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Understanding microwave heating of oils

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ABSTRACT

Our recent study found that vegetable oils, often deemed unsuitable for microwave heating, actually heat efficiently in microwave ovens. To explore the main chemical components within vegetable oil that contribute to microwave heating, we considered two hypotheses: 1) the presence of water dissolved in oil and 2) the glycerol component of oil molecule. In this research, we used the resonant cavity method to measure dielectric properties of vegetable oil with different water activities and compared vegetable oil with mineral oil (which does not contain the glycerol component). Our results revealed no significant difference in the dielectric properties or microwave heating rates between vegetable oils with low (0.16) and high (1.00) water activities, indicating that dissolved water is not a major contributor. Regardless of the water activity levels, vegetable oil heats well in microwaves, whereas mineral oil does not. The microwave heating difference was elucidated by the measured dielectric properties: the loss factor of vegetable oil (0.15) was 30 times greater than that of mineral oil (0.005). This supports our hypothesis that the glycerol component in vegetable oil contributes to microwave heating, whereas its absence in mineral oil accounts for the limited microwave heating capability. This research augments our fundamental comprehension of microwave heating of oils.

1. Introduction

Microwave heating has been considered as an effective alternative to convention heating in various food processing applications for improved heating efficiency and better product quality (Ross et al.,2023; Zhou et al, 2022; Tang, 2015). Oils are generally deemed unsuitable for microwave heating because of their low dielectric loss factor, about 1/100 that of water. However, our recent research (Zhou et al., 2023a) showed that vegetable oils, under the same experimental conditions, heat more rapidly than water in a 2450 MHz microwave oven. The experimental result was supported by computer simulations, which revealed that the electric field in oil was 10 times stronger than in water. The strong electric field led to a significant amount of microwave absorption by oil (Zhou et al., 2023a). The finding suggests new opportunities for utilizing microwave energy to electrify industrial heating of vegetable oils. Microwave heating is energy efficient and can be directly powered by renewable electric sources such as solar, wind, and hydropower, thereby offering a pathway to reduce CO_2 emissions in industrial heating processes, such as frying and cooking (Zhou et al., 2022). However, Zhou et al. (2023a) did not explain microwave heating mechanism of vegetable oils at a molecular level. Further studies are needed to understand which chemical components within vegetable oil molecules contribute to microwave heating.

Microwave heating of dielectric materials primarily relies on two mechanisms (Metaxas and Meredith, 1983): (1) *ionic conduction*: oscillation of charged ions (such as dissolved salts in foods) in an alternating electric field generates heat through internal friction; (2) *orientation polarization*: polar molecules (such as water molecules) attempt to rotate and align with alternating electric fields of microwaves. The rotations cause friction between molecules and in turn produce heat. Oils are good electrical insulators with very few ions, so ionic conduction is not likely to play an important role in microwave heating of vegetable oils. That means orientation polarization is the primary mechanism for microwave heating of vegetable oils. However, it is not clear which polar components within vegetable oils are responsible for its heating mechanism. To bridge this knowledge gap, we considered two hypotheses in this study.

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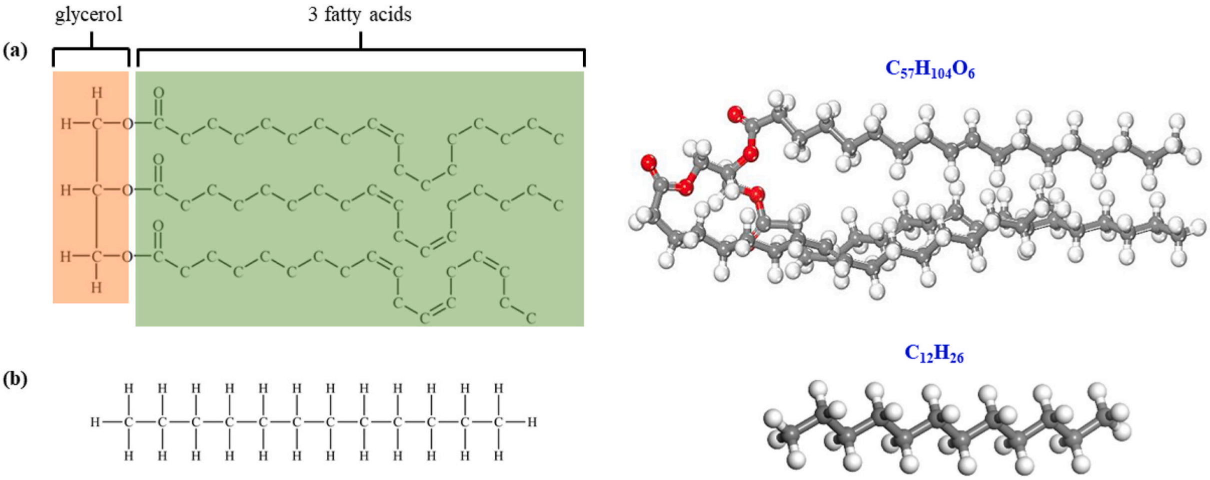


Fig. 1. Chemical (left) and molecular (right) structures for (a) triacylglycerol in vegetable oil and (b) alkane in mineral oil. Atoms are color-coded: carbon (grey), hydrogen (white), and oxygen (red). The molecular structure for triacylglycerol is adapted from Qiu et al. (2021) and for alkane from Li et al. (2019).

