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Oxidation Stability Analysis of Eco-Friendly Sunflower and Corn Oil Doped With Antioxidants

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ABSTRACT

An increasing amount of attention in investigating the substitutes for hydrocarbon-based transformer liquid insulation has been observed lately. Vegetable oils have become crucial in this field, offering a chance to support developing countries' sustainable economic progress. The main source of raw materials for the manufacturing of vegetable oils is natural feedstocks. The properties of these natural feedstocks are fundamental in characterizing the quality of vegetable oils. Interestingly, such oils often exhibit limited oxidative stability, which can cause oxidation-related alterations in some parameters, including viscosity and acid number. Hence, antioxidants must be added in order to offset these negative effects. In this paper, among the many antioxidants, tert-butylhydroquinone (TBHQ) and butylated hydroxy toluene (BHT) are blended with two representatives of vegetable oils namely sunflower oil and corn oil. Acidity, dielectric dissipation factor, viscosity, and ultraviolet-visible spectrum are the properties analyzed at different aging durations accelerated thermally. The results clearly indicate that the antioxidants slow down the oxidation process and decrease the amount of by-products due to oxidation.

Index Terms—Aging, antioxidants, liquid insulation, oxidation stability, vegetable oils

I. INTRODUCTION

Mineral oil has conventionally been utilized in transformers as a material of great cooling and insulation properties. Nevertheless, the electrical power industry is currently scrutinizing them for various reasons. Firstly, doubts about their thermal performance have arisen due to their relatively low flash and fire points, rendering them susceptible to ignition in the event of a fault. Secondly, environmental concerns emerge as mineral oils exhibit low levels of biodegradability, and high toxicity, and pose hazards to soil and water. Additionally, issues related to risk assessment are prominent, particularly in areas close to hospitals, high-rise buildings, and residential zones. The cost of mineral-insulating oils has also experienced an increase over the past 15 years [1, 2].

The industry has encountered fire incidents in power transformers due to heightened operating temperatures resulting from heavy loads. This has caused significant financial and asset damage, necessitating the implementation of failure risk assessment and asset management. The escalated operating temperatures in transformers contribute to the accelerated deterioration of oil-paper insulation, leading to a reduced lifespan. In response to these challenges, professionals from both the industry and academia are actively exploring alternatives to mineral oils. The ideal substitute should demonstrate superior thermal performance, enhance transformer lifespan, and provide an optimal assessment of the total cost of ownership. This pursuit is motivated by the goal of addressing the drawbacks of mineral oils and improving the safety, environmental impact, and cost-effectiveness of transformer systems [1-5].

Vegetable oil-based insulating liquids, in addition to fulfilling the dielectric and cooling requirements of transformers, present several advantages over mineral oils. This is primarily due to their biodegradability, higher fire points, and origin from renewable sources. The specifications for insulating liquids vary depending on the type of electrical equipment and encompass fundamental dielectric and physicochemical properties essential for insulation, efficient cooling, and long-term stability. The enduring stability of insulating fluids is a consequence of factors such as thermal endurance, hydrolytic stability, oxidation stability, and compatibility with other materials used in transformers. The primary mechanism for the degradation of vegetable oils is oxidation. Oxidation stability of liquid insulation refers to the ability of the insulating material to resist or withstand oxidation over time. Oxidation is a chemical reaction that involves the loss of electrons or an increase in the oxidation state of a substance. In the context of liquid insulation, oxidation stability is crucial because oxidation processes can lead to the formation of undesirable by-products, such as free radicals, sludge, acids, and other compounds, which can negatively impact the performance and longevity of electrical equipment. The formation process of free radicals and other by-products in vegetable oils is shown schematically in Fig. 1. Hence, the commonly accepted challenge is to seek ways to improve vegetable oil oxidation stability [2, 4, 6-8].

The main method to enhance the oxidation stability of dielectric liquids, but also other liquid types such as lubricants, is to add specific types of antioxidants [9-11]. These additives may help in the neutralization of free radicals and prevent or slow down oxidation reactions. In various studies on liquid dielectrics, synthetic antioxidants, and synergists, among various types of antioxidants, exhibit superior oxidative stability following their incorporation into insulating oils [12, 13]. There are two types of actions that antioxidants exhibit when they scavenge radicals. The first is to act as a donor while the second is to act as an acceptor. In order to restore the free radical to

