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Experimental Verification of Insulation Characteristics of Several Types of Vegetable Oils to Replace the Traditional Transformer Oil

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Abstract— Various vegetable oils are subjected to standard experiments, and the results are discussed in detail. The changes in mechanical and electrical properties of these oils, observed during standard laboratory tests, are studied. The main insulation characteristics of these oils include moisture content, acidity, flashpoint and others are compared with standard transformer oil. The tests were repeated several times to verify the reliability of the obtained results. Although the long-term use of such oils can better prove their performance, the outcomes of the laboratory tests are significant here to prematurely exclude the oil types which have poor insulation characteristics. Similarly, the current testing approach is necessary to verify the ability of available testing machines to accept certain types of oil with various chemical characteristics. The relationship between flammability and combustion concepts are clarified in the analysis of liquid insulation properties. One of the significant results in this study is the high flashpoint shown by all vegetable oils examined in this work compared with mineral oil. The olive oil was used as an example to show the effect of filtration on reducing moisture content and other impurities by comparing the performance of the oil before and after the process. This study applied two approaches-general and specific- to prioritize vegetable oils. In general approach, a broad classification of vegetable oils compared to mineral oil was given, whereas in the specific approach a numerical scoring system was generated to identify which oil performs best, taking into consideration the technical and economic factors.

Keywords— Oil; Vegetable; Mineral; Dielectric; Strength; Olive.

Nomenclature

HV	High Voltage	O	Olive oil
PCB	Polychlorinated Biphenyl	S	Sesame oil
ASTM	American Society for Testing and Materials	C	Corn oil
NEPCO	National Electric Power Company	Ca	Canola oil
DGA	Dissolved Gas Analysis	Cr	Castor oil
KOH	Potassium Hydroxide	P	Palm oil
BDV	Breakdown Voltage	Sb	Soybean oil
Sf	Sunflower oil	MO	Mineral oil
VO	Vegetable oil		

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1. INTRODUCTION

Insulation liquid, used in High Voltage (HV) and power equipment, should have two important functions. Firstly, it should act as a good electrical insulating material and, secondly, it should dissipate heat generated in the equipment. In transformer, for instance, the heat is transferred from the hot areas such as core, windings and other elements to cooling medium, such as oil or air, which dissipates heat to the surroundings. Despite the significance of the above mentioned functions, the selected liquid insulation material should be readily available, environmentally acceptable and relatively nonflammable.

For several decades, Mineral Oils (MO) produced from crude petroleum have been used widely as a cooling and insulating liquid in power system equipment such as HV capacitors, switches, circuit breakers, tap changers and bushings [1, 2]. Their widespread use is attributed to their lower cost, availability and good electrical and thermal properties. However, the safety requirements for the materials used in power systems became more demanding worldwide. Therefore, initially the search for less-fire insulating oil has led to select several nonflammable liquids such as askarel (polychlorinated biphenyl-PCB) oil. Although this liquid was widely used by the designers of high voltage equipment for its excellent non-flammability and strong dielectric strength characteristics, it became later recognized that askarel oil is environmentally hazardous and should be banned [3]. Moreover, some PCB-based oils are poor in quenching arcs in oil circuit breakers and have a limited ability to reduce the harmful arc degradation by products. This is a direct consequence of the oil's properties, which can lead to sustained arc and stressing the contacts. Therefore, these drawbacks limit their use in modern circuit breakers and load break switches.

In light of the disadvantages and the risks associated with the use of PCB-based insulating oils, there have been serious efforts to develop insulating liquids to be inexpensive, environmentally safe and nonflammable. Unfortunately, despite these efforts, MO is not completely replaced and remains in widespread use [4-7]. This is attributed to the integrated requirements, which should exist in any candidate oil such as having high impulse strength, high volume resistivity, high thermal conductivity, high flash point, low viscosity and low dielectric dissipation factor. At present, mineral oils have dominant share because of the mature technique and sufficient feedstock [8]. However, the transition from MO to alternative insulation liquids has been continuous, with candidate materials demonstrating significant improvements in properties relevant to their applications [9, 10].

In seeking proper liquid insulation, the main alternatives for the mineral oil were several types of Vegetable Oils (VOs), especially those with good oxidation stability [11]. However, some VOs are characterized by the presence of saturated fatty acids, which lead to higher viscosity, higher freezing and pour points [12]. Moreover, the presence of multiple double bonds exposes oils to oxidation, which decreases the dielectric strength of the oil [13].

Since this topic attracts various researchers, the aim of the present work is to provide an experimental verification of the main characteristics of selected VOs as alternatives to traditional MO. This study presents the main tests conducted for selected samples of vegetables and MO. Based on the results obtained, a summary table of general advantages and disadvantages of the tested VOs in comparison with currently used transformer oil is also presented. A comparison among oil prices in local and global markets will also be provided. Finally, a numerical scoring system, based on cost and oil performance will be developed to rank the oils considered in this study.

