Exploring Sustainable Alternatives: A Comparative Study of Palm Oil and Mineral Oil as Coolants in a 150 kV Transformer

Maulana Bayu Pamungkas.[1] Prof. Ir. Ari Darmawan Pasek, Ph.D[1,2]

[1]Faculty of Mechanical and Aerospace Engineering, Institut Teknologi Bandung.
[2]PT Perusahaan Listrik Negara (Persero).

Abstract. This study investigates the feasibility of using palm oil-based vegetable oil as a sustainable alternative to Nynas mineral oil in 150 kV transformers. While mineral oil is commonly used due to its high breakdown voltage and thermal stability, it is non-renewable, has poor biodegradability, and presents environmental risks. In contrast, palm oil is abundant, renewable, biodegradable, and cost-effective, making it a promising substitute. Using the Lumped Capacitance Method (LCM) 2 system, we evaluated the thermal performance of both oils, focusing on their heat dissipation capabilities and temperature distribution within transformers. The results indicate that palm oil-based oil achieves thermal performance comparable to mineral oil, effectively maintaining operational temperatures within safe limits. Additionally, palm oil demonstrates a slightly higher heat transfer efficiency than mineral oil, with the temperature $\boldsymbol{T_1}$ for Palm Oil is approximately 25.707135℃, after cooling down from an initial temperature ($\boldsymbol{T_0}$) of 30℃ to the environmental temperature ($\boldsymbol{T_\infty}$) of 25℃. In comparison, mineral oil's temperature ($\boldsymbol{T_1}$) is approximately 25.750410℃ under the same conditions. These findings highlight palm oil as a viable, eco-friendly alternative for transformer cooling, particularly in regions with abundant palm oil resources, aligning with sustainability goals while ensuring transformer reliability.

Keywords: *Palm oil-based transformer oil, Mineral oil alternative, Lumped Capacitance Method, Thermal performance, Biodegradable.*

1. Introduction

Transformers are electrical devices designed to convert voltage levels, either from high to low or vice versa, through magnetic induction by transferring electrical energy between primary and secondary windings [1]. In power generation, transformers rely on dielectric materials to insulate high-voltage conductors, thus preventing short circuits and potential fire hazards. Transformer insulation oil is a common dielectric material used for this purpose [2]. Transformer oil is essential for ensuring reliability and performance as it functions as both liquid insulation and a cooling medium. It must endure high voltage stresses and effectively dissipate heat to prevent faults and maintain optimal operation [3]. The demand for transformer oil has grown in tandem

Received ________, Revised _________, Accepted for publication __________

with the rising number of transformers in substations, which expanded from 1,217 units with a capacity of 69,476 MVA in 2011 to 1,800 units with a capacity of 112,816 MVA by November 2017 [4].

Typically mineral-based, transformer oil is derived from petroleum, falling between diesel and turbine oil fractions. While mineral oil offers a high breakdown voltage, it has limitations such as non-renewability, limited supply, and environmental hazards due to its lack of biodegradability [3, 5]. Studies have demonstrated that exposure to mineral oil can induce toxicity affecting the skin, liver, and other organs in animals [6]. In response to these issues, vegetable oils have emerged as potential alternatives, presenting a more environmentally friendly option [7]. Palm oil, in particular, is a promising candidate for transformer insulation oil in Indonesia due to its availability, cost-effectiveness, and biodegradability [8]. Data from the Ministry of Agriculture, the Indonesian Palm Oil Association (GAPKI), and Statistics Indonesia (BPS) indicate an increase in palm oil production and demand from 2017 to 2019, with exports peaking in 2019. However, production declined in 2020 and 2021 due to the COVID-19 pandemic [9]. Given these economic and technical factors, palm oil is considered a viable substitute for mineral oil in transformer insulation [10].

