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ORIGINAL ARTICLE

Experimental Evaluation on Suitability of Alternate Fluids with the Influence of Additives for Power System Transformer Applications

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Abstract
Transformers are most vibrant equipment of power system network and petroleum base mineral oil is used as dielectric insulating medium and cooling medium. At present more research works are focused towards natural esters based fluids as prospectivedisplace to traditional mineral oil, due to similar properties of transformer oil, high availability of resources, high biodegradability and environmental friendly nature. This work emphasizes on enhancement of properties of natural ester using antioxidants. Natural esters such as mustard oil, rice bran oil, punna oil and castor oil are chosen for investigation along with antioxidants such as gallic acid, citric acid, propyl gallate and tertiary butylated hydroxy quinone. Natural esters are mixed with 1 g, 2 g, 3 g and 5 g of antioxidants for the investigations. The critical properties like breakdown voltage, flash point, fire point, viscosity, interfacial tension, water content and acidity of natural esters are analyzed based on IEC/ASTM standards before and after addition of antioxidants. From this study, it is noted that antioxidants improve the characteristics of natural esters after addition of it and properties are superior to the traditional mineral oil.By the suitable proportion of fluids the 80–90% of characteristics betterment are achieved with the influence of fatty acid based additives.

Keywords Transformers · Mineral oil · Antioxidants · Natural esters · Biodegradability

1 Introduction

Power transformers are most imperative and strategic equipment in electrical networks. Without transformers, transmission and distribution of electricity for all sectors becomes highly impossible [1]. Important aspects in power transformers for uninterrupted power delivery are continuous monitoring and life assessment of insulating medium in it [2]. Dielectric fluids and solid insulation (press board and kraft paper) are basically used insulating medium in oil filled transformers. Dielectric fluids afford electrical insulation between windings (which are also provided with solid insulation for mechanical support) and cooling property by transferring heat generated inside the transformer [3].

Over 100 years, petroleum based mineral oil (transformer oil) is employed as dielectric fluids in the transformers owing to its admirable dielectric insulating properties, cooling properties and low cost [4]. Some drawbacks of transformer oil are poor biodegradability, poor recital at higher temperature and scarcity in future. Likewise transformer explosion and hazardous oil spill in the environment are also considered as downsides of mineral oil [5]. Later synthetic oils, silicone oil and esters are acquainted with the purpose for dielectric fluids. But their usages in transformers as direct replacement to mineral oil are impossible due to their higher cost and unpredicted in service performance [6].

In order to deserve optimized insulating medium with better dielectric properties, cooling properties, best grade of sustainability, least environmental influence, low cost and high resource, different alternate dielectric fluids are focused [7]. Natural esters based dielectric liquids are gaining more interest as a potential replacement to mineral oil.

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Natural esters (vegetable oils) are natural products resulting from plants and seeds. Natural esters are classified based on the structure and constitutes of triglycerides. They are assorted as saturated, mono unsaturated and poly unsaturated. The performance and critical features are predominantlybe contingent on triglycerides [8]. Oxidation nature mainly depends on the higher concentration on mono unsaturated fatty acids. Poly unsaturated fatty acids are more vulnerable to oxidation of oil [9]. Viscosity is very much high for natural esters with higher saturated fatty acids. Oils with high poly unsaturated content have low viscosity. Natural esters have advantages such as low explosiveness, high flash point and fire point temperature, ecological friendly, renewable, non-hazardous and biodegradable. These advantages encourage the focus towards vegetable oil for alternate insulating medium [10, 11]. Already some biodegradable oil based insulating mediums are developed by few industries.

Natural esters hold some disadvantage namely elevated cost, improved viscosity and pitiable oxidation stability. Generally the natural esters have poor oxidation stability due to the removal of antioxidants [12]. Antioxidant is an additive compound which is capable of slow down the oxidation reaction and thereby terminates consequent chain process. It is clear that by adding some of the low toxic antioxidant with the fluids will definitely increase the oxidation stability to a better level. The addition of antioxidant not only increases the oxidation stability but also improves the operational properties like reduction of viscosity aside from pure natural esters. Subsequently the natural esters cost elevatedassociated to mineral oil, such shortcomings is overwhelmed by the features alike less formation of gas, low oxidation and slow ageing period [13, 14]. Antioxidants are broadly classified as natural and synthetic.

Natural antioxidants are extracted from natural products and synthetic antioxidants are obtained from chemical processes. Examples for natural antioxidants are tocopherol (alpha, beta, gamma and delta) and tocotrienol (alpha, beta, gamma and delta). Butylated hydroxy toluene, Butylated hydroxy anisole, 2, 6 tert butyl phenol, tertiary butylated hydroxy quinone and propyl gallate are some of the synthetic antioxidants [15]. Antioxidants are further classified as synergist which is one form of natural antioxidants. Gallic acid, citric acid, ascorbic acid and oryzanol are some of synergists. The mechanism of antioxidant as donors are represented in Eqs. 1 and 2.

$$AH + R* \rightarrow RH + A* \tag{1}$$

$$AH + ROO* \rightarrow ROOH + A* \tag{2}$$

where, AH is the Antioxidants, A* is the free radicals of Antioxidants.

Based on the major drawbacks identified with the employment of petroleum based mineral oil like vilest bio-degradation ability, poor behaviour at elevated temperature and availability of oil resource to support the future generation, the usage of natural esters are suggested. In order to achieve superior performance of natural esters for alternate liquid insulation, there is a requirement of chemical process to enhance the properties. In this paper, the addition of natural and synthetic antioxidants additives with some natural esters for the development of environmentally suitable dielectric fluids are recommended. It is also proposed that to overcome the existing fluid drawback, the natural esters are selected based on availability of resource, biodegradability and non-hazardous environmental friendlinessnature. By the addition of food grade additives in natural esters,the new dimension in dielectric fluids for high voltage applications are anticipated for making the superior power environment with green characteristics. The various contributions of this paper for the betterment of environment is emphasized as follows:

- The highly advantageous natural esters along with the perfect addition of natural and synthetic additives for optimized transformer insulationsare identified.
- The various qualifying properties like breakdown voltage, flash point, fire point, viscosity, interfacial tension, water content and acidity are estimated with the additive based natural ester fluids.
- The mathematical based evaluation to identify the properties for intermediate additive with the functions are introduced and it is validated by analyzing the coefficient of determination.

The other portion of the paper is framed as follows. Section 2 of the paper reveals proposed methodology of this work including thepreparation of oil samples, importance and measurement techniques of critical properties. The experimental results of this works are given and discussed in Sect. 3. Mathematical evaluation is discussed in Sect. 4. Conclusion of this work is made in Sect. 5.

2 Proposed Methodology

In this effort, examinations are conceded to analyze the critical characteristics of natural esters with antioxidant additives in the aim of development of high performance environmental friendly dielectric liquids. Natural esters are selected from food grade vegetable based oils which have more obtainable resources in the near-by regions. For this work, mustard oil (MUO), rice bran oil (RBO), punna oil (PO) and castor oil (CO) is handpicked from local available manufacturer of virgin quality grade I (without the influence of chemical treatment). The different fatty

acids structures of investigating natural esters based fluids are tabulated in Table 1. Antioxidants are chosen from natural and synthetic antioxidants groups which are given in Table 2 along with technical information. Additives are added besides natural esters based fluids in the ranges pertaining to 1 g, 2 g, 3 g and 5 g. The various samples and their combinational descriptions are given in Table 3. For scrutinizing the characteristics enactment of all oil samples, breakdown voltage, flash point temperature, fire point temperature, viscosity profile (at diverse temperatures), interfacial tension, moisture content and acidity are computed based on the standards. On behalf of investigating natural esters, standards related with mineral oil are used due to non-availability of specific standards for natural esters. By using nonlinear regression analysis, the mathematical modeling is derived to figure out best fitness for all the samples prepared with various proportions of antioxidant additives.

2.1 Sample Preparations

Each test samples consist of 500 ml of natural esters with the addition of 1 g, 2 g, 3 g and 5 g of antioxidant chemicals are placed in a separate beaker. With a constant temperature of 70 °C, the samples are heated in a heating chamber to dissolve the antioxidant with esters into liquid. These liquids are then blended with a magnetic stirrer at a speed of 450–500 rpm to have uniform scattering of antioxidant additives in liquids for 30 min. The blended samples are then stockpiled in a storage ampoule for the experimental evaluation.

Table 1 Fatty acids compositions of investigating natural esters

Representation	Oil samples	Fatty acid composition (%)		
		Saturated	Mono unsaturated	Poly unsaturated
Base sample 1	Mustard oil (MUO)	12	28	60
Base sample 2	Rice bran oil (RBO)	20	45	35
Base sample 3	Punna oil (PO)	13	25	62
Base sample 4	Castor oil (CO)	16	22	62

2.2 Measurement of Properties

In view of the global guidelines, the properties of oil such as breakdown voltage, flash point, fire point, viscosity, interfacial tension, water content and acidity are analyzed.

2.2.1 Breakdown Voltage

Breakdown voltage of insulating medium defines the withstand capacity of insulating fluids [16]. Breakdown voltage is observed at a voltage which creates spark between the electrodes. The breakdown voltage is measured by using breakdown voltage test kit as endorsed by the approved IEC 60156 [17]. In view of the standard guidelines, measurement is made in test cell which consists of two spherical electrodes with a gap positioning of 2.5 mm. The oil is occupied above the externalsurface of the electrodes to a height of 40 mm. The voltage is actioned to the test cell at a rate of 2 kV/s. Breakdown voltage of oil sample is intended by taking the average of five consecutive values for the identical sample. In the middle of every estimation the time delay of 1 min is given in order to scatter the derivatives to drive out formerly the subsequent measurement. As per the standard, the breakdown voltagewould be superiorto 30 kV. Usually the pure oils have advanced breakdown voltage than the oil which has contaminations suchas moisture and acid content [18].

