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Sesame Oil with Butylated Hydroxyanisole as a Candidate Natural Ester for Transformer Insulation

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ABSTRACT

This study evaluates sesame oil modified with butylated hydroxyanisole (BHA) as a candidate eco-friendly transformer insulating liquid. Ten formulations were prepared using 500 mL sesame oil with 1-10 g BHA. Viscosity was measured using a rotational viscotester, and the laboratory-reported kinematic values were treated as estimates derived from the direct viscosity readings. Alternating-current breakdown voltage (BDV) was measured five times for each formulation, and differences among BHA loadings were evaluated using one-way analysis of variance. The estimated kinematic viscosity ranged from 33.33 to 42.59 cSt and generally decreased as BHA loading increased. The highest mean BDV was obtained at 3 g BHA/500 mL (30.24 +/- 7.94 kV), whereas the 10 g formulation showed the lowest estimated viscosity (33.33 cSt) and the second-highest BDV (25.58 +/- 3.38 kV). BDV exhibited a non-monotonic response to BHA loading. One-way ANOVA indicated significant differences among formulations ($F(9,40)=7.98$, $p<0.001$). The results identify 3 g BHA/500 mL as the most promising formulation in the current screening because it combined the highest dielectric performance with moderate viscosity. Further validation with BHA-free sesame oil, mineral-oil controls, independent formulation batches, measured density, moisture, acidity, and direct kinematic-viscosity testing is required before transformer application.

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1. INTRODUCTION

Liquid-immersed transformers depend on the insulating fluid both to withstand electrical stress and to transfer heat away from the active parts. Mineral insulating oil remains a mature reference fluid and is specified for insulation and heat-transfer service in IEC 60296, while natural esters are separately covered by IEC 62770 and maintenance guidance is provided by IEC 62975 and IEEE C57.147 [1]–[4]. The growing interest in natural esters is driven by the need for renewable insulating liquids with improved environmental and fire-safety characteristics, but their higher viscosity, sensitivity to oxidation, moisture behavior, and dielectric performance must be controlled before practical transformer use [1], [2], [4]–[7].

Viscosity and dielectric strength are particularly important because they represent different functional requirements. Viscosity influences fluid circulation and therefore cooling performance, whereas breakdown voltage reflects the ability of the liquid to withstand an increasing electrical field before failure. IEC 63012 explicitly recognizes viscosity as a parameter that can affect electrical-equipment cooling, and IEC 60156 defines the standardized power-frequency BDV test for insulating liquids [8], [9]. Experimental studies on natural esters have further shown that viscosity, moisture, molecular structure, additive concentration, and conditioning can alter dielectric performance [10]–[16]. Consequently, optimization of a vegetable-oil insulating liquid should not be based on a single response.

Sesame oil is an attractive vegetable-oil matrix because its intrinsic chemical composition directly addresses the poor oxidation stability typically associated with natural esters. It contains unique lignan-related antioxidant components, and recent experimental work has shown that sesamin, sesamolin, and sesamol can significantly suppress lipid oxidation and increase oxidation induction time [5]. These inherent self-stabilizing properties make sesame oil a highly promising base fluid for transformer insulation, provided its viscosity and dielectric strength can be optimized. In transformer-oriented research, Moosasait et al. included sesame oil among vegetable oils modified with benzyl benzoate and demonstrated that formulation changes can substantially reduce viscosity while also affecting BDV, moisture, acidity, density, and flash point [17]. These findings indicate that sesame oil has modifiable physical and dielectric characteristics, but a formulation strategy must preserve an acceptable balance among them.

Butylated hydroxyanisole (BHA) is a phenolic antioxidant that has been investigated as an additive in vegetable-oil and natural-ester formulations. Handayani et al. reported a non-linear BDV response when BHA concentration was varied in soybean oil [6]. Thangaraj et al. used BHA and butylated hydroxytoluene in blended natural esters and showed that antioxidant inclusion and preparation conditions influence viscosity and dielectric behavior [7]More recently, Afrida et al. demonstrated that BHA concentration changes both viscosity and BDV in palm-oil-based insulation, while not necessarily producing a monotonic improvement [13]. Earlier work on antioxidant-modified natural esters likewise showed that additive selection and concentration can change critical insulation characteristics [18].