2. EXPERIMENTAL SETUP

Transformer oil should be tested to verify its ability to work according to today's standards and codes. Although these standards may have slight differences among each other, they were originally set by the American Society for Testing and Material Standards (ASTM). All oil samples were tested in the liquid insulation laboratory owned and operated by the National Electric Power Company (NEPCO) in Jordan. This laboratory can perform six types of basic tests, namely dielectric test, acidity test, viscosity test, flash point test, water content test and Dissolved Gas Analysis (DGA) test. Although the main goal of these tests is to assess the insulation properties of the selected oil samples, the complementary data derived from the analysis of these tests serve as outstanding diagnostic tools for monitoring and evaluating the operational conditions of the equipment insulated by these oils [14].

Because dissolved water cannot be detected by dielectric test, and it blends at lower temperatures, the oil must stay at almost the same temperature for each test to obtain consistent results. Therefore, all experiments in this work were carried out at a temperature of 27°C. The dielectric strength oil tester is a portable device used to measure the dielectric strength of the liquid insulation. The value obtained from this test reflects the ability of oil to withstand electric stress before breaking down, and it is a key indicator of its insulating quality. During the test, a high voltage AC is applied to the oil sample contained in a special glass vessel. The voltage is applied through a homogeneous system consisting of dielectric fluid and two 12.7mm diameter spherical electrodes displaced by a 2.5mm distance from each other. The electrodes and the test cup shall be clean and dry. The testing machine design and the testing procedure are governed by the international standard IEC60156, which specifies the method for determining the dielectric Breakdown Voltage (BDV) of insulating liquid. This standard determines whether the apparatus is suitable for the test application and is used safely. The tester can accept variable values of applied voltage up to 100kV. The application of voltage should be performed in steps with a constant rate such as 2kV/sec until the breakdown occurs. The test is repeated five or six times before taking the average value of the sample breakdown. Figure 1 shows the main parts of the dielectric strength testing device.

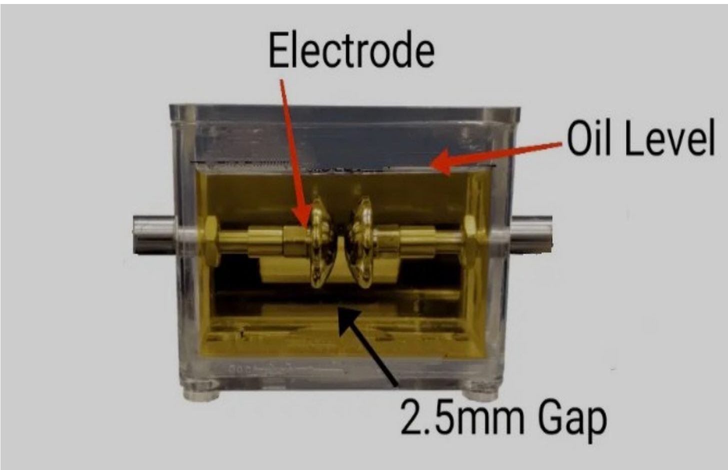

Fig. 1. Dielectric strength testing device for liquid insulation

One of the harmful properties of the oil is the acidity. The acidic components can corrode the transformer metallic parts and reduce the insulating properties of the oil. It was verified by researchers in [15] that low molecular acid significantly reduced the BDV of mineral insulating oil compared to high molecular acidity lower than 1mg KOH/g. The acidity test is one of critical procedures employed to assess the condition and quality of the oil. This test measures the acidic number which reflects the presence of acidic compounds in insulating oil. The measurement is an expression of concentration of acidic particles, acidic products or foreign components resulting from the degradation of the oil. The test is usually done by both colorimetric and automatic potentiometric titration. The first approach is a method that employs a color change to show the endpoint of a titration, whereas the second approach is used in analytical chemistry to find the concentration of a material by measuring the potential difference between two electrodes in a solution as a titrant is added. Both approaches are based on IEC62021, where a base quantity of Potassium Hydroxide (KOH) is added to a known weight or volume of transformer oil until the acidic substances are neutralized. The quantity of KOH required to neutralize the acids is then employed to calculate the acidity of the oil. The oil acidity is not a constant value but increases with time [16,17]. However, this increase is not linear but depends on several factors such as oxidation process, oil quality, temperature and water content. Some researchers have developed and suggested models to describe how the acidity of liquid insulating materials changes due to ageing processes with models focusing on parameters like acidity and other chemical indicators to assess the state of the liquid insulating materials [18].

Figure 2 shows an oil acidity tester that includes equipment for dissolving the sample and performing the titration. This tester needs equipment for preparing the sample. The testing system uses KOH as the titrant and a voltmeter to measure the endpoint, supported by data logging and printing capabilities. This voltmeter is used to measure the voltage difference between two electrodes as the titrant is added. The change in potential indicates the equivalence point (endpoint) of the titration.

Fig. 2. Oil acidity testing device.

One of the crucial tests for insulating oil is the flash point test as it measures the oil's fire hazard potential and can indicate degradation of contamination. The test determines the lowest temperature at which the oil's vapors will ignite with an external ignition source. In this case, it is easy to notice that the liquid reaches its flash point, causing its vapors to form an ignitable mixture with the air near the oil's surface. Due to the heat generated, the oil releases vapors at a certain temperature, known as its flash point, at which the vapors will briefly ignite when exposed to ignition source. The presence of bubbles can affect how quickly the oil heats up and how much vapor it releases. The flash point is measured via a special device called flash point or fire point tester. Many modern devices have the capability to measure both flash points and fire points instantaneously.