2.2.2 Flash Point and Fire Point

Flash point and fire point are used to identify the temperatures at which oil gets ignited [16]. The flash point and fire point measurement were carried out based on the standard ASTM D93. Theyare estimated by using Pensky martin flash point kit [19]. The Pensky martin flash point kit consists of a sealed test goblet in which 60 ml of oil sample is occupied and heated by using the energy regulator. A preliminary fire is coordinated to the opening on the outside locale to decide the temperature of the flash point and fire point. The flash point is characterized as where the fume inside the shut test cup blends in with air and delivers a transitory fire on the outside of the oil for not exactly a second, and if a constant fire happens on the outside of the oil, it is characterized as fire point where the fume inside the shut test cup blends in

Table 2 Investigating antioxidants

Antioxidants	Abbreviations	Source	Class	Chemical formula
Gallic acid	GA	Natural	Phenolic and organic	$C_7H_6O_5$
Citric acid	CA	Natural	Organic	$C_6H_8O_7$
Propyl gallate	PG	Synthetic	Organic	$C_{10}H_{12}O_5$
Tertiary butylated hydroxy quinone	TBHQ	Synthetic	Aromatic organic	$C_{10}H_{14}O_2$

Table 3 Samples Prepared with Natural Esters and Antioxidants

Samples prepared with base sample 1		Samples prepared with base sample 2	
Samples	Proportion	Samples	Proportion
S1	Base sample 1 + 1 g of CA	S17	Base sample 2 + 1 g of CA
S2	Base sample 1 + 2 g of CA	S18	Base sample 2 + 2 g of CA
S3	Base sample 1 + 3 g of CA	S19	Base sample 2 + 3 g of CA
S4	Base sample 1 + 5 g of CA	S20	Base sample 2 + 5 g of CA
S5	Base sample 1 + 1 g of GA	S21	Base sample 2 + 1 g of GA
S6	Base sample 1 + 2 g of GA	S22	Base sample 2 + 2 g of GA
S7	Base sample 1 + 3 g of GA	S23	Base sample 2 + 3 g of GA
S8	Base sample 1 + 5 g of GA	S24	Base sample 2 + 5 g of GA
S9	Base sample 1 + 1 g of PG	S25	Base sample 2 + 1 g of PG
S10	Base sample 1 + 2 g of PG	S26	Base sample 2 + 2 g of PG
S11	Base sample 1 + 3 g of PG	S27	Base sample 2 + 3 g of PG
S12	Base sample 1 + 5 g of PG	S28	Base sample 2 + 5 g of PG
S13	Base sample 1 + 1 g of TBHQ	S29	Base sample 2 + 1 g of TBHQ
S14	Base sample 1 + 2 g of TBHQ	S30	Base sample 2 + 2 g of TBHQ
S15	Base sample 1 + 3 g of TBHQ	S31	Base sample 2 + 3 g of TBHQ
S16	Base sample 1 + 5 g of TBHQ	S32	Base sample 2 + 5 g of TBHQ
Samples prepared with base sample 3		Samples prepared with base sample 4	
Samples	Proportion	Samples	Proportion
S33	Base sample 3 + 1 g of CA	S49	Base sample 4 + 1 g of CA
S34	Base sample 3 + 2 g of CA	S50	Base sample 4 + 2 g of CA
S35	Base sample 3 + 3 g of CA	S51	Base sample 4 + 3 g of CA
S36	Base sample 3 + 5 g of CA	S52	Base sample 4 + 5 g of CA
S37	Base sample 3 + 1 g of GA	S53	Base sample 4 + 1 g of GA
S38	Base sample 3 + 2 g of GA	S54	Base sample 4 + 2 g of GA
S39	Base sample 3 + 3 g of GA	S55	Base sample 4 + 3 g of GA
S40	Base sample 3 + 5 g of GA	S56	Base sample 4 + 5 g of GA
S41	Base sample 3 + 1 g of PG	S57	Base sample 4 + 1 g of PG
S42	Base sample 3 + 2 g of PG	S58	Base sample 4 + 2 g of PG
S43	Base sample 3 + 3 g of PG	S59	Base sample 4 + 3 g of PG
S44	Base sample 3 + 5 g of PG	S60	Base sample 4 + 5 g of PG
S45	Base sample 3 + 1 g of TBHQ	S61	Base sample 4 + 1 g of TBHQ
S46	Base sample 3 + 2 g of TBHQ	S62	Base sample 4 + 2 g of TBHQ
S47	Base sample 3 + 3 g of TBHQ	S63	Base sample 4 + 3 g of TBHQ
S48	Base sample 3 + 5 g of TBHQ	S64	Base sample 4 + 5 g of TBHQ

with air and creates a perpetual fire on the outside of the oil for over a second [20].

2.2.3 Viscosity

Viscosity of fluids indicates the resistance to flow on smooth surface that is associated with a hotness transfer capacity of fluids [16]. The oil with high viscosity takes lower hotness transfer characteristics whereas the low viscous oil has good cooling property [21]. The viscosity of oil is determined based on the recommendation in the standards ASTM D445 by using Redwood viscometer [22]. The redwood viscometer consists of oil beakerby an orifice. A 50 ml of oil is taken in oil cup and by opening the orifice, the time taken to gather the 50 ml of oil is noted to figure the viscosity [23]. The viscosity measurement is carried out at three different temperatures such as Room temperature, 60 ^{O}C and 90 ^{O}C.

2.2.4 Interfacial Tension

Interfacial tension is the molecular attractive force that occurs at the boundary of oil and water. It gives the potential of liquid to resist an external force [16]. The measurement of interfacial tension is used to detect the presence of decay and

polar contaminants [24]. In view of the standard guidelines of ASTM D971, the interfacial tension is measured by using automatic interfacial tensiometer (Ring Method). The distilled water of 50 to 75 ml is filled in a beaker over which the oil is filled. The beaker is placed in an adjustable platform where the ring is progressively lifted through the water and oil interface. The reason for oil lying on the water surface is the density difference of two liquids. Since water has a higher interfacial tension than the oil, a force is desired to isolate the ring from the surface of water. The measured force is utilized towardscomputing the interfacial tension between oil and water. Pure oil has high interfacial tension and the oil with pollutants has low interfacial tension [25]. Based on the requirements of oil as liquid insulation, the interfacial tension should be superior to 30 mN/m.

2.2.5 Water Content

Existence of water molecule in oil is unacceptable which disturbs all properties of oil. The water content in oil reacts with solid insulation of core and windings of transformer which affects the properties by producing acidic contaminants [16]. These contaminants are main reasons for further reduction in properties while transformer in service [26, 27]. Water content in oil samples are measured by Karl Fischer Coulometer with moisture sensor and it is recommended by the standards ASTM D1533 [27]. A 50 ml of sample fluid is taken in a beaker and subjected to the coulometer with moisture sensor. The moisture sensor identifies the volume of water molecule content in fluid sample and demonstrated digitally. As per standard the water content should be less than 50 ppm [28].

2.2.6 Acidity

Acid content in insulating fluid is very harmful and if the oil gets acidified the oil becomes more soluble [16]. Acidity leads to deterioration of paper insulation of winding. According to the standard ASTM D974, acidity is measured by using Karl Fischer titration method [29]. In this method the potassium hydroxide is taken as a burette solution and oil sample is taken as a pipette solution. The phenolthelene is used as a color indicator to the pipette solution. The pipette solution is titrated against the burette solution until the color change occurs. The aggregate of potassium hydroxide requisite to neutralize the hydrogen ions in one gram of oil represents the acid level. As per standard, the good insulating oil wouldtake acidity lower than 0.4 mg KOH/g.

3 Results and Discussions

In this division, measured properties of all natural esters without and with antioxidants are provided and further discussions are carried out in the various aspects such as comparison on oil properties based upon fatty acid component and different concentrations of antioxidants.

3.1 Critical Properties of Base Samples

Acute properties likebreakdown voltage, flash point temperature, fire point temperature, viscosity profile (at diverse temperatures), interfacial tension, moisture content and acidity are measured for reference oil (RO) which is a petroleum based mineral oil and base oil samples (MUO, RBO, PO and CO) consistent with the specified standard guidelines. The obtained values are tabulated in Table 4.

Pure natural esters (base samples) are mixed with various concentrations (1 g, 2 g, 3 g and 5 g) of different antioxidants (GA, CA, PG and TBHQ). Properties are measured and tabulated in Tables 5, 6, 7 and 8 for oil samples prepared with base sample 1, base sample 2, base sample 3 and base sample 4 respectively.

3.2 Effect of Antioxidants on Properties of Oil Samples

In this section, properties of all oil samples are analyzed and discussed based on the fatty acid content of base oil samples and enhancement/decrement in properties after addition of antioxidants with base oil samples. Pure natural esters (base samples) are mixed with various concentrations (1 g, 2 g, 3 g and 5 g) of different antioxidants (GA, CA, PG and TBHQ). Properties are measured and graphically represented in Figs. 1, 2, 3, 4, 5 and 6.

3.2.1 Breakdown Voltage

Values of breakdown voltages for all oil samples are illustrated in Fig. 1. From the observations, it is noted that breakdown voltage of investigated vegetable based oil is higher to that of mineral oil. Among investigated natural esters, rice bran oil has high breakdown voltage.

Higher value of breakdown voltage for vegetable oils may be owing to the fatty acid composition of natural esters based fluids. From this investigation it is inferred that oil with higher content of mono unsaturated fatty acid has developed breakdown voltage. Increase in poly unsaturated fatty acid leads to reduction in breakdown voltage.

Breakdown can be further enhanced to a greater level by adding additives compound to the vegetable oil. Breakdown

Table 4 Properties of mineral and base samples

Category	Samples	Breakdown voltage (kV)	Flash point (°C)	Fire point (°C)	Viscosity (cSt)			Interfacial tension (mN/m)	Water content (ppm)	Acidity (mg KOH/g)
					At RTP	At 60 °C	At 90 °C			
Mineral oil	RO	31	178	195	19.51	14.25	8.56	30	40	0.3
Natural esters based base oil without additives	BS1	31.4	265	275	124	37.8	22	31	38.4	0.22
	BS2	34.2	265	275	124	30.8	15.1	36	29.2	0.06
	BS3	28.8	310	320	79.2	33.8	20	33	49.1	0.35
	BS4	29.4	315	325	85.8	24.2	15.4	33	45.4	0.3

voltage has increased after addition of antioxidant additives compared to pure natural esters which is mainly due to less formation of carbon and it leads to less formation of gas.