(1) Presence of water: It is well established that pure water heats well in microwave fields due to the polar structure of water molecules (Von Hippel, 1954). Several studies reported that vegetable oils can dissolve a certain amount of water (Hilder, 1968; Yang et al., 2020). For example, Yang et al. (2020) found that peanut oil can hold up to 0.09% moisture content when exposed to high relative humidity conditions at room temperature for extended periods. Thus, we hypothesized that polar water molecules dissolved in vegetable oils contribute to microwave heating.

(2) Glycerol: Vegetable oil mainly consists of triglycerides, which are about 90% fatty acid chains and 10% glycerol (Fig. 1) (Damodaran et al., 2007). Fatty acid chains are nonpolar, so oils are generally considered nonpolar (Damodaran et al., 2007). However, glycerol, the smaller component of vegetable oil, does have some polarity (Kremer et al., 2022). Thus, we hypothesized that the polar glycerol component in oil molecules contributes to the orientation polarization and microwave heating.

Knowledge of dielectric properties of oils is important for understanding the behavior of oil molecules under the influence of microwave fields and can provide useful insight into microwave heating. The dielectric property of a material is defined as (Von Hippel, 1954):

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \tag{1}$$

where ε^* = complex permittivity relative to vacuum
ε' = dielectric constant
ε'' = dielectric loss factor

The dielectric constant (ε') represents the ability of a dielectric material to store electric energy. Dielectric loss factor (ε'') represents the ability to convert microwave energy into heat (Metaxas and Meredith, 1983):

$$P_v = 2\pi f \varepsilon_0 \varepsilon'' |\mathbf{E}|^2 \tag{2}$$

where P_v = converted thermal energy (W/m^3) from microwaves
f = microwave frequency (Hz)
ε_0 = permittivity of free space (8.854×10^{-12} F/m)
$\mathbf{E}$ = electric field strength (root mean square) inside the material (V/m)

The goal of this research was to gain fundamental understanding of how vegetable oils heat in microwaves by testing two hypotheses stated earlier. For the first hypothesis, we prepared vegetable oil samples of two different moisture contents by using the method described in Yang et al. (2020). We measured the dielectric property of these samples to understand how dissolved water influences microwave heating of oil.

For the second hypothesis, we compared the dielectric properties of vegetable oil with those of mineral oil. Mineral oil was selected because it does not contain glycerol backbones, as illustrated in Fig. 1. This comparison would reveal the contribution of the glycerol component to microwave heating. We also measured dielectric properties of pure glycerol to help explain possible contributions of glycerol component to the dielectric properties of vegetative oil. Moreover, we used measured dielectric property values in computer simulations to further support our experimental results on microwave heating.

2. Materials and methods

2.1. Oil samples

Peanut oil and engine oil were selected as the representatives of vegetable oil and mineral oil, respectively. Peanut oil (Great Value brand, Walmart Inc., Bentonville, AR, USA) and engine oil (5W-30, Exxon Mobil Corp., Spring, TX, USA) were purchased from a local grocery store (Pullman, WA, USA). Following the humidification treatment described in Section 2.2, the samples were shipped to QWED (Warsaw, Poland) for dielectric property measurements. Glycerol solutions (purity: 99.5%) were purchased from Mallinckrodt Baker, Inc. (Phillipsburg, NJ, USA).

2.2. Conditioning of peanut oil samples to different moisture contents

A humid air treatment method described in Yang et al. (2020) (Fig. 2) was used to raise the moisture content of peanut oil samples to the maximum level (saturation) at room temperature (23 °C). A 700 mL peanut oil sample was exposed to water vapor maintained at 100% relative humidity (RH) (Fig. 2a). The water activity (a_w) of the oil was measured by an RH sensor (Fig. 2b). After 4 days of humidification, the a_w of oils reached its maximum value (~ 1.00). Similarly, a different set of vegetable oil samples were conditioned to a very low water activity of $a_w = 0.16$ at room temperature. The moisture contents of the two preconditioned vegetable oil samples were determined from the measured water activities at room temperature using Eq. (8). This equation was derived from the relationships reported in Yang et al. (2020) as follows:

The moisture content of oil (MC) is related to the mole fraction of water in oil (x) by:

$$x = \frac{MC}{M_{water}} \div \left(\frac{100 - MC}{M_{oil}} + \frac{MC}{M_{water}}\right) \tag{3}$$

where x = mole fraction of water in oil

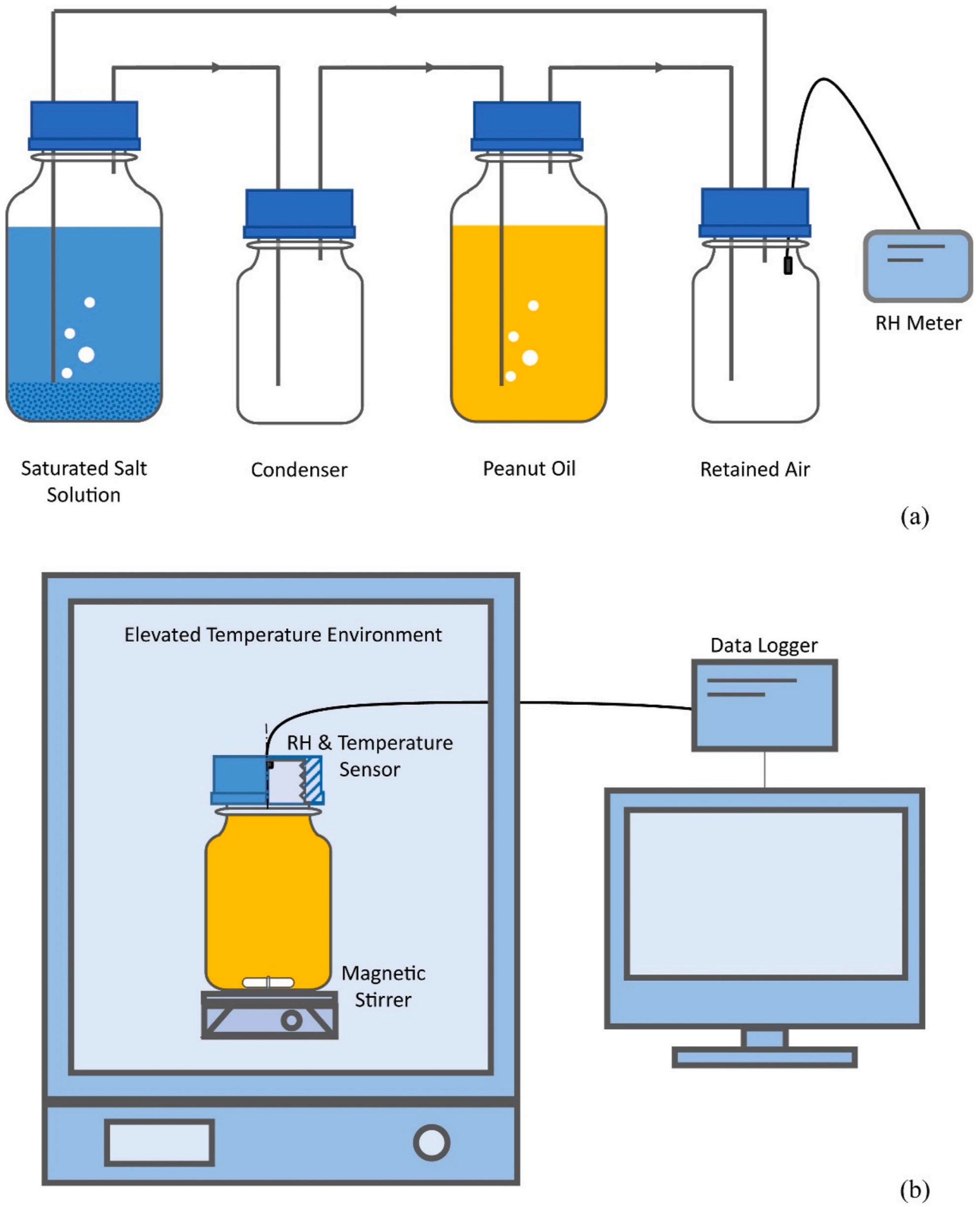


Fig. 2. (a) Experimental setup for conditioning of peanut oil to different moisture contents; (b) measurement for water activities of treated oil (from Yang et al., 2020).

