Dissolved Gas Analysis Of Flaxseed Oil And Coconut Cooking Oil Blends: Thermal Degradation And Oxidative Stability In Simulated Transformer Conditions

Gema Romadhona[1,2], Ketut Ima Ismara[3], Mutiara Nugraheni[4]
[1]Student, Faculty of Engineering, Universitas Negeri Yogyakarta, Indonesia: gemaromadhona.2023@student.uny.ac.id (Corresponding Author)
[2]Faculty of Health Science, Universitas Muhammadiyah Purwokerto, Indonesia: gema.romadhona@ump.ac.id
[3]Faculty of Engineering, Universitas Negeri Yogyakarta, Indonesia: imaismara@uny.ac.id
[4]Faculty of Engineering, Universitas Negeri Yogyakarta, Indonesia: mutiara_nugraheni@uny.ac.id

Abstract
The search for sustainable transformer insulating fluids has led to increased interest in biodegradable vegetable oils as alternatives to conventional mineral oils. This research investigates the thermal degradation and oxidative stability of flaxseed oil (100%) and a blend of flaxseed oil (50%) with coconut cooking oil (50%), subjected to thermal aging at 170°C for 5 hours with copper immersion, simulating transformer winding conditions. Dissolved Gas Analysis (DGA) was conducted using Myrkos Portable DGA MicroGC to quantify gas evolution, including H_2, CH_4, *CO*, CO_2, C_2H_4, C_2H_6, *and* C_2H_2. *The results indicate that flaxseed oil exhibits higher thermal degradation, with elevated concentrations of* CO_2, *CO*, C_2H_4 *and* C_2H_6, *suggesting increased oxidation and hydrocarbon breakdown. In contrast, the flaxseed oil-coconut cooking oil blend demonstrates improved oxidative stability, with lower gas concentrations, indicating enhanced resistance to thermal stress. The presence of copper as a catalytic agent further influences gas formation, accelerating oxidation reactions in both oil samples. These findings highlight the potential of vegetable-based insulating oils as sustainable alternatives for transformer applications. The flaxseed oil-coconut cooking oil blend emerges as a promising candidate due to its enhanced thermal stability, which could contribute to improved performance and longevity in electrical insulation systems.*
Keywords: *dissolved gas analysis, flaxseed oil, coconut cooking oil, thermal degradation, oxidative stability.*

1. INTRODUCTION

Transformer insulating oils are essential components in ensuring the safe and efficient operation of electrical power systems. Their primary functions are to serve as cooling media and electrical insulators that prevent electrical discharges and help dissipate heat from the transformer core [1], [2]. For decades, mineral oils have been the dominant choice due to their excellent thermal conductivity and dielectric strength [3]. However, concerns have emerged regarding their non-biodegradable nature and the environmental risks they pose, particularly in cases of leakage or improper disposal [4].

In response to these environmental issues, research has shifted toward developing alternative insulating oils derived from renewable and biodegradable sources. Vegetable-based oils, such as flaxseed oil and coconut cooking oil, have shown promise due to their favorable insulating properties and thermal performance [5], [6]. These natural oils not only offer strong dielectric strength and high flash points but also demonstrate good oxidative stability, which is crucial for long-term transformer operation [7], [8]. Moreover, their biodegradability supports global efforts toward sustainable and eco-friendly energy technologies [9], [10].

Within the scope of transformer maintenance and monitoring, Dissolved Gas Analysis (DGA) is a critical diagnostic method used to detect and interpret the presence of fault-related gases dissolved in insulating oil [11]. When transformers are exposed to thermal and electrical stress, the insulating oil decomposes and produces gases such as hydrogen, methane, carbon monoxide, carbon dioxide, ethylene, ethane, and acetylene [12]. The specific composition and concentration of these gases can indicate the type and severity of faults such as overheating, partial discharges, or arcing, making DGA an invaluable tool for predictive maintenance and fault prevention [13].

Another significant factor influencing gas generation in insulating oils is the presence of materials like copper within the transformer. Copper acts as a catalyst in oxidation reactions and can accelerate the degradation of insulating oil by promoting the formation of certain gases [14]. This catalytic effect not only affects the chemical stability of the oil but also compromises its insulating and cooling performance over time. Therefore, understanding the interaction between copper and alternative oils is essential for the development of more resilient insulating systems [15], [16].

Previous research states that natural ester insulating liquids offer an eco-friendly alternative to mineral oils in transformers, but their vulnerability to oxidation limits their broader application. The use of antioxidants has proven effective in enhancing the stability, performance, and safety of these natural esters, while also supporting sustainability goals [17], [18]. However, to ensure long-term environmental safety, it is essential to develop and regulate the use of non-toxic, biodegradable antioxidants that maintain high performance at low concentrations [17]. Another research also shows that blending oils led to beneficial changes in fatty acid (FA) composition without compromising oxidative stability, and the blends resisted secondary thermal degradation [19], [20], [21].

The novelty of this research lies in the application of Dissolved Gas Analysis (DGA) to evaluate the thermal degradation and oxidative stability of flaxseed oil and coconut cooking oil blends under simulated transformer operating conditions. This work explores the potential of these natural oil blends as sustainable insulating fluids, providing new insights into their degradation behavior and suitability for power transformer applications. This research aims to compare the DGA profiles of flaxseed oil and a blend of flaxseed oil (50%) with coconut cooking oil (50%) after thermal aging at 170°C for 5 hours with copper immersion. By analyzing the gas evolution patterns, this research seeks to evaluate the thermal stability and oxidative behavior of these oils, providing insights into their feasibility as alternative insulating fluids for transformers. The findings contribute to the growing body of research on biodegradable transformer oils, offering a comparative perspective on their degradation characteristics and potential applications in electrical insulation systems.

This research was conducted using selected natural oils and diagnostic tools suitable for simulating transformer environments. The research utilized a blend of biodegradable insulating oils along with standard analysis equipment to evaluate gas formation under thermal stress. All materials and instruments were chosen to support accurate observation of oil degradation behavior and gas emission patterns. This setup enabled reliable data collection to assess the oxidative stability and suitability of the oil blends for potential application in transformer systems. Some of the tools and materials used are as follows:

2. Tools and materials

2.1 Flaxseed Oil

Flaxseed oil which is obtained from flax seeds (Linum usitatissimum), as shown in figure 1 below.

Figure 1. Flaxseed Oil

Figure 2. Linum usitatissimum

Flax (Linum usitatissimum) is a versatile plant predominantly cultivated in rural regions, thriving best in clayey and siliceous soils that support its optimal growth. Its seeds have long been recognized for their diverse health benefits, commonly used in traditional remedies to address skin conditions, digestive issues, and cholesterol management. This wide range of medicinal and nutritional properties has made flaxseed a valuable agricultural crop with significant potential in the wellness and health industries [22].

