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Research article

Optical, rheological, and dielectric properties of coconut oil between 100 kHz and 30 MHz

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ABSTRACT

In this paper, the dielectric behaviour of coconut oil within the frequency range 100 kHz to 30 MHz between temperature 30 °C–50 °C has been observed. The measured values of the dielectric constant and dielectric loss show notable variation with frequency and temperature for pure coconut oil. It is noticed that the dielectric constant (ε') and dielectric loss (ε'') of coconut oil decreases with increasing temperature. The variation in the dielectric constant and dielectric loss with frequency also showed decreasing trend with frequency. UV absorbance of coconut oil for wavelengths ranging from 200 nm to 800 nm and FTIR spectra have also been recorded. The viscosity of oil between temperature 30 °C–50 °C has also been reported.

1. Introduction

Coconut is an exceptional fruit that offers consumers a revitalizing beverage through its water and a source of energy through its kernel. Fully developed kernels are useful in the extraction of coconut oil, which is a versatile cooking oil that can be further processed for industrial applications. Coconut trees are often called 'the tree of life', offer nourishing food and shelters to the local community through their leaves and abundant other products [1]. The dried kernel, or copra, was historically a significant global commodity. However, its prominence declined after World War II, partially influenced by the misconception that having high saturated fat content makes coconut oil unhealthy. Due to this false opinion and misinformation regarding the use of coconut oil, it is very low in demand and brings down its prices. However, more studies have come out in favour of health benefits of using coconut oil and the safety of its saturated fat content [2]. Coconut oil has rich content of medium-chain triglycerides (MCTs), which have been analysed as different health advantages, such as metabolism enhancer, helpful in weight loss, and cardiovascular well-being [3]. Consequently, coconut oil is becoming more widely used in various goods, such as cooking oils, dietary supplements, and cosmetics. Among its different industrial uses are a key component in soap manufacturing. Additionally, coconut oil is essential to produce methyl esters, fatty alcohols, and fatty acids, which are used in the production of detergents, emulsifiers, insecticides, and surfactants to create consumable goods. The crude oil undergoes a refining process that involves the utilization of caustic soda solution, drying, and bleaching with Fuller's earth [4].

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The oil is derived using natural or mechanical methods from the fresh mature kernel, and these processes are carefully designed to ensure that the oil remains unaltered during extraction. The coconut tree is commonly referred as the "tree of life" because of its abundant offerings including food, beverages, resources for housing, oil, and various commercial applications. Coconuts have diverse medicinal uses. In the early 1970s, Jon Kabara and his colleagues identified the medicinal potential of this oil, specifically its medium-chain fatty acids, which exhibit antibacterial, antiviral, and antifungal properties [5,6]. Lauric acid (C12:0), which founds abundantly in coconut has significant potential for various applications, including the formation of monolaurin or ML in its monoglyceride form. In recent times, there has been a surge in research efforts exploring the use of coconut oil because of its eco-friendly and biodegradable nature [7–10]. Mineral oil is a standard insulation and cooling medium but has a negative environmental impact due to non-biodegradable nature. As a result, there is research into new biodegradable oils, such as coconut oil. Coconut oil is particularly well suited for use in tropical countries, where the average temperature is between 21 °C and 30 °C, because coconut oil exhibits a lower breakdown voltage rate than mineral oil even when exposed to moisture.

High-quality food is vital for maintaining physical and mental fitness. Edible oil obtained from fresh plant sources is crucial in food preparation. It serves as a diet component and imparts distinct flavours and textures to various dishes. Dielectric properties, including the dielectric constant (ε'), dielectric loss (ε''), loss tangent (tan δ), and conductivity (σ), offer valuable insights into the quality and characteristics of vegetable oils [11]. To design a capacitive sensor that can integrate an online moisture-content meter for agricultural purposes and is as comprehensively as possible. To proceed, it is essential to determine the dielectric properties of various product types. In this study, dielectric, optical and rheological properties of coconut oil between 100 kHz and 30 MHz frequency with variation of temperature has been observed.

