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Screening of Repeatedly Heated Cooking Oil Using Physico-Chemical and Electrical Properties with GC-MS Analysis for Reckoning its Reusability

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Abstract

Consuming repeatedly heated cooking oil can have chronic effects on humans. To estimate the reusability of oil samples that underwent multiple cycles of reheating under different conditions, several factors—dielectric constant, viscosity, ultrasonic velocity, and peroxide value (PV) — were investigated. Saturated fatty acids (SFAs) and unsaturated fatty acids (UFAs) in the collected oil samples were identified by Gas Chromatography-Mass Spectrometry (GC-MS). Empirical equations were developed correlating dielectric constant, viscosity and ultrasonic velocity with UFA and SFA. The dependency factor (R^2) among the considered parameters ranges from 0.925 to 0.986. A non-destructive inspection study using ultrasonic velocity and intermolecular free length was conducted to estimate the quality of the samples. The Onsager molecular model equation for liquids was used to relate the microscopic factor, the electric dipole moment, to the macroscopic factor, the dielectric constant, to index the polarisation and dilapidation levels of the samples. The efficacy for estimating oil reusability based on specific physical factors classify oil quality and its reusability.

Keywords: Dielectric constant; dipole moment; GC- MS; heated oil, ultrasonic velocity.

1. Introduction

Vegetable oils have been used for frying, seasoning, and cooking food for centuries. Frying is an attractive method of fast cooking for its colour, texture, aroma, and crispiness [1, 2, 3]. Oil and fat are indispensable major sources of energy to the human body. It has been quantified that each person needs to consume 10–40 ml of oil daily to provide the necessary energy to remain active [2, 3, 4]. Oil stored or heated for prolonged periods undergoes chemical reactions such as oxidation, polymerisation, and hydrolysis [5, 6]. Oil subjected to deep frying undergoes physical and chemical changes, forming volatile and non-volatile degraded products that decrease its quality and nutritive value [7, 8]. During degradation, oil forms toxic chemical compounds, including peroxides, free fatty acids (FFA), aldehydes, and ketones, which can cause ailments such as colon cancer, chronic heart disease, and atherosclerosis [7, 8]. Consequently, the impact of repeatedly using heated oils for frying on public health safety was addressed by many researchers [9].

Though quality and chemical compositional analysis in oil subjected to cycles of heating are reported in early literature using analytical methods like Fourier transform infrared spectroscopy, Nuclear Magnetic Resonance spectroscopy, gas chromatography, high performance liquid chromatography, etc. such methods are time-consuming, user-oriented, cause pollution to the environment and are expensive [10-13].

Modest methods such as viscosity, density, ultrasonic velocity, refractive index, and dielectric constant can be used as eco-friendly tools for quality analysis. Viscosity is the resistance to fluid flow between liquid layers varies with the content of fatty acids. It has a direct relationship with long-chain saturated and unsaturated fatty acids (UFAs) in oil, which regulate its flow [14, 15].

Oxidation in oil converts double bonds into single bonds by adding hydrogen atoms, which increases intermolecular forces, making fluidity among molecules more difficult and thereby increasing viscosity. The *cis* form of UFA reduces closer clustering of molecules and increases the oil's flow rate, thereby decreasing viscosity. Hence, viscosity is a significant factor in determining the quality of fried oil. Proliferation in molecular clustering per unit volume in oil can be indexed by density. The agglomeration capability of oil in forming monomers, dimers, trimers, and oligomers can be studied from changes in density. However, repeated frying of oil decreases its volume, increasing its density, due to the expansion of heat and the mass transfer of oil molecules. Hence, density can also be used as another parameter to index oil degradation. The dielectric constant quantifies the total polar compounds produced in oil during deterioration.

Deteriorated non-volatile compounds are polar compounds that orient and move towards the capacitive electrodes under the applied external field. Hence, with the measured dielectric constant of oil, the degree of oil degradation can be determined. Dilapidation of oil not only affects quality but also poses a safety risk to fried foods[16].