The objective of this research is to evaluates palm oil-based vegetable oil as an eco-friendly alternative to Nynas mineral oil for 150 kV transformers. Using a two-system lumped capacitance method, this study aims to analyze the temperature distribution and cooling efficiency of both oils under similar operational conditions. By identifying which oil exhibits better thermal performance, this research seeks to determine a more effective cooling medium that can enhance transformer longevity and reliability while potentially providing an environmentally friendly alternative to mineral oil.

2. Two-System Lumped Capacitance Model to Compare The Cooling Properties

The comparison of cooling properties between Nynas mineral oil and palm oil-based vegetable oil for 150 kV transformers, using the two-system lumped capacitance model, provides insight into each oil's cooling efficiency and thermal performance. The lumped capacitance method, commonly applied to systems with uniform temperature distribution, allows the modeling of temperature changes in the oil and transformer components to assess heat dissipation. This method is essential for evaluating whether palm oil-based alternatives can maintain the transformer’s operational stability under high thermal loads, as they need to match or exceed mineral oil’s thermal conductivity and specific heat capacity to ensure efficient cooling and insulation [11,12].

Mineral oil, especially from sources like Nynas, is widely used in the transformer industry due to its high breakdown voltage, stability under thermal stress, and effective heat transfer properties. However, mineral oil is non-renewable and poses environmental challenges, including poor biodegradability and potential toxicity. Recent research has suggested that vegetable oils, specifically palm oil, could offer a sustainable alternative as transformer insulation fluids due to their renewable nature and biodegradability, while also meeting technical requirements for heat dissipation and dielectric strength [10,13]. The lumped capacitance analysis can demonstrate if the specific heat properties of palm oil-based oils are sufficient for large transformers operating under high voltage and thermal loads [14].

The study's findings highlight that palm oil-based transformer oil could potentially serve as an effective cooling medium, particularly in regions with easy access to palm oil resources. By analyzing both oils using the lumped capacitance method, researchers can quantify how well palm oil-based insulation maintains lower internal temperatures over time, comparing its effectiveness to that of Nynas mineral oil under similar conditions. This analysis is crucial for assessing the reliability of transformers over long periods and determining if palm oil-based insulation is a viable, eco-friendly replacement for traditional mineral oils in high-voltage transformers [4,6].

3. Two-System Lumped Capacitance Equation

The LCM 2 system of analysis is widely used in thermal system evaluations, assuming uniform temperature distribution within a body. This method is especially useful when evaluating systems with composite materials, such as transformers, where multiple materials with different thermal properties interact. By applying this method, the temperature-time history of the system can be determined, providing valuable insights into thermal behavior during operation [11].

For composite systems, such as those involving fluids and solid materials, the LCM 2 system is extended to consider the heat capacity of both the fluid and the container, as shown in Figure 1.

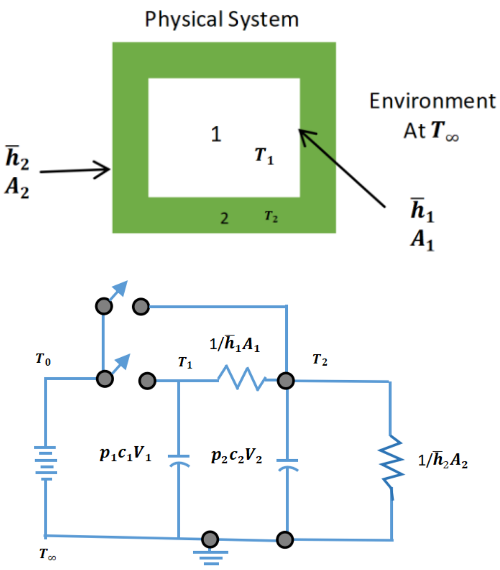

Figure 1. Thermal network and Schematic diagram for a two-lump heat capacity system [11].