Each apparatus has some common elements such as a cup (or container), in which the oil is placed, a heater used to raise the temperature of the cup and a thermometer to accurately measure the temperature at the time of the test. To perform the testing process, approximately 70 milliliters of oil specimen are filled into the test cup. The temperature of the oil is rapidly increased in the initial stage of heating, then the rate of temperature increase slows down considerably as it approaches the flash point, at which time an ignition source will cause a brief flash. The slowdown of the rate of temperature increase is due to the growth of vapor concentration. At certain time intervals, a test flame is applied, and when it causes the vapors above the test specimen to ignite, it is called a flash.

The fire point of vegetable oil is not the same as its smoke point, but it can be approximated to a higher temperature of around 230-260°C. The smoke point is the temperature at which the vegetable oil starts to produce visible smoke. To find out the fire point, it is necessary to continue the test until the flame causes the specimen to ignite and maintain burning for a minimum of 5 seconds. Figure 3 illustrates the flash point device with open cup module. Other modules have closed cup arrangement where the liquid sample is heated in a sealed container with application of an ignition source to the vapors at regular intervals to find the lowest temperature at which they ignite.

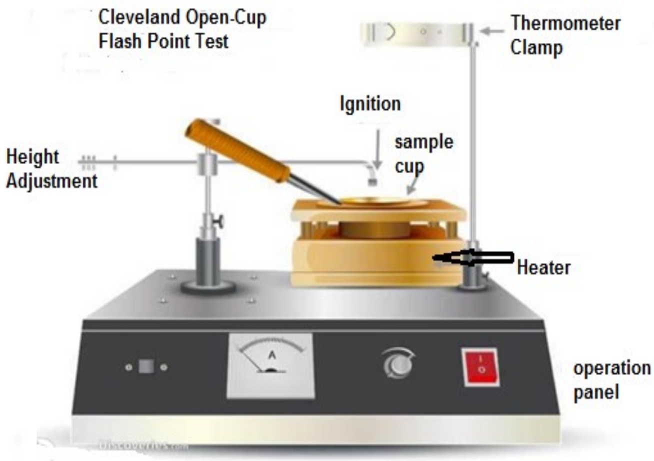

Fig. 3. Flash point testing device.

The fourth property of insulating oil to be tested here is the viscosity. The physical properties of this insulation liquid vary from one liquid to another but are generally affected by the type of the oil, its chemical composition, thermal stress, temperature, pressure, applied forces and molecular interactions and size within the liquid [19]. The oil function plays an important role in deciding the acceptable limits of viscosity. Therefore, the transformer oil is low-viscosity oil because it is used for insulation and cooling, whereas lubrication oil has high viscosity. For other applications, different degrees of viscosity are required. Since there is a strong relationship between viscosity and temperature, several standards describe how to obtain the mean molecular weight from viscosity measurements at certain temperatures. These findings were useful in selecting oils for cold climate applications [20]. In all cases, the viscosity test equipment measures a liquid's resistance to motion under an applied force. Figure 4 shows the device used for the viscosity test in this work.

Fig. 4. Viscosity testing device.

Measuring the water content of liquid insulation is a significant assessment procedure, as water can be absorbed from the atmosphere during transportation, or during oil preparation. The moisture content in the insulating oil sets a serious challenge to the operational life of the transformer. When the water content in the transformer oil exceeds a permissible level, the oil starts to lose its dielectric characteristics [21-23]. Therefore, the continuous check of water content in transformer oil is necessary to keep it at a low level and protect it from breakdown. For HV equipment, which use oil-impregnated paper, the presence of water leads to a fast degradation of such insulating material. Therefore, it is necessary to investigate the water absorption phenomenon and, using the water content tester shown in Fig. 5, assess the resulting development of water uptake. In this case, Karl Fischer Reaction method is applied with standards ASTM D-1533-88.

Fig. 5. Water content tester.

3. RESULTS

The electrical, mechanical and chemical requirements of liquid insulation are varied according to the applications and applied regulations. The above requirements have been verified through several tests, which were developed by a collaboration of specialized companies, insulating oil producers, equipment manufacturers and research laboratories. During these tests, there is an opportunity to examine the behavior of each type of oil and to decide its suitability for a specific application governed by environmental, safety and other regulations. Despite the variety of tests, the common ones are shown in Table 1.

Table 1. Main oil tests and applied standards.

Test type	Applied standards
Dielectric test (BDV)	IEC 60 156
Acidity test	IEC 62021-1,2
Flash point test	ISO2719
Viscosity test	ASTM D7042
Water content test	IEC60814

Dielectric strength is an important parameter to be initially employed for providing a comprehensive comparison between mineral and VOs. This test is a fundamental regularly scheduled procedure used to evaluate the insulation quality of transformer oil. After repeating the test six times under the same conditions, the results are shown in Fig. 6.