To safeguard consumers from grubby food products, many countries have adopted amendment guidelines that limit the levels of polar compounds in oil. 25 g per 100 g of oil is the recommended limit for polar compound content, as set by Hazard Analysis and Critical Control Points (HACCP) and the Food and Drug Administration (FDA) for health certification [17]. Repeatedly heating oil to its smoke point would change its colour and odour due to chemical changes. Refractive index indicates a colour change in oil due to the formation of peroxides, the primary degraded product of oil [18].

Attenuation of ultrasonic velocity was used to assess the physicochemical properties of meat, fish, eggs, beverages, vegetables, fruits, and packed food items, providing an index of their quality. Measurement of ultrasonic velocity is also a non-invasive method used to index the oil quality. The relationship between ultrasonic velocities and polar as well as polymer molecules has been studied by a few researchers [19-21].

The present work aims to determine the quality and reusability of oil subjected to frying cycles using simple quality indices. Oil samples subjected to different heating cycles were collected, and their physical properties, including viscosity, dielectric constant, refractive index, density, and ultrasonic parameters, were measured. These parameters were correlated with the presence of saturated and UFA in oils. A novel analysis of the relationships between macroscopic parameters, such as ultrasonic velocity and intermolecular free length (Lf), and dielectric constant and induced dipole moment in the presence of an electric field was premeditated. The study will be useful to researchers interested in designing a real-time device or formulating a comprehensive strategy to assess the quality of repeatedly used heated oil based on measured physical properties, given the importance of human health. Further, computational correlation analysis and Principal Component Analysis (PCA) are performed to explore the intrinsic relationships among the measured factors and assess their reusability.

2. Materials and Methods

Sample Preparation

To analyse the quality of heated oils for their reusability, nine samples were collected from messes, snack shops, and canteens where oil has been repeatedly used for frying food items. Each oil sample collected has been filtered to remove solid materials and stored in dark glass containers at ambient temperature (26-28°C). To conduct a comprehensive study of the physical parameters, each collected sample was further divided into three 100 ml samples; hence, 27 samples were used to study the physicochemical properties. The collected sample details are given in Table 1

Fatty Acid Measurement

JEOL GC Mate II GC-MS with HP5 column is a high resolution, double focusing instrument used for taking GCMS analysis. This instrument has been interfaced with Agilent 6890 GC with Electronic Pressure Control and a split less capillary column injector which helps GC/MS to work using EI analysis (Electron Ionization). Agilent 7673 Automatic Liquid Sampler (ALS) with 100 vial trays attached with GC lets unattended sample injections. GC-MS interface is maintained at 250º C temperature. 1µl of oil sample is dissolved in benzene and injected manually in the injector port at temperature 220º C. Helium is used as carrier gas with a flow rate of 1 ml /min. Gas column temperature is programmed as follows: 90º C held for 1 min; 12º C /min to 150º C held for 1 min; 2º C /min to 210º C held for 3 min and 10º C/ min to 250º C, held for 25 min. Selective ion mode is used in this analysis. Mass to charge is set in the range of 80 - 280 atomic mass units. The oven temperature was programmed to maintain a range of 50°-250° C. The spectrum was recorded on a computer interfaced with the instrument [14, 22].

Viscosity Measurement

The kinematic viscosity of the samples was measured using a microcontroller-based Redwood viscometer [8]. The apparatus has been cleaned with acetone each time to remove the previous oil sample completely.

Density Measurement

Density measurement has been carried out with Pycnometer with precision of ± 0.2 kgm^{-3} according to the ASTM (American Society for Testing & Materials) standard method D891-09 [8].

