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Transforming Sustainability: Blending Chemically Enhanced Soybean Oil with Used Transformer Oil for Eco-Friendly Recycling

Ali K. Khalf Allah [1], Gharib M. Taha [2], Loai S.E Nasrat [3], Hamdy A. Zahran [4], Heba S. Mandour [5*]

[1] Chemistry Department, Faculty of Science, Aswan University, Egypt
[2] Chemistry Department, Faculty of Science, Aswan University, Egypt
[3] Electrical Power& Machines Department, Faculty of Engineering, Aswan University, Egypt
[4] Oils and Fats Department, Food Industries and Nutrition Research Institute, Dokki, Cairo, Egypt
[5*] Solid Waste and Hazardous Materials Department, Ministry of Environment, Aswan, Egypt

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Abstract:

For insulation and to prevent discharge and arcing, mineral oil is frequently used in power transformers. However, because of the mineral oil's extremely low flashpoint and lack of sustainability, this can also result in an explosion in the event of a fire. In this study, a mineral oil substitute that employs waste soybean oil that has been chemically altered through transesterification and epoxidation reactions to achieve the desired properties that meet ASTM standard requirements for power transformers is proposed. After going through the transesterification and epoxidation processes, the performance of waste soybean vegetable oil for use in electrical transformers has been assessed. For fresh mineral oil FMO, used mineral oil UMO, and recycled mineral oil RMO, which is produced by mixing with synthesized soybean vegetable oil SSVO with different concentrations, the physical properties (dynamic viscosity and flash point), chemical properties (water content and acidity), and electrical properties (break-down voltage) were measured. According to these measured data, the physical characteristics of the RMO at the mixing proportion (7:3-UTO: SSVO) are higher than those of the FMO and UMO, respectively, while the water content of the RMO is significantly higher than that of the FMO but lower than that of the UMO. Additionally, the breakdown voltage values of RMO show an increase over UMO, but it is lower than FMO, and the acidity of RMO is lower than UMO and higher than FMO. All previous measurements were also taken for waste soybean vegetable oil WSVO that was used in the synthesis of SSVO, and previous values meet the limited values of ASTM. The current study suggested synthesized soybean vegetable oil as a sustainable method of utilizing waste resources, reducing environmental pollution, and promoting environmental and economic benefits, in addition to being a replacement cooling medium for liquid-filled transformers.

Keywords: Bio-Diesel, Waste soybean oil, Transformer oil, Recycling.

Corresponding author*: E-mail address: *heba23192@gmail.com* *heba.mandoor@sci.aswu.edu.eg*

Nomenclature :

WSVO	Wate Soybean vegetable oil
SSVO	synthesized soybean vegetable oil
FMO	Fresh mineral oil
UMO	Used mineral oil
RMO	Recycled mineral oil

1- Introduction

One of the costliest and most crucial tools for supplying electrical energy to homes and enterprises is the electrical transformer. The primary sources of heat generation that contribute to the rise in temperature in a running transformer are the electrical and magnetic losses of the transformer's heart and windings. A transformer's failure and ageing are thought to be mostly caused by this temperature increase, which must be eliminated via effective cooling methods. **(Bertrand et al, 2003; Takahashi et al , 2017)**

To ensure the safe operation of the transformers, petroleum-fueled oil has been used as thermal cooling and electrical insulating media for over a century. **(Rouse, ١٩٩٨; Dombek, and Gielniak, 2018).** Finding alternatives is, however, being carefully considered due to the growing problems regarding this source of energy, such as the growing demand for petroleum products in modern industrialized countries, limitations in petroleum resources, non-biodegradability, high cost, and toxicity. **(Atmanli,2015; Mariprasath and Kirubakaran, 2016)**

Numerous types of oils, including silicon oil (**Perrier and Beroual, 2009**), natural ester **(Ortiz,2018)** , and synthesized ester **(Fofana., 2013)** , have been extensively utilized and tested in the search for a workable substitute for mineral-based oil. Vegetable oils are also seen to be a suitable replacement in this regard because of their appealing qualities such renewability, low toxicity, biodegradability, minimal environmental impact, availability, and high flash point **(Qiu,2011; Sajeeb et al , 2019)**.