2. Materials and methods

2.1. Sample selection

The researchers conducted measurements on commercially available samples of coconut oil obtained from supermarkets. The required measurements were taken immediately after opening the container of the samples. All the analysis of parameters were carried out by using the standard methods of oil analysis.

2.2. Measuring system

Dielectric permittivity consists of two major components, the dielectric constant and the dielectric loss factor. The dielectric constant (ε') determines how much a material interacts with an alternating electrical field, quantifies how much electromagnetic energy is stored, reflected, and transmitted by the material, and the dielectric loss factor (ε'') assess how much energy a material dissipates as heat when, it is placed in an alternating electrical field [12–14]. The dielectric properties can be defined by the relative permittivity (ε_r) equation (1) [15].

$$\varepsilon_r = \varepsilon' - j\,\varepsilon'' \tag{1}$$

A computer-controlled impedance/phase analyser (*Hewlett–Packard 4194A)* for the measurement of electrical parameters, capacitance, and conductance from a frequency of 100 kHz to 30 MHz. The sensor used to hold the samples during observations was a concentric cylindrical capacitor. The impedance gain-phase analyser was connected to a specially constructed sample holder based on the principle of cylindrical capacitor, and the samples were placed here. The temperature of the samples was carefully maintained within a variation of 0.1 K using a Lauda thermostat (*Instech MK 2000*). The uncertainty in the calibration of the system was less than 1 %, and a reference liquid of analytical grade benzene was used. The two complex electrical permittivity factors were calculated by measuring the equivalent capacitance in parallel (C_p) and the conductance (G) of the empty and filled sample cells with coconut oil. Similar measurements were described in other research work [16,17]. The ε' and ε'' values were calculated according to the methodology used in previous works [18,19].

2.3. Measurement of dielectric properties

The relative permittivity (ε_r) measures the extent to which an electric field can polarize a material in dielectric materials. It is a function of the frequency of applied electric field and the absolute temperature of the material. The relationship between the permittivity of a material and the capacitance of a capacitor is directly proportional to each other, and the ratio of the capacitance (C) of a capacitor with a dielectric material between its plates to the capacitance (C_0) of the same capacitor without any dielectric material, where a vacuum exists between its plates, signifies this correlation. The dielectric constant (ε') can be written as the ratio of the difference of capacitance with material (C_M) and capacitance in vacuum (C_0) to the geometrical capacitance (C_G), and this whole is added by 1. The imaginary part, which is the dielectric loss factor (ε'') can also be written as the ratio of the difference of conductance with and without dielectric material to the product of angular frequency (ω) & geometrical capacitance (C_G). These dielectric permittivity factors for the oil sample were calculated using equations (2)–(4):

$$\varepsilon' = \frac{C_M - C_o}{C_G} + 1 \tag{2}$$

$$\varepsilon'' = \frac{D_M - D_o}{2\pi f C_G} \tag{3}$$

$$\tan\delta = \frac{\varepsilon'}{\varepsilon''} \tag{4}$$

The dielectric characteristics of coconut oil were investigated between the temperatures of 30 °C and 50 °C at frequencies ranging from 100 kHz to 30 MHz. Precision-inductance, capacitance, and resistance (HP-4194A, Agilent Technologies, Japan) and an Impedance Gain/Phase Analyzer were used to determine the dielectric characteristics of the oil sample using the capacitive approach. The parallel capacitance (C_p) and dissipation factor (D_p) of the oil samples were measured after a brief adjustment of the liquid dielectric test fixture. To collect and analyse the data, the equipment was interfaced with a computer. With temperatures ranging from 30.0 °C to 50.0 °C and equally dispersed frequencies between 100 Hz and 40 MHz, C_p and D_p were measured with a precision of 0.17 %. A temperature controller oil circulated bath (Julabo F-25 with high-precision of ±0.01 °C) and an external thermometer system (5627 A/1502A; Fluke, Hart Scientific, Everett, WA, USA) were used to regulate the temperature. Similar study before and after thermal treatment was reported by other researchers [20].