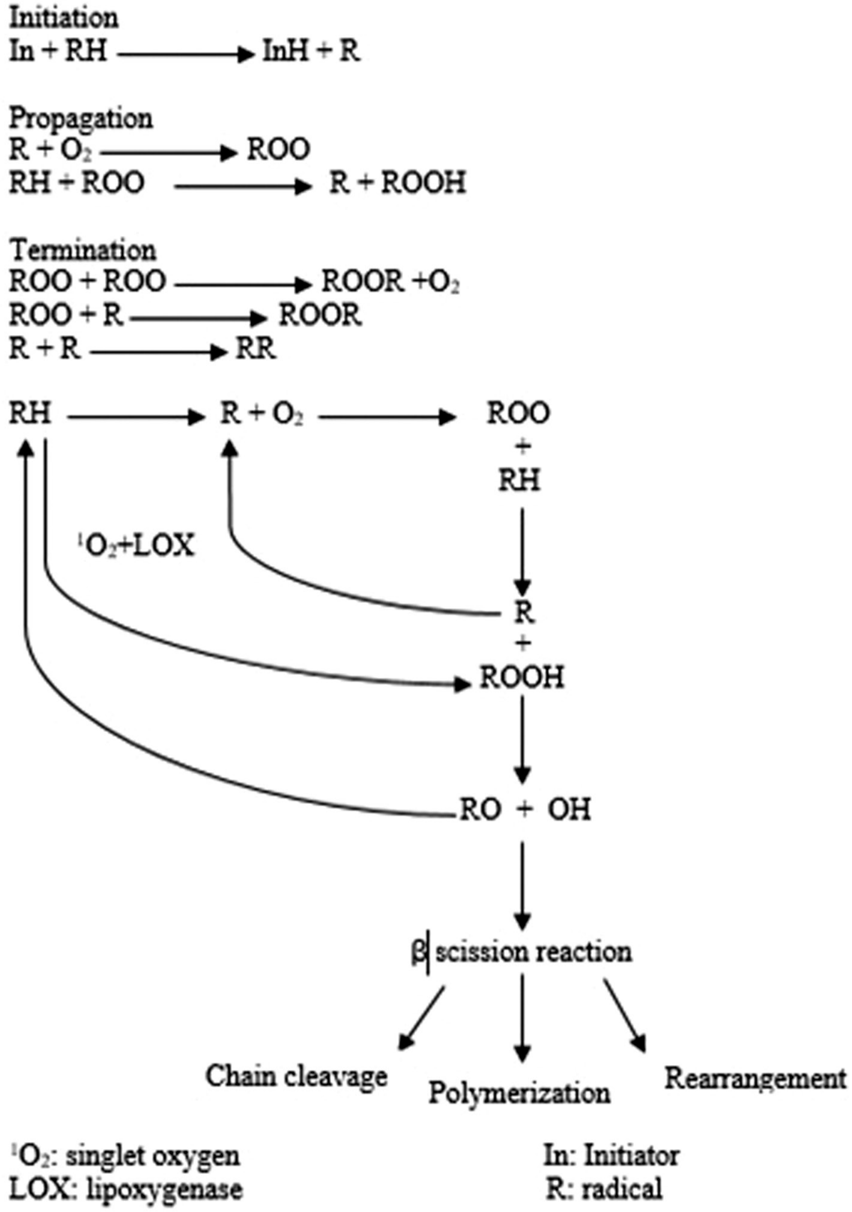


Fig. 1. Vegetable oils' chain reaction process.

its initial oil structure, the donor provides hydrogen, which is typically uncertainly linked to the carbon of the free radical in the oil structure. What the acceptor has to do is pick up the free radicals to create stable chemical compounds. Primary oxidation products may give rise to secondary oxidation products such as alcohols, ketones, aldehydes, and so forth.

When comes to details, Wilhelm et al [14] studied the antioxidant consumption level in natural ester under aging conditions by analyzing the induction time and Fourier-transform infrared spectroscopy. The results indicated that the addition of antioxidants enhances the lifespan of natural ester. Yang Xu et al [15] concentrated on evaluating the oxidation stability of vegetable oil through accelerated thermal aging at 110°C for up to 2500 hours. The oil samples underwent aging in both open and sealed conditions to simulate the oxidation process. Several parameters, including acidity, dielectric dissipation factor, DC conductivity, and viscosity, were measured to observe their reactions to the oxidation process of the vegetable oil. Karthik et al [16] analyzed properties such as breakdown voltage, acidity, interfacial tension, viscosity, water content, flash point, and fire point of corn oil, mustard oil, rice bran oil, and soybean oil with and without the addition of propyl gallate antioxidant. Miadonye et al [17] examined the relationship between spectroscopic data readings of AireSun Global transformer oil filled with vegetable oil and the kinematic viscosity, acid value, peroxide value, and oxidation stability data. They further employed well-recognized methods to empirically determine these quality characteristics. The study demonstrates how useful it is to integrate spectroscopic data to comprehend trends in the kinematic viscosity and induction time of oil specimens under transformer operating conditions. S.O. Oparanti et al [18] studied the possibilities, potential uses, and future improvements of canola oil. This study provides tutorial components and a few analyses to enhance understanding. Furthermore, it exposed the hidden qualities of canola oil as an effective cooling medium for transformers operating in extremely cold conditions and as an appropriate insulating liquid for both hermetically sealed and free-breathing transformers.

From the literature analysis, it is evident that there is a gap in analyzing the oxidation stability of vegetable oils with antioxidants under accelerated aging conditions, especially the oils that are new proposals for development in the transformer industry. Hence, in this work, vegetable oils namely sunflower oil (SO) and corn oil (CO) are mixed with synthetic antioxidants like BHT and tert-butylhydroquinone (TBHQ) at different volume fractions. The choice of the synthetic antioxidants mentioned is due to their thermal stability, effectiveness in scavenging radicals, and commercial accessibility. Although these substances are widely utilized in the petrochemical and food industries, little is known about how they can be employed in electrical insulation, especially when exposed to high temperatures. The studies are performed under aging at 120˚C for up to 60 days. Selected parameters, which are indicators of aging (oxidation), such as acidity, conductivity, viscosity, and ultraviolet spectroscopy, were examined. Moreover, antioxidant consumption and the formation of dissolved decay products are analyzed to validate the assessment of oxidation stability.

II. MATERIALS AND SAMPLE PREPARATION

The substances identified as antioxidants are used to resist the oxidation process. By capturing the free radicals that are free or free electrons that exist in the oil, the antioxidant carries out the electron scavenging process. By completely stopping the chain reaction, the quantity of free radicals is reduced to a minimum level, preventing oil oxidation and the production of peroxide. Metal chelation, synergism, and free electron scavenging are the three primary functional mechanisms of antioxidants. Antioxidant performances differ at normal and higher temperatures, but in general, the composition of antioxidants is reduced relative to their real quantity.

Table I lists the various antioxidants that are used in the study. When sludges, metal impurities, and other foreign materials are present in the oil, antioxidants can help the oil remain more stable. Based on the source and mode of action, antioxidants can be broadly divided into three groups: synergists, secondary antioxidants, and natural antioxidants. Alpha tocopherol (α-T) belongs to the natural type of antioxidants, which perform a synergistic mechanism, whereas the primary antioxidants, such as BHT, butylated hydroxy anisole (BHA), and propyl gallate (PG), are the synthetic type with function mechanisms such as free radical scavenging and metal chelation process. Similar to this, the secondary antioxidants that carry out the synergistic action, such as citric acid (CA) and ascorbic acid (AA), come from natural sources [19, 20].

The liquids tested within the studies are SO and CO, which are sourced from one of the rural natural ester oil manufacturers in India, where the availability of raw materials boosts the sunflower and corn-based natural ester oil production in this region. Generally, the oils tested, as all vegetable oils, contain saturated and unsaturated fatty acids. Hence, the performance of the vegetable oils is forced by their fatty acid content. The oils with higher amounts of saturated fatty acids are chemically stable and have higher viscosity. Further, vegetable oils with higher amounts of unsaturated fatty acids are chemically unstable and have lower viscosity. The fatty acid contents of SO and CO considered within this study are shown in Table II.

The required amount (1 liter for each sample) of fresh SO and CO are filtered with the use of Whatman paper to remove undesirable particles. Further, the oils are taken in glass containers and heated for up to 12 hours at 100°C in a vacuum chamber to reduce the water content in oils. After the thermal treatment, the water content of SO and CO oil samples reduced to 21.4 ppm and 25.6 ppm, respectively. The physicochemical properties of fresh SO and CO oils are given in Table III.