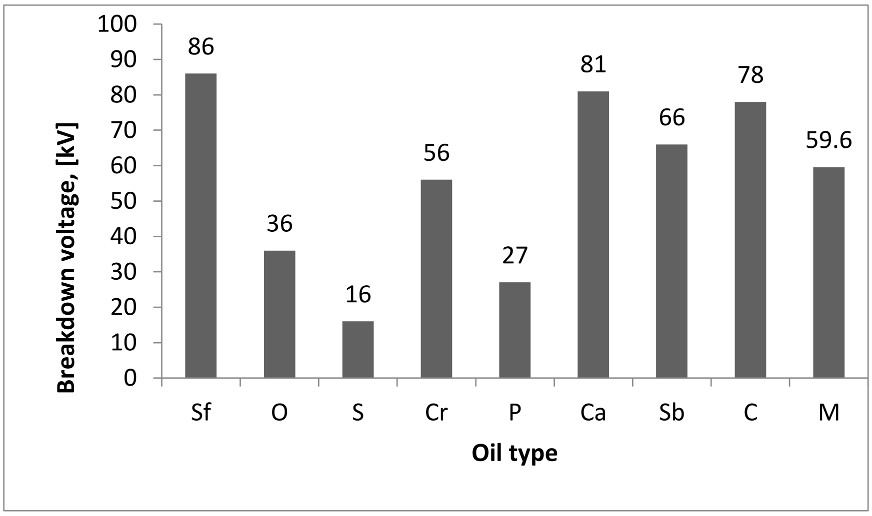

Fig. 6. The results of dielectric strength test for mineral and vegetable oils.

With the exception of olive, palm, castor and sesame oils the rest of VO samples have shown better values of breakdown voltage than mineral oil. Sunflower, canola and corn oils have illustrated the highest values of BDV, whereas the sesame oil has shown the lowest value.

One of the significant tests to assess the quality, stability, and degradation of VOs is the acidity test. This test is a critical indicator of free fatty acids and oil quality. It measures the level of oxidation and degradation but not the specific fatty acid profile of the oil. It is worth mentioning here that vegetable oils are susceptible to oxidation, and thus hermetic sealing of transformers is necessary for optimal performance and to prevent oil degradation. Figure 7 gives the results of acidity, measured for several samples of mineral and vegetable oils similar to that listed in Fig. 6.

According to the limits of acidity (0.2mgKOH/gm), set by the ASTM [24], the results have shown that almost all vegetable oils, with the exception of palm and soybean, have exceeded the acceptable values. Sunflower and olive oils have shown the highest values of acidity.

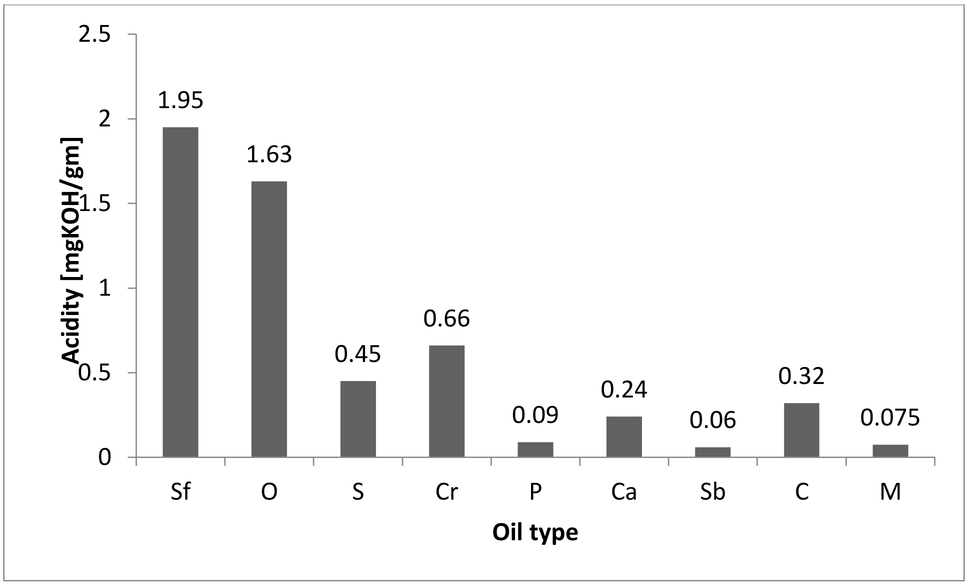

Fig. 7. The results of acidity test for mineral and vegetable oils.

Flash point test is used as an indicator of safety requirement when VOs replace mineral ones in critical places and sensitive areas such as inside buildings, in residential areas, near kindergartens, schools, hospitals or medical centers. This is attributed to the fact that VOs allow a transformer to function at a greater temperature. Figure 8 shows the results of flash point tests for the same oils listed in previous figures.

