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Experimental Study on the Effect of Natural Oils Waste on Transformer Insulating Oils

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ABSTRACT

The present work examined the influence of two dissimilar waste natural insulating oils (waste sunflower oil and waste corn oil) on the features of mineral transformer oil manufactured by Al-Dora refinery in Iraq. The primary goal is to place these two oils in the samecontext; thus, a fair compare can be made. In addition to making the mineral oil more sustainable and improving its qualities by substituting it with waste natural ester oils, the waste was produced under controlled conditions by frying sunflower and corn oils (separately) for 20 minutes at temperatures ranging from 100 to 250 °C.This was accomplished by pre-treating the (DO & WNEOs) to remove the maximum amount of water, and then adding the waste natural oils across a wide range of volume percent (20%, 40%, 60% & 80%).The electrical, physical & chemical qualities were among the essential characteristics that were noted throughout the range under study. It's interesting to note that the results showed that both oils might significantly enhance the mineral oil, mainly when concentrated at 20% of WSO/WCO. As the concentration of both WSO and WCO increased, the breakdown voltage started to decrease slightly. However, the breakdown performances of WSO or WCO are above the standard value over the examined range. The flash point was also maintained higher than the standard values throughout the entire range for both oils. While on the drawbacks, the viscosity & acidity weremore significant than the standard values at 20%, which was the ideal percentage that provided the best balance among the evaluated qualities. Finally, a modification of waste oils was carried out through a trans-esterification process to reduce the viscosity effect of sunflower and corn oils on Al-Dora oil. This modification was applied only to the blend consisting of 20% waste oil and 80% Al-Dora oil. The results demonstrated a significant improvement in blend viscosity without adversely affecting the other properties. All in all, it is anticipated that the utilization of waste lubricants could be a promising approach to enhance the characteristics of mineral oil utilized in high-voltage equipment, like transformers.

1. Introduction

The power transformer is a crucial high-voltage apparatus in the transmission network; it facilitates efficient energy flow and represents the most significant asset in the successful execution of electric utility projects.The longevity and steady operation of a transformer primarily rely on the dielectric material employed for insulation and cooling, as it mitigates the risk of failure, which can lead to economic damages during a power outage [1]. The insulation oil used in an electrical power transformer is referred to as transformer oil.It is obtained by fractional distillation and subsequent treatment of crude petroleum. That is why this oil is alias Mineral insulating oil [2]. Transformer oil serves mainly two purposes: one, it is a liquid insulation in electrical power transformers, and two, it dissipates the heat of the transformer, i.e., constitutes a coolant. Furthermore, it fulfils

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two other functions: it aids in the preservation of congenital and winding components, as they are completely submerged in oil, and another critical function of oil is to protect against direct exposure to air oxygen, given that cellulose is composed of it[2].Mineral oil possesses excellent cooling capacity, high dielectric efficiency, minimal dielectric losses, affordability, robust long-term performance, and widespread availability. These characteristics have resulted in the widespread utilization of mineral oil to the present day. Nonetheless, it adversely impacts the environment, irrespective of the insulating material's dimensions, due to its non-biodegradable nature. Significant spills transpired intermittently, resulting in the contamination of rivers and groundwater. Transformer leakage may lead to fire and explosion hazards. Moreover, mineral oil is derived from fossil fuels, which will eventually be depleted. Sustainable, eco-friendly commodities like vegetable oils are the optimal solution for replacement owing to environmental issues [3]. Currently, esters are utilized in transformers primarily for safety considerations, as they possess higher flash and fire points than mineral oils, as well as for environmental reasons, due to their superior biodegradability compared to mineral oils[4].

The term "waste natural ester oil" (WNEO) denotes vegetable oil that has undergone many uses in culinary frying processes. The gathered waste natural oil exhibits various features and offers distinct properties compared to pure vegetable oil. The use of waste natural oils as a feedstock for transformer oil is a viable solution to the issue of disposing of waste cooking oil[5]. Disposing of waste natural oil down the drain can contaminate water resources and obstruct the sewage system. Consequently, by employing waste natural oil and decreasing the expenses associated with sewage treatment [6]. The WNO has the potential of replacing the mineral oil in the power transformer, though it has its flaws, which include increased viscosity & acidity. Nonetheless, by certain chemical alterations, it can achieve efficiency comparable to that of mineral oil. The benefits of WNEO in power transformers include its elevated fire point and flash point relative to mineral oil, with a maximum operating temperature approaching 300°C, nearly twice that of mineral oil. Additionally, it is entirely biodegradable and derived from renewable sources, rendering it environmentally friendly[7].

Many studies have been published about using WNEOs with the MOs.Norazhar et al. [6] identified waste cooking oil methyl ester (WCOME) as a viable low-viscosity insulating fluid for transformers. The study aims to improve the usability of waste cooking oil (WCO), which is more economical than crude vegetable oil, by trans-esterifying it with methanol, utilizing KOH as a catalyst. The study analyzed the physical (density, flash point, pour point, viscosity), chemical (water content, acidity), as well as electrical (BDV) characteristics of WCOME.The findings revealed that WCOME exhibited lower viscosity, acidity, and water content than the original WCO, improving its suitability as an insulating fluid. After water treatment, WCOME had a water content of 156.4 ppm, aligning with IEEE C57.147 standards, and its BDV reached 30 kV, exceeding the IEEE C57.106 minimum standard by 50%. The study concluded that WCOME effectively addresses the high viscosity issue of aged natural ester (NE) insulating oils, making it a promising alternative for transformer applications.