Breakdown voltage of all base samples with antioxidant additives gives high breakdown voltage in that the base samples with 5 g of gallic acid provide higher breakdown voltage compared to other composition. This shows that the addition of gallic acid with base samples will enhance the breakdown voltage to a higher level. From the investigation, it is revealed that increase in concentration of antioxidant addition increase breakdown voltage of natural esters.

3.2.2 Flash Point and Fire Point

The changes in flash point and fire point of natural esters after addition of antioxidants are shown in Fig. 2. From this investigation, it is observed that the thermal stability nature esters are high. The formation of peroxide is less when the antioxidant additives combines with free radicals and there by controls the chain reactions. Based on the careful analyses, it is observed that the flash point and fire point temperature are advanced for natural esters subsequentlyby the addition of antioxidants compared to mineral oil.

From the investigation, it is found that the addition of antioxidant additives to natural ester shows good performance compared to additives free natural esters, in that the base fluids with 5 g of gallic acid provides higher flash and fire point temperatures. The influence of 5 g of gallic acid with base sample 3 shows high enhancement. Even though the samples prepared with 5 g of gallic acid with base sample 1, 2 and 4 gives good enhancement it is lower than base sample 3 with 5 g of gallic acid composition. Hence it is made clear that base samples have developed flash and fire point temperature when combined with antioxidant additives.

3.2.3 Viscosity

Viscosity profile of antioxidants added natural esters are showed in Fig. 3 for three diverse temperatures (at RTP, 60 °C and 90 °C). Generally when the temperature is increased, the considerable changes are observed with viscosity. Viscosity will reduce when temperature increases.

From the analysis of viscosity profile, it is evident that viscosity reduces for increase in temperature and viscosity reduces after the addition of antioxidants. Base sample with saturated fatty acid has greater viscosity and the base sample with unsaturated fatty acid has inferior viscosity. With reference to Table 4, at RTP, 60 °C and 90 °C the base sample 1, 2, 3 and 4 have high viscosities which are considerably higher than mineral oil. With the natural esters blended with antioxidant additives at RTP to 60 °C and 90 °C good decrement in viscosity is observed compared to pure natural esters

Table 5 Properties of base sample 1, before and after adding antioxidants

Category	Samples	Breakdown voltage (kV)	Flash point (°C)	Fire point (°C)	Viscosity (cSt)			Interfacial tension (mN/m)	Water content (ppm)	Acidity (mg KOH/g)
					At RTP	At 60 °C	At 90 °C			
Base sample 1, before adding antioxidants	BS1	31.4	265	275	124	37.8	22	31	38.4	0.22
Base sample 1, after adding various concentrations of antioxidants	S1	32	270	280	122	35	20	32	38	0.2
	S2	33.6	275	290	120	32	18	33	37	0.18
	S3	35.8	280	295	119	26	17	34	36	0.17
	S4	38.2	285	300	112	23	15	35	35	0.15
	S5	34	280	290	120	34	20	35	37	0.17
	S6	37.2	290	300	118	30	15	36	36	0.16
	S7	40	295	310	113	26	13	37	34	0.15
	S8	43.6	300	318	110	23	12	37	30	0.12
	S9	33.6	272	282	123	36	20	32	37	0.18
	S10	35	277	288	122.8	35	19	33	36	0.16
	S11	37.2	280	293	122.2	34.4	17	33	35	0.15
	S12	39	284	296	120	31	15	33	34	0.14
	S13	33	268	279	123	36	20	32	37	0.19
	S14	35.2	272	284	121	34	18	33	36	0.18
	S15	36.6	279	289	117	31	17	34	35.6	0.17
	S16	38	282	295	112	29	15	34	35	0.17

Table 6 Properties of base sample 2, before and after adding antioxidants

Category	Samples	Breakdown voltage (kV)	Flash point (°C)	Fire point (°C)	Viscosity (cSt)			Interfacial tension (mN/m)	Water content (ppm)	Acidity (mg KOH/g)
					At RTP	At 60 °C	At 90 °C			
Base sample 2, before adding antioxidants	BS2	34.2	265	275	124	30.8	15.1	36	29.2	0.06
Base sample 2, after adding various concentrations of antioxidants	S17	35.4	267	277	120	29	14	37	28.5	0.05
	S18	38.4	270	285	115	27.4	13	38	27	0.04
	S19	40.6	275	290	100	24.5	12	39	26.5	0.03
	S20	42.6	287	310	85	22	11	39	26	0.03
	S21	36.2	277	289	118	26	13.5	37	28	0.05
	S22	39.4	285	295	115	24	12	38	27	0.04
	S23	44.4	290	306	109	20	11	39	25	0.03
	S24	48	310	325	105	18	10	39	22	0.02
	S25	36	270	282	122	28	14	37	28	0.05
	S26	38.4	274	285	121	26	13	38	27	0.04
	S27	40	281	294	119	23	12	38	26.6	0.03
	S28	42.6	285	297	116	20	11	38	26	0.03
	S29	35.4	269	280	122	28	13.8	37	28	0.05
	S30	37.2	275	290	119	24	12	38	27	0.04
	S31	38.4	280	295	114	22	11	39	26.4	0.03
	S32	40.4	285	300	110	19	10	39	25	0.02

Table 7 Properties of base sample 3, before and after adding antioxidants

Category	Samples	Breakdown voltage (kV)	Flash point (°C)	Fire point (°C)	Viscosity (cSt)			Interfacial tension (mN/m)	Water content (ppm)	Acidity (mg KOH/g)
					At RTP	At 60 °C	At 90 °C			
Base sample 3, before adding antioxidants	BS3	28.8	310	320	79.2	33.8	20	33	49.1	0.35
Base sample 3, after adding various concentrations of antioxidants	S33	30.6	312	327	76	32	19	34	48	0.31
	S34	32.2	314	329	74.3	29.6	17.1	35	46	0.28
	S35	36.6	317	327	72	27	16.2	36	45.4	0.25
	S36	40	320	330	70	25.3	15	36	45	0.24
	S37	32.4	327	336	75	29	18	35	48	0.3
	S38	36	329	338	73	27	16	36	46	0.28
	S39	40.2	331	341	70	23	13	38	44	0.24
	S40	44.6	336	348	64	19	11	38	41	0.21
	S41	31	315	324	78	31	18	34	48	0.29
	S42	34.6	320	331	76	29	16	35	47	0.28
	S43	36	327	336	73	26	14	36	46	0.26
	S44	40.8	329	341	70	22	11	36	44	0.24
	S45	31.4	318	328	77	31	18	35	47	0.29
	S46	33.6	324	333	75	28	16	36	45	0.24
	S47	36	329	340	72	26	13	37	44	0.22
	S48	39.6	334	344	68	23	12	37	41	0.2

Table 8 Properties of base sample 4, before and after adding antioxidants

Category	Samples	Breakdown voltage (kV)	Flash point (°C)	Fire point (°C)	Viscosity (cSt)			Interfacial tension (mN/m)	Water content (ppm)	Acidity (mg KOH/g)
					At RTP	At 60 °C	At 90 °C			
Base sample 4, before adding antioxidants	BS4	29.4	315	325	85.8	24.2	15.4	33	45.4	0.3
Base sample 4, after adding various concentrations of antioxidants	S49	29	317	327	83	23	14.2	34	45	0.28
	S50	30.2	319	329	80	20.1	12	36	44	0.27
	S51	32.8	321	331	75.2	18	11	37	43	0.26
	S52	34.4	324	334	75	17.8	10.8	37	42	0.25
	S53	31.6	327	338	80	22	14	35	44	0.27
	S54	33.8	329	340	78	20	11.8	37	42	0.25
	S55	37	331	344	75	18	11	38	41	0.24
	S56	40.4	324	346	71	15	10	38	40	0.22
	S57	31.6	321	332	83	22	14	35	44	0.27
	S58	34	324	334	82	21	12	36	43	0.26
	S59	36.4	328	339	78	18	11.6	37	42	0.24
	S60	39	332	345	75	17	11	37	40	0.21
	S61	29.4	320	331	83	22	14	34	44	0.26
	S62	31.8	324	335	81	20	12	35	43	0.25
	S63	33	328	338	78	18	11.4	36	41	0.22
	S64	34.2	331	341	73	16	11	36	40	0.21