Within the literature reviewed for this study, the fundamental interaction between synthetic phenolic antioxidants (such as BHA) and the naturally lignan-rich matrix of sesame oil remains scientifically unresolved. Specifically, it is unknown how this combination alters the internal fluid friction and the electron avalanche mechanisms that govern viscosity and breakdown voltage, respectively. While non-monotonic dielectric responses to antioxidants have been observed in soybean and palm oils, it is unclear if this behavior is universal or matrix-dependent. The present work therefore screens ten BHA loadings in a fixed volume of sesame oil to jointly evaluate viscosity and AC breakdown voltage.

2. METHOD

2.1. Materials and Experimental Design

The study used sesame oil as the base liquid and BHA as the antioxidant additive. Ten formulations were prepared, each containing 500 mL sesame oil with 1-10 g BHA. The corresponding nominal BHA loadings were 2-20 g/L, equivalent to 0.2-2.0 g per 100 mL of base oil. Sample handling should minimize contamination by moisture and particles in accordance with the principles of IEC 60296 [19]Table I summarizes the experimental formulations.

Table 1 BHA Formulations in 500 mL Sesame Oil

Formulation	BHA (g)	Loading (g/L)	Nominal loading (% w/v)
F1	1	2	0.2
F2	2	4	0.4
F3	3	6	0.6
F4	4	8	0.8
F5	5	10	1.0
F6	6	12	1.2
F7	7	14	1.4
F8	8	16	1.6
F9	9	18	1.8
F10	10	20	2.0

2.2. Viscosity Measurement and Kinematic-Viscosity Estimate

Viscosity was measured with a Viscotester VT-04F using rotor No. 3, with three readings obtained for each formulation. The laboratory progress report presents kinematic-viscosity values in cSt, these values are retained in this manuscript explicitly as estimates rather than direct ASTM D445 measurements. The reported estimates are reproduced by using a working density assumption of approximately 0.90 g/cm3. Direct density measurement for each formulation and direct ASTM D445-26 verification is recommended before final publication [20].

2.3. Breakdown-Voltage Measurement

AC breakdown voltage was measured for each formulation in five repeated tests. The laboratory record indicates a 2.5 mm electrode gap; the Megger OTS80AF Oil Tester is used as the methodological reference for power-frequency breakdown testing of insulating liquids [8]. Individual breakdown values were recorded in kilovolts and summarized by the mean and sample standard deviation.

2.4. Statistical Analysis

Descriptive statistics were calculated for the BDV measurements at each BHA loading. A one-way analysis of variance (ANOVA) was applied to test the null hypothesis that mean BDV was equal across the ten formulations, with a significance level of 0.05. Because the current dataset was generated from repeated measurements on each prepared formulation rather than multiple independently prepared batches, the ANOVA is interpreted as exploratory evidence of between-formulation differences. A stronger confirmatory design would prepare multiple independent batches at the selected BHA loadings and treat the batch as the experimental unit.

3. RESULTS AND DISCUSSION

3.1. Effect of BHA Loading on Viscosity

The estimated kinematic viscosity ranged from 33.33 to 42.59 cSt (Table 2 and Fig. 1). The highest value was observed at 1 g BHA/500 mL, while the lowest value was observed at 10 g/500 mL. From 1 g to 10 g, the estimated viscosity decreased by approximately 21.7%, although local increases occurred at 4, 6-7, and 9 g. The overall pattern therefore suggests a downward tendency rather than a strictly linear dose-response relationship. This behavior is consistent with the broader observation that formulation changes can alter molecular mobility and internal friction in natural esters. Moosasait et al. experimentally reduced vegetable-oil viscosity by adding benzyl benzoate [17], while Chen et al. showed that blending natural esters can markedly reduce kinematic viscosity through changes in molecular structure and intermolecular mobility [13].