MC = moisture content of oil on wet basis (%)
M_{water} = molar mass of water molecule (~18.015 g/mol)
M_{oil} = molar mass of peanut oil molecule (~881 g/mol) (Yang et al., 2020)

Since the moisture content of oil is extremely small ($MC<0.09$) relative to 100 (Yang et al., 2020), Eq. (3) becomes:

$$x = \frac{MC}{M_{water}} \div \left(\frac{100}{M_{oil}} + \frac{MC}{M_{water}}\right) = \frac{MC}{M_{water}} \div \left(\frac{100 \cdot M_{water} + MC \cdot M_{oil}}{M_{oil} \cdot M_{water}}\right) \tag{4}$$

Considering:

$$100 \cdot M_{water} = 1801.5$$

$$MC \cdot M_{oil} \leq 0.09 \times 881 = 79$$

That is,

$$100 \cdot M_{water} \gg MC \cdot M_{oil}$$

Thus,

$$x = \frac{MC}{M_{water}} \div \left(\frac{100 \cdot M_{water}}{M_{oil} \cdot M_{water}}\right) = \frac{MC \cdot M_{oil}}{100 \cdot M_{water}} \tag{5}$$

The mole fraction of water in peanut oil (x) is related to water activity (a_w) by (Yang et al., 2020):

$$a_w = x \cdot e^{\left(\frac{1714}{T} - 2.7\right)} \tag{6}$$

where a_w = water activity of oil
T = absolute temperature (K)
Substituting Eq. (5) into Eq. (6) yields:

$$a_w = \left(\frac{MC \cdot M_{oil}}{100 \cdot M_{water}}\right) \cdot e^{\left(\frac{1714}{T} - 2.7\right)} \tag{7}$$

Rearranging terms in Eq. (7) leads to:

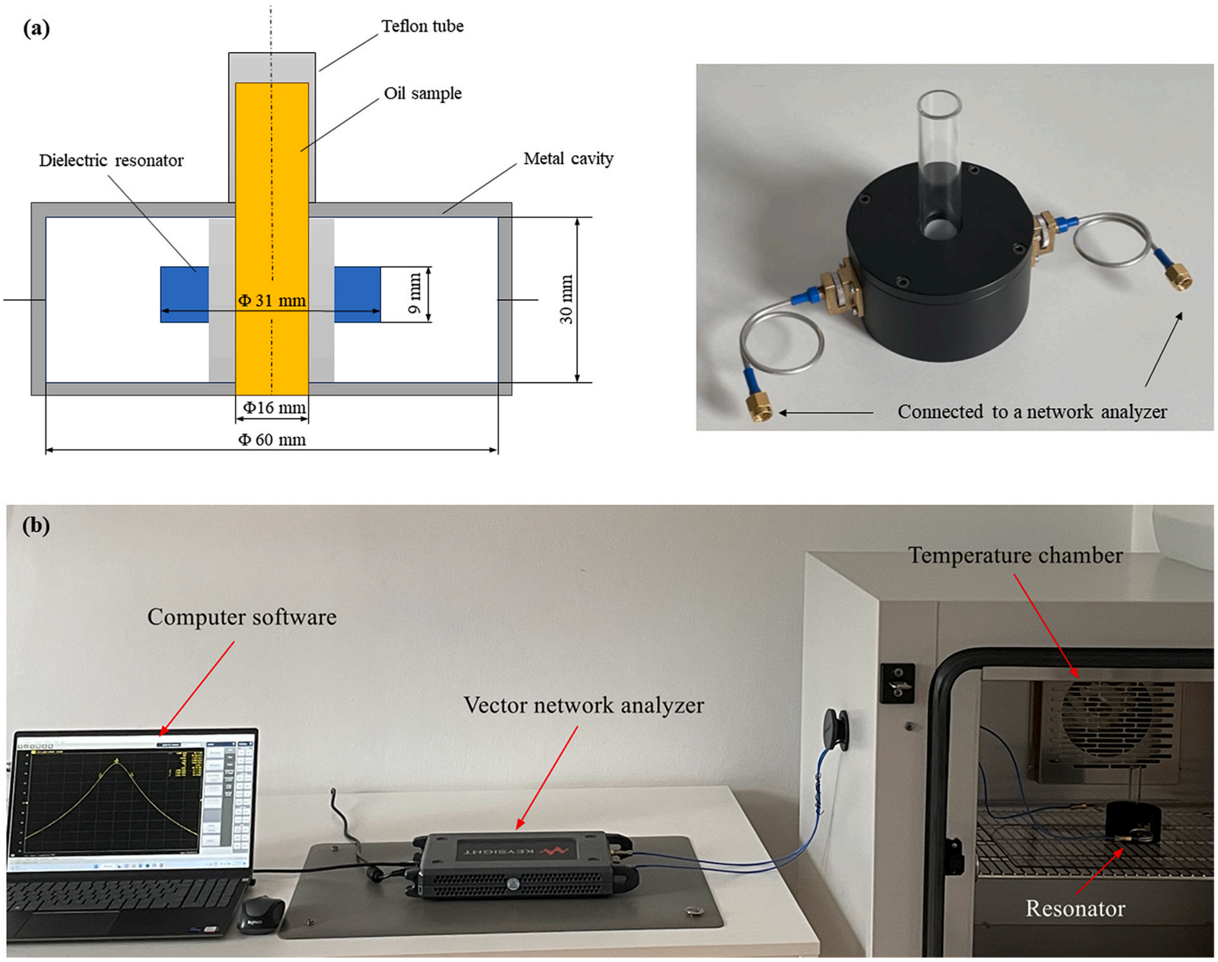


Fig. 3. (a) Schematic diagram (dimensions in mm) and photo of $TE_{01\delta}$ Resonator; (b) Experimental setup for measuring temperature-dependent dielectric property of oil samples.

$$MC = a_w \cdot \frac{100 \cdot M_{water}}{M_{oil}} \cdot e^{-\left(\frac{1714}{T} - 2.7\right)} \tag{8}$$

Using Eq. (8), we can calculate the moisture content values (MC) of peanut oil at the two different water activities (a_w) at room temperature ($T = 23$ °C or 296.15 K).

2.3. Dielectric property measurement

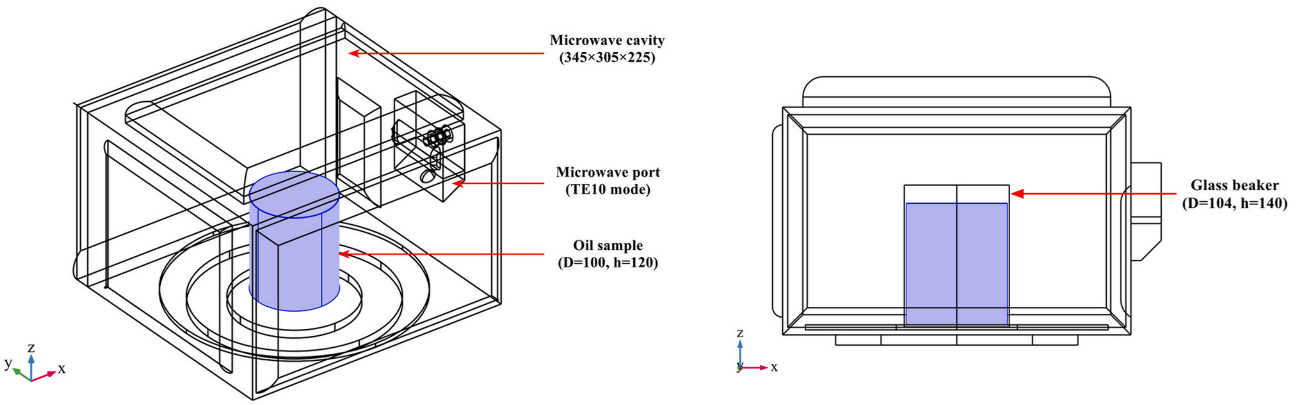
2.3.1. Measurement of dielectric properties of oil using resonant cavity method

The dielectric properties of oil samples at 2450 MHz were measured using a cylindrical resonant cavity system shown in Fig. 3 offered by QWED (Warsaw, Poland). The resonant cavity method is particularly suited for accurate measurement of low-loss materials, such as oil (Komarov et al., 2005; Krupka et al., 2021; Salski et al., 2021). The resonator consisted of a dielectric resonator (pill) located in the center of a metallic cavity (diameter of 60 mm and a height of 30 mm) (Krupka et al., 2021; Salski et al., 2021) (Fig. 3a). The resonator was designed to operate at the $TE_{01\delta}$ mode at around 2450 MHz. The $TE_{01\delta}$ mode, described in cylindrical coordinates (ρ, φ, z) is an E-field pattern in a circular cavity; the "0" means no variations in ρ direction, "1" means a single half-cycle variation in φ direction, and "δ" indicates a variation or perturbation in the z direction. In the center of the cavity, where the minimum of the electric field is expected, a Teflon tube (outer diameter: 16 mm) was located as a holder for the liquid samples (Krupka et al., 2021; Salski et al., 2021). The resonant cavity was equipped with two coupling loops to measure the transmission through the resonator with a vector network analyzer (P5008B, Keysight Inc, Santa Rosa, CA, USA).

When a dielectric sample, such as oil, was introduced into the resonant cavity, there was a perturbation in the inherent electromagnetic fields of the cavity (Regier and Schubert, 2005). This perturbation led to changes in both the resonant frequency and the Q-factor of the cavity. These changes were measured by the vector network analyzer and converted into the dielectric constant and loss factor of the inserted sample by a rigorous electromagnetic (EM) model (Salski et al., 2021). To measure the temperature-dependent dielectric property, the resonator was placed inside a temperature-controlled chamber (KMF115, Binder Inc, Germany) (Fig. 3b). The measurements of vegetable oil and engine oil samples were carried out at four temperatures: 20, 40, 60, and 80 °C. Each measurement was conducted three times.

