

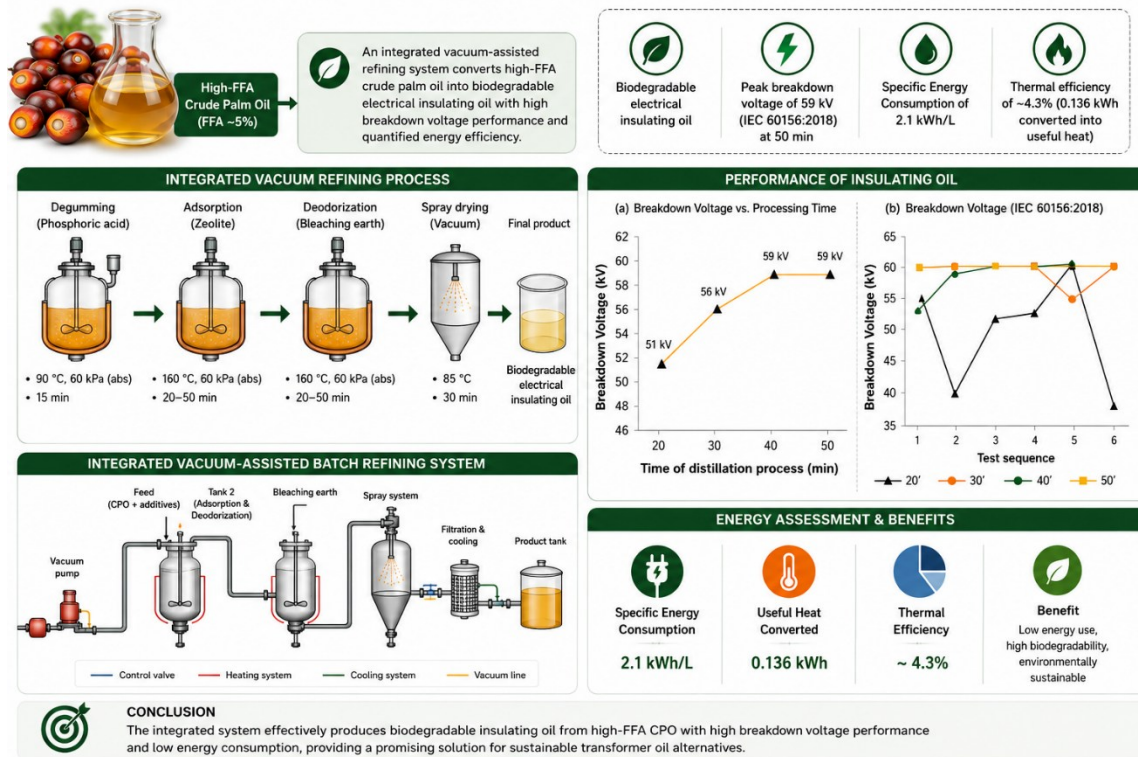
# Performance and Energy Assessment of an Integrated Vacuum Refining System for Crude Palm Oil toward Electrical Insulating Applications

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DOI: 10.15376/biores.21.3.5968-5983

## GRAPHICAL ABSTRACT



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The global transition toward environmentally sustainable technologies necessitates the development of biodegradable electrical insulating fluids. This study investigates the performance of a vacuum–fractional distillation reactor designed to convert high free fatty acid (FFA) crude palm oil (CPO) into a biodegradable electrical insulator. The reactor simultaneously performs degumming, deodorization, and vacuum spray drying, thereby enabling efficient purification and moisture removal. Experimental results demonstrated that even at a minimal processing time of 20 min, the breakdown voltage (BDV) exceeded 50 kV with the IEC 60156 (2018) test, with a peak performance of 59 kV at 50 min. The reactor achieved Specific Energy Consumption of 2.1 kWh/L. Thermal analysis indicated that 0.136 kWh was converted into useful heat, resulting in a thermal efficiency of approximately only 4.3%, primarily due to heat losses and irreversibility associated with the uninsulated laboratory-scale configuration, thereby indicating potential for improved heat utilization and energy recovery. The novelty of this work lies in the process integration, enabling treatment of high-FFA CPO in a single system, reducing operational complexity, and enables energy analysis. However, while the breakdown voltage requirement was satisfied, full compliance with IEC 62770 specifications necessitates further physicochemical characterization, which will be explored in future work.

DOI: 10.15376/biores.21.3.5968-5983

*Keywords:* Transformer; Specific energy; Breakdown voltage; Palm oil; Reactor

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## INTRODUCTION

Environmentally friendly and renewable materials have become a key focus in the development of technologies supporting the Sustainable Development Goals. Transformer oil insulators have become a concern for the environment and for the SDGs (Liu 2022). Replacing mineral oil with vegetable oil is a form of decarbonization, defined as a reduction in carbon emissions (Soni and Mehta 2023). Mineral-based insulators are inorganic and require special handling. In addition, the amount of H<sub>2</sub> generated in vegetable oil is lower than in mineral oil (Xiang *et al.* 2016). Therefore, renewable and environmentally friendly alternatives are needed.

Previous research has explored the replacement of mineral oil with environmentally friendly vegetable oils, including blending mineral oil with vegetable oil (Rouabeh *et al.* 2019). Sunflower, corn, and soybean oils are candidates to replace mineral-based transformer oil (Rafiq *et al.* 2015a; Jacob *et al.* 2021). One of the candidates, having favorable insulating properties, is crude palm oil (CPO) (Roslan *et al.* 2021). Economically, transformer oil costs twice as much as CPO. In the context of electrical insulators, mineral oils that have 10% biodegradability should be replaced with vegetable oils that have almost 100% biodegradability, such as CPO. However, CPO contains approximately 0.5% moisture, 5% acid, and 0.2% impurities (Badan Standardisasi Nasional 2006), thus requiring treatment to perform as an insulator under the IEC 62770 (2013) standards.