Ultrasonic Measurement

Ultrasonic interferometer (F-80, Mittal Enterprises, Delhi, India) working at 2 MHz frequency with an accuracy of ±0.01 ms^{-1} has been used to measure ultrasonic velocities in oil sample [8]

Refractive Index

Refractive index is the resistance offered to light passing through a liquid medium. Refractive indices of oils that endured many cycles of heating have been experimented using Abbe's refractometer (Sinotech) as per ASTM D1218. Accuracy of refractive index measurements is observed to be ± 0.0001 [11].

Dielectric Constant

Dielectric constant of oil has been experiential using DCK-001(Mittal enterprises, New Delhi, India) with the designed capacitor [23].

Measurement of Peroxide Value (PV)

Using the standard AOCS Cd 8-53 methodology, the total peroxide formed on the oil samples on oxidation has been determined [11].

Statistical Analysis

Dependencies of index parameters are scrutinized using GraphPad Prism software and are exemplified in Table 2. Data are recorded with mean ± SD. One-way ANOVA has been performed, with viscosity as the independent variable and the remaining parameters as dependent variables; the p-value has been obtained. Range of p-value less than 0.05 is considered as significant and less than 0.01 and 0.001 are considered as very significant.

3. Results and Discussion

Profiling of Collected Oil Samples

Collected samples are assorted, with their thermal history unknown; the characterisation and composition of the oil samples were profiled using GC-MS and are illustrated in Table 1. Table 1 shows the profiling of fatty acids and other products that are significantly observed. Noticeable secondary degraded chemical species, such as Palmitic diacyl ester (18%) and Palmitic ester (5.4%), have been observed. As a result of polymerisation, triolein- triglyceride formed by 3 unsaturated oleics, and tristearin formed by 3 stearic acids with glycerol were also observed. The GCMS study above illustrates that oxidation, hydrolysis, and polymerisation reactions occur in oil during repeated cycles of frying. The analytical method of GC-MS for evaluating oil quality is tedious, requires skilled operators, involves oil solvents, produces chemical pollution, and is, above all, costly. Thus, instead of analytical methods, studying the physical properties of oil will be a viable way to ascertain quality [8, 25].

Table 1. Characterization of collected heated oil sample

Sample	% of major fatty acids in oil							Other degraded product
	Palmitic C16:0	Stearic C18:0	Oleic C18:1	Linoelic C18:2	Linonelic C18:3	Arachidic C20:0	Behenic C22:0	
S_1	30.02	24.68	-	16.44	-	-	-	Palmiticdiacyl ester 18%
S_2	42.82	-	30.65	07.14	-	-	-	Triolein 14%
S_3	21.82	16.36	40.12	12.37	-	-	-	-
S_4	43.35	10.92	-	24.82	-	-	-	Tristearin 12%
S_5	14.68	22.71	30.13	12.03	-	4.36	3.10	Palmitic ester 5.4%
S_6	32.49	10.30	33.40	19.52	-	-	-	-
S_7	41.95	11.92	32.80	4.23	1.40	-	-	-
S_8	20.75	3.32	14.30	46.21	5.88	-	-	-
S_9	52.4	4.5	29.5	06.00	-	-	-	-

Physical Properties of Oil Samples

Table 2 illustrates the variation in ultrasonic velocity (UV), density, viscosity, Refractive Index (RI), and dielectric constant (DC) for the collected oil samples. Ultrasonic velocity has been calculated by measuring the distance between antinodes to antinodes current of standing waves formed in an oil column. The ultrasonic velocity varied from 1354 to 1447 m/s. Changes in ultrasonic velocity indicate changes in the chemical composition of the sample upon heating. When oil is used for deep frying food items, oxidation reactions produce peroxides, FFA, SFA, and polymer compounds, due to the addition of hydrogen bonds or the removal of water molecules, etc. [24]. Ultrasonic velocity decreases due to reflection, scattering and diffraction of the signal by the covalent and hydrogen bonds of chemical species present in oil [8, 4, 13]. Henceforth, ultrasonic velocity will be less in degraded oil as its propagation through oil is affected by saturated products formed in oil on degradation. Table 2 exhibits samples S_1 and S_2 have lower ultrasonic velocity values than other samples which indicates that these two samples have a high amount of degraded products out of all samples.