From these nutrient-rich seeds, flaxseed oil is derived through the cold-pressed method—a mechanical process that preserves the oil's natural composition by avoiding chemical solvents and excessive heat. The resulting oil is rich in Alpha-Linolenic Acid (ALA), lignans, antioxidants, and vitamin E, making it beneficial for cardiovascular health, anti-inflammatory responses, and skincare. Although its high polyunsaturated fat content makes it susceptible to oxidation, the cold-pressing technique enhances its oxidative stability. Given the rising global demand for clean-label and minimally processed products, coldpressed flaxseed oil stands out as a high-value ingredient in food, supplements, and personal care markets, offering both functional benefits and commercial appeal [23].

One of its most notable components is Alpha-Linolenic Acid (ALA), an essential omega-3 fatty acid, which typically constitutes between 52% and 63% of the oil. ALA plays a significant role in improving metabolic health, including increasing insulin sensitivity, raising HDL (good) cholesterol, and reducing LDL (bad) cholesterol oxidation factors that contribute to cardiovascular protection [24].

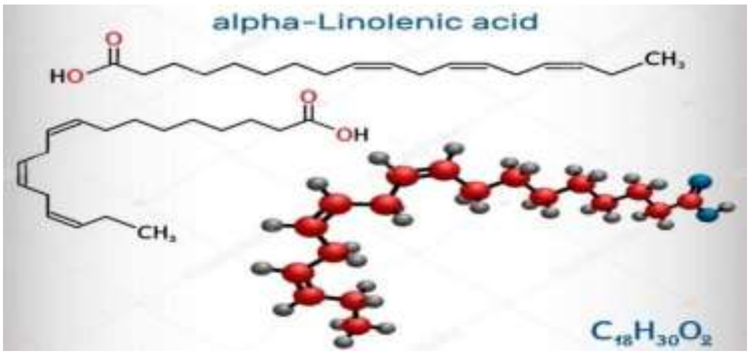

Figure 3. Alpha-Linolenic Acid (ALA)

Due to its rich bioactive profile, flaxseed oil has become a valuable subject in various scientific fields, particularly in food science, health, and industrial applications. Research has explored its oxidative stability, anti-inflammatory properties, and overall impact on cardiovascular health, highlighting its potential beyond basic nutrition. These attributes not only enhance its appeal as a functional food ingredient but also support its use in preventive health strategies and product development in nutraceuticals and wellness-focused industries. The combination of health-promoting benefits and natural processing makes flaxseed oil a promising candidate for sustainable and health-conscious innovation [25].

2.2 Coconut Cooking Oil

Coconut cooking oil, as seen in Figure 4, is a type of oil extracted from the meat of mature coconuts and is widely used in both culinary and health applications. It contains a high proportion of saturated fats, particularly medium-chain triglycerides (MCTs), which are easily metabolized by the body for energy. Known for its stability at high temperatures, coconut oil is commonly used for frying and baking, and its natural antioxidant content also supports potential health benefits such as improved digestion and antimicrobial properties [26].

Figure 4. Coconut Cooking Oil

Coconut cooking oil contains about 90-92% saturated fatty acids, with lauric acid (C12:0) as the main component at about 45-53%, which contributes to its high antimicrobial properties and oxidative stability [27].

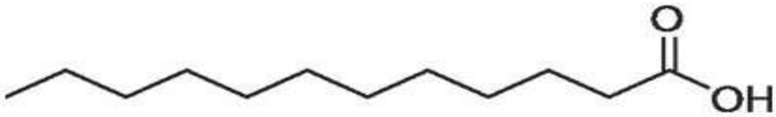

Figure 5. Lauric acid

In addition, coconut cooking oil also contains myristic, caprylic, and capric acids that belong to the medium-chain fatty acids (MCFA) group, making it more stable against oxidation than unsaturated oils such as soybean or corn oil [28], [29]. This composition makes coconut oil ideal as a base material for structured lipids due to its thermal stability and fat profile. In repeated frying applications, coconut cooking oil shows good oxidative resistance, although its quality remains affected by the temperature and frequency of heating.

2.3 Myrkos Portable DGA MicroGC

The Myrkos Portable DGA MicroGC, as seen in figure 6, is a portable instrument based on micro gas chromatography (MicroGC) specifically designed for Dissolved Gas Analysis (DGA) in transformer insulating oil.

Figure 6. Myrkos Portable DGA MicroGC

Developed by Morgan Schaffer (now part of Doble Engineering), this tool is known for its ability to deliver laboratory-quality analysis on-site within approximately two minutes after sample injection [30].

Key Features of the Myrkos Portable DGA MicroGC [31]:

a. MicroGC Technology: Utilizes micro gas chromatography to separately detect the nine key fault gases (H_2, CH_4, C_2H_2, C_2H_4, C_2H_6, CO, CO_2, O_2, and N_2) with no cross-interference.

b. Shake Test® Method: Employs a specialized syringe to extract headspace gas from oil samples, in compliance with ASTM D3612 [29] and IEC 60567 [31] standards.
c. High Portability: Equipped with a lithium-ion battery that supports wireless operation for up to 7 hours, along with a refillable carrier gas container.
d. High Accuracy and Reproducibility: Meets or exceeds international standards for detection limits and analytical precision.
e. Software Integration: Comes with PPMreport™ and Myrkos View software for data management, transformer condition diagnostics, and automatic reporting.

2.3 Electric oven
An electric oven, as seen in figure 7, is used to heat the oil to 170 °C for 5 hours.

Figure 7. Electric oven
The use of an electric oven as a heating device plays a crucial role in ensuring the consistency and validity of experimental results. Electric ovens offer precise temperature control, thermal stability, and uniform heat distribution, making them ideal for use in studies requiring controlled heating of oils to evaluate degradation characteristics, oxidative stability, or simulate field conditions.

3. METHOD
3.1 Sample Preparation
Two types of insulating oils were prepared for analysis:
1. Flaxseed oil (100%)

Figure 8. Flaxseed Oil (100 %)
2. Blend of flaxseed oil (50%) and coconut cooking oil (50%)

Figure 9. Blend of flaxseed oil (50%) and coconut cooking oil (50%)

Each oil sample was heated to 170°C for 5 hours, with copper immersion, as shown in figures 8 and 9, to simulate transformer winding conditions. The copper acted as a catalyst, potentially influencing oxidation and gas formation.

Figure 10. 100% flaxseed oil that has been heated for 5 hours with a copper bath.

Figure 11. Mixing 50% Flaxseed Oil with 50% Coconut Cooking Oil, which has been heated for 5 hours with a copper bath.