Distillation technology can convert CPO into various products, including insulating oil, cooking oil, and biodiesel (Gonzaga *et al.* 2021). The technology for refining vegetable oil involves a degumming process to separate oil and water, followed by filtration to obtain cleaner oil (Mannu *et al.* 2020), as well as the separation of solid and liquid fractions. Fractional distillation can be used to obtain several fuel products (Alex *et al.* 2021). Deodorizer technology is applicable to the refined oil process at 80 to 130 °C, with higher yields at higher temperatures (Lv *et al.* 2021). Membrane separation and vapor recompression technology, using vacuum pressures of 50 and 100 kPa, can save up to 70% of energy consumption for the distillation process. Vacuum pressure technology is also used to convert CPO into fuel (Bokhari *et al.* 2016). CPO has been developed into an insulator with promising results, but the processes are typically conducted separately from each other, motivating the development of an integrated processing system to process CPO into an insulator (Mustangin *et al.* 2024). Previous studies on biomass and oil-processing systems have emphasized the importance of energy accounting in evaluating process feasibility and operational efficiency (Chu *et al.* 2023). Energy analysis enables identification of process inefficiencies, irreversible losses, and potential opportunities for energy recovery within biomass conversion systems. Therefore, incorporating an energy-based evaluation is essential to assess the practical viability of integrated CPO-to-insulator processing (Hubbe 2021).

Vegetable-oil-based insulating fluids are inherently susceptible to oxidative and hydrolytic degradation due to the presence of unsaturated fatty acid chains and ester linkages in triglycerides. Autoxidation may occur through free-radical chain reactions initiated by heat, oxygen exposure, or residual metal catalysts, leading to peroxide formation, increased acidity, and eventual deterioration of dielectric properties. In addition, moisture can promote hydrolysis of ester bonds, generating free fatty acids and further increasing acid value. Enzymatic residues such as lipases or phospholipases, if present in inadequately refined oils, may also contribute to degradation.

The refining steps applied in this study—degumming, deodorization, and vacuum drying—are expected to mitigate some of these risks by removing phospholipids, reducing residual moisture, and eliminating volatile oxidation precursors. Nevertheless, comprehensive long-term oxidation stability testing, acid value monitoring, and accelerated aging studies are required to fully evaluate storage durability and operational reliability in insulating applications.

The refining process aims to remove impurities, reduce moisture content, and separate liquid and solid fractions (olein and stearin). Although the refining process effectively reduces moisture content, reabsorption during storage and service remains a relevant consideration. Natural ester-based insulating fluids are known to exhibit

hygroscopic behavior due to polar ester groups. Therefore, appropriate storage conditions—such as sealed containers, moisture barriers, nitrogen blanketing, and routine dehydration procedures—are necessary to maintain dielectric integrity. Similar moisture management practices are routinely applied to mineral oils and natural ester transformer fluids. Consequently, moisture control should be regarded as an operational management issue rather than solely a refining-stage parameter.

In this study, CPO was processed into a liquid electrical insulating material using an integrated vacuum processing system, and its dielectric performance was evaluated according to IEC 60156, while additional IEC 62770 property assessments remain subjects for future investigation. This research evaluates the influence of processing time on breakdown voltage performance and associated energy consumption, under the hypothesis that shorter processing times reduce energy demand. The resulting energy analysis provides quantitative insight for subsequent process refinement.

The primary novelty of this work lies in the integration of degumming, deodorization, and drying within a single vacuum-assisted batch configuration for high-FFA CPO processing. Rather than introducing a new dielectric material, this study demonstrates the feasibility of achieving satisfactory breakdown voltage performance through process integration, while providing a quantitative energy assessment to support future optimization and comprehensive physicochemical characterization. While the present work employs a laboratory-scale batch configuration for experimental control and flexibility, the integrated refining concept may be adapted to continuous processing systems in larger-scale industrial applications. The batch design should therefore be interpreted as a prototype demonstration rather than a limitation of the process architecture.