Table 2 exemplifies the measured density of heterogeneous oil samples ranging from 0.915 to 0.944 x 10^3 (kg/m^3). In general polymerisation reactions take place on successive heating of oil which results in molecular clustering of fatty acids with glycerol. This reaction forms a monomer, dimer, trimmer and oligomer with higher molecular weight and this increases the density of the oil sample. Hence density can also be used as an index to measure degradation level in oil [4].

Table 2 illustrates kinematic viscosity of collected oil samples ranging from 75.86 to 167.43 (10^{-6}m^2/s). Viscosity has been referred by many authors in literature as a quality index of oil [1, 11]. Viscosity in oil depends on single and double bonds between -C-H- in long chain fatty acids, and increases with saturated fatty acids [8, 11]. Formation of hydro-peroxides, FFA, polymers etc. along with long chain SFA leads to increase in electron number of molecules, thereby increasing inter molecular forces such as London forces, Vander Waals forces etc. resulting an increase in viscosity [3, 14]. Fig. 1 (a) illustrates the upsurge in viscosity with SFA. However the figure exhibits decrease in viscosity which is due to the *cis* form of unsaturated fatty acids in oil. Kink produced in the geometry of *cis* molecule does not allow the fatty acids to stack together, reducing the inter molecular forces with π bonds. This decreases the rotation between C=C bonds and hence long chain unsaturated FA makes the flow easier thus decreasing viscosity [8, 14, 25].

Table 2 also shows variation of refractive index (n) ranging from 1.462 to 1.474. Repeated heating results an increase in total polar compounds, and electrostatic charges which increases refractive index (n) value [10, 18, 24]. High value of refractive index is observed for oil that has undergone repeated heating, and also darkens oil colour on repetitive usage.

Table 2 also illustrates the measured dielectric constant using designed interleaved capacitance. $\varepsilon_r = C_m/C_0$, where C_m - capacitance value in the presence of oil samples, & C_0 - Capacitance value in air. Dielectric constant of samples tabulated in table 2 varies from 2.57 to 3.29. Orientation polarisation, and ionisation polarisation induced in oil on degradation increases total polar compounds present in oil which upsurges the dielectric constant of medium [19, 23, 25]. In addition, rise in dielectric constant in used oil is owing to the proliferation of degraded products like peroxide, ester, aldehyde, ketone etc [26]. At static frequency 2 MHz the polar compounds orient towards the direction of the applied field and move towards the respective electrodes. To apprehend, reusability of oil can be considered correctly with the measurement of its dielectric constant. From table 2, illustrates that sample S_1 with high dielectric constant is inferred as a highly degraded sample that should be discarded and not suitable for further frying.

Table 2. Comparison of the physico-chemical and electrical parameter of collected samples

Sample	UV 10^3(m/s)	Density 10^3 (kg/m^3)	Viscosity 10^{-4}(m^2/s)	RI	DC	PV mEqO_2/kg	Capacitance (pF)
S1	1.35± 0.07^b	0.944±0.003^a	1.67±0.09^b	1.474±0.002^a	3.29±0.01^a	19.24	8.73
S2	1.40± 0.03^a	0.943±0.024^c	1.57±0.03^b	1.472±0.003^b	2.93±0.03^b	17	7.78
S3	1.44± 0.05^c	0.930±0.013^b	1.47±0.06^b	1.466±0.003^b	2.64±0.10^b	15.02	6.98