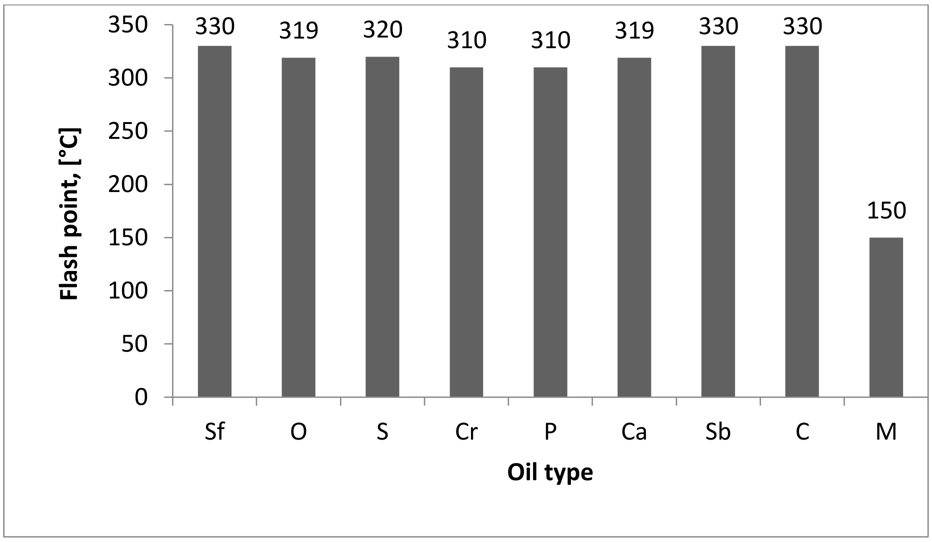

Fig. 8. The results of flash point test for mineral and vegetable oils.

The results shown in Fig. 8 have clearly revealed that all VOs have significantly higher values of flash points in comparison with MO. This finding is one of the key advantages of vegetable oils as insulating materials.

Assessing the viscosity of insulating VOs involves measuring the resistance of this oil to flow at a given temperature. In other words, the capacity to transmit heat through conduction is affected by the viscosity of insulating liquid. Therefore, high viscosity of the oil could prevent the transformer from achieving good and effective cooling. Figure 9 illustrates the results of viscosity test, performed at 40°C, for the mineral and VOs.

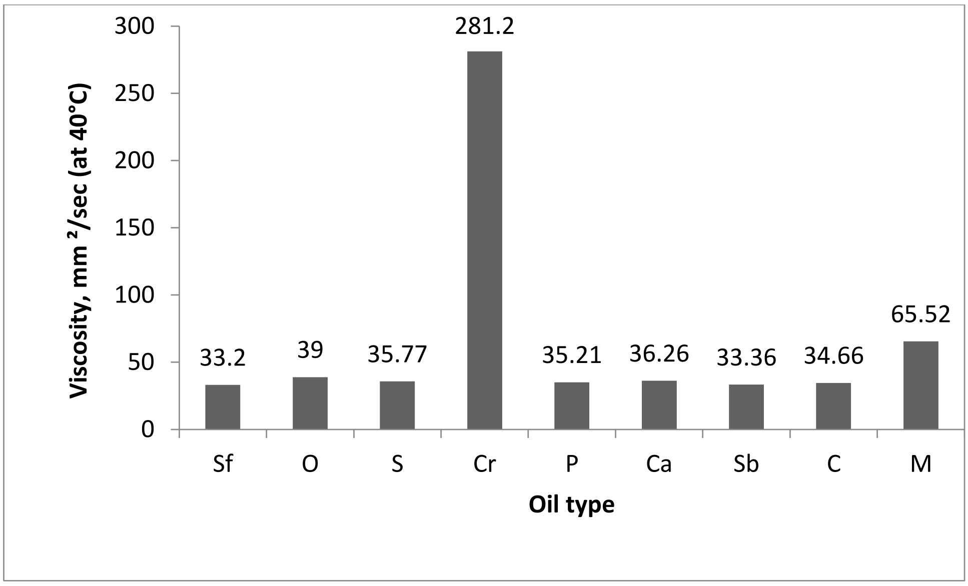

Fig. 9. The results of viscosity test for mineral and vegetable oils

With the exception of castor oil, the viscosity of all VOs is very close to each other. The viscosity of MO is almost twice that of VOs. This is attributed to the difference in chemical structure and the types of molecules they contain. Water content is a significant property of VOs that requires proper assessment. Therefore, the last set of results illustrates the water content test of vegetable and mineral oils, as shown in Fig. 10.