2.3.2. Measurement of dielectric properties of glycerol using open-ended coaxial probe method

The resonant cavity method was not able to measure the dielectric properties of samples over a broad microwave frequency range. Instead, the open-ended coaxial probe method was used to measure the dielectric properties of glycerol between 10 and 8000 MHz. The open-ended coaxial probe measurement system consists of a network analyzer (E5071C, Keysight Technologies, Inc, Santa Clara, CA, USA), dielectric probe (85070E Keysight Technologies, Inc, Santa Clara, CA, USA), a coaxial cable, a sample holder, an oil bath, a thermometer with a type-T thermocouple, and a computer (Gezahegn et al., 2021). Before measurement, the system was calibrated using an open circuit (air), a short



(a) (b)

Fig. 4. (a) Schematic diagram of the 2450 MHz microwave oven and 1 L oil sample (D = diameter, h = height) (dimensions in mm) used for computer simulation; (b) side view showing the glass beaker.

circuit (gold-plated precision shorting block), and deionized water (at 25 °C), according to the user manual of Keysight Technologies. Following calibration, the sample holder was filled with pure glycerol liquid. The probe was carefully inserted into the liquid sample, ensuring no air bubbles. An oil bath was connected to the sample holder's jacket to control the temperature of the sample during measurements. The measurements were conducted three times ($n = 3$) at temperatures of 20, 40, 60, 80, and 100 °C.

2.3.3. Debye relaxation model

The measured dielectric properties of the glycerol samples as influenced by frequency and temperature were analyzed using Debye equations. Debye (1929) developed a mathematical model to describe the relaxation behavior of solutions containing molecules with electric dipoles (polar molecules) when exposed to an external electric field. The Debye equations for the dielectric constant (real part, $\varepsilon^{'}$) and the loss factor (imaginary part, $\varepsilon^{''}$) are given by Debye (1929) and Von Hippel (1954):

$$\varepsilon^{`} = \varepsilon_{\infty} + \frac{(\varepsilon_s - \varepsilon_{\infty})}{1 + (2\pi f)^2 \tau^2} \tag{9}$$

$$\varepsilon^{``} = \frac{(\varepsilon_s - \varepsilon_{\infty})\omega\tau}{1 + (2\pi f)^2 \tau^2} \tag{10}$$

where f = frequency of the applied electric field (Hz)
ε_s = static permittivity (i.e., permittivity at zero frequency)
ε_{∞} = permittivity at infinite frequency
τ = relaxation time (s)

The relaxation time measures how quickly dipoles in a material respond to a changing electric field. When a dielectric material is subjected to an alternating electric field of microwaves, polar molecules attempt to align with the electric field. However, molecular interactions and material viscosity cause a delay in this alignment, described by the relaxation time τ. A shorter τ implies quicker reorientation of dipoles, while a longer τ indicates slower alignment. At the critical frequency f_c, the loss factor reaches its maximum value. The critical frequency is related to the relaxation time as (Von Hippel, 1954):

$$f_c = \frac{1}{2\pi\tau} \tag{11}$$

2.3.4. Penetration depth

The penetration depth (dp) of microwaves in a dielectric material is defined as the depth at which the intensity of the microwave power falls to 1/e (about 37%) of its original value at the entry surface (Von Hippel, 1954). The microwave penetration depth depends on several factors, including microwave frequency (f), dielectric constant ($\varepsilon^{'}$), and loss factor ($\varepsilon^{''}$) of the material:

$$\mathrm{dp} = \frac{c}{2\pi f \sqrt{2\varepsilon^{'}\left[\sqrt{1 + \left(\frac{\varepsilon^{''}}{\varepsilon^{'}}\right)^2} - 1\right]}} \tag{12}$$

where dp is the penetration depth, and c is the speed of light in free space (3×10^8 m/s).

2.4. Microwave heating experiments

Each 1L oil sample (including peanut oil samples with different moisture contents, and mineral oil samples) was placed in separate cylindrical beakers (diameter: 100 mm, height: 120 mm). Each oil sample was placed at the center of the cavity bottom (turntable was removed) and heated for 2 min in a 2450 MHz domestic microwave oven operating at the full power of 1200 Watts (NN-SD681S, Panasonic, Tokyo, Japan). Fig. 4 shows the schematic diagram of the microwave oven and the placement of the oil samples. To obtain the average temperature, every 30 s the microwave power was turned off, and the oil samples were stirred thoroughly by hand (the stir took about 5 – 6 s). A type T thermocouple probe (0.8 mm diameter and 0.8 s response time) was used to measure the average temperature of the oil sample after stirring.

