play a key role in the transition to greener, more sustainable transformer technologies, offering both technical and environmental advantages.

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