Penetration depth refers to the distance a charged particle can travel through a material before losing energy. In general, penetration depth is vital in many fields, including optics, materials science, and nuclear physics, as it helps determine the behaviour of waves interacting with different materials. The formula for calculating the penetration depth was discussed in our earlier paper and also by other researchers [21,22].

$$D_P = \frac{\lambda_o}{2\pi\sqrt{2\varepsilon'}}\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2} - 1\right]^{-\frac{1}{2}} \tag{5}$$

2.4. Measurement of UV absorbance and FTIR spectra

UV–vis absorption spectra were collected in the 200–800 nm range using a UV spectrophotometer (UV-1800, SHIMADZU) and a quartz cuvette with a 10 mm optical path length. Coconut oil samples were diluted in n-hexane HPLC (0.06 %, w/w).

When infrared radiation interacts with a sample, FTIR spectroscopy shows the molecular vibrations within the sample, providing details about the chemical structures [23]. FTIR spectrometer (*Spectrum-Two-114471*) was used during spectra acquisition, this instrument was equipped with a detector of deuterated triglycine sulphate and beam splitter of potassium bromide. During the measurement, FTIR spectra were obtained at frequency regions of 4000−400 cm^{-1}. FTIR spectra were displayed as transmittance values for at least two measurements.

2.5. Viscosity measurements

Viscosity is the most important quality control and assessment parameter for liquid samples, and it is often used to measure the purity and consistency of oil. Viscosity determines the resistance level that fluid exhibits against flow. By measuring the viscosity, manufacturers can ensure that the oil meets the required specifications for the intended application. The study of the viscosity of oil was carried out using the capillary viscometer method. The viscosity-temperature equation is also used to predict the viscosities of vegetable oils [24,25].

$$\ln(\eta) = A - \frac{B}{(T+C)} \tag{6}$$

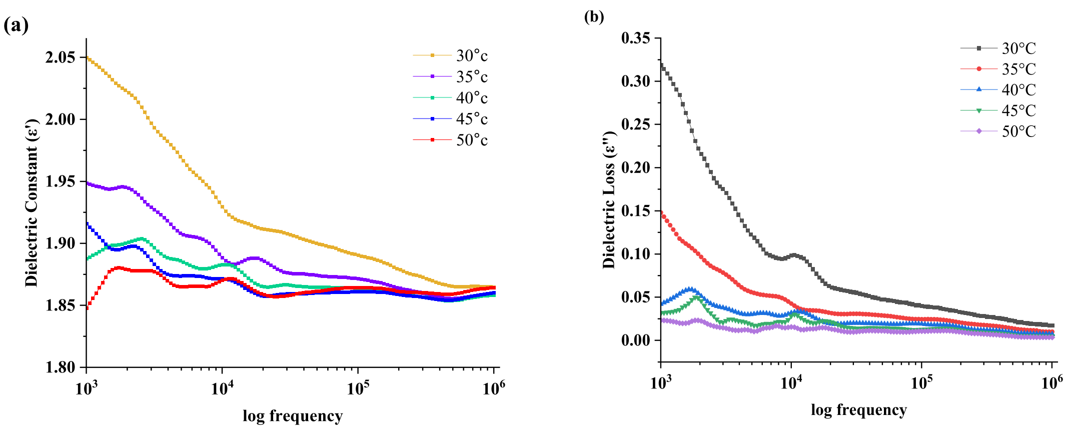

Fig. 1. (a) & (b). Variation of dielectric constant and dielectric loss in coconut oil versus frequency at the indicated temperatures.

Where η indicates viscosity of the oil sample, T indicates temperature, and A, B, and C are constants. The A, B, and C values for water at temperatures ranging from 0 °C to 100 °C: A = −5.71, B = 1830.2, C = 244.0. These values were determined experimentally and are commonly used in water engineering calculations.