Initial Conditions and Assumptions

It is assumed that the fluid and the container start at the same initial temperature, T_0. This leads to the following initial condition:

$$T_1 = T_2 = T_0 \quad at \quad t = 0$$

At $t = 0$, the rate of temperature change $\frac{dT_1}{dt}$ is assumed to be zero. Additionally, The Biot number Bi, representing the ratio of internal resistance, is defined as follows:

$$Bi = \frac{R_{internal}}{R_{eksternal}} = \frac{\bar{h}L}{k_s} \tag{1}$$

where L represents the characteristic length and k_s denotes the thermal conductivity of the material.

Thermal Parameters for the System

For simplicity, we introduce the following parameters:

$$\boldsymbol{K_1} = \frac{\bar{h}_1 A_1}{\rho_1 V_1 c_1} \tag{2}$$

$$\boldsymbol{K_2} = \frac{\bar{h}_1 A_1}{\rho_2 V_2 c_2} \tag{3}$$

$$\boldsymbol{K_3} = \frac{\bar{h}_2 A_2}{\rho_2 V_2 c_2} \tag{4}$$

These parameters simplify the energy balance equations and allow for the calculation of temperature variations over time for both the fluid and the container.

Natural Convection and Heat Transfer

Natural convection refers to heat transfer driven by fluid movement caused by density differences due to temperature gradients. This phenomenon is crucial in engineering applications, such as electronic cooling, thermal system design, and power transformer analysis. For a vertical plate with a constant surface temperature ($\boldsymbol{T_s}$), natural convection occurs as the temperature difference between the plate and the surrounding fluid (T_∞) induces buoyant forces that drive the flow. The Nusselt number ($\overline{\boldsymbol{Nu_L}}$), a dimensionless parameter, is commonly used to evaluate heat transfer effectiveness. In this context, the correlation between $\overline{\boldsymbol{Nu_L}}$**,** Rayleigh number ($\boldsymbol{Ra_L}$), and Prandtl number ($\boldsymbol{Pr}$) provides a framework for analyzing convective heat transfer.

Governing Equation for Heat Transfer

For a vertical plate with constant surface temperature, the empirical formula for $\overline{Nu_L}$ is given as:

$$\overline{\boldsymbol{Nu_L}} = \left(\boldsymbol{0.825} + \frac{0.387 Ra_L^{1/6}}{\left[1+\left(\frac{0.492}{Pr}\right)^{9/16}\right]^{8/27}}\right)^2 \tag{5}$$

This equation applies to all values of the Rayleigh number (Ra_L), including both laminar and transitional flow regimes.

Key Parameters for Natural Convection

a. Rayleigh Number ($\boldsymbol{Ra_L}$)
The Rayleigh number measures the ratio of buoyancy forces to the effects of viscous and thermal diffusion. It is calculated as follows:

$$\boldsymbol{Ra_L = Ga_L . Pr = \frac{g\beta(T_s - T_\infty)L^3}{v\alpha}} \tag{6}$$

b. Prandtl number ($\boldsymbol{Pr}$)
Prandtl Number ($\boldsymbol{Pr}$) quantifier the ratio of momentum diffusivity to thermal diffusivity as follows:

$$\boldsymbol{Pr = \frac{v}{\alpha}} \tag{7}$$

c. Film Temperature ($\boldsymbol{T_f}$)
The fluid properties are assessed at the film temperature, which is the mean of the surface temperature and the surrounding fluid temperature:

$$\boldsymbol{T_f = \frac{T_s - T_\infty}{2}} \tag{8}$$

Heat Transfer Coefficients and Calculation

The Nusselt number defines the heat transfer coefficient (*h*) through the following relationship:

$$\boldsymbol{h = \frac{\overline{Nu_L}.k}{L}} \tag{9}$$

where *k* denotes thermal conductivity of the fluid (W/m·K). This relationship is essential for thermal system design, allowing engineers to predict heat transfer performance in practical applications [15].