## EXPERIMENTAL

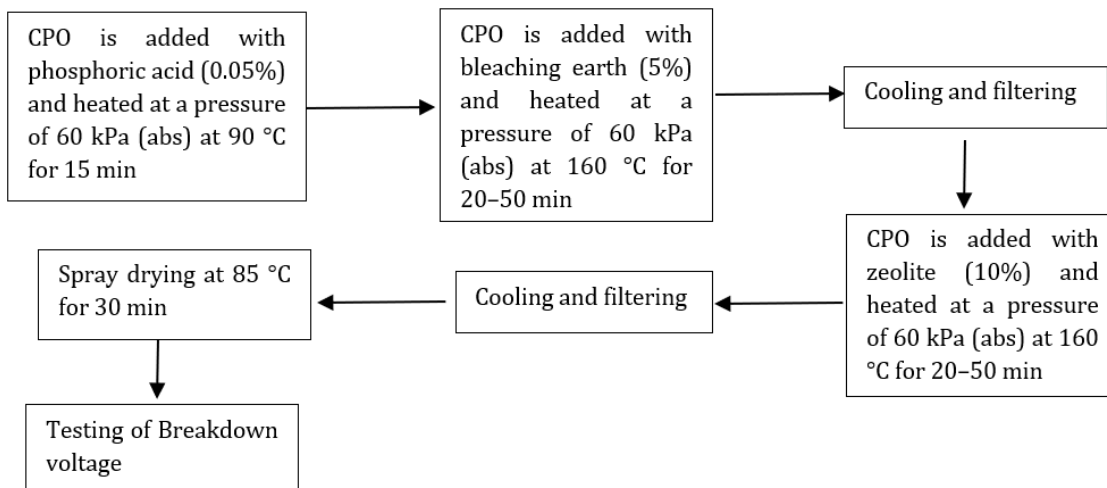
### Materials

The CPO obtained from PT Sumber Sawit, Blitar, Indonesia, had a free fatty acid content of approximately 7%. In the laboratory-scale integrated reactor, phosphoric acid, bleaching earth, and zeolite were introduced as auxiliary materials to facilitate degumming, pigment adsorption, and reduction of free fatty acid content during vacuum-assisted thermal treatment. Crude palm oil (CPO) was obtained from PT Sumber Sawit, Blitar, Indonesia, with an initial free fatty acid content of approximately 7%. All subsequent refining and distillation steps were carried out in the authors' laboratory using the integrated vacuum-assisted reactor system described in Section Methods. The laboratory distillation process employed auxiliary materials—phosphoric acid, bleaching earth, and zeolite—to remove gums, reduce pigments, and decrease acid content.

The experimental setup consisted of a reactor equipped a vacuum pump capable of operating up to 1000 mL, a 0.25 HP electric motor, three reactor tubes each with a capacity of 2000 mL (height: 300 mm x diameter: 102 mm), 2 filters, a reaction flask with a capacity of 1000 mL, and a spray system. The electric power was measured with a Lutron PC-6011SD power meter (Lutron Electronic Enterprise Co., Ltd., Taipei City, Taiwan), while the breakdown voltage was measured with a Megger Oil Test Set OTS60PB (Megger Group Limited, Dover, United Kingdom).

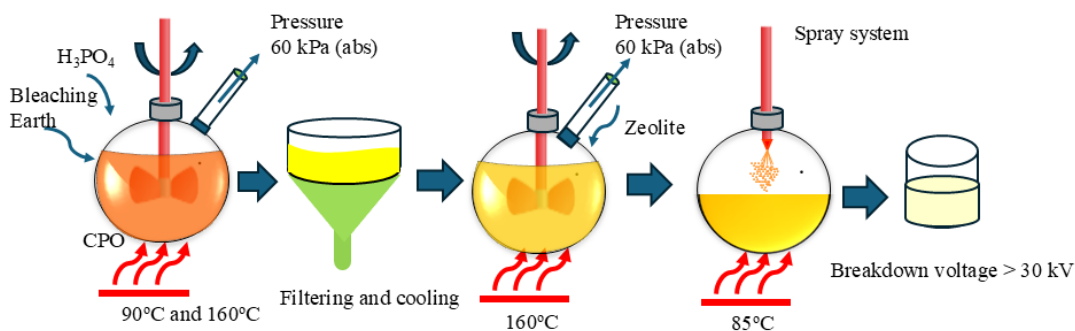
## Methods

The methodology for developing CPO into a liquid electrical insulator is illustrated in Fig. 1.



**Fig. 1.** Methodology

The treated CPO was reacted with zeolite for 20 to 50 min, followed by filtration and testing of its breakdown voltage as an electrical insulator. The overall flow process for developing electrical insulating oil from CPO is shown in Fig. 2. Although the system operates under reduced pressure to facilitate removal of moisture and volatile components, it does not employ a conventional multistage distillation column with trays or structured packing. Instead, separation occurs through vacuum-assisted thermal treatment within a stirred batch reactor configuration.



**Fig. 2.** Schematic representation of the integrated vacuum-assisted batch refining system

The system consists of vertically oriented, stirred batch reactors operated under reduced pressure. Each reactor is equipped with an electric heating element and vacuum lines to facilitate thermal treatment and volatile removal. Phosphoric acid, bleaching earth, and zeolite are introduced directly into the reactor vessel for degumming, adsorption, and deodorization steps. At the base of the system, a filtration–cooling unit enables separation of solid residues, with the refined oil collected in a bottom receiving tank. An upper pipe

includes a funnel introducing phosphoric acid, bleaching earth, and zeolite. The design includes two stages, namely degumming and deodorizing. Each batch is equipped with a temperature sensor connected to a controller for continuous temperature monitoring. The reactor design is presented in Fig. 3. A photograph of the actual reactor is shown in Fig. 4.