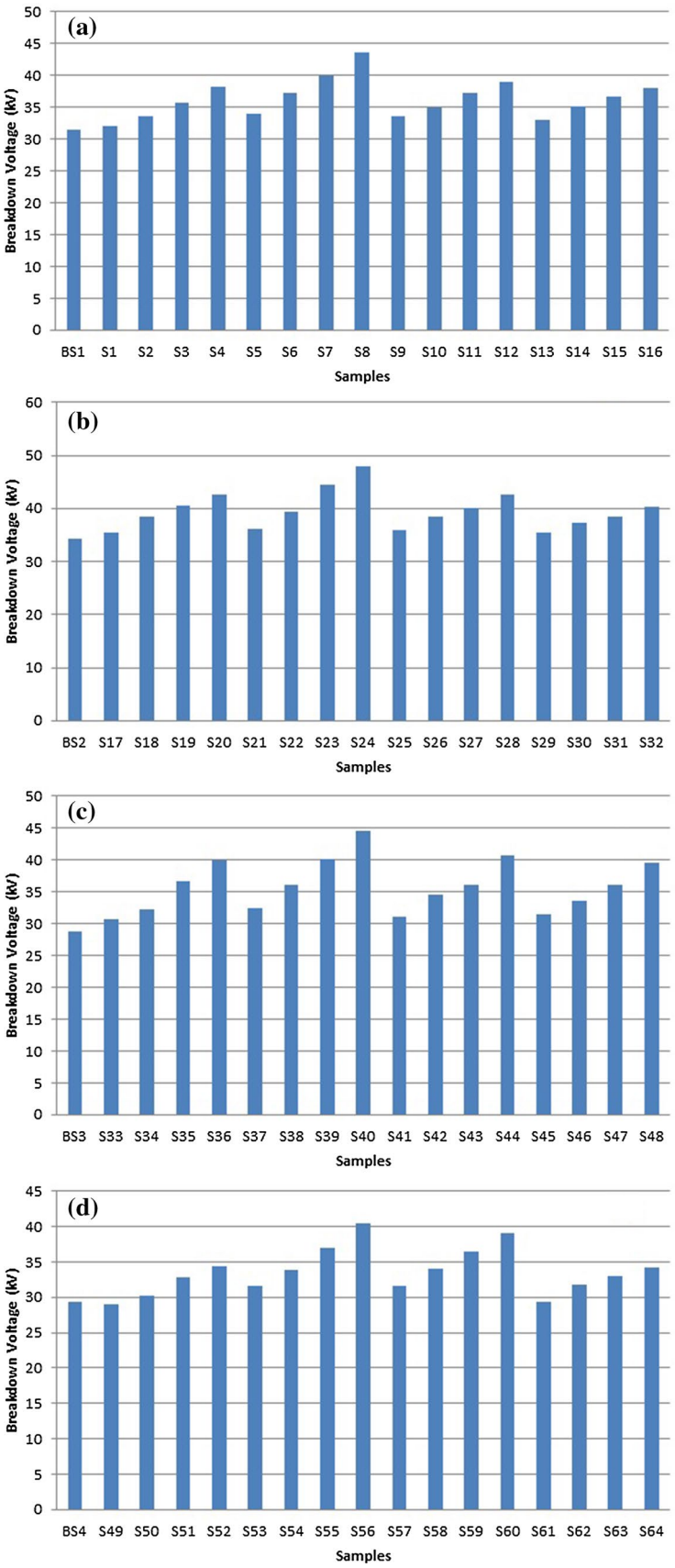

Fig. 1 Breakdown voltage of oil samples. **a** Prepared with base sample 1, **b** prepared with base sample 2, **c** prepared with base sample 3 and **d** prepared with base sample 4

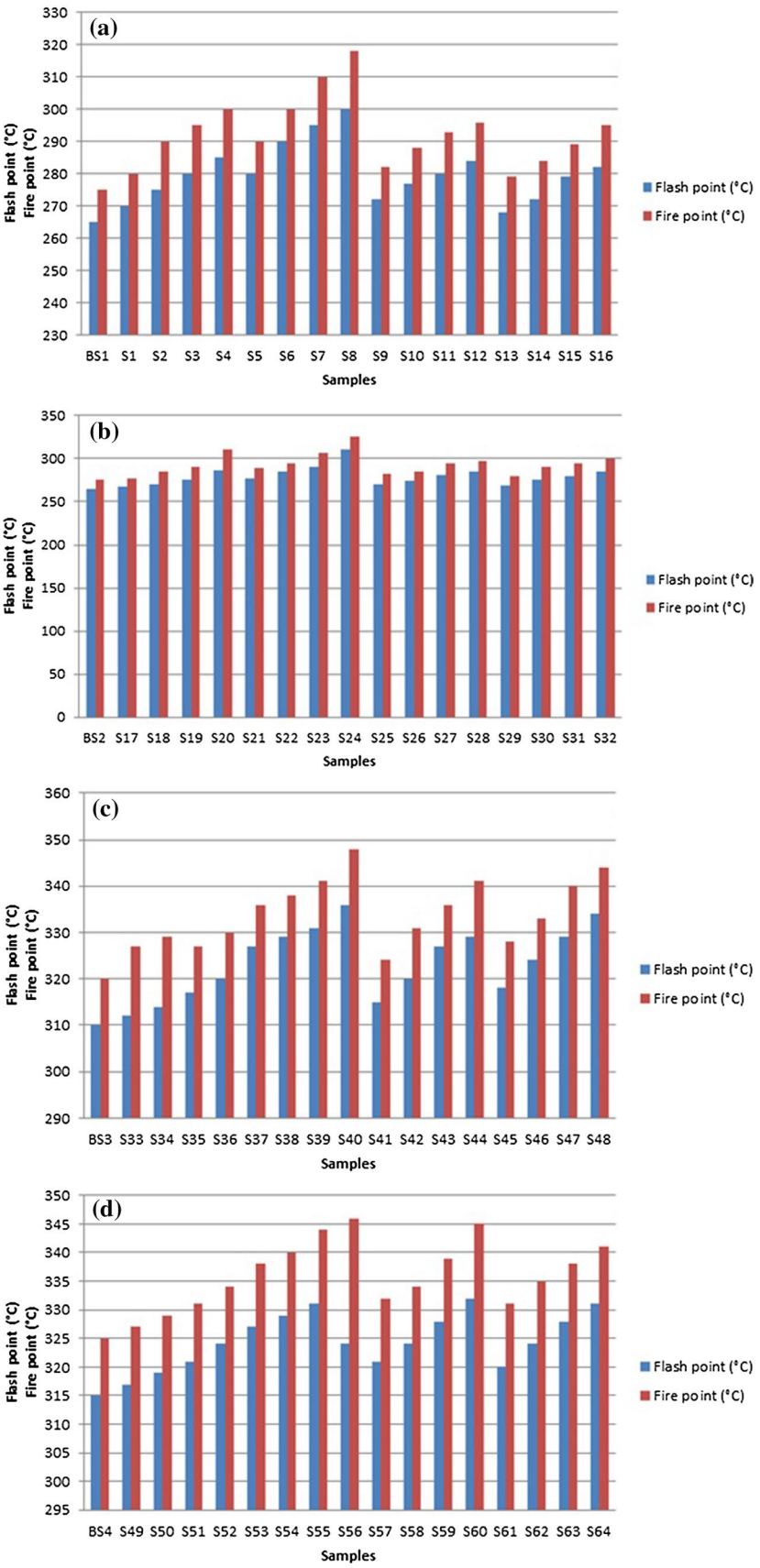

Fig. 2 Flash point and fire point temperature of oil samples. **a** Prepared with base sample 1, **b** prepared with base sample 2, **c** prepared with base sample 3 and **d** prepared with base sample 4

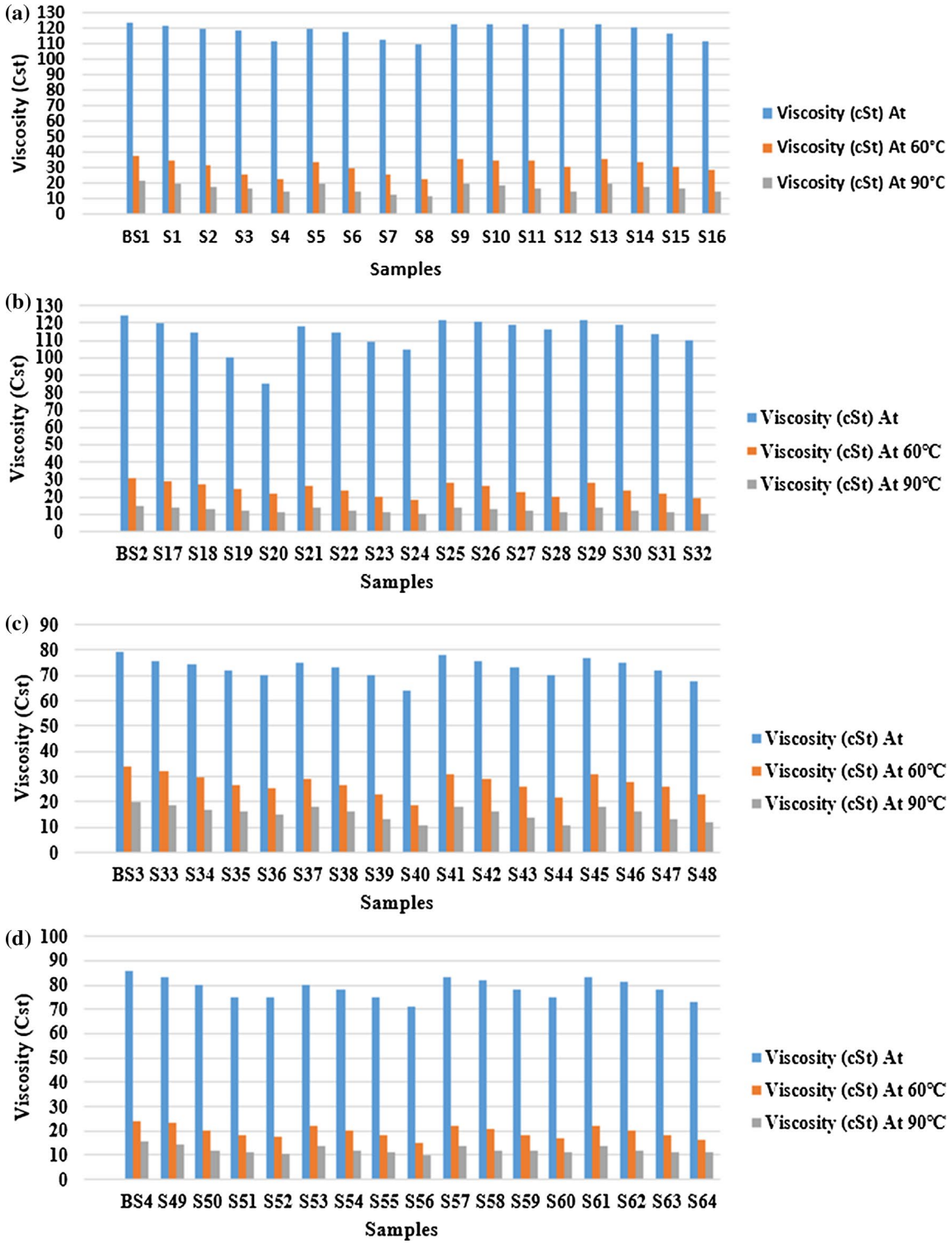

Fig. 3 Viscosities of oil samples at different temperatures. **a** Prepared with base sample 1, **b** prepared with base sample 2, **c** prepared with base sample 3 and **d** prepared with base sample 4

based base samples. This may be due to antioxidants effects such as breaking a chain reaction by emitting a fresh electrons by offsetting the radicals. The base sample 1 with 5 g of gallic acid shows very good decrement compared to other composition at RTP. When the temperature is increased to 90 °C at 12 Cst, the base sample 2 with 5 g of gallic acid