Table 2. Viscosity and Breakdown-Voltage Summary

BHA (g/500 ml)	Loading (g/l)	Estimated viscosity (cSt)	BDV mean +/- SD (kV)
1	2	42.59	16.36 +/- 7.28
2	4	37.78	15.10 +/- 1.62
3	6	36.67	30.24 +/- 7.94
4	8	38.15	22.82 +/- 8.19
5	10	35.56	16.30 +/- 6.08
6	12	37.04	21.22 +/- 7.19
7	14	38.15	11.28 +/- 1.37
8	16	34.44	14.52 +/- 2.91
9	18	38.89	6.24 +/- 4.18
10	20	33.33	25.58 +/- 3.38

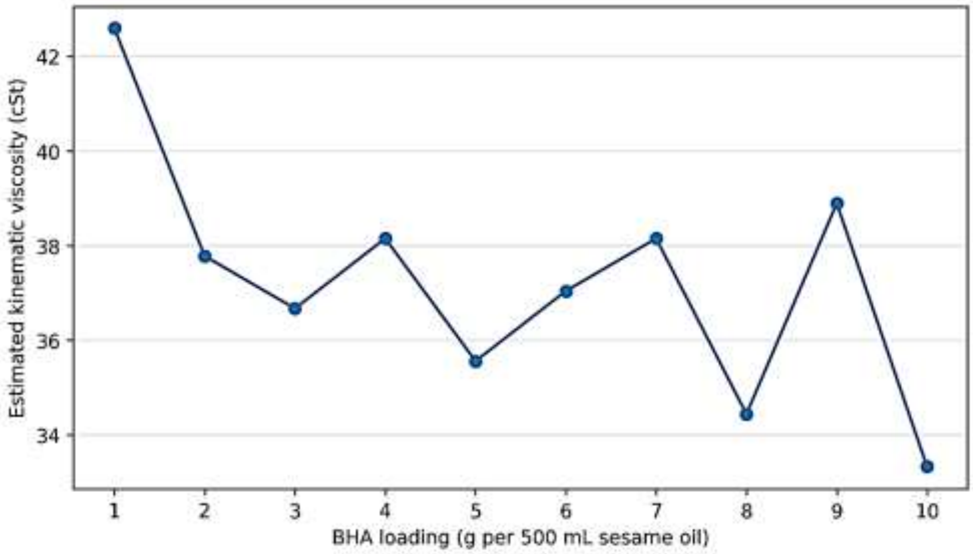

Figure 1. Estimated kinematic-viscosity trend for sesame-oil/BHA formulations.

The absolute kinematic-viscosity values should be interpreted cautiously because they are estimates derived from rotational measurements and a working density assumption, not direct capillary measurements. This distinction is important because viscosity is temperature-sensitive and because BHA addition may slightly alter density. IEC 63012 emphasizes viscosity as a performance-relevant characteristic for ester liquids because it can affect equipment cooling [9]. Therefore, the current screening is useful for ranking formulations, but ASTM D445 measurements are required before claiming compliance with a natural-ester viscosity specification.

3.2. Breakdown-Voltage Response

The five BDV measurements for each formulation are reported in Table 3. The highest mean BDV was obtained at 3 g BHA/500 mL (6 g/L), reaching 30.24 +/- 7.94 kV. The next highest value was obtained at 10 g/500 mL, 25.58 +/- 3.38 kV. In contrast, the 9 g formulation produced the lowest mean BDV, 6.24 +/- 4.18 kV. The sequence of mean values was highly non-monotonic, demonstrating that increasing BHA loading did not systematically increase dielectric strength.

Table 3. Individual Breakdown-Voltage Measurements

BHA (g)	Test 1	Test 2	Test 3	Test 4	Test 5	Mean +/- SD
1	6.1	12.6	18.3	19.6	25.2	16.36 +/- 7.28
2	14.5	13.7	17.9	14.6	14.8	15.10 +/- 1.62
3	21.5	35.3	30.1	40.6	23.7	30.24 +/- 7.94
4	31.6	31.4	16.4	20.2	14.5	22.82 +/- 8.19
5	13.2	13.3	27.1	13.0	14.9	16.30 +/- 6.08
6	33.4	14.3	19.8	20.0	18.6	21.22 +/- 7.19
7	11.4	9.2	11.7	13.0	11.1	11.28 +/- 1.37
8	11.8	16.1	11.8	14.3	18.6	14.52 +/- 2.91
9	11.4	10.1	4.2	2.7	2.8	6.24 +/- 4.18
10	21.8	23.9	27.3	24.4	30.5	25.58 +/- 3.38