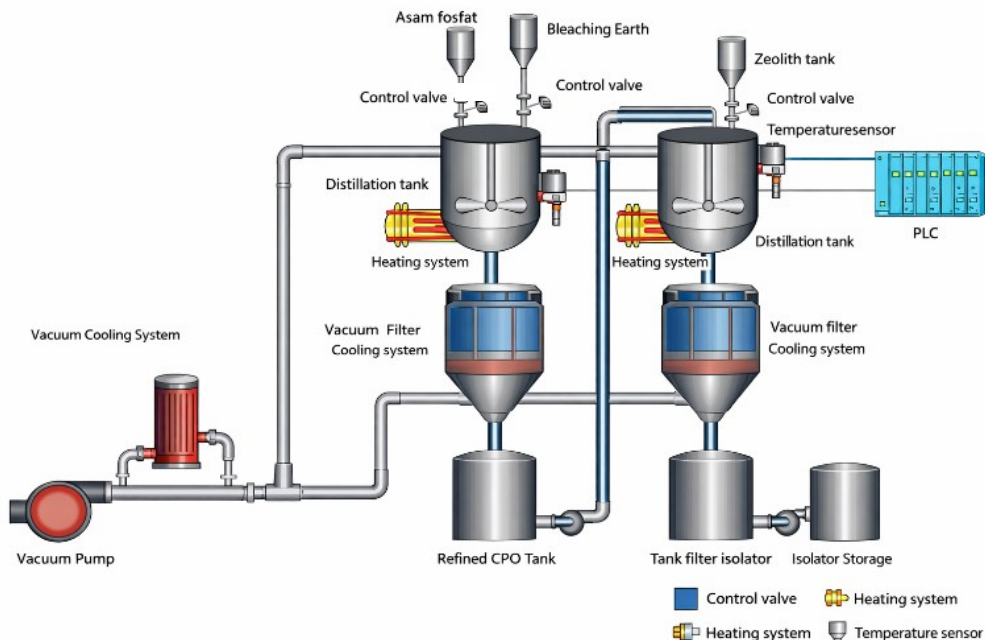


Fig. 3. Integrated refining system design

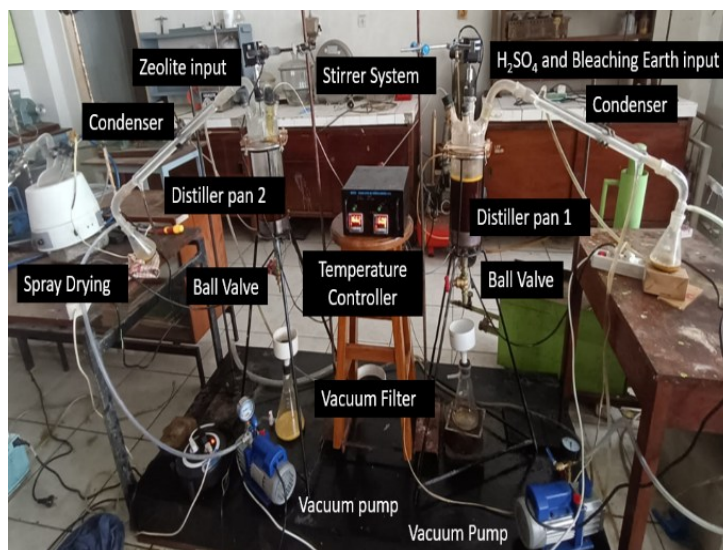


Fig. 4. The actual integrated refining system

Breakdown voltage (BDV) testing was conducted in accordance with IEC 60156 (2018) using mushroom-type electrodes with a 2.5 mm gap distance. The oil temperature during testing was maintained at 30 °C. For each processing condition, six consecutive breakdown measurements were performed, and the results are reported as mean  $\pm$  standard deviation to ensure reliability and reproducibility of the dielectric performance.

## RESULTS AND DISCUSSION

### Breakdown Voltage Parameter

In accordance with IEC 60156 (2018), each oil sample was subjected to six consecutive breakdown measurements with a 2-minute interval between tests, and the reported values represent sequential breakdown events rather than independent replicate specimens. Variability among the six breakdown events is characteristic of dielectric testing and reflects stochastic initiation of electrical discharge rather than sample heterogeneity. The results showed smaller deviations for longer processing times. The distillation process with an operating time of 20 min indicated a breakdown voltage range of 40 to 60 kV. The distillation process with an operational time of 50 min had the lowest deviation, ranging from 56 to 60 kV. These data indicate that increasing the operational time results in a more stable product. The IEC 60156 (2018) test results are presented in Fig. 5.

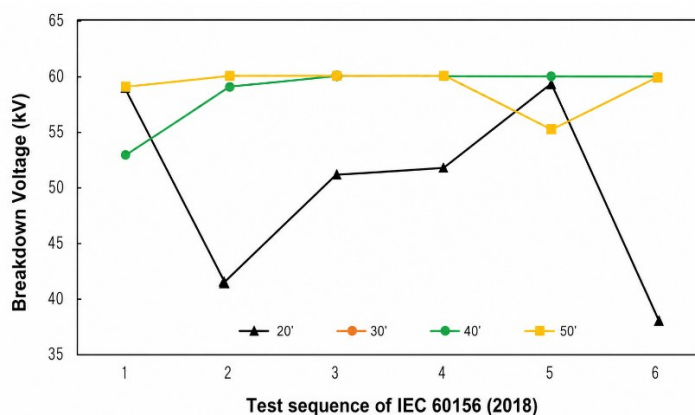


Fig. 5. IEC 60156 test values

The breakdown voltage values are presented as mean  $\pm$  standard deviation ( $n = 6$ ). At 20 min, the high variability ( $\pm 9.0$  kV) indicates incomplete stabilization of the dielectric properties. The variability decreased significantly at 30 min and reached its minimum at 40 min ( $\pm 1.5$  kV), suggesting improved homogeneity and process stability. At 50 min, although the average breakdown voltage remained relatively high, the increased standard deviation ( $\pm 6.8$  kV) indicates reduced reproducibility. Therefore, 40 min appears to have provided the most stable dielectric performance. The higher variability observed at shorter processing time may be associated with incomplete removal of residual impurities or moisture, which can influence dielectric breakdown initiation. The standard deviation results are presented in Fig. 6.