Previous studies concentrated on the impact of ageing on the qualities of various oils and described the fundamental traits of substitute liquids **(Herrera.2006; Fernández ,2013)**, mostly vegetable oils, as well as their performance after ageing to show their suitability for mineral oil replacement. They recommended the vegetable oils canola, rapeseed, soybean, and sunflower as having the finest qualities for use as novel cooling fluids. Similar research was conducted by **(Rafiq, 2015; Zaher et al., 2017; Madavan et al , 2021; Mandour et al., 2023)** , who provided a thorough report on the usage of vegetable oil in transformers and covered the crucial characteristics of the oil. It was determined that utilizing vegetable oil as transformer oil can significantly aid in reducing the environmental impact of petroleum-based products.

The AC breakdown voltage is one of the most severe properties of transformer oil. The lowest voltage that causes an electrical insulator, such as oil, to become somewhat electrically conductive is known as the breakdown voltage. **(Dang et al, 2011; Martin and Wang, 2008)** Because of this, a transformer oil's breakdown voltage needs to be sufficiently high to avoid incomplete conductivity in electricity and transformer failures. The breakdown voltage of vegetable oils has been the subject of numerous tests **(Martin., 2006; Tenbohlen and Koch., 2010)**. Despite the significant progress made in establishing vegetable oils as a possible replacement for mineral oil, the increasing need for them in developed countries may drive up the price of crops and put stress on customers, particularly those who are most at risk of being food insecure and starving **(Albers et al, 2016; Senthilkumar et al, 2021)**. In this regard, considering vegetable oil as an alternative lessens this worry and fosters a beneficial cycle for enhancing material recovery and repurposing waste resources **(Capuano, 2017**). Waste soybean oil is one sort of waste vegetable oil that can be found anywhere food is fried or cooked in oil. It is derived from the disposal of cooking oils **(Hribernik and Keg., 2009)**

The main purpose of the current study is recycling of used mineral oil and enhancement of its physical, chemical and electrical characteristics by mixing with synthetic soybean with different percentage weights and evaluating the best proportion of the mixed mineral and vegetable oils.

2. Materials and Methods

2.1. Materials

Oils: synthesized soybean vegetable oil SSVO was obtained by transesterification and epoxidation reaction of waste soybean vegetable oil WSVO mixed with 2 gm of tert-butyl hydroquinone antioxidant at the analytical and environmental chemistry lab in the faculty of science, Aswan University. Two mineral oils FMO and UMO were purchased from the Egyptian company for production and distribution of electricity in Aswan Governorate, Egypt. Whereas FMO is Dayala B, Production year 2019, UMO Dayala B was obtained from the transformer with 40 MVA, 11-66 KV .

Chemicals: anhydrous magnesium sulphate and sodium bicarbonate $NaHCO_3$ (99%) were used.

2.2.Methods

2.2.1 Recycled mineral oil sample preparation.

Waste soybean vegetable oil WSVO was filtrated to remove impurities , while the synthesized soybean vegetable oil SSVO with 2 gm of TBHQ was dehydrated by anhydrous magnesium to remove excess water , and neutralized by sodium bi-carbonate to remove an excess amount of acetic that might exist after synthesis .

The oil mixes were made by adding precise amounts of UMO to a container filled with vegetable oil (SSVO in the following concentrations (UMO: SSVO - 9:1 - 8:2 – 7:3 – 6:4 – 5:5), then stir it gently with a magnetic stirrer at 40 ◦ C for 10 minutes to ensure of complete mixing.. Vegetable oil in its degassed and dried states is particularly hygroscopic, so after preparing the mixed samples, dehydration was carried out for only 24 hours to remove fresh uptake of moisture during mixing. **(Rengaraj et al , 2022 ; Borsi , 1991)**

UMO and SSVO are mixed in a range of 0% to 50%. In Table 1, the mixing formulae are displayed. Due to the primary goal of this research, which is to use the SSVO as an alternative insulating liquid in transformers, the UMO was restricted to 50%.