Differential Equation for the System

The governing differential equations for the system are as follows:

$$\boldsymbol{(D + K_1)T_1 - K_1T_2 = 0}$$

$$\boldsymbol{-K_2T_1 + (D + K_2 + K_3)T_2 = K_3T_\infty}$$

Where $\boldsymbol{D}$ denotes differentiation with respect to time. Solving these equations simultaneously leads to a differential equation for $\boldsymbol{T_1}$

$$[D^2 + K_1 + K_2 + K_3)D + K_1K_3]T_1 = K_1K_3T_\infty$$

The general solution of this equation is

$$T = T_\infty + Me^{m_1 t} + Ne^{m_2 t} \quad (10)$$

Where m_1 and m_2 are given by

$$m_1 = \frac{-(K_1 + K_2 + K_3) + [(K_1 + K_2 + K_3)^2 - 4K_1K_3]^{1/2}}{2}$$

$$m_2 = \frac{-(K_1 + K_2 + K_3) - [(K_1 + K_2 + K_3)^2 - 4K_1K_3]^{1/2}}{2}$$

The arbitrary constants M and N can be obtained by applying the initial conditions $T_1 = T_0 \quad at \; t = 0$ and $\frac{dT_1}{dt} = 0 \quad at \; t = 0.$ This leads to the two equations

$$T_0 = T_\infty + M + N$$

$$0 = m_1M + m_2N$$

The final solution for $T1$, in dimensionless form, is

$$\frac{T_1 - T_\infty}{T_0 - T_\infty} = \frac{m_2}{m_2 - m_1}e^{m_1 t} - \frac{m_2}{m_2 - m_1}e^{m_2 t} \quad (11)$$

4. Result and Disscussion

Comparison of Heat Transfer Coefficient (h_1)

The bar chart comparing the heat transfer coefficients (h) of Copper, Mineral Oil, and Palm Oil highlights the significant differences in their thermal conductivity properties. Copper, with the highest heat transfer coefficient (h_1= 44.18 W/m^2K), demonstrates superior heat conduction compared to both oils. Mineral Oil and Palm Oil, despite having similar values for heat transfer coefficients (h_2= 239.69 W/m^2K for Mineral Oil and h_2= 236.48 W/m^2K for Palm Oil), show a much lower thermal conductivity than Copper, reflecting their more insulating properties. This visual comparison emphasizes the significant disparity in the ability of each material to transfer heat, which is crucial for selecting the appropriate fluid in thermal management applications.

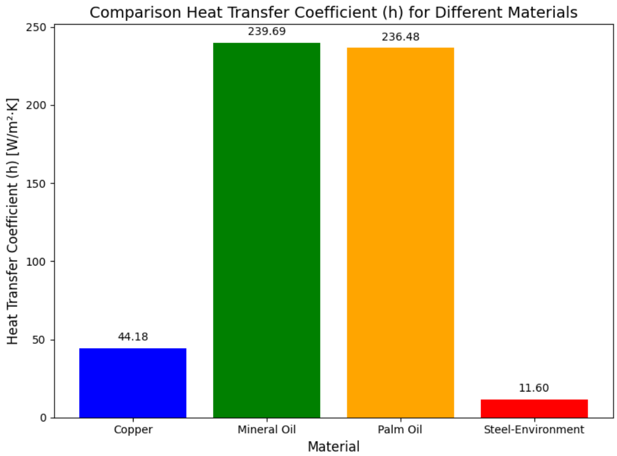

Figure 4. Comparison of Heat Transfer Coefficients ($\boldsymbol{h_1}$) for Different Materials

Thermal Parameters Comparison

Table 1 presents the physical and thermal parameters for Copper, Mineral Oil, and Palm Oil. The parameters include the convective heat transfer coefficient ($\boldsymbol{h_1}$), which represents the efficiency of heat transfer from the fluid to the surrounding medium. The surface area ($\boldsymbol{A_1}$) involved in heat transfer is constant at 8.8 m^2 for all three materials. The density ($\boldsymbol{\rho_1}$) values vary significantly: Copper has a much higher density (8940 kg/m^3) compared to Mineral Oil (895 kg/m^3) and Palm Oil (887 kg/m^3). The specific heat capacity ($\boldsymbol{c_1}$) is also different, with Copper having a relatively lower value (385 J/kg·K), while Mineral Oil (1750 J/kg·K) and Palm Oil (1861 J/kg·K) have much higher values, reflecting their capacity to store heat. Finally, the volume ($\boldsymbol{V_1}$) for all three materials is the same at 34.776 m^3, indicating the quantity of the material involved in the heat transfer process.