TABLE I. ANTIOXIDANTS TYPE AND MECHANISM

Antioxidant	Mechanism	Type
TBHQ	Free radical scavenger	Synthetic
BHT	Free radical scavenger	Synthetic
BHA	Free radical scavenger	Synthetic
PG	Metal chelators	Synthetic
CA	Synergist	Natural
AA	Synergist	Natural
α-T	Regenerators of scavengers	Natural

AA, ascorbic acid; BHA, butylated hydroxy anisole; BHT, butylated hydroxy toluene; CA, citric acid; PG, propyl gallate; TBHQ, tert-butylhydroquinone; α-T, alpha tocopherol.

TABLE II. FATTY ACID COMPOSITION OF OILS

Oil	Saturated Fatty Acids (%)	Monounsaturated Fatty Acids (%)	Polyunsaturated Fatty Acids (%)
Sunflower oil	10	34	56
Corn oil	17	24	59

The uncoated copper bar of 0.10 cm^2 surface area and 10 g of Kraft paper are made up and identified as a winding strip. Subsequently, two of these winding strips underwent a 12-hour heating process at 100°C in an air-circulating oven to eliminate moisture from the Kraft paper. The desiccated winding strips are immersed in glass containers containing SO and CO samples for blending of antioxidants and for aging processes, respectively.

To examine the efficacy of the presence of antioxidants in vegetable oils, the SO and CO oil samples are blended with varying particle volume fractions (0.25%, 0.5%, and 1%) of TBHQ and BHT antioxidants. This blending process was done using magnetic stirring and an ultrasonication process at 70°C for improved dispersion as it is typically done for nanosized additives [21, 22]. The samples prepared for this work are given in Table IV.

TABLE IV. OIL SAMPLES PREPARED

Sample Label	Description	Sample Label	Description
SO1	FSO	CO1	FCO
SO2	SO + 0.1% TBHQ	CO2	CO + 0.1% TBHQ
SO3	SO + 0.2% TBHQ	CO3	CO + 0.2% TBHQ
SO4	SO + 0.3% TBHQ	CO4	CO + 0.3% BHQ
SO5	SO + 0.1% BHT	CO5	CO + 0.1% BHT
SO6	SO + 0.2% BHT	CO6	CO + 0.2% BHT
SO7	SO + 0.3% BHT	CO7	CO + 0.3% BHT

A. Aging Procedure and Testing Methods

The SO and CO samples prepared underwent an accelerated aging test. The samples are carried in sealed glass containers and are heated to 120°C for up to 60 days in an oven without flowing oxygen. For the aged oil samples, acidity, viscosity, dissipation factor, and ultraviolet spectroscopy are assessed on 10-day intervals (10, 20, 30, 40, 50, and 60 days). The oxidation process begins when liquid insulation is exposed to heat stress in the existence of copper. As a result, the acid content of the liquid insulation rises, which lowers the liquid insulation performance and may even lead to their failure. As per the IEC 62021standard [23], the acidity of liquid insulation are evaluated. The ratio of active power to reactive power is shown by the dielectric dissipation factor, while the power loss resulting from polarization and conductivity makes up active power. Tests for the oxidation stability of insulating oil samples have utilized dielectric dissipation factor, acidity, and sludge as criteria. The dielectric dissipation factor (DDF) was measured at 90°C as per the IEC 60247 standard [24]. The resistance of insulating oil to flow or distortion under applied stress is referred to as its viscosity. It is an important characteristic that affects how well the oil performs in electrical equipment, especially power transformers. Insulating oil viscosity is tested at a certain temperature, usually between 40°C and 100°C, and is represented in millipascal-seconds (mPa•s) or centistokes (cSt) units. Herein, viscosity is measured at 40°C using Redwood Viscometer as per the ASTM D7945-21a [25]. The performance of 60-day aged oil samples is shown in Table V for comparison. Absorption spectroscopy in the ultraviolet-visible spectral band is referred to as ultraviolet spectroscopy. This means that oil absorption is an indicator of wavelength which is measured using light in the visible, near-UV, and near-infrared ranges. This means that the method helps to identify oxidation and deterioration byproducts of insulating oils because the change of the absorbance curve to longer wavelengths shows a rising amount of dissolved decay products. There is a connection between the total quantity

TABLE III. PHYSIOCHEMICAL PROPERTIES OF FRESH SUNFLOWER OIL AND FRESH CORN OIL

Properties	FSO	FCO
Breakdown voltage (kV)	62.4	56.2
Acidity (mg KOH/g)	0.0612	0.0854
Water content (ppm)	21.4	25.6
Dielectric dissipation factor at 90 ºC (–)	2.62	2.84
Viscosity at 40ºC (cSt)	48.6	42.4
Flash point (°C)	310	305
Fire point (°C)	332	324

FCO, fresh corn oil; FSO, fresh sunflower oil.

TABLE V. COMPARISON OF 60-DAY AGED OIL SAMPLES PERFORMANCE

Sample Label	Acidity	DDF	Viscosity
SO1	1.321	3.64	66.5
SO2	1.12	3.52	63
SO3	0.98	3.2	61.6
SO4	0.75	3.02	59
SO5	1.24	3.5	63.5
SO6	1.09	3.3	62
SO7	0.85	3.1	60
CO1	1.3	4.45	70.4
CO2	0.9	4.32	68.6
CO3	0.624	4.2	66.2
CO4	0.412	4.1	64.8
CO5	0.93	4.3	69.5
CO6	0.7	4.24	67.5
CO7	0.464	4.15	64