Norazhar et al [5] explored the use of waste cooking oil (WCO) as an alternative to traditional transformer insulating oil. The trans-esterification process was applied to WCO using methanol and NaOH to produce waste cooking oil methyl ester (WCOME). The electrical and chemical properties of WCOME, including BDV, acidity, and water content, were compared with unprocessed WCO. The results showed that WCOME had a 92% reduction in water content and a nearly five-fold increase in BDV, significantly improving its performance. Acidity was reduced by 90%, but it still did not meet the required standards for new insulating oils. The study concluded that WCOME could be a promising alternative

to conventional oils, but further refinement is needed to meet transformer oil standards fully.

Hafisoh et al [7] explored used cooking oil (UCO) as an alternative insulating oil for power transformers after undergoing trans-esterification to meet IEEE C57.147 standards. PO was selected based on its acidity and water content, and the process effectively removed free fatty acids (FFAs) and water. The modified UCO exhibited a BDV increase of 240% (from 2.5 kV to 6 kV), while acidity and water content were reduced by 93% and 92%, respectively. Despite slightly higher acidity, the improved BDV suggests UCO could be a viable alternative to conventional transformer oils.

Gharib et.al [8] proposed waste soybean oil (WSBO) as a substitute for MO in power transformers after undergoing trans-esterification and epoxidation to meet ASTM standards. The synthetic soybean vegetable oil (SSVO) was compared to both fresh and used MO (UMO) in terms of electrical, chemical, and physical properties. Various UMO/SSVO blends were prepared in ratios of 90/10%, 80/20%, 70/30%, 60/40%, and 50/50% to create mixed liquid insulations. Results showed that SSVO had a higher flash point and BDV than UMO, and insulation performance improved with increasing SSVO content. The 70/30 blend exhibited the best performance, maintaining properties similar to fresh MO while staying within ASTM standards despite a slight acidity decline. The study concluded that SSVO is a viable, eco-friendly alternative for liquid-filled transformers, offering economic and environmental benefits while reducing pollution.

Umar et.al [9] explored blended insulating liquids by mixing trans-esterified palm olein (POFAME) with MO in three ratios: 50/50, 75/25, and 25/75. The DC BDV was measured using the Glow 28720 DC-HV generator, and statistical analysis was performed using the Weibull probability distribution. The results showed that NE blends exhibited higher BDV compared to pure MO, with a 6.3% increase for (50% POFAME + 50% MO) and a 5.7% increase for (75% POFAME + 25% MO). These findings suggest that POFAME could be a viable alternative for transformer insulation. However, further studies on its physical, thermal, and dielectric properties are required to confirm its suitability for HV applications.

It is evident from the reviewed literature;no work puts waste sunflower oil and waste corn oil in the same context and makes a fair comparison between them. For the first time, the influence of these two oils on a mineral oil (Dora oil) is studied, to include the electrical, physical, and chemical properties. Additionally, the current study explores the idea of substituting WNEOs for local mineral oil in order to improve their main characteristics and make them more sustainable. The trans-esterification method is used to lower the viscosity and acidity at an addition rate of 20% WSO/WCO & 80% DO. The following section presents the experimental work, characterization, and results.

2. Experiments

2.1Waste Producing Method

Since it is challenging to obtain waste oils used in a controlled manner with respect to time, temperature, and number of uses, the waste oils were produced in the current study. This was achieved by frying SO & CO separately for 20 minutes at a temperature ranging from 100 to 250 °C. The process was repeated five times until noticeable changes in color and odor occurred. Between each frying cycle, the oil was allowed to cool to 100 °C before the process was repeated.

Upon completion, the oil was left to cool and filtered to remove solids generated during frying. Filtration was performed using 2-micron filter paper, with a vacuum pump applied to facilitate oil flow during the process. This procedure was carried out at room temperature as shown in Fig.1.

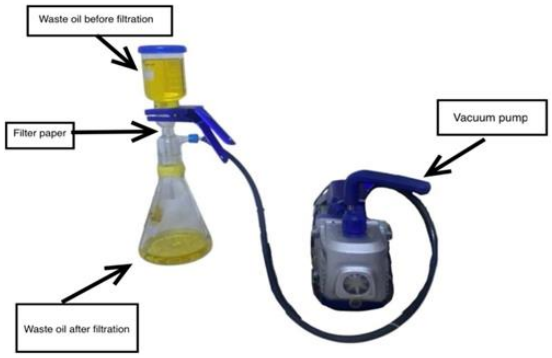

Figure 1. Filter System of WSO/WCO.

2.2 Pre-treatment

At this stage, it's significant to eliminate or, at the very least, reduce the oil's water content as much as possible because high water content negatively impacts the transformer's performance. Because of this, a basic rig was created for the dehydration of the oils. As seen in Fig.2, the rig is made up of a steel vessel that is insulated by a layer of glass wool and has a vacuum pump installed. Inside the steel container is a conical flask that has been filled with a specific amount of oil. The flask has two holes: one for a vacuum pump and one for a thermometer to check the temperature of the oil inside the glass container. It also has a sealed rubber cover to keep air out. Employing the vacuum pump is necessary to enable efficient water evaporation at moderate temperatures; subsequently, variations to oils' chemical structure due to heating are not envisaged. In this process, the vacuum pressure was kept at approximately 12 psi (80% of full vacuum). The DO was heated at 60-70◦C for 6 hours, while WSO/WCO was heated at 80-90◦C for 24 hours to reduce the moisture content. Experimentally, these conditions have been found to be optimal for preserving the structural integrity of both oils (i.e., DO, SO/CO&WSO/WCO) without including changes .After treatment, the oils were left to cool until they reached the equilibrium state with ambient temperature, and now they were ready to be mixed. It is essential to mention here that this treatment reduced the WSO & WCO water content from 200 ±20 ppm to about (67 & 97) ppm and DO from 70 ±10 ppm to about (15.99) ppm, making them more suitable as insulating fluids.