3. Results and discussion

The dielectric spectra of the sample were fitted by the models described in Section 3 using a non-linear minimum square procedure. The uncertainties in the model parameters were estimated using the linear regression method.

3.1. Study of dielectric properties

3.1.1. Dielectric constant and dielectric loss of coconut oil

Fig. 1 (a) & (b) show the decreasing dielectric constant and dielectric loss with frequency at the indicated temperature for coconut oil. Vegetable oils are expected to exhibit a decreasing trend in their dielectric constant with increasing frequency. This is because the dielectric constant is related to the orientation polarization of molecules in the material. When the frequency increases, these dipoles are unable to reorient quickly enough to keep up with quick changes in the field, which lowers overall polarization. When the dipoles of molecule cannot be properly oriented with the rapid change in the electric field, then the dipoles experience friction-like resistance, leading to energy dissipation as heat. This contributes to the decrease in dielectric loss with increasing frequency [26].

It is inferred in Fig. 2 (a) & (b), the decreasing trend of the dielectric constant and dielectric loss with temperature at the indicated frequency for coconut oil. Researchers were also reported previously that vegetable oils exhibit a decreasing trend in their dielectric constant and loss with increasing temperature [27,28]. This is because the polarization of molecules in vegetable oil is affected by temperature. At low temperatures, the polarization response of the molecules is slower, resulting in a higher dielectric constant and loss. However, as the temperature increases, the polarization response becomes faster, resulting in a lower dielectric constant and loss. The rate at which the dielectric constant and loss decrease with increasing temperature is determined by the activation energy of vegetable oil molecules. The activation energy is required to overcome the energy barriers associated with the polarization of the molecules.

3.1.2. Penetration depth of coconut oil

Fig. 3 shows the variation of penetration depth with the temperature at the indicated frequency. The graph shows that a minor increasing trend of penetration depth trend with rise in temperature and penetration depth decreases respectively when frequency increases. It means that the lower radio frequency waves can travel deeper into the coconut oil than higher frequency waves. The sharper rise at 2 MHz compared to higher frequencies is due to a combination of the dielectric properties, temperature effects, frequency-dependent absorption in the material. The dielectric properties of coconut oil may result in more efficient absorption or scattering of the electromagnetic waves, leading to deeper penetration. The penetration depth was found to be almost linear for high frequencies; however, nonlinearity was found in low-frequency regions. Similar behaviour has also been reported by other researchers [29]. Decreasing trend in penetration depth between 35 °C to 50 °C may be attributed to removal of volatile contents present in traces in oil sample, a similar behaviour was also reported for edibles oils– Olive, Coconut, Soybean and Canola in the temperature region 28 °C–50 °C [30].

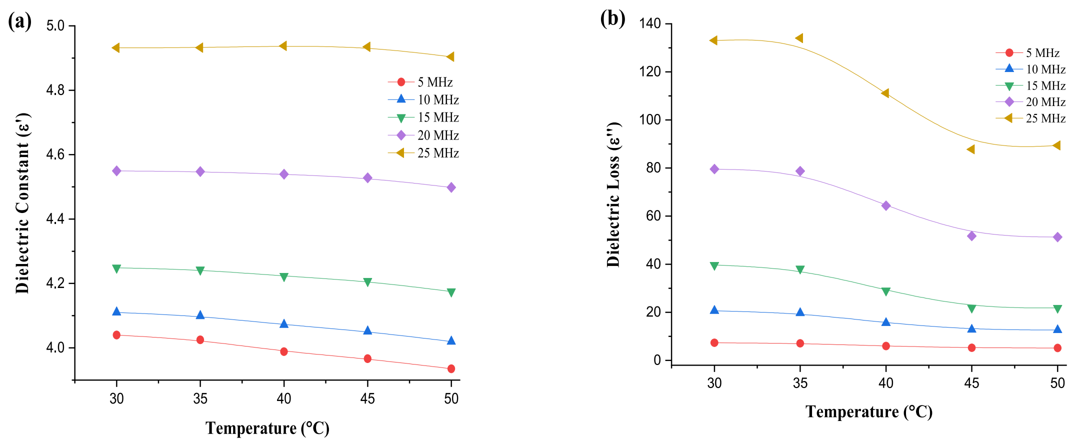

Fig. 2. (a) & (b). Variation of dielectric constant and dielectric loss in coconut oil sample versus temperature at indicated frequencies.