S4	1.45± 0.04[b]	0.915±0.009[b]	1.22±0.05[b]	1.462±0.001[a]	2.86±0.05[c]	16.5	7.59
S5	1.42± 0.08[c]	0.938±0.015[b]	1.53±0.07[c]	1.471±0.003[b]	2.57±0.07[c]	14.5	6.82
S6	1.44± 0.06[b]	0.929±0.010[b]	1.25±0.06[c]	1.465±0.002[a]	2.63±0.06[b]	15.07	7.01
S7	1.43± 0.14[b]	0.933±0.007[a]	1.37±0.02[a]	1.467±0.003[b]	2.78±0.03[a]	15.8	7.25
S8	1.42± 0.09[b]	0.939±0.011[b]	1.39±0.08[c]	1.470±0.003[c]	2.82±0.07[b]	16.3	7.49
S9	1.43± 0.07[b]	0.915±0.004[a]	1.46±0.07[a]	1.469±0.001[a]	2.79±0.05[b]	16	7.41

Peroxide value of fresh cooking oil has PV values less than 10 milli equivalent/kg. Since the collected oil samples were at different random heating condition, the PV values were observed to be >>10 mEqO_2/kg [11, 18]. The high PV is because of the large amount of saturated free fatty acids and the radicals formed. Table 2 shows a linear proliferation between the experimented peroxide value with the measured capacitance using LCR meter with the dependency factor R^2= 0.997 (p<0.0001). The related empirical equation was obtained through least square fitting as given as equation (1).

$$\boldsymbol{PV} = 0.408\,\boldsymbol{C} \times 10^{-12} + 0.862 \tag{1}$$

Relation between Physical Parameters and Fatty Acids

Physical and chemical properties of oil are contingent on the type of fatty acids (FA) present [24] Saturated and unsaturated fatty acid profiles of oil samples are found and listed in table 1. Correlation between viscosity (η) and molecular weight of saturated fatty acid and unsaturated fatty acid has been carried out for the considered oil samples and the resultant equations are represented as eqs. (2) and (3).

$$\eta = 2.121\boldsymbol{SFA} + 25.58 \tag{2}$$

$$\eta = -0.62\,\boldsymbol{UFA} + 151.8 \tag{3}$$

A linear positive correlation R^2 is obtained as 0.962 for eq. (2) & a negative linear variation of viscosity with a dependency of R^2= 0.919 with UFA in eq. (3) clearly indicates that viscosity decreases with increase in UFA. It is inferred that viscosity of oil increases due to saturated long chain fatty acids and other degraded products in oil. Saturated long chain fatty acids will exhibit a *trans* form, hence molecular interaction between fatty acids will be extensive to increase the viscous nature of oil. Moreover presence of non-volatile degraded complexes like re-cyclic monomers, dimers, trimers and oligomers with high molecular weight retards the flow of oil increases its viscosity [26, 27, 28]. Fig. 1(b) illustrates the variation of viscosity with UFA of the collected oil samples.

Fig. 1 (c)& (d) illustrates the dependence of ultrasonic velocity (v) with saturated and unsaturated fatty acid. The figure exemplifies the relation between UV and SFA. Ultrasonic velocity has been correlated with SFA and UFA and the resultant correlation equations obtained are given in eqs. (4) & (5) respectively.

$$v = -3.66\,\boldsymbol{SFA} + 0.710 \tag{4}$$

$$v = 2.21\,\boldsymbol{UFA} + 0.368 \tag{5}$$

Considering linear negative correlation with least square fitting, dependency parameter R^2 is obtained as 0.9298 for SFA and 0.874 for UFA. Saturated fatty acids are one of the dominant degradation products formed in repeated cycles of heating that decreases UV by the loss of wave. As stated earlier, low value of ultrasonic velocity indicates the presence of a high quantity of degraded products. From the figure, it is evident that ultrasonic velocity is less when SFA is high. When content of SFA in oil increases, density of oil also increases that increases the reflection coefficient and decrease the transmission coefficient i.e. ultrasonic velocity. Whereas unsaturated fatty acids are loosely bounded due to *cis* form in long chain fatty acids with less inter molecular forces and the propagation of UV is reduced [8, 15, 28]. Hence in oil, higher value of ultrasonic velocity indicates its good quality.