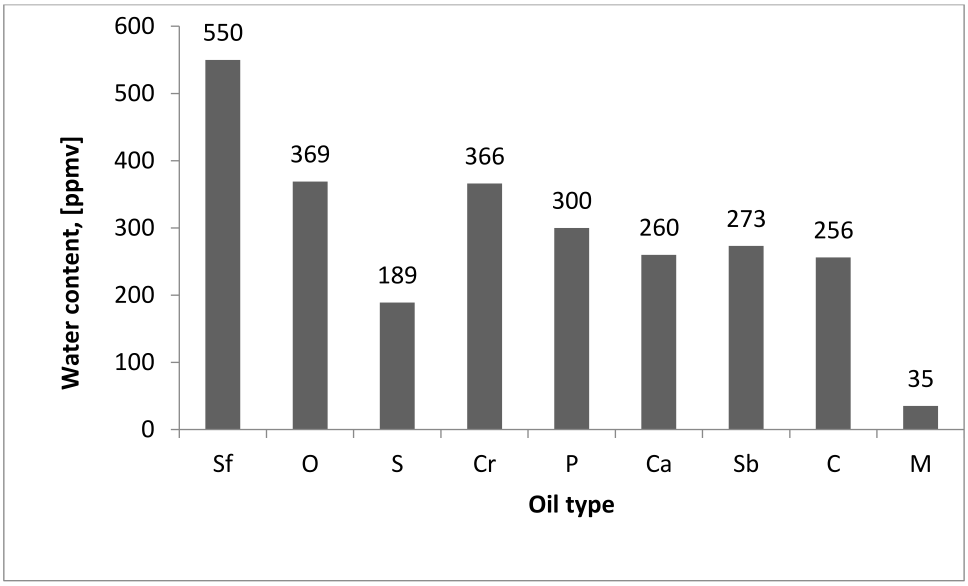

Fig. 10. The results of water content test for mineral and vegetable oils.

The results of water content test have shown that VOs are varied in the amount of water they contain. In this test, the sunflower oil has the highest amount of water content followed by olive and castor oils. The lowest water content among the examined VOs was found in the oil extracted from the sesame seeds. The difference in the obtained results of water content of the inspected VOs is mainly attributed to the processing method, the purpose, the age and the grade of the oil. On the other hand, some of these VOs are edible, which makes the requirements for water content different from that for insulation purposes [25, 26].

To generally assess the overall properties of vegetable insulating oils in comparison with conventional transformer oil, we will summarize such characteristics under categories

"ADVANTAGES" or "DISADVANTAGES" as shown in Table 2.

Table 2. Summary of strong and weak characteristics of tested vegetable oils.

Oil Type	Advantages	Disadvantages
Sunflower	Dielectric strength, flash point and viscosity	Water content and acidity
Olive	Viscosity, flash point	Dielectric strength, acidity, water content
Sesame	Viscosity, flash point	Dielectric strength, acidity, water content
Castor	Flash point	Dielectric strength, acidity, water content, viscosity
Palm	Flash point, viscosity	Dielectric strength, acidity, water content,
Canola	Dielectric strength, flash point, viscosity	Water content, acidity
Soybean	Dielectric strength, acidity, flash point, viscosity	Water content
Corn	Dielectric strength, flash point, viscosity	Acidity, water content

Although such classification is based on the obtained results of the conducted tests, the decision to use a certain type of VO instead of MO depends on prioritizing specific insulation properties like viscosity, breakdown voltage or flash point, as vegetable oils have different strengths and weaknesses such as high flash point and water content. Therefore, designers, manufacturers, operators and owners of power transformers often evaluate the diverse insulation properties of VOs differently, balancing factors like lower environmental impact (biodegradability, higher flash point) against performance trade-offs (viscosity, thermal properties, compatibility), maintenance needs, and costs, as these eco-friendly alternatives present both advantages and challenges compared to traditional mineral oils. Generally, the test results have shown that high acidity and water content are common disadvantages of examined VOs, whereas the high flash point is the common advantage of such oils.

Although VOs are renewable and eco-friendly alternatives to mineral oil in industrial applications like transformers, they are generally more expensive to produce and process than mineral oil. To enhance their quality and suitability for industrial use, crude VOs often undergo costly refining processes such as degumming, neutralization, bleaching and deodorization [27]. On the other hand, the growth of the VO oil sector would enhance the agricultural economy of agrarian nations, helping to reduce the cost of imported mineral oil.

To assess the economic side of using insulating VOs for power transformers instead of MO, it is necessary to compare the costs of these oils. However, these costs can be different for different VOs according to the country of origin, availability, process technology, quality and others. Nevertheless, Fig. 11 shows a sample of such prices as obtained from global and local sources, where the black columns refer to the prices in global market, whereas grey columns refer to oil prices in local market (Jordan) [28-30].

At the end of this work, it is necessary to apply a new assessment method (numerical scoring system) to allow for ranking VOs based on measurable properties rather than just qualitative descriptions, facilitating a superior selection process. In general, some of VO properties are better than MO as insulation liquids (flash point and viscosity), whereas other properties (such as acidity and water content) are worse. Moreover, VOs are generally more expensive and have widely different costs compared to mineral oil. Since the number of examined vegetable oils is eight (8), the best ones, which exhibit higher values of BDV and flash point, are given eight (8) marks, whereas the oil types with the lowest values of such properties are given one (1) mark. On the contrary, the VOs with lower values of acidity, viscosity, water content and cost are given higher marks, whereas the ones with higher values are given lower marks. The results of this scoring system are shown in Table 3.