Table (1). UMO/SSVO mixture (recycled mineral oil – RMO)

Samples symbol	UMO	SSVO
R1	90 %	10 %
R2	80 %	20 %
R3	70 %	30%
R4	60%	40%
R5	50%	50%

2.2.2 *Testing methods*

2.2.2.1 *Dynamic Viscosity*

Brook field viscometer was used to estimate the dynamic viscosity at 40◦C, the synchronous motor has been replaced by a stepping motor. A torque transducer transforms the torsion of the spring into electrical tension which can then be converted into viscosity by the electronic card. **(Nuriziani et al ., 2016; ASTM D445-21., 2003)**

2.2.2.2 *Flash Point*

At normal temperature, the liquid dielectric's flash point and fire point are measured using the Penky Martin flash point apparatus. The test cell is filled with a test sample, and the temperature is gradually raised externally. When a temperature flash happens, it is referred to as the "flash point," and when a continuous temperature fire occurs, it is referred to as the "fire point." **(ASTM D2162-06., 2006; Samikkannu et al ., 2021)**

2.2.2.3Water Content

Using a Metrohm 899 Karl Fischer coulometer, the water content of the oil was determined by ASTM D1533. The Karl-Fischer coulometer uses chemical analysis to ascertain the amount of water present by adding a reagent—an iodine solution—in carefully measured proportions. **(Castañeda., 2015)**

2.2.2.4 Acidity

Calculating the amount of potassium hydroxide required to neutralize the acid in a liquid dielectric is how acidity is determined. **(IEC 62021-1, 2003)**

2..2.2.5 Breakdown *voltage*

Using an automatic breakdown voltage measurement device made by Megger, the AC breakdown voltage of a liquid dielectric is measured. To assess breakdown voltage, a test cell with a 2.5-mm sphere electrode arrangement is employed. The average of six measurements is used to determine the liquid dielectric breakdown voltage. **(IEC 60156, 1995)**

3. Results and Discussion

Transformer oil is typically a blend of different hydrocarbon chemicals, including aromatic, paraffin, hexane, naphthenic, and benzene. It is typically obtained by the fractionation and subsequent processing of crude oil. This oil is also named Mineral Insulating Oil for this reason. electrical apparatus Oil primarily performs two tasks: it insulates electrical devices against heat by acting as a liquid, and it also serves as a fluid by dissipating heat. In addition to those, this oil has extra two important uses **(Toudja et al., 2014)**. First, because the core and winding are completely submerged in oil, it aids in maintaining them. But transformer oil has a problem which is low bio-degradability, short long term sustainability and low fire point, so by examining chemical, physical and electrical properties of the power transformer, mineral oil has a superior cooling capability so that it was employed to limit heat generation although its viscosity is affected by the ageing of the oil, according to the following numerical studies of (FMO) **(Samuel Pakianathan., 2013)** . **Table 2**

Table (2): critical characteristics of FMO, UMO,WSVO and SSVO

Critical characteristics	**Tests**	**(FMO)**	**(UMO)**	**(WSVO)**	**(SSVO)**
Physical characteristics	Dynamic viscosity at 40 ◦ C (mPa)	9.102	11.02	24.3	14.76
	Flash point (◦C)	146	125	129.6	235.7
Chemical characteristics	Water content (mg/kg^{-1})	25	48	130	39.5
	Acidity (mg/KOH)	0.05	0.4	0.1	0.06
Electrical characteristics	Break down voltage (kv)	45	28	10.5	38.3

According to **Anu (2023),** the dynamic viscosity value of FMO is 9.102 mPa, which is somewhat like MO's viscosity but larger than the viscosity value of MO which was 7.2 than was reported at **Michel and Boris.(2011**). The Mark-Houwink-Sakurada equation states that the viscosity of oil depends on the average molecular weight **(Valdés et al ., 2016)**.It comparison to FMO and UMO, it is substantially higher in SSVO and WSVO. the dynamic viscosity values of WSVO was similar to that was measured by Davies **(2016**) which was 24.5 , The viscosity of the oil is significantly influenced by ageing and severe oxidation**.(Yang et al , 2014)** .