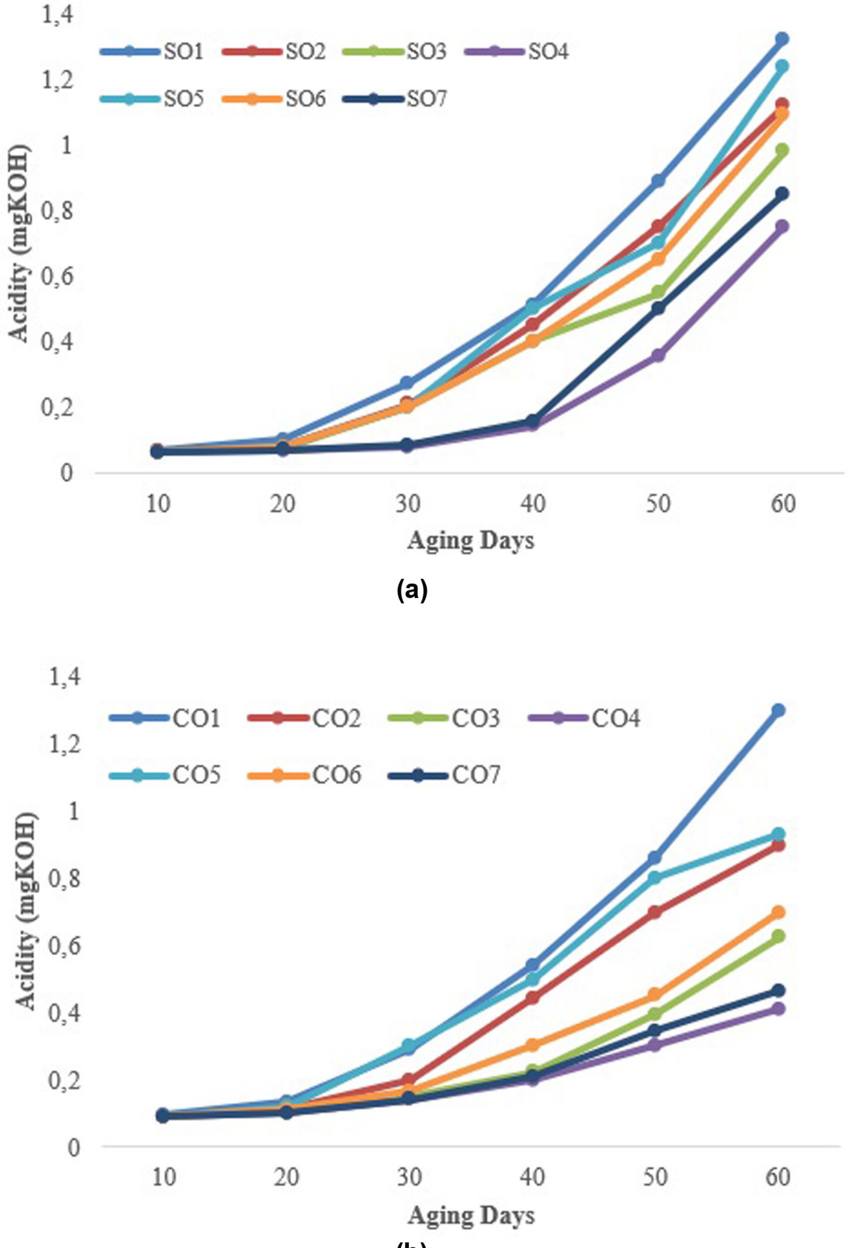
DDF, dielectric dissipation factor.

of dissolved degradation products in the oil and the area over the absorbance curve.

III. RESULTS

Fig. 2 illustrates the results of the acidity value for all the conditions of the studies. It is seen from this figure that all the oil samples exhibit an increasing tendency to age, while the acid values of the pure oil samples peak at every stage of aging. Regarding the unaged state, the acidity of the pure and antioxidant blended samples is consistent in every instance. For the 10-day aged samples also reported almost similar trends. With the increase in aging, there is a notable difference between pure and antioxidants blended samples are recorded. When comparing the acidity of 60-day aged pure SO and CO samples with antioxidants blended SO and CO samples, the rate of rise in acid content is higher in pure oil samples at every instance. When comparing the performance of antioxidants, TBHQ blended oil samples have lesser acidity than BHT blended oil samples. Moreover, the particle volume ratio has an impact on acidity of oil samples. With the increase in particle volume ratio acidity of both SO and CO oil samples gets reduced.

Acids, alcohols, and peroxides are formed in considerable numbers when the antioxidants are absent. Additionally, as the acidity increases, the contaminated particles dissolved in the oil samples increase, which leads to an increase in dielectric losses and decreasing resistivity. During the oxidation process, organic long-chain fatty acids are created. These long-chain fatty acids produced in



(a)

(b)

Fig. 2. Acidity of pure and antioxidants blended sunflower oil (a) and corn oil (b) samples at different aging periods.

SO and CO samples do not aggressively affect insulating materials. Remarkably, natural esters under thermal aging conditions have a larger acid content than mineral oil, according to [26]. It is summarized that because of a decline in the free radical chain process, pure vegetable oil samples have larger acid contents than antioxidant blended oil samples.

The DDF, conductivity, and relative permittivity of a material determine its dielectric characteristics. Dipolar interactions and ionic conduction are the major processes that lead to the dissipation of electromagnetic energy, further modifying the DDF in the contents. When utilizing an electric field, the interactions among ions and dipoles produce both intra- and intermolecular friction. This generates heat throughout the material's total volume [27]. The results concerning the DDF are shown in Fig. 3. At the unaged and 10-day aged conditions, there are not many variations in both the pure and antioxidants blended oil samples. Once the aging continued, the dissipation factor of the 60-day aged oil samples increased to a maximum of 28% for the SO sample and 36% for the CO sample. Similarly, the acidity of unaged and 10-day-aged oil samples is almost the same. However, for the 60-day-aged oil samples, the acidity increased to a maximum of 95% for SO and 93% for CO.

While comparing the TBHQ and BHT antioxidants' performance, TBHQ blended oil samples have a lesser dissipation factor than the BHT blended oil samples. In addition, with the increase in particle volume ratio, the dissipation factor of both SO and CO oil samples gets reduced.