Overall, the breakdown voltage increased with processing time. However, at the shortest processing time of 20 min, the breakdown voltage was approximately 50 kV, which is well above the minimum standard requirement of 30 kV. The breakdown voltage value for a processing time of 30 min is based on previous research (Mustangin *et al.* 2024). This demonstrates that a heating duration of 20 min is sufficient to obtain a high breakdown voltage. The shorter the heating duration, the less energy is required. Regarding breakdown voltage, the 20-min heating time still met the requirements; however, the resulting oil still appeared darker compared to conventional transformer insulating oil, which is typically clear to light yellow in color. This indicates that color bodies or residual impurities had not been fully removed at shorter processing times.

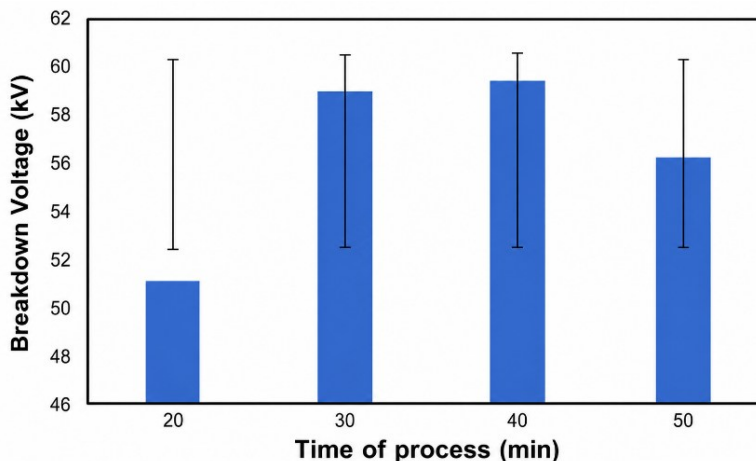


Fig. 6. Standard deviation results

Breakdown voltage values over time are presented in Fig. 7. The experimental data show an increasing trend from 20 to 40 min, followed by only marginal improvement at 50 min. These results indicate that dielectric performance stabilizes beyond 30 to 40 min, suggesting diminishing returns with prolonged processing. The observed trend is consistent with previous studies on CPO and coconut oil, which reported that higher temperatures enhance breakdown voltage (Jamail *et al.* 2017; Yao *et al.* 2018). Overall, the findings demonstrate that the integrated reactor configuration can effectively transform CPO into an insulating oil, extending previous studies that treated CPO in separate processing steps. The olein fraction was used as an insulator, while the stearin fraction could be separated at a temperature of 17.3 °C (Haryati *et al.* 1997). Breakdown voltage was affected by impurities (Danikas *et al.* 2020). Impurities in olein must be reduced using filters (Aliwarga *et al.* 2019).

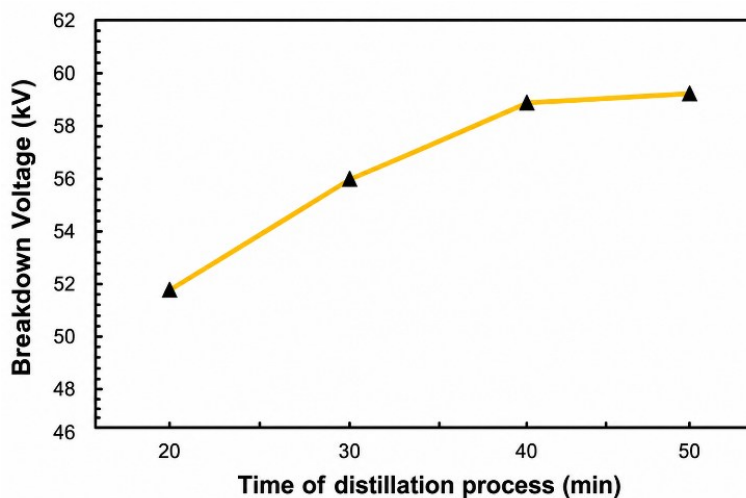


Fig. 7. Breakdown of voltage over time

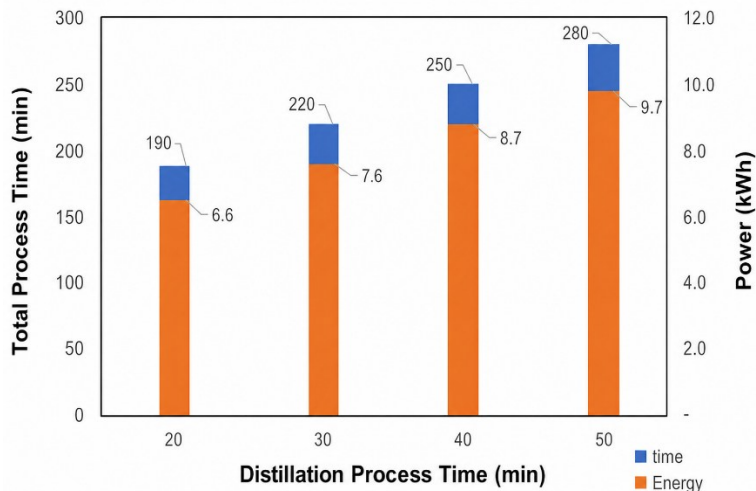
## Energy Utility

The electrical power required for the stirrer was 0.059 kW per unit, for a total of 0.118 kW for two units. The electric power of each vacuum pump was 0.15 kW, resulting in a total of 0.3 kW for two units. The electric power for each heater was 0.52 kW, giving a total of 1.04 kW for two units. One spray-drying unit required 0.45 kW, and the spray system required 0.046 kW, bringing the total installed power consumption to 1.96 kW. The energy used depended on the equipment operating time, resulting in a total energy consumption of 3.16 kWh. The energy required to process 1.5 L of CPO was 3.16 kWh. Based on the measured electrical input, the process exhibited a specific energy consumption of approximately 2.1 kWh/L for laboratory-scale production of CPO-based insulating fluid. Reported total process energy inputs for biodiesel production from waste cooking oil are on the order of 30 MJ/L ( $\approx 8.3$  kWh/L), and these values represent system-level energy inputs (Mohammadshirazi et al. 2014). Detailed data and calculations of energy utilities are presented in Table 1.