The copper immersion simulation process is carried out to replicate actual conditions inside a transformer, where insulating oil is in direct contact with metallic components such as copper windings. In this simulation, copper strips are immersed in the oil samples, both 100% flaxseed oil and a 50:50

flaxseed-coconut oil blend, during thermal aging at 170°C for five hours. Copper acts as a catalyst that accelerates oxidation and thermal degradation reactions, thereby promoting the formation of dissolved gases such as carbon monoxide (CO), carbon dioxide (CO_2), and light hydrocarbons. This treatment is essential for evaluating the thermal stability and oxidative resistance of the oils under extreme operational conditions typically encountered in transformer environments.

3.2 Dissolved Gas Analysis (DGA)

DGA was performed using Myrkos Portable DGA MicroGC, a gas chromatography-based system designed for transformer oil diagnostics. The following gases were analyzed:

1. Hydrogen (H_2)
2. Methane (CH_4)
3. Carbon Monoxide (CO)
4. Carbon Dioxide (CO_2)
5. Ethylene (C_2H_4)
6. Ethane (C_2H_6)
7. Acetylene (C_2H_2)

Gas extraction was carried out using a syringe-based method to capture headspace gas from the heated oil samples. This method ensured that the gases present in the insulating oil were accurately captured for analysis. The analysis was conducted immediately after the heating process, at normal temperature, to avoid any loss of dissolved gases.

3.3 Experimental Setup

A step-by-step overview of the experimental process is provided in the following flowchart, figure 12.

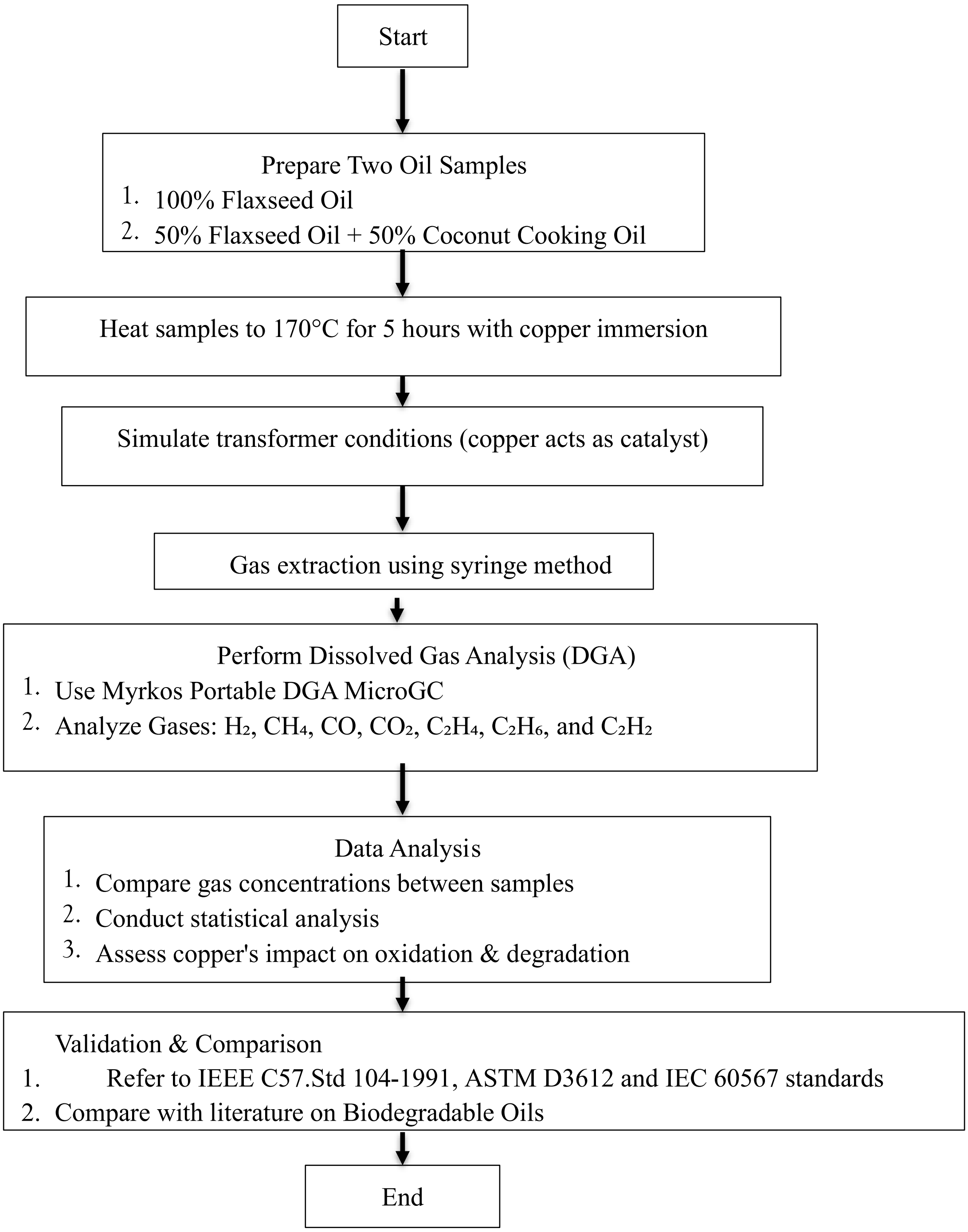

Figure 12. Flowchart

1. Oil samples were placed in a controlled heating chamber.
2. Copper immersion was maintained throughout the heating process.
3. Gas extraction was performed using a syringe method, with the Shake Test® process, which is a shaking method to release dissolved gases from the oil into the headspace of the syringe.
4. After the gas is extracted, inject the gas into the Myrkos micro gas chromatography (MicroGC) system. The system will separate and measure the concentration of the main gases.
5. The analysis results are displayed through the PPMreport™ software.
6. DGA measurements were taken immediately after heating, at normal temperature.

3.4 Data Analysis

For the data analysis, the gas concentrations detected during DGA were compared between the pure flaxseed oil and the blended oil sample (50% flaxseed oil, 50% coconut oil) using descriptive statistical methods. Mean gas concentrations for each oil sample were calculated to provide a general overview of the degradation levels. This helped to quantify and summarize the overall levels of each gas (H_2, CH_4, CO, CO_2, C_2H_4, C_2H_6, and C_2H_2) generated during thermal aging. Transformer oil diagnostic criteria conform to standards established by IEEE C57.Std 104-1991 [32], ASTM D3612 [29] and IEC 60567 [31] to ensure that the findings were consistent with industry standards for oil degradation.

3.5 Validation and Comparison

The results of the gas analysis were cross-referenced with existing literature on the degradation behavior of natural oils used in transformers. This validation process helped to benchmark the findings against established research on the performance and stability of biodegradable oils under similar thermal and oxidative stress conditions.