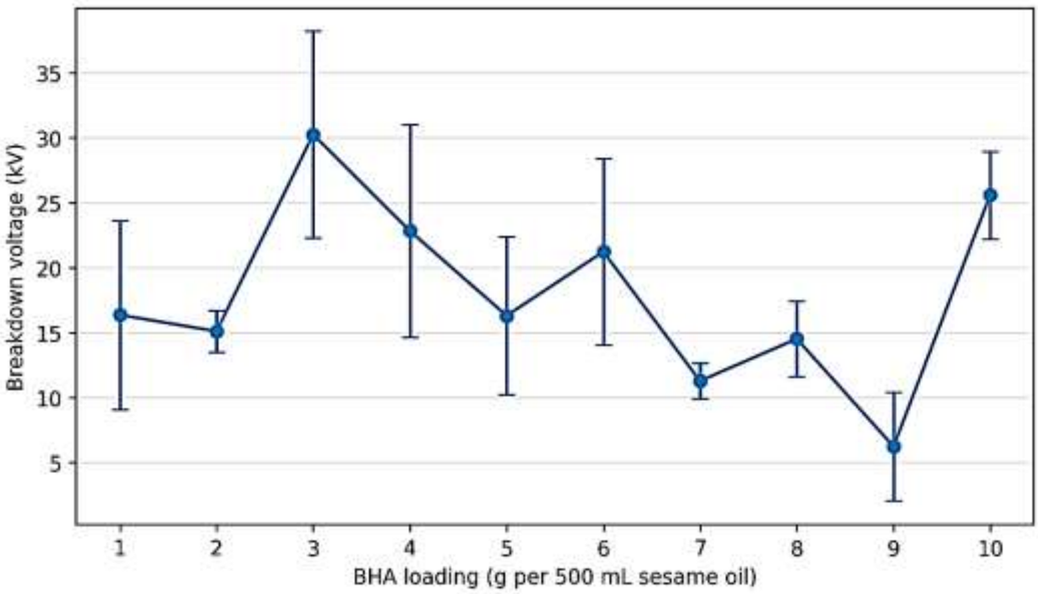

Figure 2. Mean breakdown voltage with one standard deviation for each BHA loading.

The non-monotonic pattern agrees with experimental reports in other vegetable-oil systems. Handayani et al. observed that a BHA concentration that slightly improved soybean-oil BDV was followed by a decrease at a higher BHA concentration [6]. Afrida et al. similarly found that BHA/BHT modification of palm oil did not generate a simple concentration-dependent improvement [21]. Thangaraj et al. showed that antioxidant concentration and preparation conditions jointly influence natural-ester performance [7]. These studies support the interpretation that BHA acts within a multivariable liquid system; dielectric strength can also be affected by moisture, particles, dissolved gases, electrode condition, temperature, and the molecular composition of the base ester. Experimental studies of natural esters under varying moisture, temperature, molecular structure, and nanomaterial loading likewise show concentration- and condition-dependent BDV responses [11], [14]–[16], [22]

3.3. ANOVA of Breakdown Voltage

The one-way ANOVA yielded $F(9,40)=7.98$ with $p<0.001$, indicating statistically detectable differences among the ten formulation groups in the current repeated-measurement dataset. The between-group sum of squares was 2252.096, compared with 1254.356 within groups (Table 4). Thus, the observed differences cannot be described only as small fluctuations around one common mean. Nevertheless, because the measurements are repeated readings from prepared formulations rather than results from independently replicated formulation batches, the inferential result should be interpreted as screening-level statistical evidence. Independent-batch replication is required for a stronger causal conclusion about BHA loading.