Fig. 1 (e & f) exemplifies the correlation of dielectric constant (ε_r) with SFA and UFA. Dielectric constant correlated with SFA and UFA and the corresponding correlation equations obtained are given as eqs. (6) and (7).

$$\varepsilon_r = 0.036\,\boldsymbol{SFA} + 0.006 \tag{6}$$

$$\varepsilon_r = -0.012\,\boldsymbol{UFA} + 0.003 \tag{7}$$

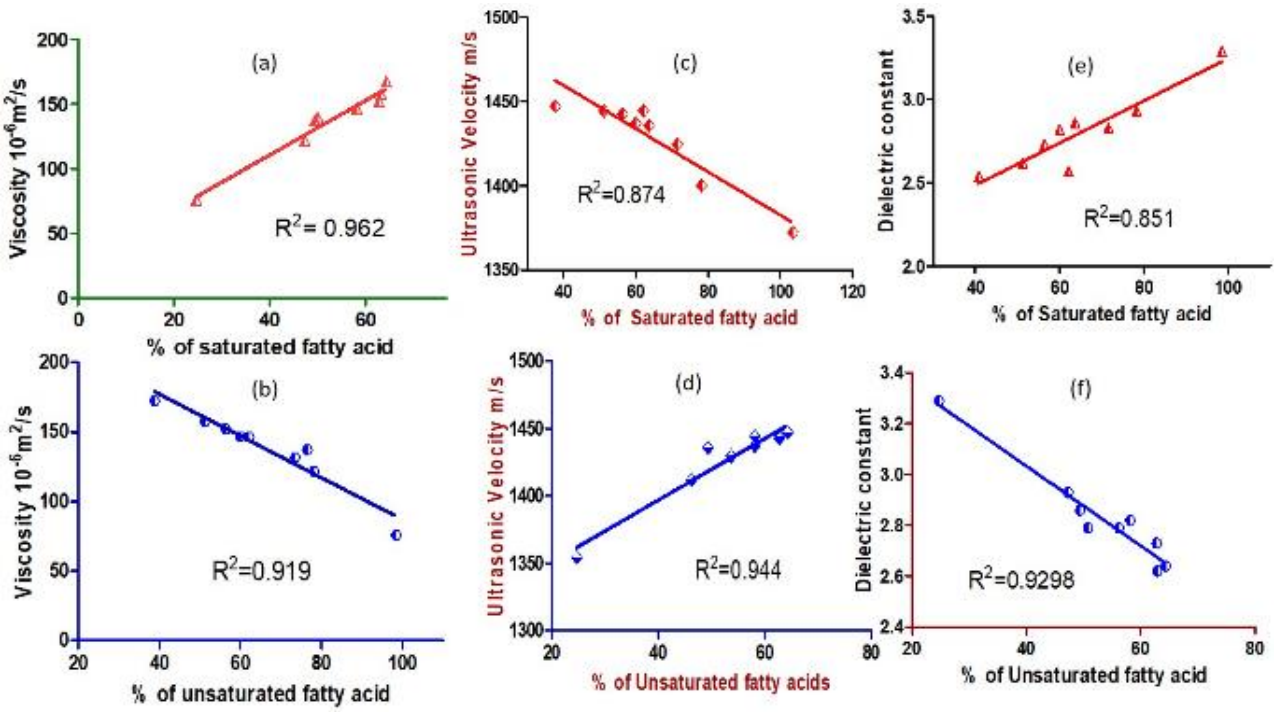

Fig.1 Dependency of Viscosity with (a) saturated & (b) unsaturated, Ultrasonic velocity with (c) saturated & (d) unsaturated, Dielectric constant with (e) saturated & (f) unsaturated fatty acids

Correlation between Physical Parameters

Correlation coefficient R^2 is obtained as 0.944 for SFA and 0.851 with UFA. Dielectric constant can be used to measure the quality of oil. Non- volatile polar compounds like peroxides, SFA, FFA, oligomers etc. formed due to oxidation, hydrolysis, polymerisation changes the position of electrons, chain length and molecular weight [27, 28]. Dielectric constant is highly affected by saturated C16: 0 and C18: 0 fatty acids.