4. RESULTS AND DISCUSSION

The following is the analysis of the results of the Dissolved Gas Analysis (DGA) of flaxseed oil that has been heated to 170°C with copper dyeing for 5 hours, using the Myrkos Portable DGA MicroGC tool. This experiment simulates the condition of the insulating oil in a transformer interacting with a copper conductor. 4.1 Flaxseed Oil

The Dissolved Gas Analysis (DGA) research detects oil degradation due to heating or overcurrent in the transformer system. DGA is used to detect dissolved gases in insulating oils, which can give an indication of thermal degradation or oxidation. Based on the results given for 100% flaxseed oil are presented in table 1 below.

Tabel 1. Measurement Results: Flaxseed Oil 100%

No	Measurement	Concentration	Significance in DGA
1	H_2 (Hydrogen)	25 ppm	Early indications of mild thermal degradation.
2	CH_4 (Methane)	0 ppm	No indication of mild hydrocarbon degradation.
3	CO (Carbon Monoxide)	319 ppm	Indicates oil degradation.
4	CO_2 (Carbon Dioxide)	1728 ppm	High concentration, indicating thermal degradation of oil.
5	C_2H_4 (Ethylene)	26 ppm	Indication of oil heating at high temperatures
6	C_2H_6 (Ethane)	4669 ppm	High concentration, indicating degradation of hydrocarbons due to heating.
7	C_2H_2 (Acetylene)	0 ppm	No indication of high energy release, such as arcing
8	TDCG	0.50 %	Caution

Hydrogen (H_2) is the lightest and most readily formed gas, and its increased concentration often provides an early warning before other gases appear in significant quantities. When present with acetylene (C_2H_2), H_2 can indicate the presence of an electric arc. The presence of H_2 at low levels (25 ppm) indicates that the degradation is mildly thermal, not electrical. According to IEEE C57.Std 104-1991 [32]ASTM D3612 [29] and IEC 60567 [31] standards, high concentrations of gases such as CO_2 and C_2H_6 can indicate thermal degradation of the oil due to prolonged heating. The presence of significant amounts of CO also indicates oxidation, which can be influenced by the presence of copper as a catalyst. An increased concentration of C_2H_4 indicates a hot spot or overheating in the metal components or the oil itself. Unlike acetylene (C_2H_2), ethylene does not exhibit an electric arc, but rather a purely thermal disturbance. C_2H_4 accompanied by high C_2H_6 (4669 ppm) indicates that degradation of saturated hydrocarbons is underway. No C_2H_2 is detected, indicating that the disturbance is thermal, not electrical. Previous studies support this, showing that copper immersion in natural ester oils significantly increases the rate of oxidation and gas generation, particularly CO and CO_2, due to its catalytic effect on free radical reactions during thermal stress [33]. TDCG – Total Dissolved Combustible Gas (TDCG) includes: H_2, CH_4, C_2H_2, C_2H_4, C_2H_6, CO, and CO_2. Measured as a percentage (%), used to assess the level of degradation or disturbance. A TDCG value of 0.5% indicates that flammable gases such as hydrogen [H_2], ethylene [C_2H_4] dissolved in transformer insulating oil have reached the early warning threshold based on international standards. According to IEC 60599 [34] and IEEE C57.104 [32], a value of 0.5% is not an emergency, but should be monitored because it indicates the beginning of the degradation process. If left unchecked, it can develop into serious damage, such as a short circuit or transformer fire.

4.1.2 Graph

The graphs in the PPMreport™ software can be seen in figures 13 and 14 below.

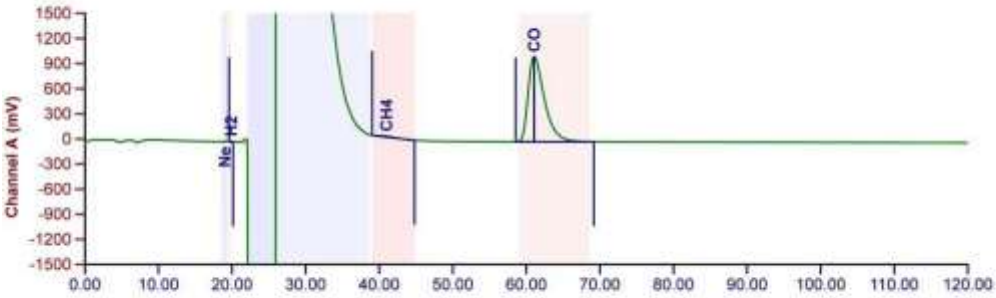

Figure 13. Gas Evolution Analysis and Signal Intensity Over Time in Flaxseed Oil 100% - Channel A

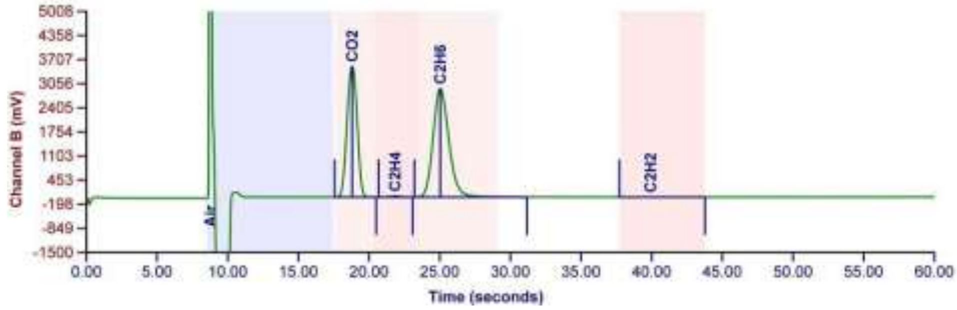

Figure 14. Gas Evolution Analysis and Signal Intensity Over Time in Flaxseed Oil 100% - Channel B X-Axis: Channel A, Time in seconds (0 – 120 seconds).
X-axis (Time): Channel B, 0 - 60 seconds, indicates the gas retention time in the analysis system.
Y-axis: Response of Channel A in millivolts (-1500 mV to 1500 mV).
Y-axis (Response Channel B): -1500 mV to 5008 mV, indicating gas detection intensity. Green line: Indicates changes in signal intensity over time.

4.1.3 Gas Peak Identification

This graph in figures 13 and 14 shows the nine major gas peaks based on the time of their occurrence, as presented in table 2 below.

Table 2. Gas retention time of 100% flaxseed oil

No	Gas	Retention time	Characteristics
1	Ne (Neon)	± 20 seconds	Fast, light, low polarity
2	H_2 (Hydrogen)	± 20 seconds	Fast, light, low polarity
3	CH_4 (Methane)	± 40 seconds	Slow, saturated hydrocarbons or double bonds
4	CO (Carbon Monoxide)	± 60 seconds	Slowest, polar molecules
5	Air	± 10 seconds	Fastest, light gas mixture
6	CO_2 (Carbon Dioxide)	± 20 seconds	Fast, light
7	C_2H_4 (Ethylene)	± 22 seconds	Intermediate, Unsaturated Hydrocarbons, slightly heavier
8	C_2H_6 (Ethane)	± 25 seconds	Intermediate, Saturated Hydrocarbons, slightly heavier
9	C_2H_2 (Acetylene)	± 40 seconds	Slow, Unsaturated hydrocarbons, double bonds

Retention time helps to separate and identify degradation gases with high accuracy. Small, non-polar gases (Ne, H_2, Air) tend to be faster, while polar gases such as CO are retained longer.