Table 4. One-Way Anova for Breakdown Voltage

Source	*SS*	*df*	*MS*	*F*	*p*
Between BHA groups	2252.096	9	250.233	7.980	<0.001
Within groups	1254.356	40	31.359	-	-
Total	3506.452	49	-	-	-

3.4. Integrated Evaluation of Viscosity and Dielectric Performance

When viscosity and BDV are considered together, two formulations stand out. The 3 g formulation produced the highest mean BDV (30.24 kV) while retaining a moderate estimated viscosity of 36.67 cSt. The 10 g formulation produced the lowest estimated viscosity (33.33 cSt) and the second-highest BDV (25.58 kV), with lower BDV dispersion than the 3 g formulation. In contrast, some low-viscosity formulations, such as 8 g/500 mL, showed relatively low BDV. Therefore, lower viscosity did not automatically correspond to higher dielectric strength. This reinforces the need for multi-response evaluation of insulating liquids.

The 3 g formulation is consequently identified as the most promising formulation in the present screening, not as a final optimized transformer oil. IEC 62770 treats natural ester as both an insulating and heat-transfer medium and requires evaluation across multiple properties rather than BDV alone [1]. Field and laboratory studies also show that natural-ester performance depends on viscosity, moisture, acidity, thermal aging, molecular structure, and compatibility with solid insulation [10], [13], [22], [23]. The 3 g formulation should therefore be re-prepared in independent batches and compared with BHA-free sesame oil and a mineral-oil control. Density, water content, acid value, flash point, oxidation stability, and direct kinematic viscosity should then be measured before broader transformer-oriented conclusions are drawn.

This study also has two methodological limitations that should be resolved before final submission. First, the current viscosity values in cSt are estimated rather than directly measured by ASTM D445. Second, a BHA-free sesame-oil control was not included in the final dataset reported here, so the percentage improvement caused by BHA cannot yet be quantified relative to the untreated base oil. These limitations do not invalidate the screening result, but they restrict the conclusion to comparative ranking among the ten BHA-containing formulations. The next experimental stage should prioritize independent replication of 3 g and 10 g formulations, untreated sesame oil, and a commercial mineral-oil reference.

3.5. Implications for Transformer-Fluid Development and Next Validation Stage

The present results are best interpreted as a formulation-screening stage within a broader transformer-fluid development pathway. Natural esters are not evaluated only by their initial AC breakdown voltage; they must also remain serviceable under thermal stress, moisture exchange, oxidation, and contact with cellulose insulation. IEC 62770 defines natural esters as insulating and heat-transfer liquids, while IEC 62975 and IEEE C57.147 emphasize maintenance, condition assessment, and fluid handling over service life [1], [2], [4]. Experimental transformer studies similarly show that the physical and chemical properties of natural esters evolve during operation and aging [12], [23]. Therefore, the formulation that performs best in an initial BDV screen should be regarded as a candidate for a structured validation sequence rather than as a finished product.

A logical next step is to compare the 3 g and 10 g formulations with untreated sesame oil and a commercial mineral insulating oil under identical sample-conditioning and test procedures. This comparison would distinguish the actual BHA contribution from the intrinsic properties of sesame oil and would provide a reference against IEC 60296 mineral-oil behavior [3]. The selected formulations should then be characterized for measured density, kinematic viscosity at 40 degC, water content, acid value, flash point, and oxidation stability. Repeating BDV after controlled thermal aging would help determine whether the initial dielectric advantage of the 3 g formulation is retained as the liquid oxidizes. Such an aging-centered approach is supported by studies in which natural esters, coconut oil, and modified ester systems exhibited property changes that depended on molecular composition and thermal history [11]–[13], [16], [22].

The comparatively large standard deviation observed for the 3 g formulation also has engineering significance. A transformer insulating liquid is required to provide reliable rather than occasional dielectric performance. The 3 g formulation contained individual BDV values between 21.5 and 40.6 kV, whereas the 10 g formulation was more tightly clustered between 21.8 and 30.5 kV. This difference suggests that subsequent work should examine not only the mean BDV but also the probability distribution of breakdown. Natural-ester breakdown is a statistical event, and studies using Weibull and normal distributions have shown the value of estimating low-probability failure voltages rather than relying only on arithmetic means [14], [15]. Increasing the number of independent batches and breakdown observations would make such reliability analysis possible for the sesame-oil/BHA system.