From the above discussion, it is clear that physical parameters can be correlated with fatty acids and can be used as a oil quality indices.

Table 3 illustrates the relationship between the considered physical parameters. Correlation between these factors was calculated by fitting in a quadratic equation using least squares method. Dependency coefficient R^2 lies between 0.925-0.986 shows that the parameters are highly dependent. Viscosity and dielectric constant correlation exhibits a positive linear variation with R^2= 0.925. This is due to an increase in polar compounds like peroxides, FFA, and triglycerides which increase both the dielectric constant and viscosity of oil hence these parameters could be used to design a real time quality analyser.

Relation between the dielectric constant, and ultrasonic velocity (UV) is negatively correlated (R^2 = 0.948) as eq. (8).

$$\varepsilon_r = -4.16\,x10^{-3}\,UV + 8.716$$

Negative coefficient also validates the decrease of UV and increase of DC as illustrated in Fig. 1(c) and (e) with respect to SFA.

Viscosity and UV also negatively correlates with a dependency factor R^2 = 0.986. Viscosity decreases with UFA and UV increases with UFA which validates the results of variation of viscosity and UV shown in Fig. 1(b) and 1(d).

The present study emphasizes that the measurement of physical parameter are highly suitable, low cost, eco-friendly, and accurate compared to analytical methods.

Ultrasonic Study in Characterizing Molecules in Sample

In order to strengthen the study, macroscopic parameter UV is related with a microscopic parameter inter-molecular free length[15]. Table 4 illustrates the variation of ultrasonic wave velocity in samples and the associated parameters acoustic impedance (Z), Adiabatic compressibility (β), inter-molecular free length (L_f).

Calculated Z is a measure of quantification of the ultrasonic wave transmitted by the interface separating two media of different density due to the variation in the molecular clustering that forms due to SFA. With the less value of acoustic impedance in table 4, sample S1 is inferred as the highly degraded sample compared to other samples.

When an ultrasonic wave propagates through a sample at room temperature, adiabatic compressibility exhibits a small decrease in volume due to compression of ultrasonic wave. Table 4 exhibits a higher value of β for S_1 as it is inversely related with UV which implies the content of a large amount of SFA.

One of the imperative intermolecular properties in liquid is molecular free length L_f that defines the distance covered by acoustic waves amidst the different types of fatty acids in oil samples. Inter-molecular free length is the ratio of available volume to the surface area of the molecule. Reduced free length in oil samples S_3, S_4, S_6 and S_7 is due to presence of *cis* UFA that occupy more area compared to the clustered saturated fatty acids. To conclude, molecular free length provides information on molecular packing density, types of inter-molecular interactions and molecular motion determines oil quality [8].

Dielectric Constant in Characterising the Electric Dipole Moment in Oil Sample

Theoretical eqs. (9-11) for polar liquid was given by Onsager molecular model. For a polar liquid: μ - permanent electric dipole moment of a molecule, ε_r - dielectric constant of the liquid, and μ* is the induced dipole moment by the external applied electric field. Dipole moment μ exemplifies the interaction of molecules with all permanent dipole and

long-range fields in dielectric liquid. Onsager molecular model equations are given below: [29].

$$\mu = \frac{(n^2+2)(2\varepsilon+1)}{3(2\varepsilon+n^2)}\mu_0 \quad (9)$$

Table 3: Inter-correlation between physical parameters & statistical coefficients in quadratic fitting