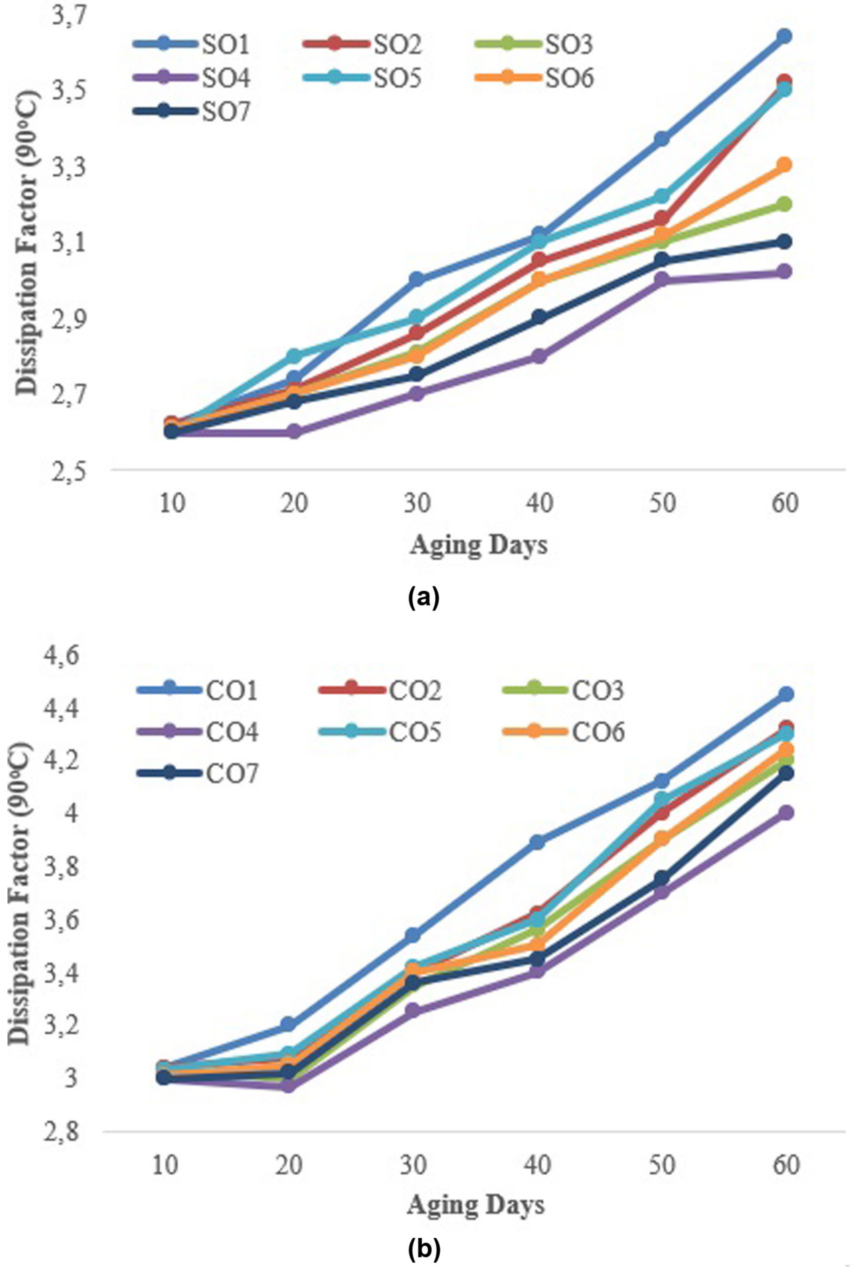


Fig. 3. Dielectric dissipation factor of pure and antioxidants blended sunflower oil and corn oil samples at different aging periods.

The DDF in ester-based insulation liquid is determined by molecular weight, which is mostly influenced by the fatty acid profiles of the individual esters (triglycerides). SO and CO have molecular weights of 872.33 g/mol and 887.04 g/mol, respectively [28]. It is clear that the molecular weight of CO samples is slightly higher than that of SO samples. Higher quantities of hydrogen bonds are being created. Higher heat energy is produced as a result of increased intermolecular contact, which raises the dielectric dissipation factor.

In contrast to pure samples, antioxidant blended oil samples have a lesser dielectric dissipation factor. An increased DDF value indicates the presence of oxidation-related contamination in oil samples. Generally, resistivity and dielectric dissipation factors are related because similar substances have an impact on both of these characteristics.

The viscosity of vegetable oils is generally high due to their specific chemical compositions (triglycerides, glycerol, and fatty acid chains) and molecular structures. Moreover, vegetable oils often contain a higher proportion of unsaturated fatty acids. Unsaturated fatty acids have double bonds in their carbon chains, introducing kinks and bends in the molecular structure. These kinks hinder the close packing of molecules, resulting in higher viscosity [29]. The unaged SO and CO oil samples are high due to the above reasons. In the pure and antioxidant blended samples with copper catalyst, oxidation occurs in response to heat stress and the viscosity rises as a result. In antioxidants blended oil samples, antioxidants are essential since they slow down the oxidation mechanism and cause the viscosity to drop compared to the pure oil samples, as seen in Fig. 4. Among TBHQ and BHT antioxidants, TBHQ antioxidants slow down the viscosity increase rate compared to BHT.

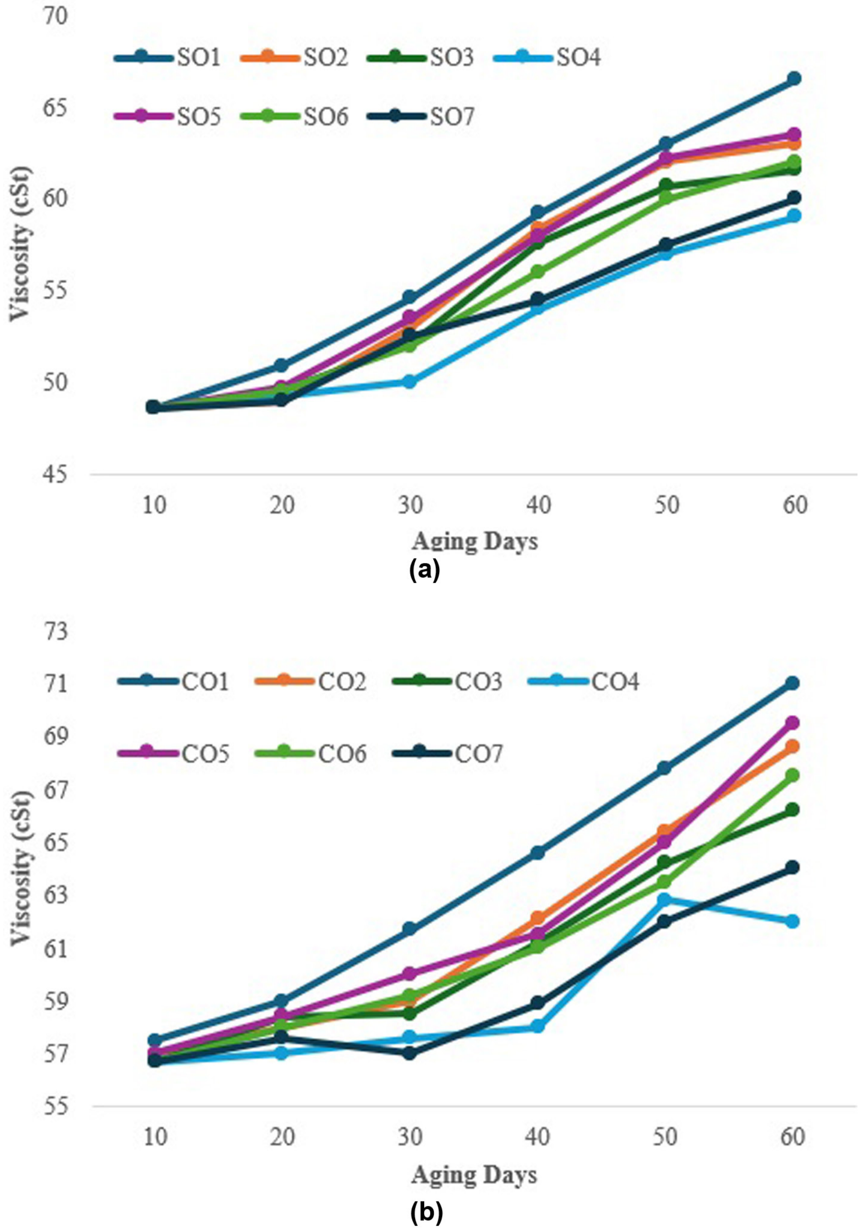


Fig. 4. Viscosity of pure and antioxidants blended sunflower oil and corn oil samples at different aging periods.