Finally, the response pattern itself provides a useful formulation insight. The results do not support the assumption that a larger antioxidant loading continuously improves electrical performance. Instead, viscosity tended to decrease with increasing BHA loading, while BDV exhibited multiple local maxima and minima. Comparable concentration-dependent behavior has been reported when antioxidants or nanoparticles were added to vegetable and ester insulating liquids [6], [7], [14], [15], [21], [22]. This suggests that an optimal formulation should be selected by multi-response criteria and confirmed experimentally at a narrower concentration interval around the most promising region. For example, future work may test BHA loadings between 2 and 4 g per 500 mL using smaller increments, while simultaneously monitoring moisture, acidity, density, and oxidation indicators. Such a design would determine whether the apparent optimum near 3 g is reproducible and whether a nearby concentration offers a better balance between BDV magnitude, BDV variability, viscosity, and long-term stability.

3.6. Comparison with Related Vegetable-Oil Insulation Studies

The magnitude of the present results should be compared with previous studies cautiously because vegetable-oil dielectric properties depend strongly on oil source, refining history, moisture, electrode geometry, temperature, and conditioning. Moosasait et al. demonstrated that sesame oil itself can respond substantially to a viscosity-modifying additive, confirming that the base oil is formulation-sensitive [17]. In soybean oil, Handayani et al. found that the BHA level associated with the best BDV was not the highest among the concentrations tested [6]. In palm oil, Afrida et al. likewise reported concentration-dependent changes in viscosity and BDV after BHA/BHT addition [13]. These results provide an important context for the local maximum observed at 3 g BHA in the present work.

Other natural-ester studies show the same broader principle even when different modification strategies are used. Chen et al. improved viscosity by blending esters with different molecular structures [13]; Sarpataky et al. and Siddique et al. showed that nanoparticle type and concentration can either increase or decrease dielectric strength [14], [15]; and Ye et al. demonstrated that temperature and molecular structure can produce non-linear breakdown behavior [16], [22]. These observations indicate that dielectric-liquid optimization is fundamentally a multi-factor problem. The present sesame-oil/BHA screening contributes a distinct antioxidant-based dataset to this broader body of evidence, but its most valuable outcome is the identification of a narrow candidate region for more rigorous follow-up rather than a claim of universal superiority over established transformer fluids.

Table 5. Position of the Present Study Relative to Selected Experimental Literature

Study	Liquid/modification	Relevant observation
Moosasait et al. [9]	Vegetable oils incl. sesame oil + benzyl benzoate	Viscosity was reduced; other electrical/chemical properties also changed.
Handayani et al. [11]	Soybean oil + BHA/phenol	BHA response was non-linear across tested concentrations.
Thangaraj et al. [12]	Blended natural esters + BHA/BHT	Antioxidant level and preparation conditions affected performance.
Afrida et al. [13]	Palm oil + BHA/BHT	Viscosity and BDV changed with antioxidant concentration.
Present study	Sesame oil + 1-10 g BHA/500 ml	3 g gave the highest mean BDV; 10 g gave the lowest estimated viscosity.

4. CONCLUSION

Ten sesame-oil formulations containing 1 to 10 g BHA per 500 mL were screened using viscosity and AC breakdown-voltage measurements. The estimated kinematic viscosity ranged from 33.33 to 42.59 cSt and generally declined with increasing BHA loading, although the response was not strictly linear. Breakdown voltage was strongly non-monotonic. The 3 g formulation produced the highest mean BDV of 30.24 +/- 7.94 kV with an estimated viscosity of 36.67 cSt, while the 10 g formulation produced the lowest estimated viscosity of 33.33 cSt and the second-highest BDV of 25.58 +/- 3.38 kV. One-way ANOVA of the repeated BDV measurements indicated significant differences among formulations ($F(9,40)=7.98$, $p<0.001$). These results identify 3 g BHA/500 mL sesame oil as the most promising formulation for further validation. However, the formulation should not yet be considered transformer-ready. Confirmatory work should include BHA-free and mineral-oil controls, independent formulation batches, direct density and ASTM D445 viscosity measurements, moisture and acidity analysis, oxidation-aging tests, and compatibility evaluation with transformer solid insulation.

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