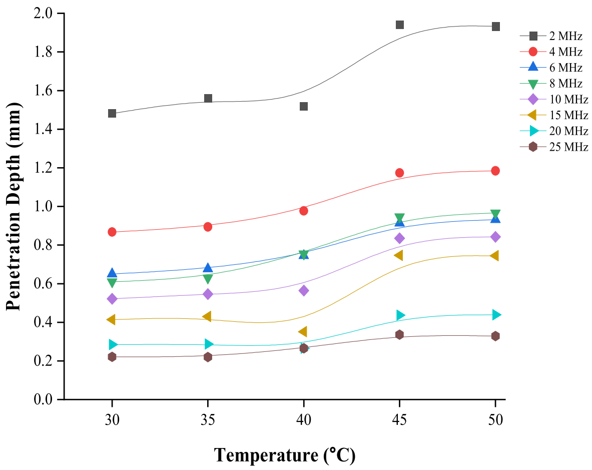

Fig. 3. Variation of penetration depth in coconut oil versus temperature at the indicated frequency.

3.2. *Study of optical properties*

3.2.1. *UV–visible spectra of coconut oil*

It is inferred in Fig. 4, there is an absorption peak at a wavelength of 292 nm (UV–B region) with an absolute value of 0.309. This result indicates that coconut oil showing absorption in the UV-B region is used as an applicant on the skin for protection against UV radiation from the sun. Eni Widiyati reported that coconut oil has a good characteristic with a high sun protection factor (SPF) value [31]. UV–vis absorption of a few edible oils in UV-B region has also been studied, and it has been reported that coconut oil is useful to protect human skin from UV radiation [32].

3.2.2. *FT-IR spectra of coconut oil*

As shown in Fig. 5, the strong peak around 1743 cm^{-1} is assigned to the carbonyl (C═O) stretching vibration of esters, which is the most abundant functional group in fats and oils, and the peaks around 2850 and 2925 cm^{-1} are assigned to the asymmetric and symmetric CH_2 stretching vibrations of the alkyl chains. Medium chain triglycerides (MCTs), the main component of coconut oil, can be easily identified by a strong, sharp peak near 1743 cm^{-1} due to the ester carbonyl group [33].

3.3. *Study of rheological properties*

3.3.1. *Effect of temperature on viscosity of coconut oil*

Viscosity of oil is an important rheological property for characterization of oil quality, the value of viscosity is directly associated with higher content of unsaturated oil. Fig. 6 shows variation of viscosity of coconut oil sample for temperature between 30 °C and 50 °C. When the temperature increases, a decreasing viscosity trend is observed. Because the kinetic energy of the molecules increases with increasing temperature, which helps them for rapid movement and in more frequent collisions. The rapid movement and collisions between molecules also decrease the cohesive force between the molecules, which reduces the resistance to flow and causes the

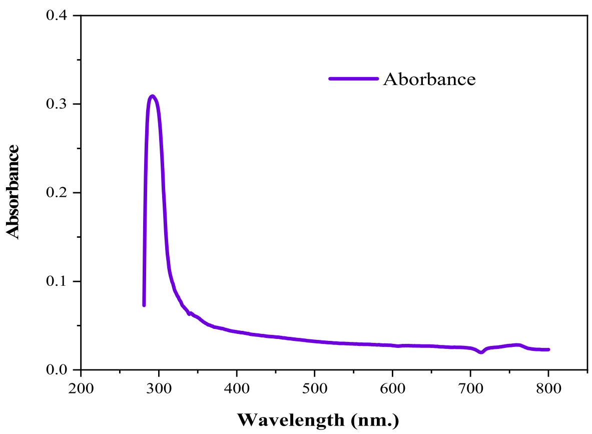

Fig. 4. UV absorbance curve of coconut oil sample with wavelength.