Physical parameter	A x10^{-5}	B x 10^{-2}	C	R^2
Viscosity and Dielectric constant	16	3.4	4.197	0.925
Ultrasonic Velocity and Dielectric constant	-	- 41.6	8.716	0.948
Ultrasonic Velocity and Viscosity	4.7	- 12.7	86.59	0.986

$$\mu^* = \frac{\varepsilon(n^2+2)}{(2\varepsilon+n^2)}\mu_0 \quad (10)$$

And hence $$\frac{\mu^*}{\mu} = \frac{3\varepsilon}{(2\varepsilon+1)} \quad (11)$$

Table 4. Calculated property acoustic impedance, adiabatic compressibility, molecular free length and ratio of electric dipole moment in oil sample

UV (m/s)	(Z) 10^6 (kg/m²s)	Adiabatic compress-ibility (β) 10^{-10} ($N^{-1}m^2$)	Molecular free length (L) 10^{-10}	μ*/μ
1350	1.274	5.81	0.23	1.302
1400	1.320	5.41	0.223	1.281
1440	1.339	5.19	0.218	1.261
1450	1.326	5.2	0.218	1.277
1420	1.332	5.29	0.22	1.256
1440	1.338	5.19	0.218	1.260
1430	1.334	5.24	0.219	1.271
1420	1.33	5.28	0.22	1.274
1430	1.308	5.34	0.222	1.272

Onsager has stated that the ratio μ * / μ should lie between 1 – 1.5 for a polar liquid. Substituting the measured dielectric constant in the above equations, table 4 illustrates that the ratio μ * / μ lies between 1.256 to 1.306 implies that the taken samples have permanent dipoles in addition to induced dipoles due to the external field. The greater the value of μ*/μ, the smaller the dipole axis linked to its molecular dimension. S_1 and S_2 samples exhibit a high ratio of electric moments compared to other oil samples. Table 4 data illustrate that the values of the ratio μ* / μ obey Onsager theory and also exemplify that the samples are heated oil. The above correlation between microscopic molecular factors and macroscopic parameters such as viscosity, ultrasonic velocity, and dielectric constant confirms its use in oil quality analysis.

Computational Correlation Analysis of All Parameters

Computational correlation analysis among the parameters, namely ultrasonic velocity, density, viscosity, refractive index, dielectric constant, peroxide values, capacitance, acoustic impedance, adiabatic compressibility, and molecular free length also has been studied. These input parameters indicate whether the amount of SFA and the formed degraded products is high, medium or low. Positive correlation has been obtained between ultrasonic velocity and acoustic impedance, as both parameters depend on molecular clustering or packing density and are negatively correlated with other parameters. Similarly the density factor had strong positive correlation with viscosity and refractive index as the density factor increases due to the packing density of molecules, and long chain SFA. Its negative correlation with ultrasonic velocity is due to the scattering, reflection, and refraction of ultrasonic wave and decreases its transmission in oil sample. Viscosity parameter had a positive correlation with refractive index, indicating it is a good quality factor, and a negative correlation with UV and Z due to the increase in the quantity of SFA and polymers. The dielectric constant showed a strong positive correlation with PV, capacitance, β, and Lf, as it behaves similarly to DC and depends on polar compounds in oil, making it a good quality index. Its negative correlation with UV and Z indicates the presence of long-chain free fatty acids.

4. Conclusions

The present study reveals that changes in FA in oil during repetitive heating vary the physical and chemical parameters such as viscosity, ultrasonic velocity, dielectric constant, and PV. Profiled SFA and UFA using GCMS were highly correlated with the measured physical and chemical indices of the collected samples. The physical parameters could serve as a promising indicator of oil quality, as they are highly correlated with one another. A novel approach to fitting experimental values to the Onsager theoretical model equations, relating macroscopic parameters such as UV and DC to microscopic parameters such as Lf and μ, can infer the oil's degradation level. The carried-out computational heat map correlation and Principal Component Analysis (PCA) also indicate that the physical parameters can be used more effectively in oil reusability assessment than other chemical and analytical methods.

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