The flash point value of FMO is 146 ◦ C was higher than of flash point value of pure mineral oil estimated by **Rengaraj et al .(2022)** , When compared to palm kernel epoxy alkyl ester, which has a flash point of 148 ◦ C, (SSVO) 235.7 had a greater flash point and it was higher than of WSVO , while the flash point of WSVO was less than measured flash point value of soybean 175 ◦ C by **Sylvain and Kouame(2011)** .

The water content value of FMO which is 25 mg/kg^{-1} was less than the measured water content value of Naphthenic Mineral oil (A) which was 70 mg/kg^{-1} **(Perrier et al , 2006)** As calculated by **Muhammad et al.(2020**), the water content value of SSVO (39.5 mg/kg^{-1}) was lower than waste cook methyl ester**.** According to Table 2, the water content of (WSVO) and SSVO is significantly larger than that of FMO, but lower than that of UMO. Moisture has caused the saturation limit SSVO to be substantially higher than the FMO limit. Even though SSVO had better electrical properties than UMO, FMO had a higher relative break-down voltage value. **(Singha et al., 2014; Liao et al , 2011)**

In the meantime, the acidity of SSVO is 0.06 mg/KOH less than the acidity value of WCOME 0.2578 mg/KOH. As demonstrated in Table 2, SSVO has a slightly greater acidity than FMO and a lower acidity than UMO and WSVO. Since the acidity value in SSVO is different from FMO, it has no effect on the cellulose insulation. In FMO and UMO, as opposed to SSVO, acid generation occurs after chain off, chain continuity, and chain breaking out. Thus, FMO contains lower molecular acids like formic, acetic, and levulinic acids, but SSVO contains a higher proportion of higher molecular fatty acids like oleic acid and linoleic acid. These acids do not speed up paper ageing, however lower molecular acids react with paper and have an impact on paper ageing. **(Mariprasath and Kirubakaran., 2016)**

Because mineral oil comprises hydrocarbon components with varying compositions, the average breakdown voltage values for SSVO are 38.3 kV, which is significantly greater than that for UMO and WSVO as shown in Table 2.When this oil combines with oxygen, it produces carbon monoxide, carbon dioxide, hydrogen, and sludge, all of which effectively impair the oil's ability to break down **(Jeong et al ., 2012**) . Contrarily, SSVO has a higher proportion of unsaturated fatty acids as a result; this causes SSVO to have a higher viscosity when compared to FMO and UMO, which restricts particle movement within the oil. (**Bala et al, 2011; Dwivedi et al, 2013)**

The ageing of transformers is slowly dependent on how quickly its entire insulation, and particularly the oil, ages. The oxidation of oil and the deterioration of its insulating and cooling characteristics are caused by thermal and mechanical forces. Foreign particles and moisture are other elements that affect how well oil conducts electricity and how quickly it fails. The viscosity and acidity of the oil started to increase because of foreign particles and moisture and due to the high humidity and the presence of small particles of water content the dielectric strength reduced. One of the primary implications is that all the measurable metrics stated above should be considered. **(Viet et al., 2011)**

Table (3). Critical characteristics of RMO

Critical characteristics	Tests	Recycled Mineral Oil (RMO)					ASTM
		R1	R2	R3	R4	R5	
Physical characteristics	Dynamic viscosity at 40 ◦ C (mPa)	9.91	10.19	11.87	12.31	14.49	≤ 0.358-15.8 mPa
	Flash Point (◦C)	195.5	205.91	201.78	221.13	215.67	≥ 135 ◦C
Chemical characteristics	Water content (mg/kg^{1})	44.01	45.3	40.01	44.92	46.7	≤ 500 mg/kg^{-1}
	Acidity (mg/KOH)	0.3	0.2	0.07	0.1	0.2	Max 0.5 mg/KOH
Electrical characteristics	Breakdown voltage (kV)	29.5	30.3	36.5	33.2	34.1	25-40 kV