Fresh oil samples typically exhibit transparency to monochromatic light in the ultraviolet-visible (UV/Vis) spectrum. As the relative content of dissolved decay products increases, the absorbance curve undergoes a shift towards longer wavelengths. Dissolved decay products found in insulating oils consist of a variety of substances such as acids, peroxides, ketones, and aldehydes. These substances are partially adsorbed on the extensive surface of the insulating paper, contributing to the power transformers' premature aging. Therefore, the detection of by-products in insulating oil serves as an indicator of oil aging [30].

The ultraviolet-visible (UV/Vis) spectrum proves to be a valuable technique for assessing dissolved decay products in oil samples. The quantitative measurement of the content of these decay products is determined by analyzing the integral of the area beneath the absorbance curve. In Fig. 5A-G, the trend of UV/Vis absorbance for both SO and CO oil samples at the different aging days is displayed as a function of wavelength.

The fresh SO and CO oil samples (without antioxidants) displayed almost similar absorbance responses as shown in Fig. 5A. In the 10 days-aged pure and antioxidants blended oil samples, slight differences in absorbance values are noted as shown in Fig. 5B and C. When the samples are aged (50 and 60 days) as shown in Fig. 5D-E, the increase in absorbance is slow for higher concentrations of antioxidant blends. For the pure and lower antioxidant concentration blends, a drastic increase in absorbance values is recorded.

The absorbance curve is shown to change as aging days rise, and the area across the curves that results from this shift also rapidly increases, suggesting that pure SO and CO oil samples' degradation is accelerating. The antioxidants blended SO and CO oil samples have a reduced area under the absorbance curve, indicating their efficacy in delaying the pace at which pure oil samples degrade.

IV. DISCUSSION

Vegetable oils are protected from the oxidation process by the antioxidants TBHQ and BHT blended with the SO and CO oil samples at various volume fractions. The antioxidants blended with oil samples are able to reduce harmful free radicals by neutralizing the free radicals and breaking the cycles that cause oxidative deterioration. There are three basic steps of the free radical oxidation mechanism as shown earlier in Fig. 1 likely initiation, propagation, and termination—that are commonly seen in lipid-containing systems, such as vegetable oils. An initiator (In) combines with a lipid molecule (RH [Alkyl group + Hydrogen]) during initiation, abstracting a hydrogen atom and producing a free radical (R•). The chain reaction continues during the propagation phase when the lipid radical combines with molecular oxygen (O_2) to generate a peroxyl radical (ROO•), which then combines with another RH to generate hydroperoxide (ROOH) and yet another radical. In the termination stage, radicals are neutralized using different combinations, like ROO• + ROO• or R• + R•, to produce non-radical products, such as ROOR (organic peroxides) or RR (aryl groups), which stop the chain reaction. Alternative routes involving lipoxygenase (LOX) and singlet oxygen ($^1O_2$) that produce radicals via enzymatic or photochemical reactions are also depicted in Fig. 1. RH to generate hydroperoxide can break down into hydroxyl (OH•) and alkoxyl (RO•) radicals, which can then proceed via β-scission and cause molecular rearrangement, polymerization, or chain breakage. The structural disintegration and quality