4.1.4 Data Interpretation

Retention Time: Each gas has a different retention time, indicating a unique interaction with its analysis system. For example, H_2 and Ne appear almost simultaneously, signifying that they both have similar characteristics in the separation method used. Previous studies have established that retention time is critical in identifying specific gases during Dissolved Gas Analysis (DGA) and depends heavily on the gas's physical properties and the carrier gas used [35].

Signal Intensity: The magnitude of the peak gives an indication of the concentration of the gas, with a higher signal indicating a larger amount in the sample. According to research by [36] the signal intensity in gas chromatography can be directly correlated with transformer oil degradation stages, where elevated levels of gases like C_2H_2, C_2H_4, and CH_4 signal various types of thermal or electrical faults. These studies reinforce the reliability of chromatographic data in the condition monitoring of insulating oils. The appearance of air peaks is not used to diagnose equipment failure, but rather to aid in initial validation and verification before critical gases such as CO, C_2H_2, or C_2H_4 are detected. If the air peaks are excessive or inconsistent, there could be a system leak or suboptimal column conditions.

4.2 Mixture of Flaxseed Oil 50% Coconut Cooking Oil 50%

The following (table 3) is the analysis of the results of the Dissolved Gas Analysis (DGA) from a mixture of 50% flaxseed oil and 50% coconut cooking oil that has been heated to 170°C with copper dyeing for 5 hours, using the Myrkos Portable DGA MicroGC tool. This experiment simulates the condition of the insulating oil in a transformer interacting with a copper conductor.

Table 3. Measurement Results: mixture of 50% flaxseed oil and 50% coconut cooking oil.

According to IEEE C57.Std 104-1991 [32] ASTM D3612 [29] and IEC 60567 [31] standards, the relevance of Dissolved Gas Analysis (DGA) is crucial in diagnosing the condition of transformer oil.

No	Measurement	Concentration	Significance in DGA
1	H_2 (Hydrogen)	0 ppm	No indication of mild thermal degradation.
2	CH_4 (Methane)	0 ppm	No indication of mild hydrocarbon degradation.
3	CO (Carbon Monoxide)	68 ppm	Indicates the presence of mild oxidation of the oil.
4	CO_2 (Carbon Dioxide)	1138 ppm	High concentration, indicating thermal degradation of oil.
5	C_2H_4 (Ethylene)	10 ppm	Indication of oil heating at high temperatures.
6	C_2H_6 (Ethane)	1119 ppm	High concentration, showing degradation of hydrocarbons due to heating.
7	C_2H_2 (Acetylene)	0 ppm	No indication of high energy release such as arcing.
8	TDCG	0.13 %	Low degradation

Combinations of C_2H_4 and C_2H_6 can indicate overheating of the transformer oil. High concentrations of gases such as CO_2 and C_2H_6 can indicate thermal degradation of the oil due to prolonged heating. Acetylene (C_2H_2) is often an indication of arcing or serious electrical faults. The presence of significant amounts of CO also indicates oxidation, which can be affected by the presence of copper as a catalyst. The TDCG value of 0.13% is below the 0.25% threshold, indicating no significant damage. The oil is still functioning optimally as an insulating and cooling medium.

4.2.1 Graph

The graphs in the PPMreport™ software can be seen in figures 15 and 16 below.

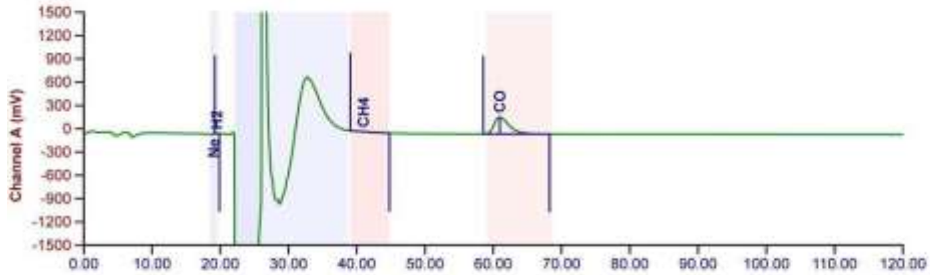

Figure 15. Gas Evolution Analysis and Signal Intensity Over Time in Flaxseed Oil 50% and Coconut Coking Oil 50% Blend - Channel A

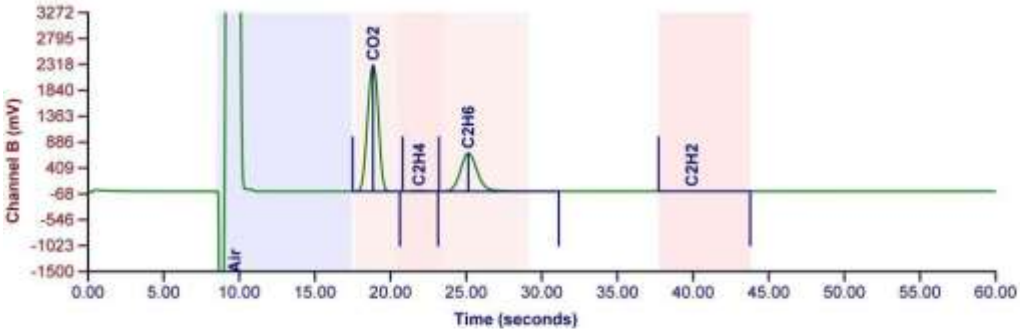

Figure 16. Gas Evolution Analysis and Signal Intensity Over Time in Flaxseed Oil 50% and Coconut Cooking Oil 50% Blend - Channel B
X-Axis: Channel A, Time in seconds (0 – 120 seconds).
X-axis (Time): Channel B, 0 - 60 seconds, indicates the gas retention time in the detection device.
Y-axis: Channel A, Detection signal intensity in millivolts (-1500 mV to 1500 mV).
Y-axis (Response Channel B): -1500 mV to 3272 mV, indicating gas detection intensity.
Green Line: Represents a change in signal intensity over time, indicating gas detection at specific points.

4.2.2 Identified Gas Peaks

This graph in figures 15 and 16 shows the nine major gas peaks based on the time of their occurrence, as presented in table 4 below.