Triglycerides, which are essentially what vegetable oil is made of, are naturally created when three fatty acids and the tri-alcohol glycerol are esterified. The linear hydrocarbon chains that make up the fatty acids are terminated by a carboxylic function. Triglycerides normally include 8 to 22 carbon atoms, and these compounds have an even number of carbon atoms. The chain can be saturated or primarily mono-, di-, and tri-unsaturated. Compared to mineral oils, vegetable oils are biodegradable and have very low toxicity. Additionally, it lacks volatile organics, and halogens. It has been widely employed in power transformer designs because of its electrical insulating capability. **(Abdelmalik et al, 2011)**

According to data illustrated in Table (3), the addition of SSVO with different concentrations to UMO causes several changes in critical properties and makes it reach to the ASTM standard limits and the FMO, which allows it to be reused and reduces it toxicity.

A liquid dielectric's viscosity is an important feature of the process of impregnation and heat transmission. Additionally, it is a crucial factor in developing a transformer's heat transmission system. Low viscosity and strong specific heat capacity are required for enhanced heat transferability (**Mehta et al, 2016**).

Viscosity values in which mixing of (UMO) with (SSVO) caused a decrement in the dynamic viscosity values in ratios R1, R2 and R3, While in ratios R4 and R5 the Dynamic viscosity values of (UMO) increased, but all values still in ASTM standard, the dynamic viscosity values of the R3 ratio was close to (FMO) (**Kumar et al , 2016) Figure (1)**

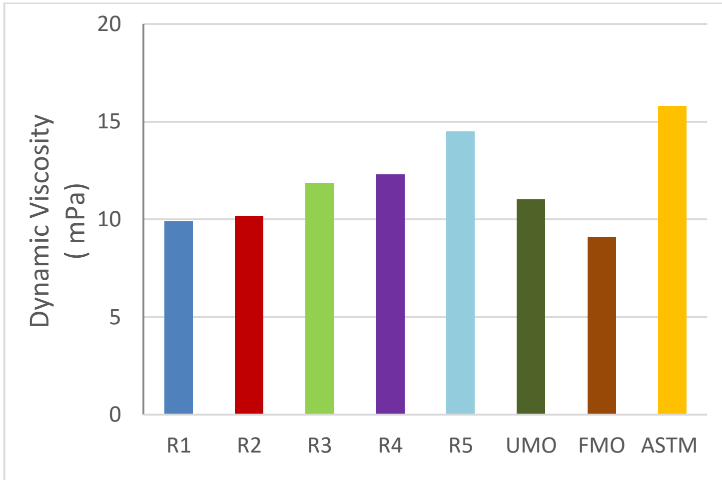

Fig (1) Dynamic Viscosity comparison between (RMO), (UMO) and (FMO)

As shown in (**Figure 2)** the flash point values of UMO increased with the addition of (SSVO) and the values were higher than the flash point of the FMO, the highest flash point value was for the R5 ratio and the lowest flash point values were for R1 and R3 ratios all of the flash point values are in the available ASTM standard values **(Samikannu et al, 2021) .**