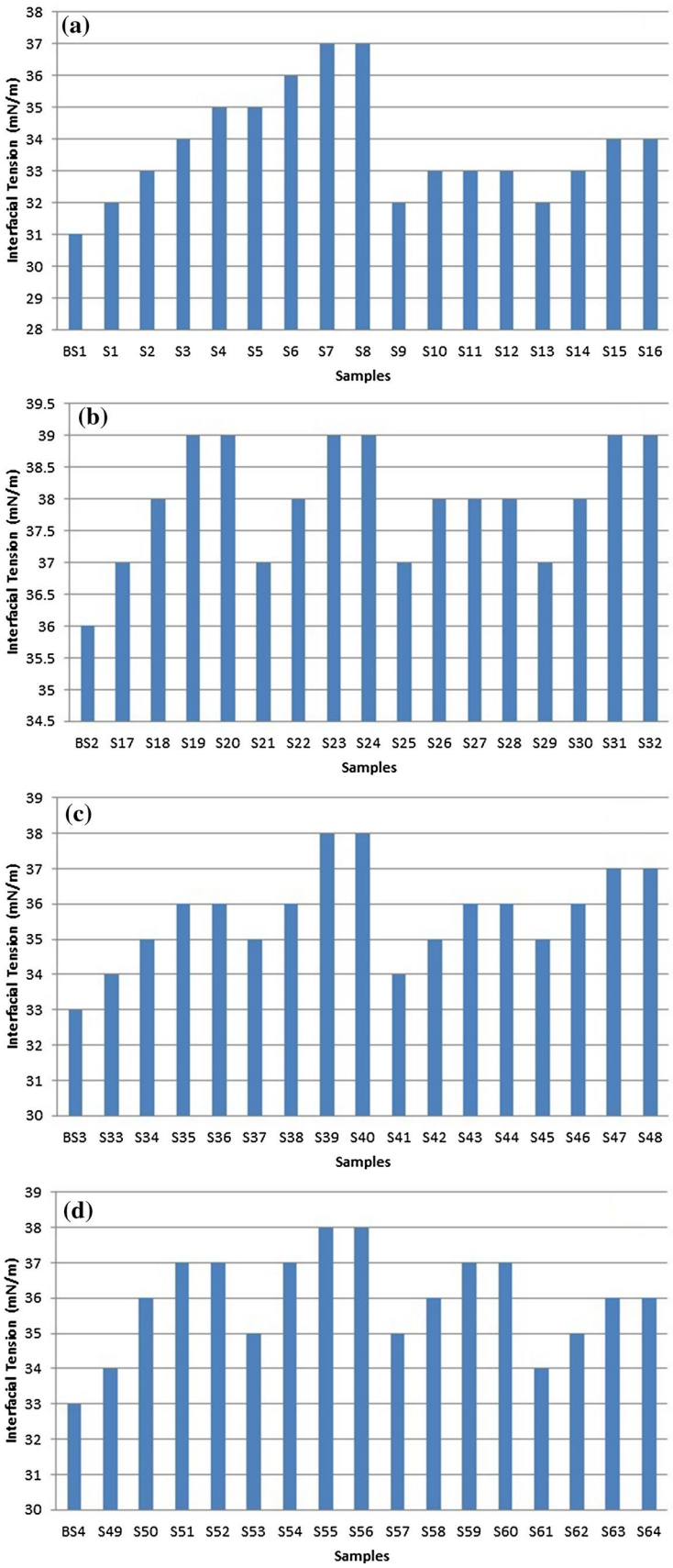

Fig. 4 Interfacial tension of oil samples. **a** Prepared with base sample 1, **b** prepared with base sample 2, **c** prepared with base sample 3 and **d** prepared with base sample 4

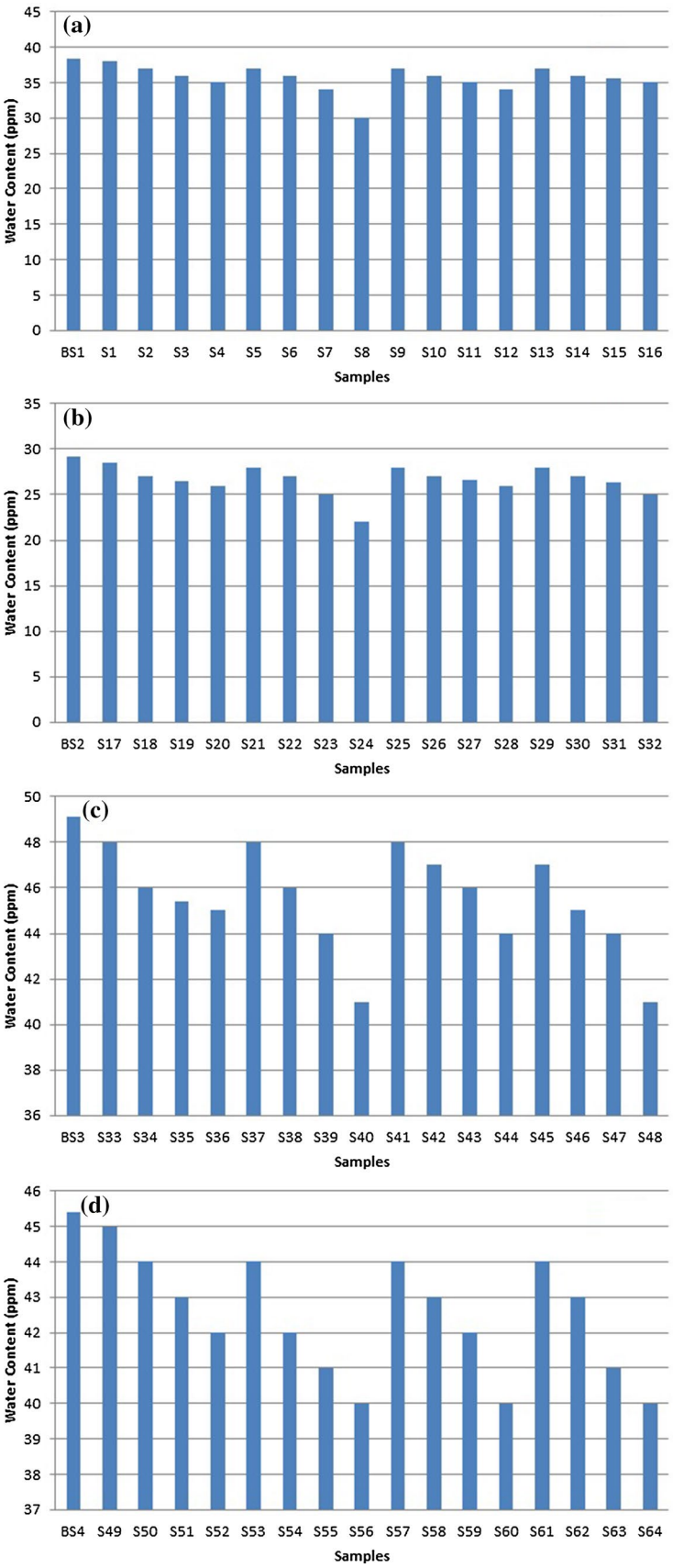

Fig. 5 Water content of oil samples. **a** Prepared with base sample 1, **b** prepared with base sample 2, **c** prepared with base sample 3 and **d** prepared with base sample 4