Table 4. Gas retention time in a mixture of 50% flaxseed oil and 50% coconut cooking oil

No	Gas	Retention time	Karakteristik
1	Ne (Neon)	± 20 seconds	Nonpolar and very light
2	H_2 (Hydrogen)	± 20 seconds	Nonpolar and very light
3	CH_4 (Methane)	± 30 seconds	Nonpolar but heavier than H_2
4	CO (Carbon Monoxide)	± 60 seconds	Polar gases
5	Air	± 10 seconds	Very fast because it is nonpolar and light.
6	CO_2 (Carbon Dioxide)	± 20 seconds	Fast, light
7	C_2H_4 (Ethylene)	± 25 seconds	Unsaturated hydrocarbons , eavier than air
8	C_2H_6 (Ethane)	± 30 seconds	Saturated hydrocarbons, slightly heavier
9	C_2H_2 (Acetylene)	± 40 seconds	Unsaturated hydrocarbons, double bond

Retention time in gas chromatography indicates how long a gas is retained in the column before being detected. The presence of air peaks is not used to diagnose equipment failures, but rather to aid in initial validation and verification before critical gases such as CO, C_2H_2, or C_2H_4 are detected. If the air peaks are excessive or inconsistent, there may be a system leak or suboptimal column conditions.

4.3 Influence of Copper in the Heating Process

Copper is known as a catalyst in the oxidation reaction of oils. Studies show that the presence of copper can accelerate the formation of CO and CO_2, as well as increase the degradation of hydrocarbons that produce high amounts of C_2H_6 [37]. Transition metals like copper can catalyze oxidation in natural esters, leading to increased gas generation.

[38] reported that copper enhances the oxidation rate of natural esters, while copper catalyzes the degradation of insulating oils, increasing the formation of polar degradation products and dissolved gases [39]. Similarly, the immersion of copper strips in ester-based insulating oils resulted in increased gas evolution under thermal stress [40].

The DGA results showed that heating flaxseed oil 100% and a mixture of flaxseed oil 50% and coconut cooking 50% with copper at 170°C for 5 hours caused significant thermal degradation, especially in the form of increased CO_2, CO, and C_2H_6. This aligns with previous findings, which reported that copper acts as a pro-oxidant in ester-based insulating oils, accelerating molecular breakdown under thermal stress [33]. The presence of copper likely acts as a catalyst in the oxidation process of oil, supporting the hypothesis that metal contamination inside transformers can significantly influence oil stability and aging behavior [33]. This suggests that copper likely acts as a catalyst in the oxidation process of the oil blend, accelerating the decomposition reactions and gas generation. These findings are consistent with previous research and highlight the importance of controlling metal contamination in transformers using natural ester insulating oils [41].

4.4 Comparison of Dissolved Gas Composition

The following (table 5 and figure 19) is a comparative analysis of the results of the Dissolved Gas Analysis (DGA) from pure flaxseed oil with Blend of 50% flaxseed oil and 50% coconut cooking oil.

Table 5. Comparison of DGA measurements on 100% flaxseed oil with 50% flaxseed oil and 50% coconut cooking oil blend

No	Measurement result	FO 100%)	FO (50%) and CCO (50%) Blend	Difference	Percentage	Explanation
1	Hydrogen (H_2)	25 ppm	0 ppm	25 ppm	100 %	Indication of improvement
2	Methane (CH_4)	0 ppm	0 ppm	0 ppm	0 %	No indication of Partial Discharge (PD)
3	Carbon Monoxide (CO)	319 ppm	68 ppm	251 ppm	78,68 %	Oxidation is more significant in flaxseed oil than in mixtures.
4	Carbon Dioxide (CO_2)	1728 ppm	1138 ppm	590 ppm	34,15 %	Thermal degradation is higher in flaxseed oil than in blends.

5	Ethylene (C_2H_4)	26 ppm	10 ppm	16 ppm	61,54 %	Indications of oil heating are higher in flaxseed oil.
6	Ethane (C_2H_6)	4669 ppm	1119 ppm	3.550 ppm	76,05 %	Hydrocarbon degradation is higher in flaxseed oil than in blends.
7	Acetylene (C_2H_2)	0 ppm	0 ppm	0 ppm	0 %	There is no indication of high energy release, such as arcing, in both oils.
8	TDCG	0.50 %	0.13 %	0,37 %	74 %	Indication of improvement

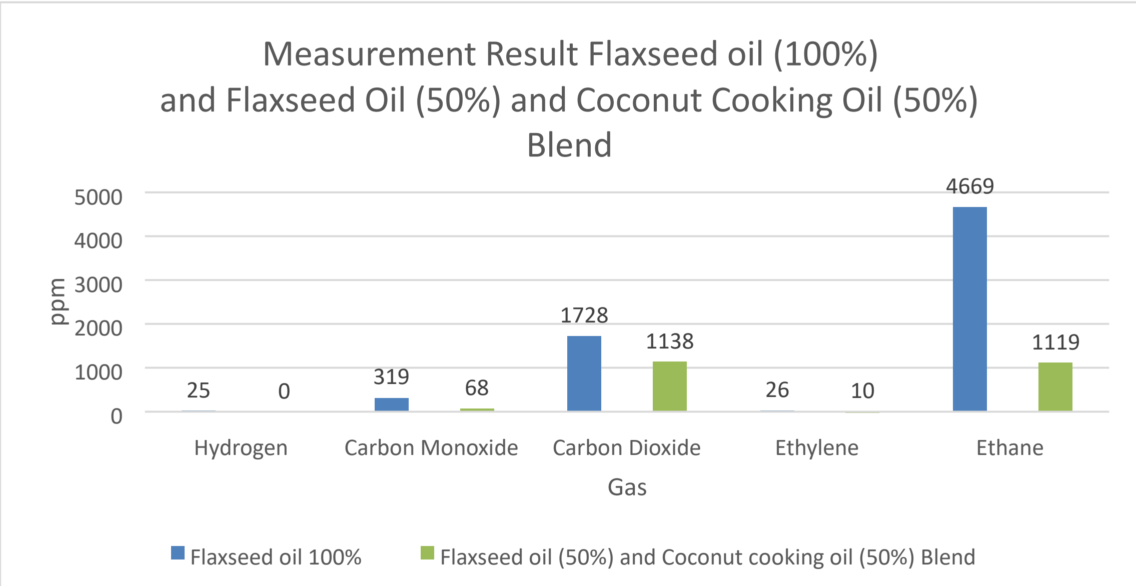

Figure 17. Comparison graph of DGA measurements on 100% flaxseed oil with 50% flaxseed oil and 50% coconut cooking oil blend

The table 5 and figure 17 above shows that pure flaxseed oil shows higher thermal degradation compared to a mixture with coconut oil, as seen from the high H_2, CO, CO_2, C_2H_4, and C_2H_6. The mixture of flaxseed oil and coconut oil has better thermal stability, with a lower concentration of degradation gases. H_2 gas in pure Flaxseed Oil is 25 ppm, indicating mild thermal degradation, h2 was not detected in the mixture with coconut cooking oil. Methane (CH_4) 0 ppm indicates no indication of light hydrocarbon degradation in both oils. a 74% reduction in TDCG indicates that the blend with coconut cooking oil suppresses the formation of thermal degradation gases such as H_2, CO, CO_2, C_2H_4, and C_2H_6. Coconut cooking oil is rich in lauric acid and a natural antioxidant that acts as a free radical scavenger, thereby slowing degradation reactions. According to IEEE C57.Std 104-1991 [32] IEC 60599 [34] and ASTM D3612 [29], a TDCG value of 0.13% is considered safe and indicates adequate chemical stability for longterm applications. This synergistic potential can be utilized in the formulation of environmentally friendly insulating fluids.