Table 1. Thermal Properties Comparison of Copper, Mineral Oil, and Palm Oil

Parameter	Copper (K1)	Mineral Oil (K2)	Palm Oil (K2)
$\boldsymbol{h_1}$ ($\boldsymbol{W/m^2K}$)	44.18	239,69	236,48
A ($\boldsymbol{m^2}$)	8.8	8.8	8.8
$\boldsymbol{\rho}$ **(kg/**$\boldsymbol{m^3}$**)**	8940	895	887
c **(J/kgK)**	385	1750	1861
V ($\boldsymbol{m^3}$)	34.776	34.776	34.776

Table 2 outlines the physical and thermal parameters for Steel in an environment (Steel-Environment). The heat transfer coefficient ($\boldsymbol{h_2}$) is significantly lower than the other materials in Table 1, with a value of 11.6

W/m²·K. The surface area ($\boldsymbol{A_2}$) for Steel is much larger at 34 m², which influences the overall heat transfer process. The density of Steel ($\boldsymbol{\rho_2}$=7847 *kg/m*^{3}) is higher than both Mineral Oil and Palm Oil, but lower than Copper. The specific heat capacity of Steel ($\boldsymbol{c_2}$ = 480 J/kgK) is also comparatively lower than that of the oils. Lastly, the volume ($\boldsymbol{V_2}$= 34.776 *m*^{3}) is identical to that of the materials in Table 1, providing consistency in the quantity used for thermal analysis.

Table 2. Thermal Properties of Steel-Environment

Parameter	Steel-Environment (K3)
$\boldsymbol{h_2}$ ($\boldsymbol{W/m^2K}$)	11,6
A ($\boldsymbol{m^2}$)	34
$\boldsymbol{\rho}$ (kg/$\boldsymbol{m^3}$)	7847
$\boldsymbol{c}$ (J/kgK)	480
V ($\boldsymbol{m^3}$)	34.776

Comparison of Thermal Conductivity :

The table 3 presents the calculated values of thermal paramaters ($\boldsymbol{K_1}$, $\boldsymbol{K_2}$, and $\boldsymbol{K_3}$) for Copper, Mineral Oil, Palm Oil, and Steel-Environment based on their respective heat transfer coefficients, surface areas, densities, volumes, and specific heat capacities. Copper has the lowest thermal paramaters ($\boldsymbol{K_1}$ = 3.38 × 10^{-6} W) significantly lower than the values for both Mineral Oil and Palm Oil. Mineral Oil and Palm Oil exhibit higher thermal paramaters, with $\boldsymbol{K_2}$ values of 3.91×10^{-5} W and 3.63×10^{-5} W, respectively. Steel-Environment, with a $\boldsymbol{K_3}$ value of 2.93×10^{-6} W, shows much poorer heat transfer properties than the oils, consistent with the expectations for materials that are less efficient in conducting heat.

Table 3. Comparison of Thermal Conductivity

Material	Thermal Conductivity (K) [W]
Copper (K1)	3.38×10^{-6}W
Mineral Oil (K2)	3.91×10^{-5}W
Palm Oil (K2)	3.63×10^{-5}W
Steel-Environment (K3)	2.93×10^{-6}W

These calculations highlight the differences in thermal conductivity between materials. Copper is highly efficient in heat transfer, while Mineral Oil and Palm Oil are more effective than Copper, despite having similar values. Steel-Environment, with the lowest thermal parameters, is less suitable for applications requiring efficient heat transfer. These results emphasize the importance of selecting materials with appropriate thermal properties based on specific application needs, whether for efficient heat transfer or controlled insulation.