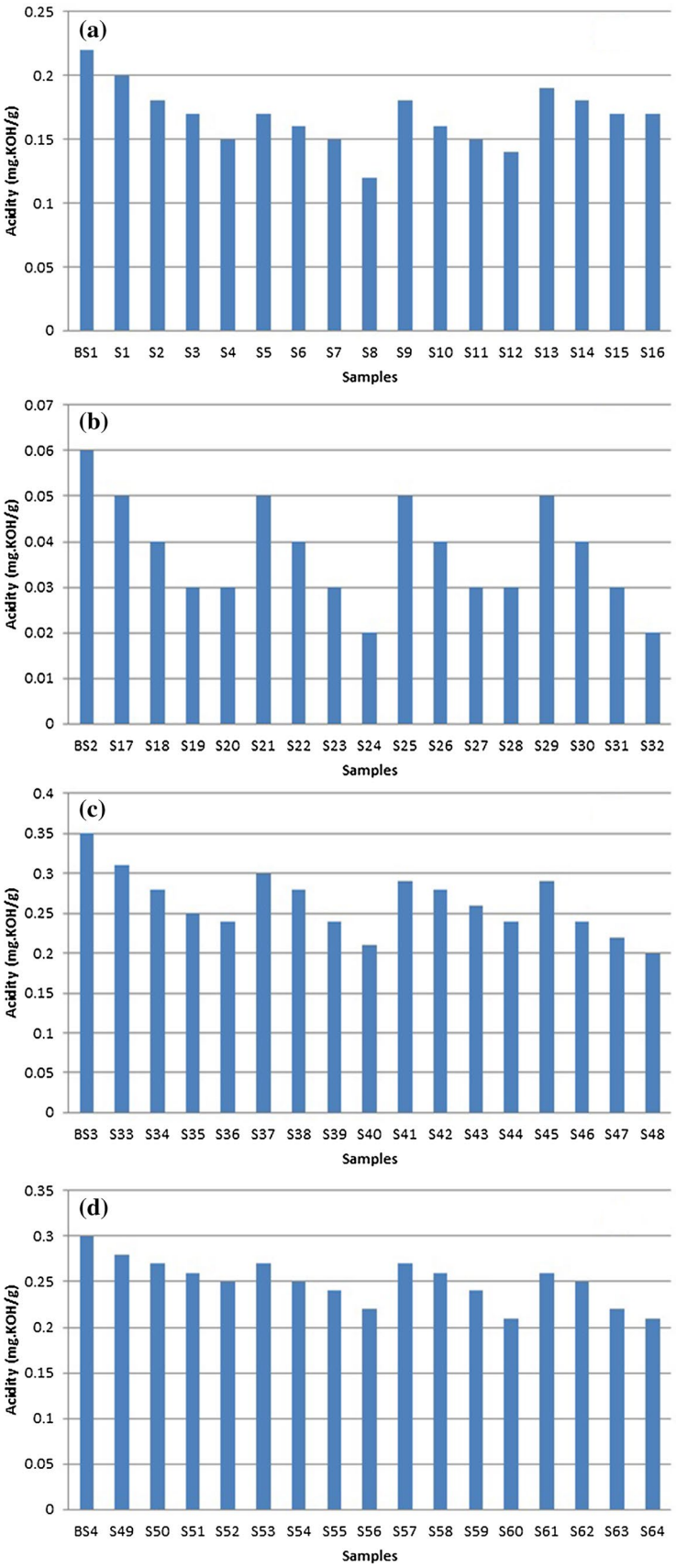

Fig. 6 Acidity of oil samples. **a** Prepared with base sample 1, **b** prepared with base sample 2, **c** prepared with base sample 3 and **d** prepared with base sample 4

gives good decrement than base samples 1, 3 and 4 due to high unsaturated fatty acid content.

3.2.4 Interfacial Tension

Interfacial tension is helpful for deciding the occurrence of polar impurities and oil rot items. Great new oil for the most part displays high interfacial tension. Oil oxidation pollutants bring down the interfacial strain. The interfacial tension of all oil samples are presented in Fig. 4.

Since the exploration, it is clear that the interfacial tensions of natural esters based fluids are higher than the limits. After adding antioxidant compounds, the interfacial tension are enhanced to a high level and this enhancement indicates the purity of natural esters. It is also inferred that the base sample 2, 3 and 4 with 5 g of gallic acid and base sample 2 with 5 g of citric acid and TBHQ has high interfacial tension than other composition. The enhancement of interfacial tension under the influence of antioxidant additives indicates the reduction of water content that leads to acidity of a high level thereby achieve pure form of oil samples with less content of polar pollutants and other deterioration products.

3.2.5 Water Content

Moisture (water) content is designated as the amount of water molecules available in a material. Good natural ester based fluids mustconsumefewer water content molecule. When the water content molecule is reduced to low level, the acidity will be reduced which leads to high interfacial tension and breakdown voltage. The pictorial representations of water content of all samples are represented in Fig. 5.

After the examination, it is noted that the natural esters based fluids have higher water content than mineral oil other than base sample 2 which has lower water content. Reduction of water content of base samples is obtained by addition of antioxidant additives.Based on the analysis, it is inferred that the base sample 2 with 5 g of gallic acid shows good decrement than other compositions.Compared to the pure natural esters, the base sample 1, 2, 3 and 4 with 5 g of gallic acid gives lower water content with antioxidants which increases the purity of samples to a higher level.

3.2.6 Acidity

Acidity improves the oxidation practice in oil. Good natural ester based fluids would have fewer acidity. Acidity of oil samples are graphically represented in Fig. 6.

From the analysis, it is found that other than base sample 2, all other base samples are found to have high acidity compared to mineral oil. Since the investigation, it is observed that the addition of antioxidant additives to natural esters reduces acidity to a considerable level. The base sample 2 with 5 g of gallic acid and TBHQ gives good decrement of acidity compared to other composition. Similarly the base sample 1 with 5 g of gallic acid and base sample 3 and 4 with 5 g of TBHQ shows good decrement.

Enhancement/decrement in properties of oil samples after adding antioxidants with base oil samples are analyzed to know the influence of additives on the oil properties. Enhancement/decrement percentages in properties for all oil samples equipped with antioxidants are tabulated in Tables 9, 10, 11 and 12 for oil samples prepared with base sample 1, base sample 2, base sample 3 and base sample 4 respectively.

By comparing the obtained recorded experimental results with the various results of surveys, it is witnessed that the selected composition of fluids with the influence of diverse quantity of additives elevates the performance of fluids. The percentage of property enhancement and decrement of investigated additives based oil samples are analyzed. It is well recognized that addition of antioxidant additives with various base samples offer optimized property enrichment. The crucial properties like breakdown voltage, flash point, fire point and interfacial tension shows elevating behavior with the influence of 5 g of Gallic acid. Similarly, the challenging properties like viscosity, water content and acidity shows extreme declining behavior with the addition of 5 g of Gallic acid. Overall, it is well witnessed that 5 g of Gallic acid offers extreme property enrichment than other investigated antioxidant additives due to its phenolic and organic nature which are far superior to the results studied in surveys.

4 Mathematical Evaluation

For determining relations between different parameter variables, statistical based regression analysis is utilized as a unique tool [30]. Regression tool is also useful to develop mathematical relations (equations) among the variables. It is assorted as linear, exponential, logarithmic and nonlinear regressions based on the change of parameters with respect to other variables. The mathematical equations can be derived by doing regression analysis on linear, nonlinear, exponential and logarithmic scales for various parameters. Generally linear correlation coefficient (r) and coefficient of determination (r^2) are measured to validate the relationship between variables while performing regression analysis. These values indicate the perfect fitting of data in the curves. For linear regression analysis, both linear correlation coefficient (r) and coefficient of determination (r^2) exists. Only the coefficient of determination (r^2) exists for nonlinear regression. The range of values for coefficient of determination (r^2) is between 0 to 1. The value of '1' specifies the apt fitting of data [30].

Table 9 Enhancement/decrement in properties of antioxidant added base sample 1

Samples	Enhancement percentage (%)								
	In breakdown voltage	In flash point	In fire point	In Viscosity			In interfacial tension	In water content	In acidity
				At RTP	At 60 °C	At 90 °C			
S1	1.91	1.89	1.82	− 1.61	− 7.41	− 9.09	3.23	− 1.04	− 9.09
S2	7.01	3.77	5.45	− 3.23	− 15.34	− 18.18	6.45	− 3.65	− 18.18
S3	14.01	5.66	7.27	− 4.03	− 31.22	− 22.73	9.68	− 6.25	− 22.73
S4	21.66	7.55	9.09	− 9.68	− 39.15	− 31.82	12.90	− 8.85	− 31.82
S5	8.28	5.66	5.45	− 3.23	− 10.05	− 9.09	12.90	− 3.65	− 22.73
S6	18.47	9.43	9.09	− 4.84	− 20.63	− 31.82	16.13	− 6.25	− 27.27
S7	27.39	11.32	12.73	− 8.87	− 31.22	− 40.91	19.35	− 11.46	− 31.82
S8	38.85	13.21	15.64	− 11.29	− 39.15	− 45.45	19.35	− 21.88	− 45.45
S9	7.01	2.64	2.55	− 0.81	− 4.76	− 9.09	3.23	− 3.65	− 18.18
S10	11.46	4.53	4.73	− 0.97	− 7.41	− 13.64	6.45	− 6.25	− 27.27
S11	18.47	5.66	6.55	− 1.45	− 8.99	− 22.73	6.45	− 8.85	− 31.82
S12	24.20	7.17	7.64	− 3.23	− 17.99	− 31.82	6.45	− 11.46	− 36.36
S13	5.10	1.13	1.45	− 0.81	− 4.76	− 9.09	3.23	− 3.65	− 13.64
S14	12.10	2.64	3.27	− 2.42	− 10.05	− 18.18	6.45	− 6.25	− 18.18
S15	16.56	5.28	5.09	− 5.65	− 17.99	− 22.73	9.68	− 7.29	− 22.73
S16	21.02	6.42	7.27	− 9.68	− 23.28	− 31.82	9.68	− 8.85	− 22.73

Table 10 Enhancement/decrement in properties of antioxidant added base sample 2

Samples	Enhancement percentage (%)								
	In breakdown voltage	In flash point	In fire point	In Viscosity			In interfacial tension	In water content	In acidity
				At RTP	At 60 °C	At 90 °C			
S17	3.51	0.75	0.73	− 3.23	− 5.84	− 7.28	2.78	− 2.40	− 16.67
S18	12.28	1.89	3.64	− 7.26	− 11.04	− 13.91	5.56	− 7.53	− 33.33
S19	18.71	3.77	5.45	− 19.35	− 20.45	− 20.53	8.33	− 9.25	− 50.00
S20	24.56	8.30	12.73	− 31.45	− 28.57	− 27.15	8.33	− 10.96	− 50.00
S21	5.85	4.53	5.09	− 4.84	− 15.58	− 10.60	2.78	− 4.11	− 16.67
S22	15.20	7.55	7.27	− 7.26	− 22.08	− 20.53	5.56	− 7.53	− 33.33
S23	29.82	9.43	11.27	− 12.10	− 35.06	− 27.15	8.33	− 14.38	− 50.00
S24	40.35	16.98	18.18	− 15.32	− 41.56	− 33.77	8.33	− 24.66	− 66.67
S25	5.26	1.89	2.55	− 1.61	− 9.09	− 7.28	2.78	− 4.11	− 16.67
S26	12.28	3.40	3.64	− 2.42	− 15.58	− 13.91	5.56	− 7.53	− 33.33
S27	16.96	6.04	6.91	− 4.03	− 25.32	− 20.53	5.56	− 8.90	− 50.00
S28	24.56	7.55	8.00	− 6.45	− 35.06	− 27.15	5.56	− 10.96	− 50.00
S29	3.51	1.51	1.82	− 1.61	− 9.09	− 8.61	2.78	− 4.11	− 16.67
S30	8.77	3.77	5.45	− 4.03	− 22.08	− 20.53	5.56	− 7.53	− 33.33
S31	12.28	5.66	7.27	− 8.06	− 28.57	− 27.15	8.33	− 9.59	− 50.00
S32	18.13	7.55	9.09	− 11.29	− 38.31	− 33.77	8.33	− 14.38	− 66.67