4 CONCLUSION

This study presents a comparative analysis of Dissolved Gas Analysis (DGA) for 100% flaxseed oil and a blend of flaxseed oil (50%) and coconut cooking oil (50%), which were subjected to thermal aging at 170°C for 5 hours with copper immersion. The findings highlight significant differences in gas evolution patterns, indicating variations in thermal stability and oxidative degradation between the two oil processes. The results indicate that pure flaxseed oil exhibits higher thermal degradation and oxidation, as evidenced by increased concentrations of H_2, CO, CO_2, C_2H_4 and C_2H_6. In contrast, the flaxseed oilcoconut cooking oil blend exhibits better oxidative stability, with lower gas concentrations, indicating improved resistance to thermal stress. The blend of flaxseed and coconut cooking oils emerges as a promising candidate due to its better thermal stability, which can contribute to improved performance and longevity of electrical insulation systems. By mixing of coconut cooking oil results in better thermal stability and can be a candidate for sustainable insulating oil. The presence of copper as a catalytic agent further influences gas formation, accelerating the oxidation reaction in both oil samples. These findings underscore the potential of vegetable insulating oils as a sustainable alternative to conventional mineral oils in transformer applications.

REFERENCES

1. [1] S. Sorte, A. Salgado, A. F. Monteiro, D. Ventura, N. Martins, and M. S. A. Oliveira, "Advancing Power Transformer Cooling: The Role of Fluids and Nanofluids—A Comprehensive Review," Mar. 01, 2025, Multidisciplinary Digital Publishing Institute (MDPI). doi: 10.3390/ma18050923.
2. [2] Y. Luo et al., "Transformer oil electrical-thermal characteristics analysis and evaluation," AIP Adv, vol. 14, no. 7, Jul. 2024, doi: 10.1063/5.0206033.
3. [3] A. Hamdi, I. Fofana, and M. Djillali, "Stability of mineral oil and oil-ester mixtures under thermal aging and electrical discharge," IET Generation, Transmission & Distribution, Jun. 2017, doi: https://doi.org/10.1049/ietgtd.2016.1970.
4. [4] J. Jacob, P. Preetha, and S. T. Krishnan, "Review on natural ester and nanofluids as an environmental friendly alternative to transformer mineral oil," Jun. 01, 2020, Institution of Engineering and Technology. doi: 10.1049/ietnde.2019.0038.
5. [5] T. C. Balachandra and S. V. Kulkarni, "Dielectric Recovery and Insulating Properties of Coconut Oil and Transformer Oil," Emerging Research in Computing, Information, Communication and Applications, Springer, Singapore., vol. 928, pp. 719–728, 2023, doi: https://doi.org/10.1007/978-981-19-5482-5_62.
6. [6] Z. Huang et al., "Electrical and thermal properties of insulating oil-based nanofluids: A comprehensive overview," 2019, Institution of Engineering and Technology. doi: 10.1049/iet-nde.2018.0019.
7. [7] T. Madhujith and S. Sivakanthan, "Oxidative Stability of Edible Plant Oils," Bioactive Molecules in Food, Springer, Cham, Jun. 2018, doi: https://doi.org/10.1007/978-3-319-54528-8_94-1.
8. [8] O. Shutenko and S. Ponomarenko, "Analysis of Ageing Characteristics of Transformer Oils under LongTerm Operation Conditions," Iranian Journal of Science and Technology - Transactions of Electrical Engineering, vol. 46, no. 2, pp. 481–501, Jun. 2022, doi: 10.1007/s40998-022-00492-7.
9. [9] M. Karthik, R. S. S. Nuvvula, C. Dhanamjayulu, and B. Khan, "Appropriate analysis on properties of various compositions on fluids with and without additives for liquid insulation in power system transformer applications," Sci Rep, vol. 14, no. 1, Dec. 2024, doi: 10.1038/s41598-024-68714-y.
10. [10] P. Pranav, E. Sneha, and S. Rani, "Vegetable oil-based cutting fluids and their behavioral characteristics in machining processes: A review," Industrial Lubrication and Tribology, vol. 73, no. 9, 2021, doi: https://doi.org/10.1108/ILT-12-2020-0482.
11. [11] R. Nivetha, S. Simmaky, and S. Sivakanthan, "Analysis of oxidative stability and fatty acids profile of coconut oil and flaxseed oil blends," Grasas y Aceites, vol. 75, no. 3, Jul. 2024, doi: 10.3989/gya.0318231.
12. [12] A. Wajid et al., "Comparative Performance Study of Dissolved Gas Analysis (DGA) Methods for Identification of Faults in Power Transformer," Int J Energy Res, vol. 2023, 2023, doi: 10.1155/2023/9960743.
13. [13] R. Rabail, R. M. Aadil, A. Sahar, and M. A. Zia, "Nutritional and physicochemical analysis of edible oil blend with improved ratios of cardioprotective nutritional indices and physicochemical properties," Journal of Food Measurement and Characterization, vol. 18, no. 5, pp. 3584–3594, May 2024, doi: 10.1007/s11694-024-02429-6.
14. [14] M. S. Ali, A. H. Abu Bakar, A. Omar, A. S. Abdul Jaafar, and S. H. Mohamed, "Conventional methods of dissolved gas analysis using oil-immersed power transformer for fault diagnosis: A review," Mar. 01, 2023, Elsevier Ltd. doi: 10.1016/j.epsr.2022.109064.
15. [15] B. Nouri and M. Ojaghi, "Power Transformer Fault Diagnosis via Gas Chromatography: A Comprehensive Review of Techniques and Standards," vol. 2, no. 4, pp. 17–29, 2022, doi: 10.30503/EECS.2024.479067.1061.