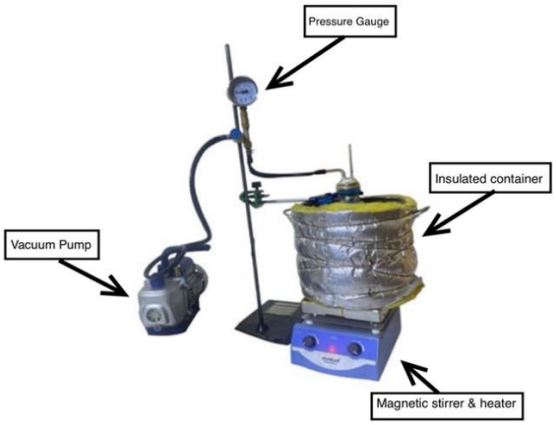

Figure 2. The Process of Pre-treatment of Oils.

2.3 Trans-esterification process of WSO/WCO to reduce viscosity

A " trans-esterification " reaction is the chemical reaction among the triglycerides of natural esters and alcohol to give fatty acid methyl ester and glycerol. Either a homogeneous or heterogeneous base catalyst is present when this reaction occurs. Examples of these catalysts are NaOH, CaOH, and KOH. A diagrammatic representation of the chemical reaction is presented in Fig. 3. The segregation of glycerol from the triglyceride results in a sharp drop in the pour point temperature of natural esters, and this can be attributed to the elimination of glycerol, which is the spine of easy crystallization of the oil. Even additional so, eliminating glycerol decreases the proportion of O-H hydrogen bonding in the oil, which, subsequently, lowers the average molecular mass of the oil and, in turn, decreases the rate at which the fatty acid crystallizes [10].

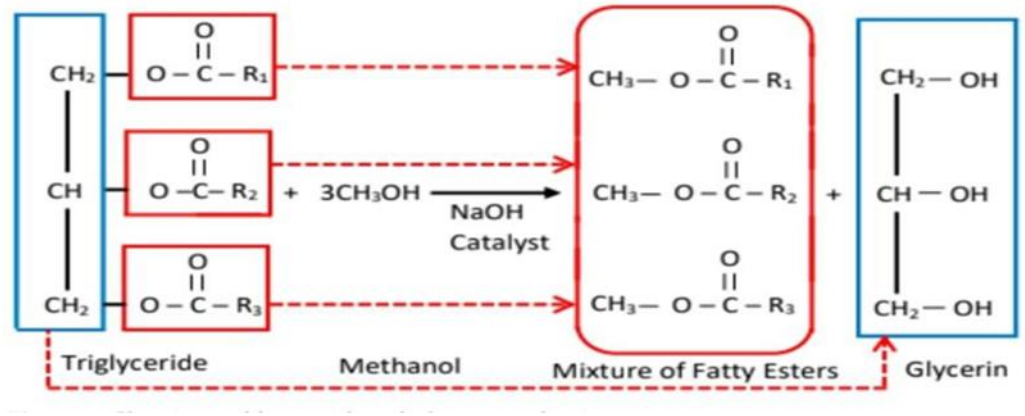

Figure 3. The chemistry of producing methyl ester from fatty acids [10].

Glycerol's removal from the oil lowers the average molecular weight, which in turn lowers the liquid's dynamic viscosity. Equation (1) theoretically illustrates this, showing a direct correlation between average molecular weight and dynamic viscosity. Furthermore, the resistive frictional force between the methyl ester's layers is decreased when glycerol is eliminated.

$$\mu = K\overline{M}^{\alpha} \qquad (1)$$

Where M is the average molecular weight, [μ] is the dynamic viscosity, and K & αare constants that are directly influenced by solvent and temperature [10].

2.3.1 Trans-esterification process

In the trans-esterification process, 600 mL of dehydrated WSO/WCO was placed into a 1000 mLbeaker and stirred at 500 rpm; simultaneously, the oil was heated until its temperature reached 55 - 60°C. During this process, 150 mL of methanol and 4.5g of sodium hydroxide catalyst were added to a flask; the catalyst was then dissolved in methanol using a magnetic stirrer, forming a methyl oxide solution. This dissolution process took approximately 30 minutes to complete [5].The reaction was carefully controlled, ensuring it did not exceed 60°C to prevent methanol evaporation. Once the solution was thoroughly mixed, it was transferred to another 1000 mL beaker, where the waste oils (WSO&WCO) and methanol underwent the trans-esterification reaction. After 48 hours, the reaction resulted in the separation of the mixture into two distinct layers: fatty acid methyl esters (FAME) as the upper layer and glycerol as the lower layer, as shown in Fig.4. A.

Figure 4.(a) Fatty esters and glycerin in the separation funnel, (b) Fatty esters and water in the separation funnel.

Only the uppermost layer, FAME, was chosen for the further processing stages. The ME from the upper layer of the beaker was meticulously transferred to another beaker and rinsed with 300 mL of hot distilled water to eliminate any remaining glycerol. The oil was agitated at 500 revolutions per minute for 10 minutes at a regulated temperature of 100°C during the washing process.Following this, the mixture was transferred into a separation funnel and left undisturbed for 30 minutes to ensure the complete removal of soap, as shown in Fig.4. This washing procedure was repeated twice to eliminate any remaining methanol and NaOH from FAME.The final product obtained from this process is referred to as MEWSO/MEWCO. Subsequently, the MEWSO/MEWCO was subjected to further heating for 48 hours at a temperature exceeding 90°C to ensure the complete evaporation of any residual water content.

2.4 Oil Blends Preparation

After the drying process of oils, the oils are ready to be mixed. The blending was performed across a wide range of compositions, starting from 0% (pure DO) to 100% (pure WNEO) with an increment of 20%. The blending process was conducted under controlled conditions using a magnetic stirrer and a vacuum pump for one hour at a temperature range of (45-50°C), as shown in Fig.5. Subsequently, the blend was allowed to cool to room temperature, after which the samples were collected for further testing. The sample numbers and corresponding mixing ratios were listed in Table 1.