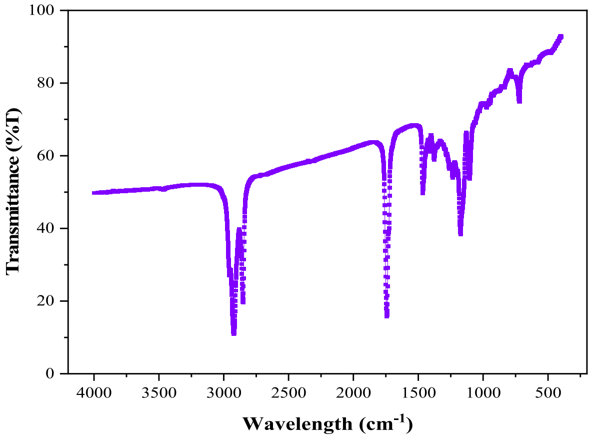

Fig. 5. FTIR spectra of coconut oil.

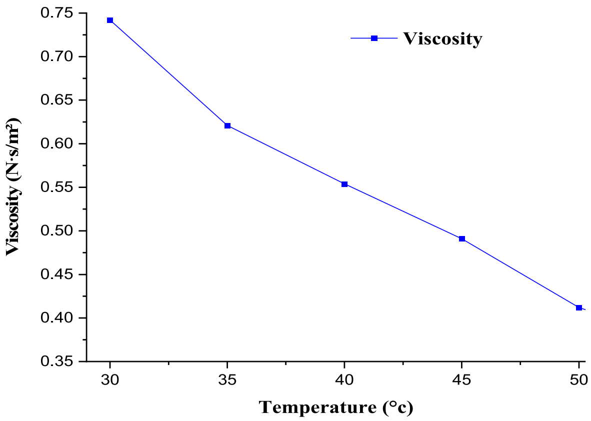

Fig. 6. Variation of viscosity of coconut oil sample with temperature.

viscosity to decrease. Similar result was previously reported by other researchers [34].

4. Conclusion

This study proposes the development of an instrument that uses dielectric properties measurement for assessing the oil quality. Electrical properties like dielectric constant, dielectric loss, and loss tangent are suitable for non-destructive sensing of oil quality. The analysis revealed that the dielectric constant correlates with the applied frequency and temperature. The UV result indicates that coconut oil could be used as an applicant on the skin for protection against UV radiation from the sun. The samples can be treated as a solution, and the utilization of the theory for electrical double-layer capacitors can be considered. While coconut oil may not penetrate the skin or hair deeply, it is still often used in skincare and haircare products for its moisturizing and conditioning properties. Analysis of coconut oil using Fourier Transform Infrared Spectroscopy (FTIR) revealed important details about its molecular composition. The functional groups contained in the coconut oil sample were represented by distinctive absorption peaks in the FTIR spectrum. The investigation of temperature-dependent viscosity fluctuation of coconut-oil has yielded significant insights into the rheological behaviour of material and potential uses. This phenomenon can be explained by the fact that when temperature rises, molecule mobility increases and intermolecular forces decrease, leading to an improvement in fluidity. Further research could investigate compositional changes and other factors that affect coconut oil viscosity, as well as how the oil performs industrial applications at different temperatures.

Data availability statement

Not applicable.

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CRediT authorship contribution statement

Venkatesh Mishra: Investigation, Formal analysis, Data curation. **Satyendra Pratap Singh:** Writing – original draft, Validation, Software. **Mamta Singh:** Methodology, Conceptualization. **Vishal Singh Chandel:** Writing – review & editing, Visualization. **Rajiv Manohar:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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