16. [16] R. Rabail, M. A. Shabbir, A. Sahar, A. Miecznikowski, M. Kieliszek, and R. M. Aadil, "An intricate review on nutritional and analytical profiling of coconut, flaxseed, olive, and sunflower oil blends," Molecules, vol. 26, no. 23, Dec. 2021, doi: 10.3390/molecules26237187.
17. [17] E. O. Obebe, Y. Hadjadj, S. O. Oparanti, and I. Fofana, "Enhancing the Performance of Natural Ester Insulating Liquids in Power Transformers: A Comprehensive Review on Antioxidant Additives for Improved Oxidation Stability," Apr. 01, 2025, Multidisciplinary Digital Publishing Institute (MDPI). doi: 10.3390/en18071690.
18. [18] S. A. Ghani, Z. A. Noorden, N. A. Muhamad, H. Zainuddin, M. I. H. C. Abdullah, and I. S. Chairul, "Dielectric strength improvement of natural ester insulation oil via mixed antioxidants: Taguchi approach," International Journal of Electrical and Computer Engineering, vol. 7, no. 2, pp. 650–658, 2017, doi: 10.11591/ijece.v7i2.pp650-658.
19. [19] A. Dhyani, P. K. Singh, R. Chopra, and M. Garg, "Enhancement of Oxidative Stability of Perilla Seed Oil by Blending It with Other Vegetable Oils," J Oleo Sci, vol. 71, no. 8, pp. 1135–1144, 2022, doi: 10.5650/jos.ess22013. 20. [20] D. Kmiecik, M. Fedko, A. Siger, and P. Ł. Kowalczewski, "Nutritional Quality and Oxidative Stability during Thermal Processing of Cold-Pressed Oil Blends with 5:1 Ratio of ω6/ω3 Fatty Acids," Foods, vol. 11, no. 8, Apr. 2022, doi: 10.3390/foods11081081.
21. [21] A. Dhyani, R. Chopra, P. K. Singh, and M. Garg, "Palm olein and perilla seed oil blends for the improvement of nutritional and thermal stability," Grasas y Aceites, vol. 74, no. 3, Jul. 2023, doi: 10.3989/gya.0220221. 22. [22] Midlands, "The Science Behind Cold-Pressed Flaxseed Oil: Why It Matters for Manufacturers," Nutrition. [Online]. Available: https://www.midlandsnz.com/the-science-behind-cold-pressed-flaxseed-oil-why-it-matters-formanufacturers
23. [23] L. Sarmiento, "Linum usitatissimum: Properties, Benefits, Uses and Cultivation of Flax or Linseed." [Online]. Available: https://en.jardineriaon.com/very-common-flax.html
24. [24] Z. Amini, A. Azizian, and A. Eyvazi, "Nutritional and Chemical Properties of Cold-Pressed Flaxseed Oil Compared to Solvent-Extracted Oil," 2025. [Online]. Available: www.mkscienceset.com
25. [25] J. Yang et al., "The composition, extraction, analysis, bioactivities, bioavailability and applications in food system of flaxseed (Linum usitatissimum L.) oil: A review," Dec. 01, 2021, Elsevier Ltd. doi: 10.1016/j.tifs.2021.09.025.
26. [26] P. M. Divya, B. S. Roopa, C. Manusha, and P. Balannara, "A concise review on oil extraction methods, nutritional and therapeutic role of coconut products," Feb. 01, 2023, Springer. doi: 10.1007/s13197-022-05352-0. 27. [27] E. Subroto, V. P. Yarlina, A. P. Ramadhani, and A. Din Pangawikan, "The Extraction, Purification, and the Recent Applications of Coconut Oil in Food Products-A Review," Article in International Journal of Emerging Technologies in Learning (iJET), vol. 11, no. 5, pp. 234–240, 2021, [Online]. Available: https://www.researchgate.net/publication/350042656
28. [28] J. Carlos, O. Santos, J. Santos Martins, and M. Maria Da Conceição, "Thermoanalytical Study of Coconut Oil (Cocosnucifera L.)," IOSR Journal of Applied Chemistry (IOSR-JAC, vol. 15, no. 7, pp. 60–68, 2022, doi: 10.9790/5736-1507016068.
29. [29] ASTM D3612-02, "Standard Test Method for Analysis of Gases Dissolved in Electrical Insulating Oil by Gas Chromatography 1."
30. [30] Doble Engineering Company, "Myrkos: Portable dissolved gas analyzer." [Online]. Available: Myrkos - Doble Engineering Company
31. [31] IEC 60567 INTERNATIONAL STANDARD NORME INTERNATIONALE Oil-filled electrical equipment-Sampling of free gases and analysis of free and dissolved gases in mineral oils and other insulating liquidsGuidance Matériels électriques immergés-Échantillonnage de gaz libres et analyse des gaz libres et dissous dans les huiles minérales et d'autres liquides isolants-Recommandations. 2023. [Online]. Available: www.iec.ch
32. [32] IEEE guide for the interpretation of gases generated in oil-immersed transformers. Institute of Electrical and Electronics Engineers, 1992.
33. [33] A. S. Pillai and A. Linsely, "Effect of copper as a catalyst on the dielectric properties of insulating oils used in transformers," International Journal of Advanced Manufacturing Technology, vol. 130, no. 1–2, pp. 147–162, Jan. 2024, doi: 10.1007/s00170-023-12475-x.
34. [34] "IEC-60599-2022". Mineral oil-filled electrical equipment in service - Guidance on the of dissolved and free gases analysis
35. [35] D. Com, "Guide for Interpreting Dissolved Gases in Liquid-filled Transformers."
36. [36] B. Nouri and M. Ojaghi, "Power Transformer Fault Diagnosis via Gas Chromatography: A Comprehensive Review of Techniques and Standards," vol. 2, no. 4, pp. 17–29, 2022, doi: 10.30503/EECS.2024.479067.1061.
37. [37] Y. F. Shi, S. Ma, and Z. P. Liu, "Copper-based catalysts for CO2 hydrogenation: a perspective on active sites," EES Catalysis, vol. 1, no. 6, pp. 921–933, Nov. 2023, doi: 10.1039/d3ey00152k.
38. [38] S. Randhawa and T. Mukherjee, "Effect of Copper and Iron on the oxidation of vegetable oil During Aging," Journal of Food Composition and Analysis, vol. 143(11), no. 107575, Apr. 2025, doi: https://doi.org/10.1016/j.jfca.2025.107575.
39. [39] X. Hu, H. Cong, X. Zhang, Y. Wang, Y. Du, and Q. Li, "Catalytic Effects of Iron and Copper on Degradation of Natural Esters at Different Temperatures," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 32, no. 1, pp. 342–348, Feb. 2025, doi:10.1109/TDEI.2024.3460732.
40. [40] I. S. Chairul, S. A. Ghani, M. S. A. Khiar, N. A. Bakar, M. S. Johal, and M. N. M. Din, "Effects of DBDS and DBPC antioxidants on the corrosion of copper strips immersed in transformer oil," Bulletin of Electrical Engineering and Informatics, vol. 13, no. 5, pp. 3043–3050, Oct. 2024, doi: 10.11591/eei.v13i5.8196.

41. [41] N. Zimmerman and R. Bass, “Consideration of Ester-Based Oils as Replacements for Transformer Mineral Oil Portland General Electric,” 2014. [Online]. Available: www.pdx.edu/power-lab/