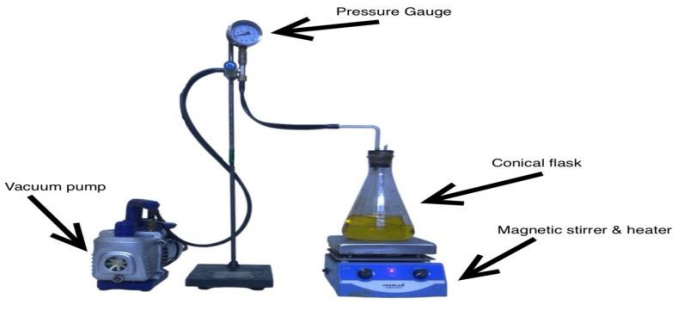

Figure 5: Oil Blending Process.

Table 1: Mixing Ratios of Oils

Sample No.	Mixing Ratio (by volume)	Waste Natural Oil Percent
#1	DO (100) \ WSO or WCO (0)	0%
#2	DO (80) \ WSO or WCO (20)	20%
#3	DO (60) \ WSO or WCO (40)	40%
#4	DO (40) \ WSO or WCO (60)	60%
#5	DO (20) \ WSO or WCO (80)	80%
#6	DO (0) \ WSO or WCO (100)	100%
# 7	DO (80) \ MEWSO or MEWCO (20)	20%

3. Results and discussion

3.1 Results of WNEOs

3.1.1 Breakdown voltage

Breakdown voltage was tested according to IEC 60156. As shown in Fig.6, the highest increase in BDV was observed in the mixtures of 20% WSO/ WCO with 80% DO and 100% WSO. This increase in BDV can be attributed to the molecular interactions between the ester molecules, which help delay or obstruct the propagation of streamers within the oil [1]. Furthermore, the presence of polar compounds in WNEOs aids in the more uniform distribution of the electric field, thereby reducing the likelihood of electrical breakdown [11].

In mixtures containing (40%, 60%, and 80% WSO/WCO with DO), the BDV was slightly lower than that of the 20% WSO/WCO mixture, but it remained above the acceptable range for transformer oils [2]. The increase in polar compounds and the formation of generated gases act as obstacles, resulting in a reduction of BDV in blends with higher ratios.

The gradual development of streamers across the top and lower electrodes is crucial in the electrical breakdown of dielectric fluids. The application of an electric field results in the creation of ions and electrons, with the ground electrode, being at the lowest potential, receiving the streamers from the source. The linkage between the two electrodes generates an arc flow, resulting in the electrical breakdown of the dielectric fluid[1].

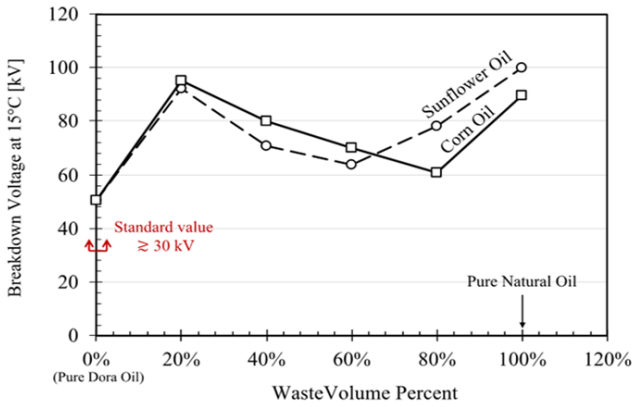

Figure 6: Breakdown Voltage for DO, WSO & WCO Mixtures.

3.1.2 Dielectric Constant

As presented in Figs.7 (A, B) The dielectric constant of the blended samples (WSO/WCO &

DO) was noticeably lower than that of the refined (SO/CO). This reduction is primarily attributed to oxidative degradation, a key process that occurs during frying and the formation of unstable peroxide compounds when oils are heated to around 160°C. These intermediates decompose rapidly under thermal stress, contributing to the observed decline in dielectric performance [12].

Elevated frying temperatures increase the kinetic energy of polar molecules, promoting molecular disorder and hindering the alignment of dipoles with the electric field. This misalignment reduces the fluid's ability to store electrical energy, as reflected by the lower dielectric constant values [12].

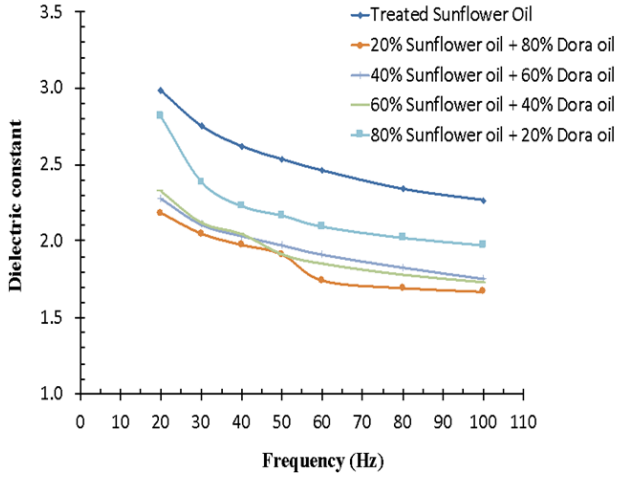

Figure (7.A): Dielectric Constant for DO & WSO Mixtures.