In this work, nonlinear regression tool is used to analyze the relation between properties of oil and concentration of antioxidant additives. The mathematical equations of properties are also developed for all antioxidants used in this investigation work. Various concentrations(x) of antioxidants are 1 g, 2 g, 3 g and 5 g. For all natural esters and antioxidants, the properties such as breakdown voltage (BV), flash point (FP1), fire point (FP2), viscosity (V), interfacial tension (IT), water content (WC) and acidity (A) are organized in Tables 13, 14, 15, 16, 17, 18 and 19

Table 11 Enhancement/decrement in properties of antioxidant added base sample 3

Samples	Enhancement percentage (%)								
	In breakdown voltage	In flash point	In fire point	In viscosity			In interfacial tension	In water content	In acidity
				At RTP	At 60 °C	At 90 °C			
S33	6.25	0.65	2.19	− 4.04	− 5.33	− 5.00	3.03	− 2.24	− 11.43
S34	11.81	1.29	2.81	− 6.19	− 12.43	− 14.50	6.06	− 6.31	− 20.00
S35	27.08	2.26	2.19	− 9.09	− 20.12	− 19.00	9.09	− 7.54	− 28.57
S36	38.89	3.23	3.13	− 11.62	− 25.15	− 25.00	9.09	− 8.35	− 31.43
S37	12.50	5.48	5.00	− 5.30	− 14.20	− 10.00	6.06	− 2.24	− 14.29
S38	25.00	6.13	5.63	− 7.83	− 20.12	− 20.00	9.09	− 6.31	− 20.00
S39	39.58	6.77	6.56	− 11.62	− 31.95	− 35.00	15.15	− 10.39	− 31.43
S40	54.86	8.39	8.75	− 19.19	− 43.79	− 45.00	15.15	− 16.50	− 40.00
S41	7.64	1.61	1.25	− 1.52	− 8.28	− 10.00	3.03	− 2.24	− 17.14
S42	20.14	3.23	3.44	− 4.04	− 14.20	− 20.00	6.06	− 4.28	− 20.00
S43	25.00	5.48	5.00	− 7.83	− 23.08	− 30.00	9.09	− 6.31	− 25.71
S44	41.67	6.13	6.56	− 11.62	− 34.91	− 45.00	9.09	− 10.39	− 31.43
S45	9.03	2.58	2.50	− 2.78	− 8.28	− 10.00	6.06	− 4.28	− 17.14
S46	16.67	4.52	4.06	− 5.30	− 17.16	− 20.00	9.09	− 8.35	− 31.43
S47	25.00	6.13	6.25	− 9.09	− 23.08	− 35.00	12.12	− 10.39	− 37.14
S48	37.50	7.74	7.50	− 14.14	− 31.95	− 40.00	12.12	− 16.50	− 42.86

Table 12 Enhancement/decrement in properties of antioxidant added base sample 4

Samples	Enhancement percentage (%)								
	In breakdown voltage	In flash point	In fire point	In viscosity			In interfacial tension	In water content	In acidity
				At RTP	At 60 °C	At 90 °C			
S49	− 1.36	0.63	0.62	− 3.26	− 4.96	− 7.79	3.03	− 0.88	− 6.67
S50	2.72	1.27	1.23	− 6.76	− 16.94	− 22.08	9.09	− 3.08	− 10.00
S51	11.56	1.90	1.85	− 12.35	− 25.62	− 28.57	12.12	− 5.29	− 13.33
S52	17.01	2.86	2.77	− 12.59	− 26.45	− 29.87	12.12	− 7.49	− 16.67
S53	7.48	3.81	4.00	− 6.76	− 9.09	− 9.09	6.06	− 3.08	− 10.00
S54	14.97	4.44	4.62	− 9.09	− 17.36	− 23.38	12.12	− 7.49	− 16.67
S55	25.85	5.08	5.85	− 12.59	− 25.62	− 28.57	15.15	− 9.69	− 20.00
S56	37.41	2.86	6.46	− 17.25	− 38.02	− 35.06	15.15	− 11.89	− 26.67
S57	7.48	1.90	2.15	− 3.26	− 9.09	− 9.09	6.06	− 3.08	− 10.00
S58	15.65	2.86	2.77	− 4.43	− 13.22	− 22.08	9.09	− 5.29	− 13.33
S59	23.81	4.13	4.31	− 9.09	− 25.62	− 24.68	12.12	− 7.49	− 20.00
S60	32.65	5.40	6.15	− 12.59	− 29.75	− 28.57	12.12	− 11.89	− 30.00
S61	0.00	1.59	1.85	− 3.26	− 9.09	− 9.09	3.03	− 3.08	− 13.33
S62	8.16	2.86	3.08	− 5.59	− 17.36	− 22.08	6.06	− 5.29	− 16.67
S63	12.24	4.13	4.00	− 9.09	− 25.62	− 25.97	9.09	− 9.69	− 26.67
S64	16.33	5.08	4.92	− 14.92	− 33.88	− 28.57	9.09	− 11.89	− 30.00

respectively. The validations of mathematical equations are measured by calculating the coefficient of determination (r^2) for each equation. The mathematical functions are useful to calculate the properties for intermediates ranges of antioxidants.

For every sample with antioxidants, properties such as breakdown voltage, flash point, fire point, viscosity, interfacial tension, water content and acidity are derived as mathematical function of concentration of antioxidants using nonlinear regression analysis. These mathematical equations

Table 13 Regression function for breakdown voltage

Oil samples	Breakdown voltage (kV)	Coefficient of determination (r^2)
MUO + CA	$BV = 0.020x^3 - 0.381x^2 + 2.599x + 29.76$	1
RBO + CA	$BV = 0.058x^3 - 1.033x^2 + 5.691x + 30.68$	1
PO + CA	$BV = -0.090x^2 + 2.051x + 28.56$	0.999
CO + CA	$BV = -0.070x^2 + 1.368x + 27.71$	0.999
MUO + GA	$BV = 0.06x^3 - 1.046x^2 + 5.92x + 29.06$	1
RBO + GA	$BV = 0.029x^3 - 0.618x^2 + 4.850x + 31.93$	1
PO + GA	$BV = 0.053x^3 - 0.981x^2 + 6.166x + 27.16$	1
CO + GA	$BV = 0.026x^3 - 0.492x^2 + 3.493x + 28.57$	1
MUO + PG	$BV = 0.013x^3 - 0.273x^2 + 2.126x + 31.73$	1
RBO + PG	$BV = 0.051x^3 - 0.88x^2 + 4.678x + 32.15$	1
PO + PG	$BV = 0.093x^3 - 1.534x^2 + 7.546x + 24.89$	1
CO + PG	$BV = 0.040x^3 - 0.724x^2 + 4.289x + 27.99$	0.998
MUO + TBHQ	$BV = 0.045x^3 - 0.797x^2 + 4.274x + 29.47$	1
RBO + TBHQ	$BV = 0.038x^3 - 0.661x^2 + 3.511x + 32.51$	1
PO + TBHQ	$BV = 0.037x^3 - 0.652x^2 + 3.892x + 28.12$	1
CO + TBHQ	$BV = 0.053x^3 - 0.926x^2 + 4.806x + 25.46$	0.998

are very much useful to find out the properties for intermediate concentrations of antioxidants. These equations are also useful for finding optimized concentration of antioxidants at which oil samples have superior properties. Most of the derived equations have values nearer to one forcoefficient of determination (r^2). These values show exact fitting of data in the equations.

5 Conclusion

Literally it is more significant that the insulating fluid mustofferimprovedstabilityamongstimprovedefficient performances againstdecreased environmental impact. In order to stumble on the alternate dielectric medium which has progressive properties, this effort is exploring the vegetable based oils like mustard oil, rice bran oil, punna oil and castor oil by blending with some of the natural and synthetic antioxidant compounds. With the help of individual focus, the assessmentelucidates that the behaviour of vegetable seed based oils with antioxidants become superior and in that the concert of 5 g of gallic acid with base sample 2 provides elevatedbetter properties than other samples due to the presence of high saturated and mono un-saturated fatty acids with low poly un-saturated fatty acids. This betterment is possible with high saturated, mono un-saturated fatty acids with low poly un-saturated fatty acids along with the influence of phenolic and organic nature based antioxidants. All oil samples have greater characteristics than that of traditional mineral oil is observed. During experiments, oil samples never get decelerate due to less formation of carbon in it. The cost is greaterrelated to mineral oil but such downside is overwhelmed by gentle ageing rate, improved oxidative stability and fewerdevelopment of gasses. By using the vegetable oil as a surrogate to mineral oil the environment becomes green. The use of vegetable oil offers the hands when insufficiencyarises with mineral oil which have a renewable resource so this methodology is extreme in technical and environmental aspects. Henceforth the completeexaminationaccomplishes that the vegetable oil blended with antioxidant is a suitable surrogate to mineral oil for transformer application. In future, the proposed work may be enhanced by analyzing the ageing behaviour for the identified vegetable oil with nanoparticles as additives.