**Table 1.** Electrical Energy Consumption of Processing Equipment

Equipment	Qty	Power (kW)	Total Power (kW)	Time (h)	Energy (kWh)
Heater for the pan	2	0.52	1.04	2.0	2.08
Stirrer	2	0.059	0.118	2.0	0.236
Vacuum pump	2	0.15	0.30	2.0	0.60
Heater for spray drying	1	0.45	0.45	0.5	0.225
Spray system	1	0.046	0.046	0.5	0.023

The total electrical energy consumption increased by approximately 1 kWh as the processing time extended from 20 to 50 min. This near-linear relationship indicates that energy demand was primarily governed by operating duration. The regression analysis and graphical representation were performed using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA). The corresponding time–energy relationship is presented in Fig. 8.



**Fig. 8.** Process time and energy consumption

The energy required for the process duration of 20, 30, 40, and 50 min corresponded to 20%, 23%, 27%, and 30%, respectively. The difference in energy demand between the lowest and highest values was only 10%, indicating that variations in processing time within this range had a limited impact on total energy requirements. The percentage of electrical energy required for each process duration is presented in Fig. 9.

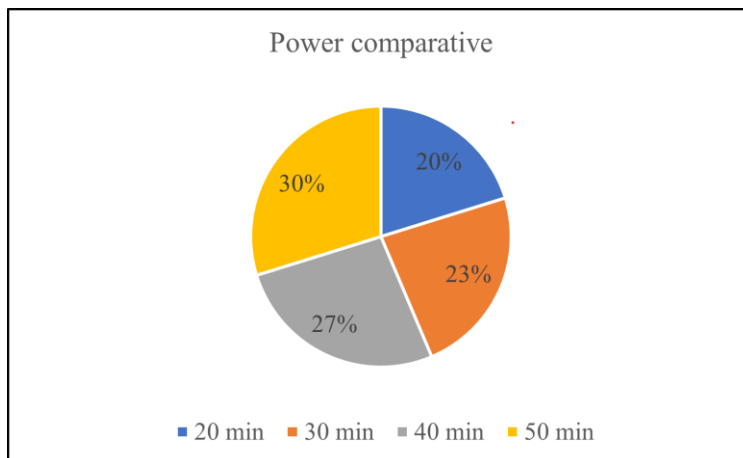


Fig. 9. Percentage of energy consumption *versus* process time

### Energy Analysis

An evaluation of the reactor performance requires analysis based on the data is provided in Table 2.

Table 2. Input Parameter

Parameters	Value	Unit
Feed_Volume	1.5	L
Density	0.91	kg/L
Cp_liquid	2.6	kJ/(kg·°C)
T_in	30	°C
T_out_degum	90	°C
T_out_deodor	160	°C
Ambient_T	25	°C
Moisture fraction	0.2	%
Moisture after processing	0.12	%
Heat latent	2,257	KJ/kg

Energy analysis of the reactor starts by determining the feed mass, as expressed shown in Eq. 1,

$$m_f = V_f \cdot \rho \cdot \quad (1)$$

where ( $V_f$ ) is the feed volume (L), and ( $\rho$ ) is the density (kg/L). The input energy to the system, which represents the electrical energy consumed by each piece of equipment, is given in Eq. 2, while the total energy for all equipment is expressed in Eqs. 2 through 3,

$$E_i = P_i \cdot t_i \quad (2)$$

$$E_{\text{total}} = \sum_{i=1}^n (P_i \cdot t_i) \quad (3)$$

where ( $P_i$ ) is the power of the  $i$ -th equipment (kW), and  $t_i$  is the operating time of the  $i$ -th equipment (h).

To calculate the energy, temperature rise data at each stage is required, as expressed in Eqs. 4 to 6:

$$\Delta T_{\text{degum}} = T_{\text{degum}} - T_{\text{in}} \quad (4)$$

$$\Delta T_{\text{deodor}} = T_{\text{deodor}} - T_{\text{degum}} \quad (5)$$

$$\Delta T_{\text{total}} = \Delta T_{\text{degum}} + \Delta T_{\text{deodor}} \quad (6)$$

The useful sensible heat for heating the liquid is calculated as expressed in Eq. 7:

$$Q_{\text{sensible}} = m_f \cdot c_p \cdot \Delta T_{\text{total}} \quad (7)$$

The amount of water mass evaporated affects the total energy required, as expressed in Eq. 8,

$$m_{\text{air}} = m_f \cdot X_{\text{moisture}} \quad (8)$$

where  $X_{\text{moisture}}$  is the moisture fraction (0–1).

The amount of energy required to evaporate water, which represents latent heat, is expressed in Eq. 9,

$$Q_{\text{latent}} = m_{\text{air}} \cdot h_{fg} \quad (9)$$

where ( $h_{fg}$ ) is the evaporation latent calorie (kJ/kg).