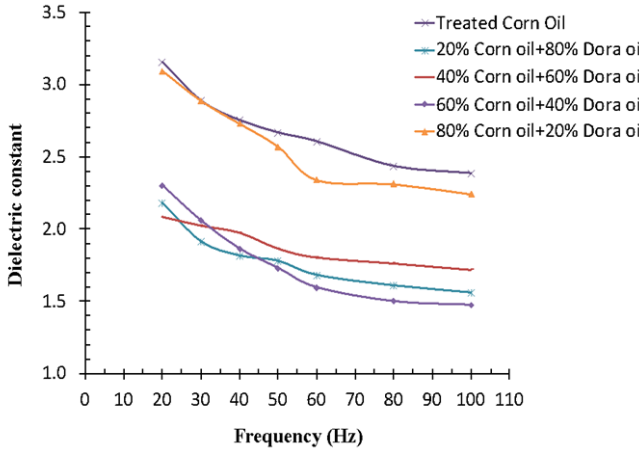

Figure (7.B): Dielectric Constant for DO& WCO Mixtures.

Furthermore, an inverse relationship was observed between frequency and dielectric constant. At higher frequencies, dipole rotation is limited, weakening orientation polarization. As frequency increases further, this polarization effect diminishes, and dipole polarization becomes the dominant mechanism. Such frequency-dependent behavior was evident across all tested oil samples, with more significant changes occurring at lower frequencies [13].

3.1.3 Kinematic Viscosity

kinematic viscosity was measured according to ASTM D445.It increased significantly with the rising proportion of WSO/WCO when blended with DO, demonstrating the direct impact of waste oil content on the molecular interactions within the mixture. In waste oils, particularly those subjected to frying operations (WSO/WCO), viscosity is primarily influenced by the degree of unsaturation, the structural configuration of fatty acid chains, and the overall chain length. However, additional factors, notably oxidation, polymerization, and thermal degradation, exert a more pronounced influence on viscosity enhancement in waste oils [14].

Repeated exposure to high frying temperatures induces substantial thermal degradation in waste oils, promoting the formation of FFAs and high-molecular-weight polymeric compounds. These oxidation and polymerization processes contribute significantly to the increase in viscosity, making WNEOs consistently more viscous than MOs [15]. The progressive formation of polymeric species during extended frying not only elevates viscosity but also alters the molecular structure of the oils. Additionally, hydrolysis reactions and the generation of low-molecular-weight decomposition products further influence the viscosity of waste oils during frying. These chemical transformations degrade the physical and electrical properties of the oils, thus impacting their potential use as insulating fluids. A strong positive correlation

between viscosity and acid value has been observed, indicating that higher acid content is associated with increased viscosity levels in waste oils [16]. However, in this study, despite the anticipated degradation reactions, the electrical properties of the waste oils remained within acceptable ranges for insulating applications.

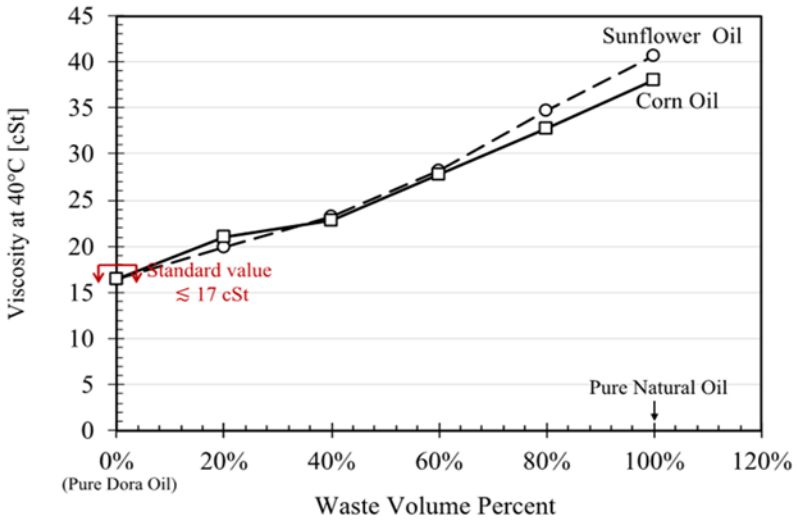

Figure (8): Kinematic viscosity for DO, WSO & WCO Mixtures.

3.1.4 Flash point

Edible esters are considered fire-safe and are recommended for use as coolants and insulating agents, making them ideal candidates for MOs. This significantly reduces the risk of fire or explosions when the transformer is exposed to high temperatures due to overloads or faults [17].

Flash point was measured according to ASTM D93.When blending (WSO/WCO + DO), an increase in the flash point was observed as the ratio of WSO/WCO in the blend increased, as shown in Fig.9.This increase is likely due to several factors, such as the higher molecular weight of WNEOs compared to MOs [17].

WSO/WCO blends exhibited higher flash points, likely due to their exposure to high temperatures during the cooking process [18]. Additionally, the flash point is influenced by the inability of the air-oil vapor mixture to ignite below the flash point temperature [14]. The low vapor pressure and low volatility of WNEOs, owing to strong intramolecular interactions, also contributed to the increased flash point. As a result, WNEOs are less flammable than MOs, making them more suitable for use in environments with high thermal, high-loading, and high-voltage transformers [19, 20].

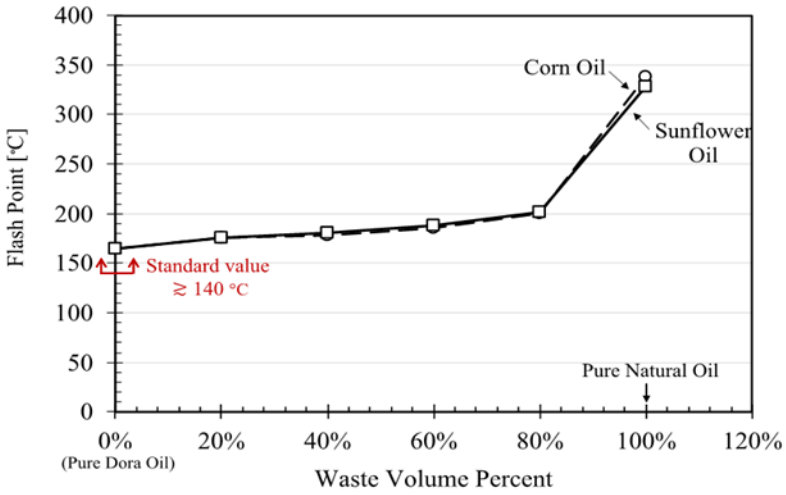

Figure (9): Flash point for DO, WSO & WCO Mixtures.