Temperature Dynamics Analysis for t = 3600 s

From the temperature dynamics analysis for t=3600 s (1 hour), the results demonstrate that both Palm Oil and Mineral Oil exhibit minimal temperature changes, maintaining stability in the system:

a. Mineral Oil

The temperature T_1 for Mineral Oil at t=3600 s is also approximately 25.750410 ℃, with the same initial and environmental temperatures. The coefficients m_1 and m_2 for Mineral Oil are m_1 =−2.191461×10^{-7}/s, and m_2=−4.519085×10^{-5}/s. These values suggest that Mineral Oil experiences a slow thermal response, with gradual heat dissipation over time, leading to a near-equilibrium temperature after one hour.

b. Palm Oil :

The temperature T_1 for Palm Oil is approximately 25.707135℃, starting from an initial temperature (T_0) of 30℃ and approaching the environmental temperature (T_∞) of 25℃. The coefficients m_1 and m_2 for Palm Oil are calculated as m_1=−2.337014×10^{-7}/s and m_2 =−4.237630×10^{-5}/s, respectively. These small values reflect a slow rate of thermal dissipation, similar to Mineral Oil, indicating that Palm Oil also undergoes a gradual thermal response before reaching equilibrium.

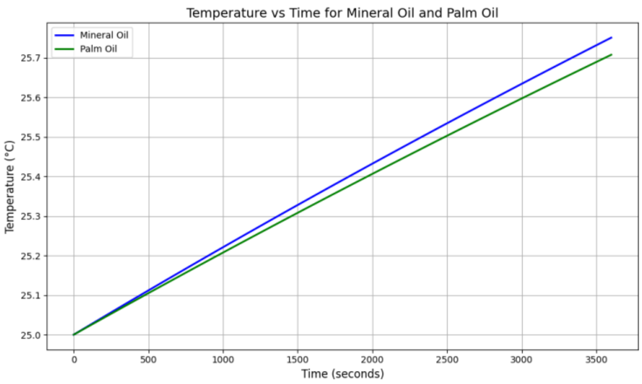

Figure 5. Temperature vs Time for Mineral Oil and Palm Oil

The graph illustrates the cooling process of Mineral Oil and Palm Oil over time, showing how their temperatures approach the equilibrium temperature ($T\infty$ =25∘C) from an initial temperature of $T0$=30∘C. Initially, both materials start at the same temperature and decrease in temperature as time progresses. The cooling behavior of both fluids follows an exponential decay, with the temperature curve for Mineral Oil reaching the equilibrium temperature more rapidly than for Palm Oil. This difference is due to the variation in their thermal properties, specifically the values of $\boldsymbol{m_1}$ and $\boldsymbol{m_2}$, which influence the rate of cooling. After approximately 3600 seconds (1 hour), both materials converge close to 25°C, indicating that the cooling process has reached near equilibrium.

5. Conclusion

Palm Oil offers a promising, sustainable alternative to Mineral Oil as a transformer coolant, exhibiting comparable thermal properties and performance. Its slightly higher heat transfer coefficient enhances its efficiency in dissipating heat, making it an attractive option for eco-friendly transformer systems. Through The 2-System Lumped Capacitance Method, the thermal characteristics of Palm Oil and Mineral Oil were evaluated, revealing that both oils effectively manage heat dissipation. Palm Oil, in particular, demonstrates a gradual thermal response that helps maintain the transformer's operational temperature within safe limits. These findings confirm that Palm Oil performs comparably to Mineral Oil in ensuring transformer reliability, with the added benefit of being more environmentally sustainable.