Based on the previous calculations, the total useful heat can be approximated using the general heat as expressed in Eq. 10:

$$Q_{\text{useful}} = Q_{\text{sensible}} + Q_{\text{latent}} \quad (10)$$

Since the process consists of two heating stages (degumming and deodorizing), the sensible heat is expressed in Eq. 11 :

$$Q_{\text{sensible}} = m_f \cdot c_p \cdot (\Delta T_{\text{degum}} + \Delta T_{\text{deodor}}) \quad (11)$$

When evaporation occurs, the latent heat value is expressed in Eq. 12:

$$Q_{\text{latent}} = m_{\text{water, evap}} \cdot h_{fg} \quad (12)$$

Based on the data obtained, the thermal efficiency can be defined as expressed in Eq. 13:

$$\eta_{\text{thermal}} = \frac{Q_{\text{useful}}}{E_{\text{total}}} \times 100\% \quad (13)$$

Subsequently, the calculation of the Specific Energy Consumption (SEC) can be carried out as expressed in Eq. 14:

$$SEC = \frac{E_{\text{total}}}{m_{\text{distillate}}} \quad (14)$$

The measured moisture content decreased from 0.2% to 0.12% after processing. The specific heat capacity of the oil ( $C_p = 2.6 \text{ kJ/kg}\cdot^\circ\text{C}$ ) was obtained from previously published studies and applied in the present energy calculations (Mustangin 2025). This value corresponds to the elevated temperature range (up to  $160^\circ\text{C}$ ) employed during deodorization, where vegetable oil heat capacity is known to increase with temperature. This corresponds to an evaporated water mass of approximately  $0.00109 \text{ kg}$ , yielding a latent heat requirement of about  $0.00068 \text{ kWh}$ . Compared to the sensible heating demand ( $\approx 0.093 \text{ kWh}$ ), the latent heat contribution represents less than 1% of the total useful heat. Therefore, the overall thermal efficiency is predominantly governed by sensible heating of the oil, and the influence of moisture evaporation on the efficiency estimation is minimal. Consequently, the low overall thermal efficiency is primarily associated with heat dissipation to the surroundings rather than the energy required for moisture removal.

The calculation results for the energy analysis are presented in Table 3.

**Table 3.** Energy Analysis of the Reactor

Metric	Value	Unit
Total_Energy_Input	3.16	kWh
Feed_Mass	1.36	kg
DeltaT_degum	60	$^\circ\text{C}$
DeltaT_deodor	70	$^\circ\text{C}$
Q_useful_sensible_kWh	0.128	kWh
Q_latent_kWh	0.00068	kWh
Q_useful_total_kWh	0.129 kWh	kWh
Thermal_Efficiency	4.0	%
Specific_Energy_Consumption	2.11	kWh/L
Distillate_Mass	1.12	kg

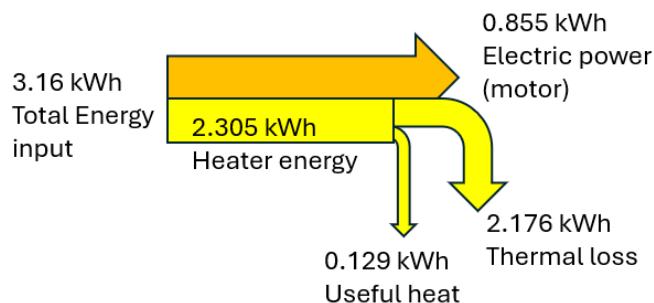
The specific energy consumption increased from  $1.4$  to  $2.1 \text{ kWh}\cdot\text{L}^{-1}$  as the processing time extended from 20 to 30 min, while breakdown voltage improved from approximately 50 to 56 kV. Beyond 30 min, the incremental gain in dielectric strength became marginal relative to the additional energy demand, indicating diminishing returns.

The Sankey diagram illustrating the energy distribution of the equipment is presented in Fig. 10. The term “thermal losses” ( $2.176 \text{ kWh}$ ) represents the difference between the heater energy supplied ( $2.305 \text{ kWh}$ ) and the useful heat absorbed by the oil ( $0.129 \text{ kWh}$ ). These losses include convective and radiative heat dissipation from the uninsulated glass reactor surface, heat accumulation within the reactor body, vapor discharge losses, and heater control inefficiencies inherent to batch laboratory operation.

To assess the physical plausibility of this low thermal efficiency, an order-of-magnitude heat-loss estimation was performed. The cylindrical glass reactor (height  $0.30 \text{ m}$ , diameter  $0.102 \text{ m}$ ) has an external surface area of approximately  $0.112 \text{ m}^2$  per tube, corresponding to a relatively high surface-area-to-volume ratio ( $\sim 75 \text{ m}^2/\text{m}^3$ ) for a  $1.5 \text{ L}$  batch. Assuming natural convection ( $h \approx 10 \text{ W/m}^2\text{K}$ ), an average temperature difference of approximately  $95 \text{ K}$ , and a heating duration of  $2 \text{ h}$ , the estimated convective heat loss per tube is on the order of  $0.2 \text{ kWh}$ , with additional radiative losses of approximately  $0.1 \text{ kWh}$ . When accounting for three reactor tubes and auxiliary fittings, the total external heat dissipation may approach  $1$  to  $2 \text{ kWh}$ . This magnitude is comparable to the experimentally observed energy discrepancy, supporting the interpretation that the low thermal efficiency

primarily reflects prototype-scale heat dissipation associated with an uninsulated laboratory configuration rather than intrinsic thermodynamic limitations of the process.