Table 14 Regression Function for flash point

Oil samples	Flash point (°C)	Coefficient of determination (r^2)
MUO + CA	$FP1 = 0.083x^3 - 1.5x^2 + 8.916x + 262.5$	1
RBO + CA	$FP1 = 0.047x^3 - 0.711x^2 + 4.802x + 262.8$	1
PO + CA	$FP1 = 0.022x^3 - 0.427x^2 + 3.127x + 309.2$	0.998
CO + CA	$FP1 = 0.036x^3 - 0.622x^2 + 3.613x + 313.9$	1
MUO + GA	$FP1 = 0.222x^3 - 3.861x^2 + 20.02x + 263.6$	1
RBO + GA	$FP1 = 0.208x^3 - 3.25x^2 + 16.29x + 263.7$	1
PO + GA	$FP1 = 0.041x^3 - 0.666x^2 + 3.708x + 323.9$	1
CO + GA	$FP1 = -0.267x^2 + 2.593x + 324.7$	0.999
MUO + PG	$FP1 = 0.108x^3 - 1.866x^2 + 9.841x + 263.9$	1
RBO + PG	$FP1 = 0.025x^3 - 0.616x^2 + 5.675x + 264.9$	1
PO + PG	$FP1 = 0.047x^3 - 1.044x^2 + 7.802x + 308.1$	1
CO + PG	$FP1 = 0.038x^3 - 0.727x^2 + 4.911x + 316.7$	1
MUO + TBHQ	$FP1 = 0.022x^3 - 0.594x^2 + 5.627x + 262.9$	1
RBO + TBHQ	$FP1 = 0.111x^3 - 1.972x^2 + 11.13x + 259.7$	1
PO + TBHQ	$FP1 = 0.111x^3 - 1.972x^2 + 11.13x + 308.7$	1
CO + TBHQ	$FP1 = 0.063x^3 - 1.177x^2 + 7.086x + 314.0$	1

Table 15 Regression function for fire point

Oil samples	Fire point (°C)	Coefficient of determination (r^2)
MUO + CA	$FP2 = 0.222x^3 - 3.861x^2 + 20.02x + 263.6$	1
RBO + CA	$FP2 = 0.208x^3 - 3.25x^2 + 16.29x + 263.7$	1
PO + CA	$FP2 = 0.091x^3 - 1.4x^2 + 5.558x + 322.7$	1
CO + CA	$FP2 = 0.036x^3 - 0.622x^2 + 3.613x + 323.9$	1
MUO + GA	$FP2 = 0.161x^3 - 2.955x^2 + 17.73x + 275.0$	1
RBO + GA	$FP2 = 0.066x^3 - 1.116x^2 + 8.883x + 281.1$	1
PO + GA	$FP2 = 0.033x^3 - 0.516x^2 + 3.316x + 333.1$	1
CO + GA	$FP2 = -0.122x^2 + 2.229x + 335.9$	0.999
MUO + PG	$FP2 = 0.105x^3 - 1.927x^2 + 11.04x + 272.7$	0.998
RBO + PG	$FP2 = -0.033x^3 + 0.266x^2 + 2.433x + 279.3$	1
PO + PG	$FP2 = 0.138x^3 - 2.444x^2 + 13.36x + 312.9$	1
CO + PG	$FP2 = -0.061x^2 + 2.114x + 329.9$	1
MUO + TBHQ	$FP2 = 0.086x^3 - 1.522x^2 + 8.963x + 271.4$	1
RBO + TBHQ	$FP2 = 0.222x^3 - 3.861x^2 + 20.02x + 263.6$	1
PO + TBHQ	$FP2 = 0.052x^3 - 1.088x^2 + 7.897x + 321.1$	1
CO + TBHQ	$FP2 = 0.077x^3 - 1.372x^2 + 7.572x + 324.7$	1

Table 16 Regression function for viscosity (at RTP)

Oil samples	Viscosity at RTP (cSt)	Coefficient of determination (r^2)
MUO + CA	$V = -0.061x^3 + 0.905x^2 - 4.288x + 125.4$	1
RBO + CA	$V = 0.221x^2 - 6.353x + 126.4$	0.999
PO + CA	$V = -0.020x^3 + 0.4x^2 - 2.754x + 78.37$	1
CO + CA	$V = 0.213x^2 - 3.210x + 85.82$	0.997
MUO + GA	$V = 0.127x^2 - 2.520x + 122.4$	0.999
RBO + GA	$V = 0.161x^2 - 3.208x + 120.9$	0.998
PO + GA	$V = -0.030x^3 + 0.494x^2 - 3.269x + 77.80$	1
CO + GA	$V = -0.025x^3 + 0.45x^2 - 3.175x + 82.75$	1
MUO + PG	$V = -0.003x^3 + 0.026x^2 - 0.256x + 123.2$	1
RBO + PG	$V = -0.008x^3 + 0.15x^2 - 1.391x + 123.2$	1
PO + PG	$V = -0.022x^3 + 0.427x^2 - 3.127x + 80.72$	1
CO + PG	$V = 0.019x^3 - 0.238x^2 - 0.419x + 83.63$	1
MUO + TBHQ	$V = -0.013x^3 + 0.277x^2 - 2.736x + 125.4$	1
RBO + TBHQ	$V = -0.025x^3 + 0.533x^2 - 4.425x + 125.9$	1
PO + TBHQ	$V = -0.025x^3 + 0.45x^2 - 3.175x + 79.75$	1
CO + TBHQ	$V = -0.027x^3 + 0.472x^2 - 3.222x + 85.77$	1

Table 17 Regression function for interfacial tension

Oil samples	Interfacial tension (mN/m)	Coefficient of determination (r^2)
MUO + CA	$IT = 0.016x^3 - 0.3x^2 + 1.783x + 30.5$	1
RBO + CA	$IT = 0.013x^3 - 0.277x^2 + 1.736x + 35.52$	1
PO + CA	$IT = 0.013x^3 - 0.277x^2 + 1.736x + 32.52$	1
CO + CA	$IT = 0.041x^3 - 0.75x^2 + 3.958x + 30.75$	1
MUO + GA	$IT = 0.013x^3 - 0.277x^2 + 1.736x + 33.52$	1
RBO + GA	$IT = 0.013x^3 - 0.277x^2 + 1.736x + 35.52$	1
PO + GA	$IT = -0.083x^2 + 1.25x + 33.83$	1
CO + GA	$IT = 0.041x^3 - 0.75x^2 + 3.958x + 31.75$	1
MUO + PG	$IT = 0.027x^3 - 0.472x^2 + 2.222x + 30.22$	0.999
RBO + PG	$IT = 0.027x^3 - 0.472x^2 + 2.222x + 35.22$	0.998
PO + PG	$IT = 0.013x^3 - 0.277x^2 + 1.736x + 32.52$	1
CO + PG	$IT = 0.013x^3 - 0.277x^2 + 1.736x + 33.52$	1
MUO + TBHQ	$IT = 0.013x^3 - 0.277x^2 + 1.736x + 30.52$	1
RBO + TBHQ	$IT = 0.013x^3 - 0.277x^2 + 1.736x + 35.52$	1
PO + TBHQ	$IT = 0.013x^3 - 0.277x^2 + 1.736x + 33.52$	1
CO + TBHQ	$IT = 0.013x^3 - 0.277x^2 + 1.736x + 32.52$	1

Table 18 Regression function for water content

Oil samples	Water content (ppm)	Coefficient of determination (r^2)
MUO + CA	$WC = -0.016x^3 + 0.3x^2 - 1.783x + 39.5$	1
RBO + CA	$WC = -0.036x^3 + 0.622x^2 - 3.113x + 31.02$	1
PO + CA	$WC = -0.048x^3 + 0.836x^2 - 4.171x + 51.38$	1
CO + CA	$WC = -0.016x^3 + 0.3x^2 - 1.783x + 46.5$	1
MUO + GA	$WC = -0.005x^2 - 0.708x + 37.60$	0.998
RBO + GA	$WC = 0.017x^2 - 0.843x + 28.74$	0.998
PO + GA	$WC = -0.036x^3 + 0.622x^2 - 3.613x + 51.02$	1
CO + GA	$WC = -0.044x^3 + 0.772x^2 - 4.005x + 47.27$	1
MUO + PG	$WC = -0.016x^3 + 0.3x^2 - 1.783x + 38.5$	1
RBO + PG	$WC = -0.023x^3 + 0.407x^2 - 2.056x + 29.67$	1
PO + PG	$WC = -0.019x^3 + 0.322x^2 - 1.830x + 49.52$	1
CO + PG	$WC = -0.019x^3 + 0.322x^2 - 1.830x + 45.52$	1
MUO + TBHQ	$WC = -0.023x^3 + 0.407x^2 - 2.056x + 38.67$	1
RBO + TBHQ	$WC = -0.023x^3 + 0.386x^2 - 1.996x + 29.63$	1
PO + TBHQ	$WC = -0.05x^3 + 0.816x^2 - 4.1x + 50.33$	1
CO + TBHQ	$WC = 0.061x^2 - 1.114x + 45.02$	0.999

Table 19 Regression function for acidity

Oil samples	Acidity (mg KOH/g)	Coefficient of determination (r^2)
MUO + CA	$A = 0.007x^2 - 0.040x + 0.233$	1
RBO + CA	$A = 0.002x^2 - 0.017x + 0.064$	1
PO + CA	$A = 0.008x^2 - 0.052x + 0.354$	1
CO + CA	$A = 0.003x^2 - 0.017x + 0.295$	1
MUO + GA	$A = 0.003x^2 - 0.018x + 0.185$	1
RBO + GA	$A = 0.003x^2 - 0.017x + 0.065$	1
PO + GA	$A = 0.001x^2 - 0.020x + 0.319$	0.998
CO + GA	$A = 0.007x^2 - 0.040x + 0.303$	1
MUO + PG	$A = 0.007x^2 - 0.040x + 0.212$	1
RBO + PG	$A = 0.002x^2 - 0.017x + 0.064$	1
PO + PG	$A = -0.009x + 0.298$	0.999
CO + PG	$A = -0.008x + 0.277$	0.998
MUO + TBHQ	$A = 0.002x^2 - 0.017x + 0.204$	1
RBO + TBHQ	$A = 0.003x^2 - 0.017x + 0.065$	1
PO + TBHQ	$A = -0.001x^3 + 0.020x^2 - 0.102x + 0.373$	1
CO + TBHQ	$A = -0.015x + 0.275$	0.997

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