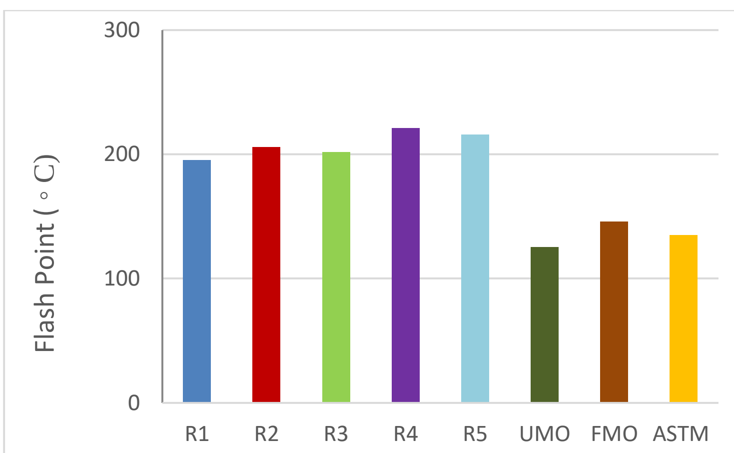

Fig (2) Flash Point values comparison between (RMO),(UMO) and (FMO)

Water content values of UMO started to decrease in all RMO ratios except in R4 and R5 in which the water content back to increased, the nearest water content value for FMO was for the R3 ratio which reaches to the standard ASTM values. (**Yushi et al, 2017**) (**Figure 3)**

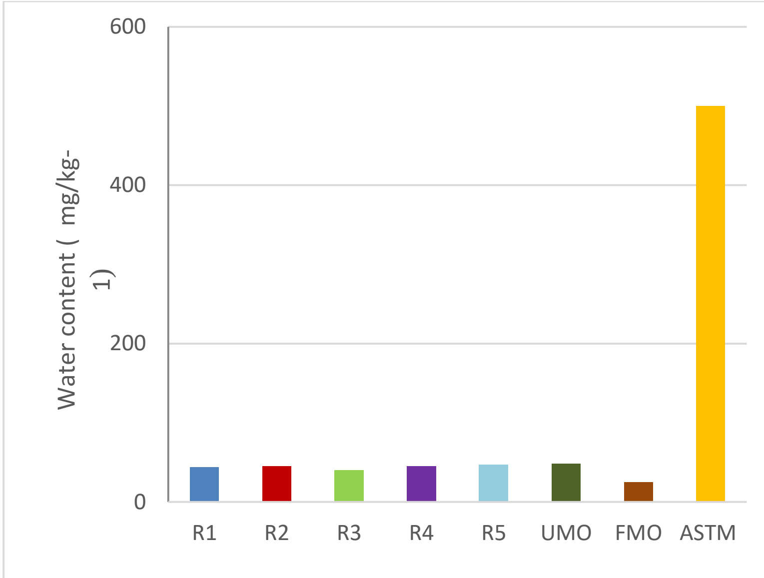

Fig (3) Water Content values comparison between (RMO), (UMO) and (FMO)

Acidity values started a decrement by the mixing UMO oil with SSVO, according to **(Figure 4)** and **Table (3),** the acidity of UMO is more than that of RMO ratios. the highest acid value was for R1 ratio, while the lowest acid value was for R3 ratio. **(Muhamad et al, 2012)**

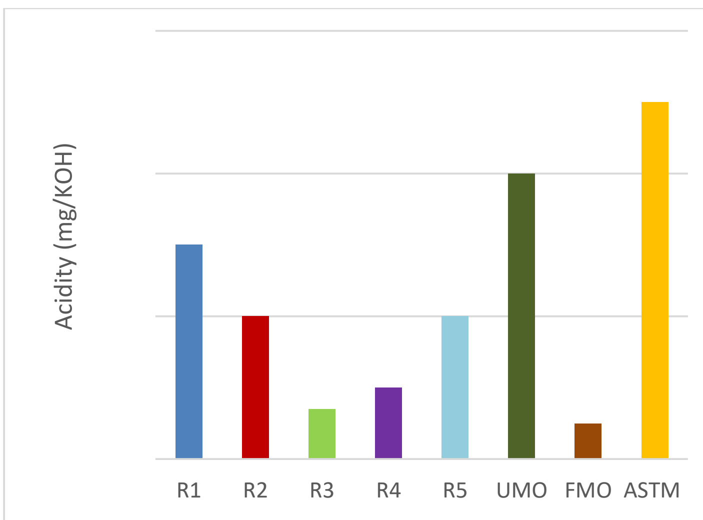

Fig (4) Acidity values comparison between (RMO), (UMO) and (FMO)