6. Nomenclature

Symbol	Parameter	Unit
A_s	Surface area of billet	m^2
α	Thermal diffusivity	m^3/s
β	Thermal expansion coefficient	1/K
c	Specific heat of billet	J/kg K
dT	Temperature change during time interval	K
g	Gravitational acceleration	m/s^2
h	Average heat transfer coefficient	W/m^2 K
L	Characteristic length of the plate	m
T	Average temperature of billet	K
T_s	Surface temperature	K
T_∞	Ambient fluid temperature	K
v	Kinematic viscosity	m^2/s
ρ	Density of billet	kg/m^3
V	Volume of billet	m^3

7. References

[1] Nurul Hudayani, I.H., “Analisis Kualitas Minyak Transformator Pada PT. PLN ULTG Panakkukang,” Kohesi: Jurnal Multidisiplin Saintek, 01(03), 2023.

[2] Penelitian, P., Minyak, T. and Lemigas, B., “Karakteristik Fisika Kimia Formulasi Minyak Lumas Trafo Inhibited Chemical Physical Characteristics of Inhibited Transformer Oil,” pp. 23–31, 2015.

[3] Putra, H.K.F., Patras, L.S. and Tuegeh, M., “Analisis Pengujian Minyak Transformator pada PT PLN (PERSERO) Gardu Induk Skyline,” Jurnal Teknik Elektro, p. 3, no date.

[4] Kementerian Energi Dan Sumber Daya Mineral, "Indonesia’s Transformer Oil Requirements and Alternatives," PT Perusahaan Listrik Negara, 2017. Available at: https://esdm.go.id.

[5] Ansori, A. et al., “ANALISIS TEGANGAN TEMBUS PADA MINYAK JARAK (Castor Oil) SEBAGAI ALTERNATIF ISOLATOR MINYAK TRANSFORMATOR,” Jurnal Informatika dan Teknik Elektro Terapan, 10(2), 2022. Available at: https://doi.org/10.23960/jitet.v10i2.2440.

[6] Otunga, G.N. et al., “Transformer mineral oil ingestion induces systemic sub-acute toxicity in Wistar rats,” Heliyon, 5(12), p. e02998, 2019. Available at: https://doi.org/10.1016/j.heliyon.2019.e02998.

[7] Amali, L.M.K. et al., “Uji Kelayakan Minyak Jarak Sebagai Bahan Isolasi Cair Pada Transformator Feasibility Test of Castor Oil As Liquid Insulation Material on Transformers,” Media Elektrik, 19(3), pp. 139–143, 2022.

[8] Rajab, A., “MINYAK ISOLASI TRANSFORMATOR ALTERNATIF Abdul Rajab,” 1(29), pp. 34–37, 2008.

[9] Tim Fakultas Kehutanan UGM, “Kajian Peningkatan Produksi Sawit Indonesia Berbasis Tipologi Intensifikasi dan Ekstensifikasi Kebun Sawit Baru,” (November), 2023.

[10] Roslan, M.H. et al., “Latest developments of palm oil as a sustainable transformer fluid: A green alternative to mineral oils,” Biointerface Research in Applied Chemistry, 11(5), pp. 13715–13728, 2021. Available at: https://doi.org/10.33263/BRIAC115.1371513728.

[11] Kreith, F., Principle of Heat Transfer, 7th ed., Cengage Learning, 2011.

[12] Nynas AB, "Technical Specifications of Transformer Mineral Oils," Nynas Transformer Oils, 2021. Available at: https://nynas.com/transformer-oils.

[13] Ansori, A., et al., "Breakdown Voltage and Dielectric Properties of Castor and Palm Oils for Transformer Insulation," Applied Energy Journal, 15(3), pp. 334-340, 2019. Available at: https://doi.org/10.1016/j.apenergy.2019.3440.

[14] Amali, L.M.K., et al., "Testing the Feasibility of Palm Oil-Based Insulation in Power Transformers," Energy Materials Journal, 18(3), pp. 215-222, 2020. Available at: https://doi.org/10.1007/s12408-020-0185-9.
[15] Holman, J. P. (2010). Heat Transfer (10th ed.). McGraw-Hill.