3.1.5 Density

Density was measured according to ASTM D4052 at 15°C; the densities of WNEOs are significantly higher than that of DO. This increase in density can be attributed to the reduction in the kinetic energy of the oil molecules, leading to stronger intermolecular forces that bring the molecules closer together, reducing volume and increasing density [21]. Thermal oxidation, especially during frying, plays a critical role as oxygen reacts with unsaturated fatty acids, forming high-molecular-weight compounds. As shown in Fig.10, when blending (WSO/WCO&DO) in different proportions, an increase in density was observed with a higher ratio of WSO/WCO. This change in density significantly influences heat transfer by natural convection and the buoyant movement of gas bubbles within the liquid. The variation in density is mainly driven by differences in the chemical composition of the oils [22].

Results regarding the density changes of WSO and WCO after repeated frying cycles indicate a more pronounced density variation in WSO than in WCO. This suggests a more excellent formation of polymeric compounds in WSO, likely due to the presence of π-bonds, which increase molecular rigidity and restrict the flexibility of (C-C) bonds. Reactions such as oxidation, polymerization, and hydrolysis during frying and heating contribute to the formation of polymeric compounds, explaining the observed differences in density changes among the studied oils [23].

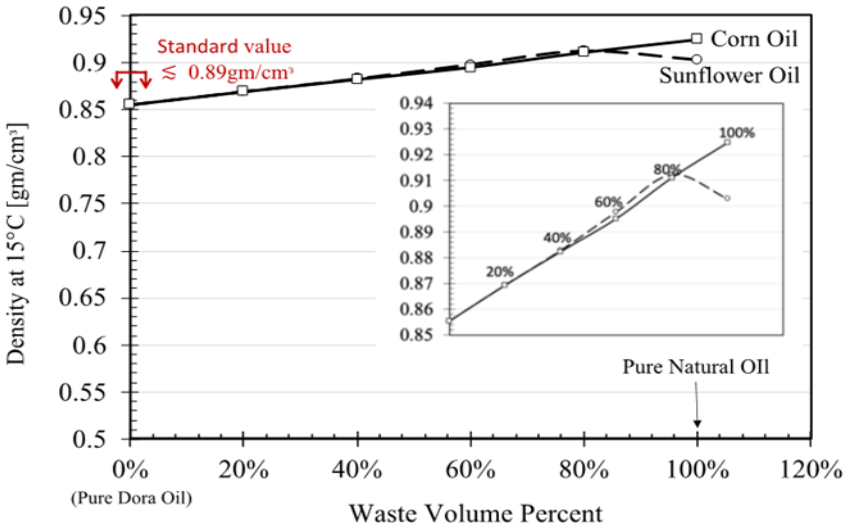

Figure (10): Density for DO, WSO & WCO Mixtures.

3.1.6 Acidity

Acidity plays a vital role in assessing the oxidative stability of MOs. Unlike WNEOs, WNEOs do not undergo hydrolysis, meaning that any increase in their acidity is attributed solely to oxidation. In contrast, WNEOs inherently exhibit higher acidity values due to their composition and susceptibility to oxidation and hydrolysis [20].

Acidity was calculated according to the standard ASTM D974. As illustrated in Fig.11, increasing the blending ratio of WSO/WCO with DO results in a corresponding rise in acidity across all tested blends. This increase is mainly due to the presence of high-molecular-weight fatty acids, such as oleic and linoleic acids, in WNEOs [8]. Additionally, the presence of carboxylic functional groups in WNEOs plays a significant role in elevating the acid value, especially when the oils are exposed to heat during frying [20].

During frying, oils undergo oxidation, leading to the formation of hydroperoxides, which decompose into secondary oxidation products such as alcohols, ketones, aldehydes, and acids. The increase in FFA can be attributed to the moisture content of fried food, which accelerates oil hydrolysis. Water is known to facilitate the breakdown of triacylglycerols, producing monoacylglycerols, diacylglycerols, glycerol, and FFAs. However, FFA content remains a dynamic parameter, as these acids are continuously formed while also evaporating due to their sufficient vapor pressure at frying temperatures. As a result, FFA content alone is not a highly reliable indicator of frying oil degradation, as it is challenging to distinguish between FFAs generated by oxidation and those formed through hydrolysis. Additionally, low-molecular-weight FFAs may be lost due to volatilization during frying [24].

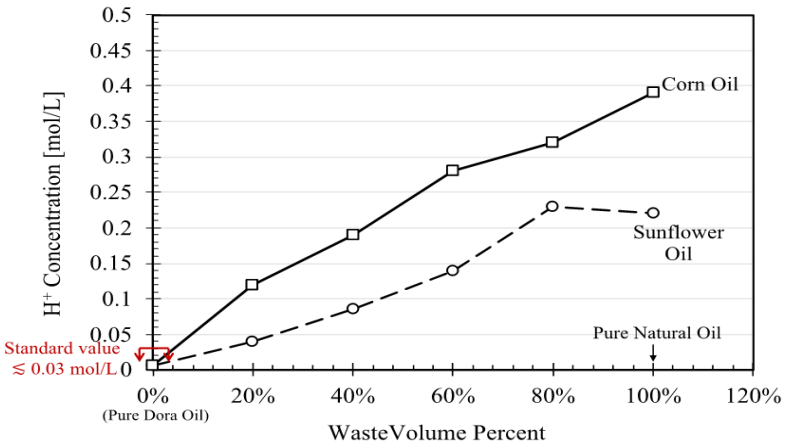

Figure (11): Acid number for DO, WSO&WCO Mixtures.