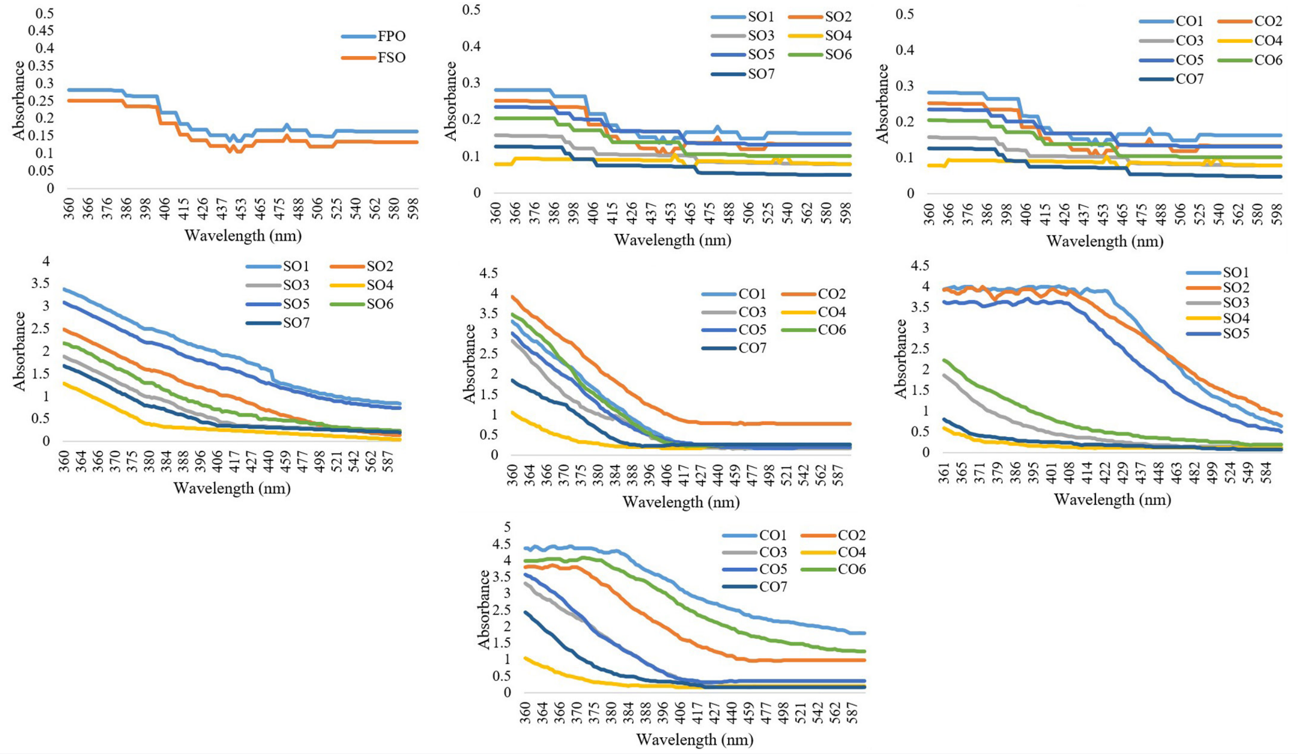


Fig. 5. Ultraviolet-visible spectrum of pure and antioxidants blended sunflower oil (SO) and corn oil (CO) samples at different aging periods: (a) Fresh SO and CO, (b) 10-day aged SO, (c) 10-day aged CO, (d) 50-day aged SO, (e) 50-day aged CO, (f) 60-day aged SO and (g) 60-day aged CO.

deterioration in oils during oxidative stress are largely explained by these secondary degradation mechanisms.

The formation of free radicals is the first sign of the oxidation process in vegetable oils, and antioxidants prevent them from forming. Free radicals have the potential to produce more reactive substances and accelerate the deterioration process of vegetable oils. Moreover, vegetable oils' unsaturated fatty acids have double bonds that can break down due to a chain reaction in which free radicals can start and spread. Free radicals are stabilized by antioxidants by giving them hydrogen and turning them into more stable compounds, which protect the structural strength of fatty acid chains and stop them from interacting with other molecules in the oil. Moreover, they can react with lipid radicals to produce lipid-antioxidant complexes. By interacting via a lipid-free radical, they can possibly postpone or impede the initiation stage, or they can hinder the propagation process by interacting with an alkoxy or peroxy radical. Through this process, antioxidants slow down the oxidation process overall, by preventing peroxides, acids, and dissolved decay products from forming in the first place. Certain antioxidants can chelate, or bind, to metal ions, like iron or copper, which can function as oxidation catalysts. Antioxidants prevent these metal ions from contributing to the promotion of oxidative processes in vegetable oil by hiding them.

Since the aging has begun, the amount of antioxidants in the oil samples has gradually decreased, while the acidity value varies at a low level, suggesting a sluggish creation. Continuous antioxidant reduction causes the acidity value to rapidly increase after 20 days of aging. This is followed by the production of dissolved decay products, which is demonstrated by an increase in decay products at 30 days of aging. Slow acidity generation is transitioning to fast generation mode. The acidity value peaks at 60 days of aging, when the antioxidant is virtually completely consumed. Generally, TBHQ is a white, crystalline powder that forms no compounds with copper and iron ions like gallate and is only weakly soluble in oils and fats. In comparison to BHT, it is usually thought to be more efficient in vegetable oils. Hence, the TBHQ blended oil samples perform better than the BHT blended oil samples.

Esters can engage in hydrogen bonding as hydrogen-bond acceptors, which gives them water solubility. In addition to being more soluble in water, SO and CO oils will hydrolyze at a faster rate and absorb more moisture in the process. The creation of long-chain fatty acids is the result of this process. As a result, the SO and CO samples' acid numbers will increase since a greater acid number denotes an amount of dryness that keeps Kraft paper dry, which lowers the rate at which the cellulose and oil deteriorate.

With the increase in acidity and dissolved decay products due to the increase in aging, have an impact on the DDF and viscosity of both pure and antioxidants blended SO and CO oil samples.

A significant production of decay products is indicated by the absorbance of the UV-vis spectrum. With the increase in aging duration, acids dominate over generation. This causes a further increase of decay products, indicated by area under the absorbance curve. There is a correlation between the total quantity of dissolved decay products in the oil samples and the area under the absorbance curve due to oxidation or aging of the oil. The analysis of each test sample's area under the curve yields the degradation trending rate.

V. CONCLUSION

The impact of tert-butylhydroquinone (TBHQ) and BHT antioxidants at different volume fractions (0.25%, 0.5%, and 1%) on SO and CO are analyzed under accelerated aging (120°C) condition up to 60 days. Acidity, dielectric dissipation factor, viscosity, and ultraviolet-visible spectrum are the properties measured at every 10 days and the investigated results are summarized.

When comparing the pure SO and CO samples and antioxidants blended SO and CO samples, the degradation rate of antioxidants blended natural ester oils properties like acidity, dielectric dissipation factor, viscosity, and ultraviolet-visible spectrum are less. Hence, the oxidation process and its by-products like peroxides, water, and dissolved decay products cause an increase in the acidity, dielectric dissipation factor, and viscosity of pure SO and CO samples. In turn, the case of U-V spectrum results clearly illustrate that the antioxidants blended SO and CO samples degradation activity is lesser than pure SO and CO samples. This evidently shows that the presence of antioxidants slows down the oxidation process and decreases the amount of created by-products.

With an increase in antioxidant particle volume concentration, the degradation rate of SO and CO samples above-mentioned properties slows down and the oxidation stability of SO and CO samples gets improved. Among antioxidants, the TBHQ antioxidant blended oil samples degradation rate is slightly lesser than the BHT antioxidant blended oil samples. The vegetable oils work with current insulation materials, especially cellulose-based paper, where chemical reactions over time may change insulation effectiveness. Furthermore, over long operating times, the dielectric strength and cooling efficiency may be impacted by the viscosity and moisture absorption properties of natural esters. Their performance under dynamic load settings presents another difficulty, as varying electrical and thermal stress may hasten degradation in a different way than under steady-state circumstances.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – M.R., P.R.; Supervision – P.R.; Materials – M.R.; Data Collection and/or Processing – M.R.; Analysis and/or Interpretation – M.R., P.R.; Literature Search – M.R., P.R.; Writing – M.R., P.R.; Critical Review – P.R.