The relatively low thermal efficiency (4.0% relative to total installed power and 5.4% relative to thermal input alone) is primarily attributable to the laboratory-scale, uninsulated reactor configuration. The system exhibits a high surface-area-to-volume ratio of approximately  $75 \text{ m}^2/\text{m}^3$  for a 1.5 L batch, which promotes substantial convective and radiative heat losses to the ambient environment. In addition, the absence of vapor heat recovery and the reliance on time-based rather than demand-controlled heater operation further contribute to overall energy inefficiency.



**Fig. 10.** Sankey diagram of energy

Decomposition of the energy budget shows that heaters dominated the input (> 60%), suggesting thermal insulation and heat recovery around the deodorization section as primary levers for reducing specific energy consumption (SEC). Improving thermal efficiency and reducing specific energy consumption are essential not only in transformer oil processing but also in larger energy systems such as combined heat and power (CHP) plants. In such systems, the fuel heat utilization factor ranges from 69 to 76%, and optimization efforts can yield energy savings of 10 to 21% (Smolkin *et al.* 2025). This similarity underscores that enhancing energy efficiency is a universal challenge across energy-intensive technologies, including the development of biodegradable transformer insulating fluids.

Table 4 compares the CPO-based insulating fluid with other vegetable oils in terms of dielectric strength, biodegradability, and processing energy. The CPO-based oil shows the highest breakdown voltage (50 to 59 kV), outperforming waste cooking oil (27 kV), soybean oil (21 kV), and sunflower oil (38 to 45 kV), under similar testing standards. Its biodegradability (~ 98%) is also comparable to soybean and sunflower oils (> 95%), confirming its environmental suitability. The required processing energy (2.1 kWh/L) falls between waste cooking oil (1.6 kWh/L) and sunflower biodiesel (3.67 to 4.89 kWh/L). It should be noted that the reported specific energy consumption reflects laboratory-scale operation without thermal insulation, heat recovery, or process optimization. Therefore, extrapolation to industrial-scale production requires careful techno-economic assessment and scale-up validation

### Future Work

Future work should prioritize improving thermal insulation, implementing demand-based heater control, and integrating heat recovery systems to minimize energy losses and enhance overall thermal efficiency. Scaling analysis and continuous-flow reactor configurations should also be investigated to improve scalability and thermal performance.

In addition, comprehensive long-term stability assessments—including thermal aging, viscosity measurement, and accelerated oxidation tests—are necessary to evaluate durability under operational conditions. Advanced compositional analysis, such as high-performance liquid chromatography (HPLC), gas chromatography (GC), or fatty acid methyl ester (FAME) profiling, is recommended to quantify changes in fatty acid distribution, free fatty acid content, and minor polar compounds after processing. Such analyses would enable a clearer mechanistic correlation between compositional modification and dielectric performance improvement. These detailed analytical investigations were beyond the scope of the present proof-of-concept study, which focused primarily on dielectric evaluation and process integration. Comprehensive life-cycle and techno-economic assessments are required to evaluate large-scale feasibility of converting CPO to insulating fluids (Reeb *et al.* 2014). Furthermore, life cycle assessment (LCA), techno-economic analysis, and field-scale transformer testing are required to validate environmental sustainability and commercial feasibility.

**Table 4.** Comparison of CPO-Based Insulating Oil with Other Oil Processes

Parameter	CPO-Based (This Study)	Waste Cooking Oil	Soybean	Sunflower Oil
Breakdown Voltage (kV)	50 to 59	27 (Oparanti <i>et al.</i> 2025)	21 (Egbuna <i>et al.</i> 2016)	38 to 45 (Rafiq <i>et al.</i> 2015b)
Biodegradability (%)	~98	-	> 95	> 95
Energy Utility (kWh/L)	2.1	8.3 (Mohammadshirazi <i>et al.</i> 2014)	1.78 (Pradhan <i>et al.</i> 2010) (biodiesel)	3.67 to 4.89 (Randelli 2009) (biodiesel)

## CONCLUSIONS

1. Integrated vacuum-assisted processing of high-FFA CPO enabled degumming, deodorization, and drying within a single batch configuration. At a processing time of 20 min, the resulting oil achieved breakdown voltage values exceeding 50 kV, meeting the minimum dielectric requirement. Higher and more stable dielectric performance was observed at 30 to 40 min ( $\approx 58$  to 60 kV), while further extension to 50 min yielded only marginal improvement relative to the additional energy input. These results indicate that 30 to 40 min represents a practical operating window under the present laboratory-scale conditions.
2. The system exhibited a specific energy consumption of 2.1 kWh·L<sup>-1</sup>. The useful heat recovered was 0.136 kWh, corresponding to a thermal efficiency of approximately 4.0% relative to the total electrical energy input and 5.4% relative to the heater (thermal) energy input alone. Although the dielectric performance requirements were satisfied, a substantial portion of the supplied energy was dissipated as heat, highlighting the need for improved thermal insulation, demand-based heater control, and potential heat recovery integration in future system development.

3. The energy analysis highlights that prototype-scale heat dissipation, rather than intrinsic thermodynamic limitations, governs the low thermal efficiency. This finding underscores the importance of thermal design optimization in future scale-up efforts.

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Article submitted: December 24, 2025; Peer review completed: February 11, 2026;

Revised version received: February 23, 2026; Accepted: April 16, 2026; Published: May 15, 2026.

DOI: 10.15376/biores.21.3.5968-5983