3.1.7 Water content

Water content was calculated according to the standard ASTM D6304. As shown in Table 2, the water content in (WSO/WCO + DO) mixtures was reduced compared to vegetable oils before frying. This reduction is mainly attributed to the water loss dynamics during frying, which occurs in distinct stages. Initially, thermal energy is conveyed from the oil to the food surface with minimal water vaporisation. When the surface temperature attains the boiling point of water, moisture begins migrating into the oil, forming vapor bubbles, marking the surface boiling stage. As frying progresses, a crust forms on the food surface, limiting further moisture migration and reducing the evaporation rate (rate reduction stage). In the final phase (bubble ending stage), the evaporation rate drops significantly, and moisture loss reaches equilibrium [25].

Thus, (WSO/WCO) have already undergone significant dehydration during the frying process, resulting in lower mixtures' inherent water content.

However, when the WSO/WCO proportion increased in the mixture with DO, the water content also rose. This is explained by the hydrophilic nature of ester oils, which absorb moisture more readily and reach saturation faster than MOs [26]. Although DO is engineered to be water-repellent, blending it with WSO/WCO compromises its moisture resistance. The presence of polar compounds and the higher viscosity of WNEOs enhance moisture retention and lead to more significant inhomogeneity within the blend [27]. Maintaining minimal moisture in transformer oils is essential, as excess water degrades the dielectric strength by creating voids and promoting insulation failure [28].

Table 2: Water content values

Property	**DO**	**WSO**	**WCO**	**20% WSO**	**40% WSO**	**60% WSO**	**80% WSO**	**20% WCO**	**40% WCO**	**60% WCO**	**80% WCO**
Water content	15.99	67	97	30	38	39	49	20	25	35	42

3.2 Trans-esterification Results (containing 20% waste oils)

3.2.1 Breakdown voltage

As shown in Table (3), mixtures of (20% MEWSO/MEWCO & 80% DO) exhibited a significant BDV increase following trans-esterification. This enhancement is attributed to the synergistic molecular interaction between MEWSO/MEWCO and DO, which results in a more stable structural arrangement that strengthens dielectric performance [29].

The rise in BDV is due not only to favorable chemical interactions but also to the inherently high dielectric characteristics of fatty acid methyl esters (FAMEs), which slow the breakdown process and support more excellent electrical stability [29,30]. Consequently, using MEWSO/MEWCO as partial replacements for mineral oil in transformer applications, even in systems containing residual MO, poses no operational incompatibility or risk [29].

This suggests that MEWSO/MEWCO and DO mixtures can serve as promising alternative dielectric fluids due to their enhanced insulating properties and environmental advantages [31].

Table 3: Breakdown Voltage Values

Property	20% MEWSO & 80% MO	20% MEWCO & 80% MO
Breakdown voltage	80	85

3.2.2 Dielectric Constant

As shown in Table(4), blending (20% MEWSO/MEWCO & 80% DO) resulted in a noticeable increase in the dielectric constant compared to (20% WSO/WCO & DO) blends and DO alone. This enhancement is primarily attributed to the presence of polar ester functional groups (C=O and C–O). These groups promote more potent polarization effects, contributing to the improved dielectric properties of the mixture [32].

Additionally, the higher absolute water content and more excellent solubility of ME compared to MO further influence the dielectric behavior. Water, being highly polar, enhances the system's ability to store electrical energy, leading to an increase in the dielectric constant as the ester content rises. This characteristic makes trans-esterified oils a promising alternative for transformer insulation, as higher dielectric constants contribute to improved cooling efficiency and enhanced operational safety [32].

As with other insulating fluids, the dielectric constant of MESO/MECO mixtures decreases with increasing frequency. At higher frequencies, molecular rotation becomes limited, hindering effective alignment with the electric field and resulting in a reduction in orientation polarization. As the frequency continues to rise, this polarization effect diminishes, leaving dipole polarization as the primary mechanism. This phenomenon, known as dielectric dispersion, was observed across all oil samples, with MEWSO and MEWCO maintaining higher dielectric constants than DO throughout the frequency spectrum [33, 30].

Table 4: Dielectric Constant for DO, MEWSO & MEWCO Mixtures

Frequency (Hz)	DO after treatment	20% MEWSO & 80% DO	20% MEWCO & 80% DO
20	3.9714	6.2641	6.3908
30	3.8788	5.6416	5.7634
40	3.8021	5.3042	5.3773
50	3.7448	5.1787	5.3444
60	3.6803	5.1702	5.2067
80	3.6778	5.0995	5.1555
100	3.6705	5.0630	5.1129

3.2.3 Kinematic viscosity

When blending (20% MEWSO/MEWCO & 80% DO), the kinematic viscosity decreased by 61.62% after the trans-esterification process compared to the (20% WSO/WCO & 80% DO) and DO alone, as shown in Table (5). This viscosity reduction is attributed to the removal of glycerol, which has a high viscosity, thereby decreasing the resistive force acting between the layers of MEs [34, 33].

Consequently, blends with lower viscosities enhance heat dissipation efficiency, thereby improving the transformer's capacity, lifespan, and operational safety [35]. The viscosity difference between WSO/WCO and MEWSO/MEWCO is due to the conversion of large triglyceride molecules into a lighter, linear chain of ME molecules [36]. As a result, MESO/MECO exhibits improved fluidity at lower viscosities, meeting one of the essential criteria for its suitability as an insulating fluid in transformers [33].

Notably, higher unsaturation levels lead to lower viscosity. This occurs because double bonds introduce kinks in fatty acid chains, preventing close molecular packing and enhancing fluidity [37]. Therefore, the low viscosity of MESO & MECO indicates superior cooling performance compared to NEO dielectrics [38]. Consequently, the trans-esterification of large-molecule esters into short-chain molecules is a widely adopted method for improving viscosity [39].