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REFERENCES

1. I. Fernández, A. Ortiz, F. Delgado, C. Renedo, and S. Pérez, "Comparative evaluation of alternative fluids for power transformers," *Electr. Power Syst. Res.*, vol. 98, pp. 58–69, 2013. [CrossRef]
2. P. Rozga et. al., "Next-generation ester dielectric liquids: Some key findings and perspectives," *IEEE Electr. Insul. Mag.*, vol. 40, no. 5, pp. 23–35, 2024. [CrossRef]
3. P. Rozga, A. Beroual, P. Przybylek, M. Jaroszewski, and K. Strzelecki, "A review of synthetic ester liquids for transformer applications, Energies," *Energies*, vol. 13, no. 23, p. 6429, 2020. [CrossRef]
4. Z. Shen, F. Wang, Z. Wang, and J. Li, "A critical review of plant-based insulating fluids for transformer: 30-year development," *Renew. Sustain. Energy Rev.*, vol. 141, 110783, 2021. [CrossRef]
5. C. Perrier, and A. Beroual, "Experimental investigations on insulating liquids for power transformers:mMineral, ester, and silicone oils," *IEEE Electr. Insul. Mag.*, vol. 25, no. 6, pp. 6–13, 2009. [CrossRef]

6. *CIGRE Working Group D1.30 - Oxidation Stability of Insulating Fluids*, No. 526, 2013.
7. U. M. Mohan Rao, Y. R. Sood, and R. K. Jarial, "Oxidation stability enhancement of a blend of mineral and synthetic ester oils," *IEEE Electr. Insul. Mag.*, vol. 32, no. 2, pp. 43–47, 2016. [CrossRef]
8. D. Szczesniak, and P. Przybylek, "Oxidation stability of natural ester modified by means of fullerene nanoparticles," *Energies*, vol. 14, no. 2, p. 490, 2021. [CrossRef]
9. S. R. Valantina, and P. Neelamegam, "Antioxidant potential in vegetable oil, Research," *J. Chem. Environ.*, vol. 16, pp. 87–94, 2012.
10. S. C. Lourenco, M. Moldao-Martins, and V.D. Alves, "Antioxidants of natural plant origins: From sources to food industry applications, Molecules," vol. 24, p. 4132, 2019. [CrossRef]
11. R. D. Jeruto, L. A. Onyango, A. Nakhumicha, and S. Omwoma, "Comparing synthetic and natural antioxidants in vegetable oils: Effects on oxidation and oil quality," *Asian J. Appl. Chem. Res.*, vol. 15, no. 4, pp. 119–137, 2024. [CrossRef]
12. A. Schaut, S. Autru, A. D. Rop, and S. Eeckhoudt, "Effects of Irgamet 30 as additive in transformer oil," *IEEE Trans. Dielectrics Electr. Insul.*, vol. 19, no. 1, pp. 175–180, 2012. [CrossRef]
13. R. Madavan, S. Balaraman, and S. Subbaraj, "Multi-criteria decision-making methods for grading high-performance transformer oil with antioxidants under accelerated ageing conditions," *IET Gener. Transm. Distrib.*, vol. 11, pp. 4051–4058, 2017. [CrossRef]
14. H. M. Wilhelm, L. Tulio, R. Jasinski, and G. Almeida, "Aging markers for in-service vegetable oil-based insulating fluids," *IEEE Trans. Dielectrics Electr. Insul.*, vol. 18, no. 3, pp. 714–719, 2011. [CrossRef]
15. Y. Xu, S. Qian, Q. Liu, and Z. D. Wang, "Oxidation stability assessment of a vegetable transformer oil under thermal aging," *IEEE Trans. Dielectrics Electr. Insul.*, vol. 21, no. 2, pp. 683–692, 2014. [CrossRef]
16. 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, 17814, 2024. [CrossRef]
17. A. Miadonye, M. Amadu, J. Stephens, and T. O'Keefe, "Correlation of tangible quality parameters of vegetable-based transformer fluids," *Heliyon*, vol. 9, no. 4, e14763, 2023. [CrossRef]
18. S. O. Oparanti, I. Fofana, R. Jafari, R. Zarrougui, and A. A. Abdelmalik, "Canola oil: A renewable and sustainable green dielectric liquid for transformer insulation," *Industrial Crops and Products*, vol. 215, 118674, 2024. [CrossRef]
19. S. A. Smith, R. E. King, and D. B. Min, "Oxidative and thermal stabilities of genetically modified high oleic sunflower oil," *Food Chem.*, vol. 102, pp. 1208–1213, 2006. [CrossRef]
20. D. Krishnaiah, R. Sarbatly, and R. Nithyanandam, "A review of the antioxidant potential of medicinal plant species," *Food Bioprod. Process.*, vol. 89, no. 3, pp. 217–233, 2011. [CrossRef]
21. F. Atalar, A. Ersoy, and P. Rozga, "Experimental investigation of the effect of nano particles on the breakdown strength of transformer liquids by harmonic current analysis," *Electr. Power Syst. Res.*, vol. 221, 109390, 2023. [CrossRef]
22. A. Ersoy, F. Atalar, and H. Hiziroğlu, "A study on particle size effect of polyurethane-mica composites," *IEEE Access*, vol. 12, pp. 679–688, 2024. [CrossRef]
23. IEC 62021–3. *Insulating Liquids – Determination of Acidity – Part 3: Test Methods for Non-mineral Insulating Oils*, 2014.
24. IEC 60247. *Insulating Liquids – Measurement of Relative Permittivity and Dielectric Dissipation Factor (tanδ) and DC Resistivity*, 2004.
25. ASTM D7945-21a, *Standard Test Method for Determination of Dynamic Viscosity and Derived Kinematic Viscosity of Liquids by Constant Pressure Viscometer*, 2023.
26. J.-I. Jeong, J.-S. An, and C.-S. Huh, "Accelerated aging effects of mineral and vegetable transformer oils on medium voltage power transformers," *IEEE Trans. Dielectrics Electr. Insul.*, vol. 19, no. 1, pp. 156–161, 2012. [CrossRef]
27. M. Kanno, N. Oota, T. Suzuki, and T. Ishii, "Changes of ECT and dielectric dissipation factor of insulating oils due to ageing in oxygen," *IEEE Trans. Dielectrics Electr. Insul.*, vol. 8, no. 6, pp. 1048–1053, 2001. [CrossRef]
28. E. Truzzi et al., "A novel qNMR application for the quantification of vegetable oils used as adulterants in essential oils," *Molecules*, vol. 26, no. 18, p. 5439, 2021. [CrossRef]
29. S. K. Subburaj, M. Rengaraj, and R. Mariappan, "Evaluating critical characteristics of vegetable oil as a biodegradable insulating oil for transformer," *Int. J. Emerg. Electr. Power Syst.*, vol. 21, no. 5, 20200128, 2020. [CrossRef]
30. ASTM D6802-02, *Test Method for Determination of the Relative Content of Dissolved Decay Products in Mineral Insulating Oils by Spectrophotometry*, 2010.

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