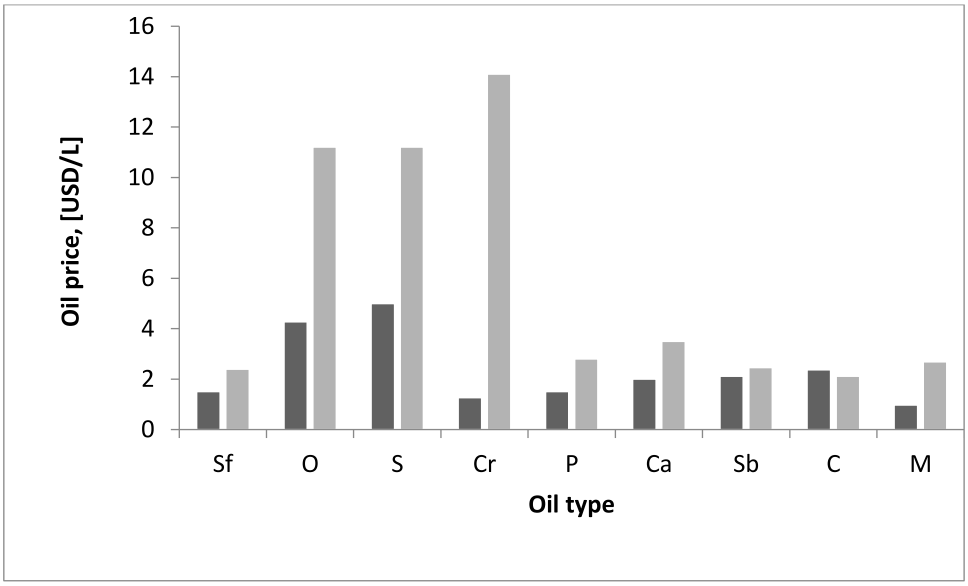

Fig. 11. Insulating oil prices in local market (Jordan) (grey) and global market (black).

Table 3. Numerical scoring system for ranking vegetable oils.

Oil Type	BDV	Flash point	Acidity	Viscosity	Water content	Cost	Total Score
Sunflower	8	8	1	8	1	6	32
Olive	3	4	2	2	2	2	15
Sesame	1	5	4	4	8	1	23
Castor	4	2	3	1	3	8	21
Palm	2	2	7	5	4	7	27
Canola	7	4	6	3	6	5	31
Soybean	5	8	8	7	5	4	37
Corn	6	8	5	6	7	3	35

4. DISCUSSION

It has been found from the tests conducted that many vegetable insulating oils have better insulation properties than mineral oil. However, some types of VOs have shown inconsistent results under different tests. Breakdown voltage of 50% of examined VOs was higher than that of MO. The specific type of vegetable oil, its age, and the presence of moisture can all affect the BDV and the overall electrical performance of the oil. These findings are supported by several studies [31-33] which concluded that VOs have shown higher insulating capacity than MO. Different vegetable oils have different dielectric properties, ageing degrades these properties over time, and moisture is a key contaminant that reduces BDV. Therefore, the samples which have shown a low BDV may be subjected to a high level of moisture, which significantly reduces their dielectric strength. In a previous work [14], it was shown that because most of olive oil in Jordan comes from continuously irrigated farms, this high-water content in the oil from these farms explains its low BDV. On the other hand, sesame and palm oils have low BDV due to their natural chemical composition, which can be affected by water absorption, oxidation and the presence of conductive contaminants that can ease insulation breakdown. Therefore, it is logical to conclude that vegetable oils with low BDV can be used as replacements for mineral oil on the condition of refinement and water removal.

The acidity test has revealed that VOs generally have higher acidity than mineral oils due to their chemical composition and susceptibility to hydrolysis and oxidation. Vegetable oils are composed of triglycerides with free fatty acids, making them more susceptible to hydrolysis and oxidation, which increases their acidity. Unlike VOs, mineral oils being hydrocarbon-based have a different chemical structure and do not undergo hydrolysis and cannot breakdown to form free fatty acids decreasing their acidity. Although palm oil acidity was slightly higher than MO, it was the lowest among all VOs due to processing methods that quickly deactivate lipase enzyme, responsible for breaking down the oil into free fatty acids. In general, low molecular acid significantly reduces the BDV of MO compared to higher molecular acids. This is because low molecular acids have a greater impact on the breakdown voltage of MO than high molecular acids.

The flash point test has clearly shown that VOs generally have a higher flash point than mineral oil, leading to a less probability of ignition and burning out. This is attributed to their larger, complex fat molecules, which require more energy to vaporize and form ignitable vapors. The specific fatty acid composition of the oil plays a significant role, as a higher percentage of single or double bonds can lead to a higher flash point. It is important to emphasize that the flash point is not the same as the auto ignition temperature, which is the temperature at which a substance will spontaneously ignite without any external ignition source. The higher flash point of VOs means that they need a higher temperature to reach its ignition point and initiate the risk of fire. The significant difference in flash point values between MO and VOs emphasizes the importance of using these oils in transformers serving in places with strict fire regulations. This set of results agrees well with the findings of other researchers [31,33]. As one of the important properties of insulating liquid, the viscosity of several vegetable insulating oils was tested and analyzed in this work. The high viscosity results in increased temperatures of transformer between 10 and 30°C. The higher viscosity, however, has also its positive aspect since it implies reduced spread in case of spillage conditions [31]. The majority of these oils have shown a low viscosity in comparison with transformer oil. However, the viscosity of castor oil was rather high due to its high concentration of ricinoleic acid containing a hydroxyl group which makes the oil thicker than other vegetable oils. The low viscosity of examined vegetable oils will add another significant property to modern transformers in addition to the high flash point. The low viscosity of vegetable oils is important for efficient cooling and better circulation of oil inside the transformer. Therefore, the replacement of MO with vegetable one will lead to smooth and longer operational life of transformers.