Table 5: Kinematic viscosity values

Property	20% MEWSO & 80% MO	20% MEWCO & 80%MO
Kinematic viscosity	12	11.8

3.2.4 Flash point

As demonstrated in Table (6), when blending (20% MEWSO/MEWCO & 80% DO), the flash point increased after the trans-esterification process of SO/CO, compared to the flash point of DO alone .

However, the flash point of the blends was comparable to that of the (20% SO/CO & 80% DO) blend. This increase suggests that excess methanol was effectively removed, as the presence of methanol would lower the flash point significantly if not recovered [40].

The blends' higher flash point is attributed to the presence of FAMEs, which are non-volatile compounds that contribute to raising the flash point [36].

Consequently, MEWSO/MEWCO's flash point meets the flash point requirements typically associated with conventional insulating oils (MOs). This makes MEWSO/MEWCO a viable

option for applications where high flash points and safe operational conditions are critical [38].

Table 6: Flash point values

Property	20% MEWSO & 80% MO	20% MEWCO & 80% MO
Flash point	176	176

3.2.5 Density

The density of methyl esters (MEs) is generally influenced by the number of esters and the residual methanol content. The properties of MEs are primarily affected by the choice of vegetable oils and, to a lesser extent, by the purification steps applied [41]. As presented in Table (7), a slight decrease in density was observed after the trans-esterification of WSO/WCO, specifically in the (20% MEWSO/MEWCO & 80% DO) blend, when compared to the blend containing (20% WSO/WCO & 80% DO). However, the density remained higher than that of DO alone. This decrease in density is attributed to the removal of glycerol, a common by-product in both oils [42]. The chemical transformations during trans-esterification lead to the formation of lighter methyl esters [34]. The resulting increase in molecular motion weakens intermolecular forces, leading to greater spacing between molecules, which further reduces the density [43]. Although the density of both blends was below the standard limit, MEWSO/MEWCO meets the criteria for use as insulating oil in oil-filled transformers [44].

Table7: Density values

Property	20% MEWSO & 80% MO	20% MEWCO & 80% MO
Density	0.8629	0.8624

3.2.6 Acidity

When a blend containing (20% MEWSO & 80% DO) was prepared, an increase in acidity was observed following the trans-esterification process compared to both the (20% WSO & 80% DO) blend and DO alone, as shown in Table (8). This increase is attributed to the hydrolytic susceptibility of methyl esters (MEs), which readily undergo hydrolysis in the presence of even trace amounts of moisture, leading to the formation of FFAs. Moreover, the hygroscopic nature of MEs complicates acidity reduction, making them more prone to acid buildup compared to MOs [38].

Conversely, in the (20% MECO & 80% DO) blend, a decrease in acidity was observed after trans-esterification when compared to the (20% WCO & 80% DO) blend. This reduction in acid value indicates a successful conversion of FFAs during trans-esterification, which is essential for improving the stability and overall quality of transformer oils [34].

Table 8: Acid number values

Property	20 % MEWSO& 80%MO	20% MEWCO& 80% MO
Acidity	0.06	0.03

3.2.7 Water content

As shown in Table (9), when 20% MEWSO/MEWCO was blended with 80% DO, the water content remained within permissible limits,is attributed to continuous heating at 100°C during the pre-treatment phase, which facilitated moisture removal, followed by efficient phase separation using a separation funnel. Furthermore, residual water was progressively eliminated through post-processing techniques [7, 45]. However, it was slightly higher than that of pure DO. This increase is attributed to the presence of ester groups in MEs, which are more polar and hydrophilic compared to the triglyceride structures in vegetable oils. The higher polarity of ME molecules enhances their affinity for water, resulting in slightly more excellent moisture absorption [38].

Previous studies on NE dielectrics have indicated that vegetable oils' high water saturation capacity is beneficial, as it allows them to absorb more moisture from insulating paper compared to MOs, thereby slowing down the insulation's aging process [38].

Table 9: Water Content Values

Property	20% MEWSO & 80% MO	20% MEWCO & 80% MO
Water content	29	25

4. Conclusions

The study highlighted the potential for producing environmentally friendly and sustainable transformer oils by utilizing WNEOs. These oils showed promise as viable and eco-friendly alternatives to traditional TOs.

1- The blends of (WSO & DO) exhibited an initial increase in BDV at 20% WSO, followed by a gradual decline as WSO content was increased. Despite this decrease, BDV remained within a functional range. Flash point was improved, likely due to oxidation products acting as stabilizers. However, dielectric properties were affected, with a decrease in dielectric constant, attributed to the interaction between polar compounds and oxidation products. Additionally, with the increase in the percentage of WSO, increased water content, acidity, and viscosity were observed due to oxidative degradation. Based on these findings, the optimal blend for stable performance was determined to be 20% WSO and 80% DO.

2- The trend was similar to (WCO & DO) blends. At 20% WCO, BDV initially was improved but decreased as the WCO content increased. Flash point was improved with higher WCO content, but water content, acidity, and density increased due to oxidation. The optimal blend for stable performance was 20% WCO and 80% DO.

3- The blend of (20% MESO & 80%DO) resulted in improvements in BDV, viscosity, flash point and water content. However, acidity and dielectric constant exceeded optimal levels due to FFAs and residual polar compounds .

4- A similar pattern was observed in blends of (20% MECO & 80% DO), with improvements in BDV, flash point, viscosity, water content, and a reduction in acidity due to the effective removal of FFAs. However, the dielectric constant was increased due to residual polar compounds that were not fully removed after the trans-esterification process.

5-Based on these results, the mixtures (MEWSO / MEWCO and DO) appear to be a promising alternative to mineral transformer oils. However, due to the acidity of the (MEWSO

and DO) mixture, future research should focus on reducing it, potentially by incorporating kaolin clay.

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