Depending on contaminants like acid and water content that are present in liquid insulation, breakdown voltage incidents of that insulation are spread across nature **(ASTM D93, 2006**). Additionally, it offers important details regarding transformer insulation system design requirements **(Madavan et al , 2015**) . The best assessment of breakdown voltage is given in Table 3 by the average breakdown voltage of five subsequent measurements of the breakdown voltage of RMO. Additionally, it is beneficial to conduct a comparison between RMO, UMO, and FMO ratios. It can be shown from (**Figure 5**) that UMO oil has a lower breakdown voltage than RMO ratios.

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Breakdown voltage values showed in.(**Figure 5)** an increment in the addition of SSVO to UMO, the highest break down voltage value was for R1 ratio, all the breakdown voltage values of RMO oil were in the available values of standard ASTM except the 9:1 ratio .

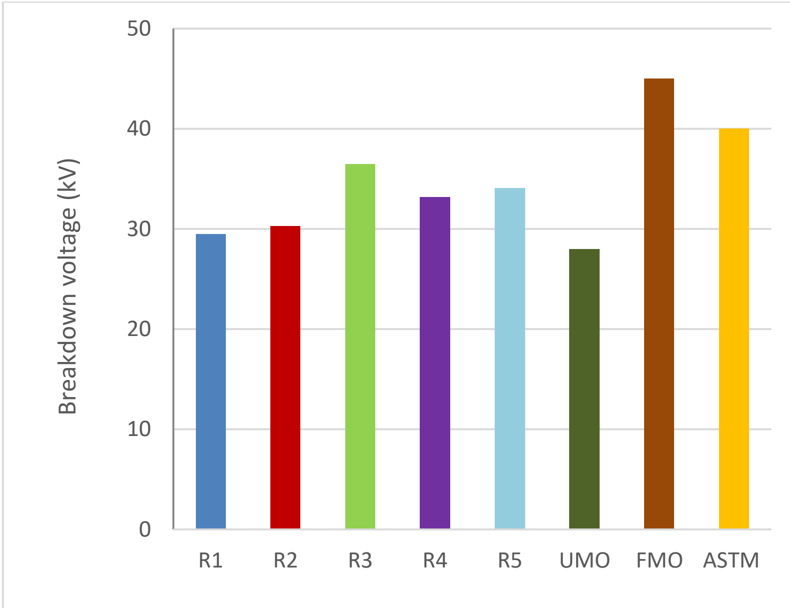

Fig (5) Breakdown Voltage values comparison between (RMO), (UMO) and (FMO)

Conclusion

In conclusion, compared with literature reviews this study has highlighted the potential of synthetic vegetable oil, particularly waste soybean vegetable oil, as an environmentally friendly alternative to petroleum-derived mineral oil in transformers by the applied experimental tests. The experimental investigation encompassed a comprehensive evaluation of the physical, chemical, and electrical properties of synthesized soybean oil in comparison to both fresh and used mineral oils. Moreover, we formulated mixed liquid insulations by blending synthetic soybean oil with used mineral oils at varying ratios and subjected them to rigorous scrutiny. Our findings reveal that synthetic soybean vegetable oil exhibited superior performance in terms of breakdown voltage and flash point when compared to used mineral oil. Furthermore, as the mixing ratio of synthetic soybean oil in the mixed liquid insulations increased, their performance improved until it reached the R3 ratio. Even though the acidity of the applied mineral oil began to decrease, the R3 ratio remained in compliance with ASTM standards and displayed qualities like fresh mineral oil. It's worth noting that both synthesized soybean oil and mixed liquid insulations had higher viscosities compared to fresh mineral oil, underscoring their potential as viable and sustainable alternatives in transformer applications.

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