One of the measures for VOs suitability for insulation purposes is the assessment of their water content. The presence of water within the liquid insulation has several negative impacts, such accelerating the aging process of the oil, decreasing the BDV, and causing operational risks for transformers. The high moisture accelerates insulation degradation and can form bubbles. The negative effect of moisture is directly related to its volume within the liquid insulation. This is attributed to the higher thermal conductivity of the water compared with that of oil, which finally leads to a reduction in the insulation performance. The variation in the water content is ascribed to many factors such as processing methods, storage conditions, and oil age. The results of this work are supported by the findings of previous work [14].

The comparison of VO characteristics with MO properties has revealed that the majority of insulating vegetable oils have better viscosity and flash point values, whereas they are worse in water content and acidity. This general classification of vegetable oils assists in initial selection of the desired type of such oils according to the applied regulations. Therefore, Table 2 was introduced to summarize the strong and weak insulation properties of VOs in comparison with MO. A similar general classification was done by other researchers and summarized in [26]. Modern techniques should be employed to enhance the strong properties of insulating vegetable oils (viscosity and flash point), while mitigating their weaker characteristics (acidity, BDV and water content) to improve their adoption as a sustainable, high voltage insulating material.

Filtration process is necessary to improve the VO characteristics through removing the moisture and impurities such as solid particles, gums and other contaminants that affect oil's stability [26]. The filtration process, for example, removes waxes from oils extracted from sunflower seeds and corn. To reduce water content in vegetable oils, some advanced filtration methods, such as membrane filtration, are specifically designed. Among advanced membrane methods are ultra filtration and nanofiltration, which are specifically designed to separate components based on pore size and other properties. This allows for the removal of water and other impurities while retaining the oil. Although filtration is a common process used to purify many VOs, we will focus here on its effect on olive oil.

The olive oil is filtered by forcing oil under pressure to pass through a series of absorbents to remove free water, sludge and other suspended contaminants. The filtration process was carried out at a room temperature of 30°C because filtration at a temperature under 20°C will significantly increase the viscosity, whereas filtration at temperature above 40°C will complicate water separation from olive oil. The complication at higher at higher temperatures is more related to the potential for damaging the oil's quality rather than complicating water separation itself. When the filtration process was repeated six times, the water content was reduced to 50% of that for fresh olive oil. This has led to an increase in the dielectric constant by 100% without affecting the viscosity and flash point characteristics. Although further filtration improves the dielectric properties, the improvement rate is decreased. Finally, to solve the problem of air bubbles in olive oil, it is allowed to release such air through evacuator or simply by leaving the oil sample to settle down for a reasonable period.

One of the important aspects of VOs is economic assessment. The adoption of such oils is heavily influenced by cost analysis, including refining processes, higher initial purchase prices and maintenance considerations. Therefore, the final prices of insulating VOs are influenced by several factors like crude oil type, impurity levels, seed availability, refining techniques, and transportation. Although this variety of factors affecting VO prices is reflected in both global and local (Jordan) markets, as shown in Figure 11, global market prices were less variable and, therefore, selected for further analysis. This analysis is essential to identify opportunities to reduce the final costs of insulating VOs, facilitating a complete techno-economic assessment.

To provide an overall evaluation and a clear, systematic methodology to objectively assess and rank the oils considered in this study, a numerical scoring system was implemented. Despite the general, conflicting descriptions of vegetable oils' advantages and disadvantages compared to MO, this system assigns each oil type an appropriate score, as shown in Table 3. Although this weighting system has revealed that soybean oil performs best overall, there are some oil types, such as corn and sunflower oil, which have good scores. However, vegetable oils with lower scores require further refinement and reduced cost to be used as alternatives to MO in transformers.

5. CONCLUSIONS

According to the results of this study, the use of insulating vegetable oils is technically viable for electric utilities, especially those facing problems with conventional mineral oil. In general, the insulation of vegetable oils has shown a good functionality, and for some parameters, they have exceeded standard criteria. Therefore, properties like high flash point, viscosity and good BDV often exceed traditional standards, whereas parameters like acidity may require improvements or processing to match mineral oil. The use of insulating vegetable oils increases the useful life of transformers and significantly reduces the environmental risk of petroleum oil. The problem of contamination and low dielectric strength of some insulating vegetable oils was solved by sequential filtration. This method is not only simple, but it is also cost effective. To assess and rank the oils considered in the study, two approaches were followed. The first approach was general with a purpose to show which vegetable oils are better or worse than mineral oil. The second approach was more specific with a numerical scoring system and cost consideration of vegetable oils examined. This weighting system has shown that soybean oil performs best overall, followed by corn and sunflower oils. Although the main purpose of this research was achieved, it creates new discussions on the development of future techniques focusing on processing and purification of insulating vegetable oils. This requires more investment in research, which happens only when there is a greater awareness of the environmental and sustainable development aspects of insulating vegetable oils. In future, it is planned to carry out a detailed analysis of the long-term use of insulating vegetable oils concerning initial and running costs. Finally, this study will be expanded to allow for significant contributions to society and scientific community.

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