2.5. Computer simulations and sensitivity analysis

A computer simulation model (Fig. 4) solving Maxwell's and heat transfer equations based on the finite-element method (FEM) was developed in our previous study (Zhou et al., 2023a). The governing equations, boundary conditions, time steps, meshing setting, and computer configuration were described in Zhou et al., 2023a–c. In the computer simulation of this study, a glass beaker with a height of 140 mm and a diameter of 104 mm was included, as shown in Fig. 4b. The following properties of the glass were used in the simulation: specific heat, $C_p = 753$ J/kg·K; thermal conductivity, $k = 1.38$ W/m·K; dielectric constant $\varepsilon' = 6$; loss factor $\varepsilon'' = 0.03$ (COMSOL Material Library, 2023).

There were two types of heat loss from the oil sample during microwave heating.

1) Conduction from the oil to the glass:

$$q_{\mathrm{cond}} = k_g \frac{\left(T_{\mathrm{oil}} - T_{\mathrm{glass,out}}\right)}{d} A_{glass} \tag{13}$$

where k_g = thermal conductivity of the glass (W/m·K)
T_{oil} = oil temperature (°C)

Table 1
Thermal properties of vegetable oil and mineral oil at 25 °C.

	Vegetable oil [a]	Mineral oil [b]
Density, kg/m^3	882	852
Thermal conductivity, W/m·K	0.158	0.133
Specific heat, J/kg·K	2128	1902

[a] Data from Hoffmann et al. (2018).
[b] Data from Nadolny and Dombek (2017).

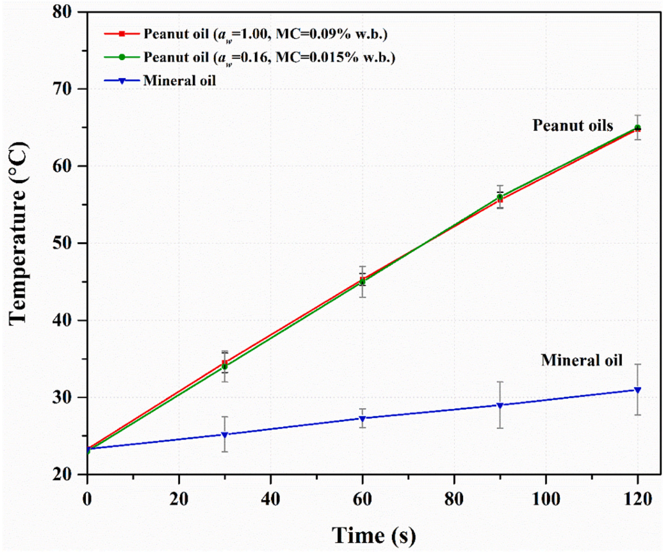


Fig. 5. Average temperature increases of 1L vegetable oil and mineral oil samples when heated in a 2450 MHz, 1200 W microwave oven. The peanut oil samples had different water activities (a_w) and moisture contents (MC, on wet basis). (n = 3).

$T_{glass,\ out}$ = outer surface temperature of the glass (°C)
d = thickness of the glass (~2 mm)
A_{glass} = surface area of the glass in contact with the oil (m^2)

2) Convection from the glass to the air, and from the oil top surface to the air

$$q_{\text{conv}} = h_c\left(T_{\text{glass,out}} - T_\infty\right)A_{glass} + h_c\left(T_{\text{oil}} - T_\infty\right)A_{top} \tag{14}$$

where h_c = convective heat transfer coefficient (10 W/m^2·K)
T_∞ = air temperature in the microwave oven (~25 °C)
A_{glass} = surface area of the glass exposed to air (m^2)
A_{top} = top surface area of the oil (m^2)

At the oil-glass boundary, the inner surface temperature of the glass ($T_{\text{glass, in}}$) was equal to the temperature of the oil:

$$T_{\text{glass,in}} = T_{\text{oil}} \tag{15}$$

The glass beakers used in the experiment had a very thin wall (~ 2 mm), and a high thermal conductivity (~ 1.4 W/m·K) as compared to oil (~ 0.1 W/m·K), so it is reasonable to assume the temperature gradient across the glass thickness was negligible. That is,

$$T_{\text{glass,in}} = T_{\text{glass,out}} = T_{\text{oil}} \tag{16}$$

By substituting Eq. (16) into Eqs. (13) and (14), the heat losses by conduction and convection can be simplified to a direct convective heat transfer from the oil to the air:

$$q_{\text{total}} = h_c\left(T_{\text{oil}} - T_\infty\right)A \tag{17}$$

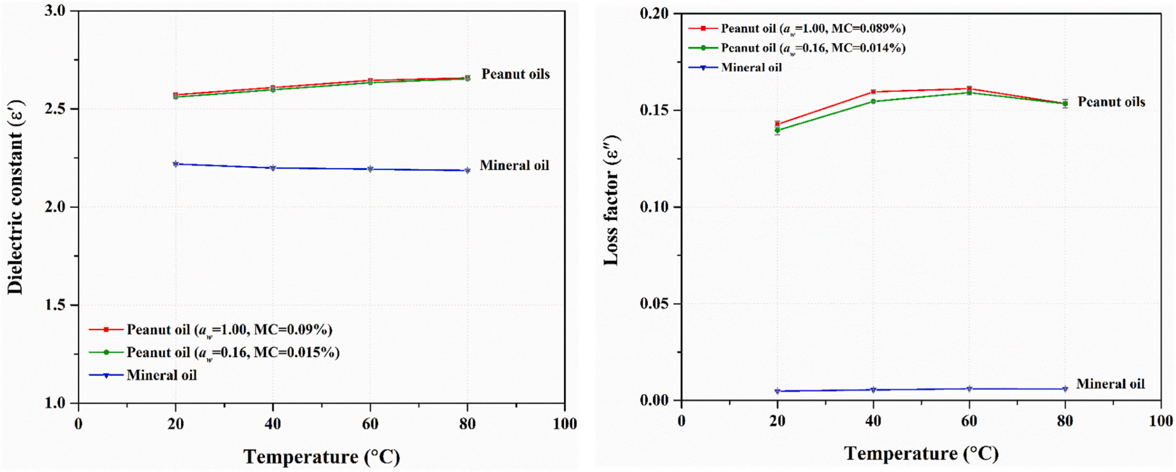
where A (m^2) is the total surface area exposed to air ($A_{glass} + A_{top}$).

In this study, the measured dielectric properties of vegetable and mineral oil samples at 2450 MHz were used in the computer simulation. Also, another set of simulations was run for a sensitivity analysis to demonstrate the influence of different loss factor values (ε'' = 0.001, 0.005, 0.01, 0.05, 0.1) on microwave heating rates of samples. The measured dielectric constant (ε') for the peanut and mineral oil samples were similar (ranging from 2.2 to 2.6, see below), so we used an average value of ε' = 2.4 in the sensitivity analysis. The specific heat for the peanut and mineral oil samples were similar (C_p = 2128 J/kg·K for peanut oil, and C_p = 1902 J/kg·K for mineral oil, Table 1), so an average value of 2000 J/kg·K was used.

3. Results and discussion

3.1. Microwave heating of oils

Fig. 5 shows the temperature increases of vegetable oil and mineral oil samples under the same microwave heating conditions. The average heating rate of the vegetable oil samples was about 33 °C/min, more than 10 times that of mineral oil (~3 °C/min).



(a)

(b)

Fig. 6. (a) Dielectric constant and (b) loss factor of peanut oil and mineral oil samples at various temperatures at 2450 MHz. The peanut oil samples had different water activities (a_w) and moisture contents (MC, on a wet basis). The resonant cavity method was used for measurements (n = 3).

Table 2
Dielectric properties and penetration depth (dp) of vegetable oil, mineral oil, glycerol, and water at 2450 MHz.

Temperature (°C)	Dielectric properties ($\varepsilon' - j{\cdot}\varepsilon''$)				Penetration depth (dp, mm)			
	Vegetable oil	Mineral oil	Glycerol	Water[a]	Vegetable oil	Mineral oil	Glycerol	Water
20	2.6 – *j*·0.14	2.2 – *j*·0.0048	7.0 – *j*·4.1	78.2 – *j*·10.3	222	6027	13.0	16.7
40	2.6 – *j*·0.16	2.2 – *j*·0.0055	8.5 – *j*·6.4	73.5 – *j*·5.8	196	5236	9.4	28.6
60	2.6 – *j*·0.16	2.2 – *j*·0.0061	11.4 – *j*·9.5	68.8 – *j*·3.6	197	4711	7.4	44.5
80	2.7 – *j*·0.15	2.2 – *j*·0.0060	16.3 – *j*·12.2	62.2 – *j*·2.4	211	4778	6.8	63.7

[a] Data from Gezahegn et al. (2021).

To quantify the absorbed microwave power, the following energy balance equation was used:

$$P = mC_p\frac{\Delta T}{\Delta t} \tag{18}$$

where P = absorbed microwave power (W)
m = mass of the sample (kg)
$^{\Delta T}/_{\Delta t}$ = average heating rate of the sample (°C/s)
C_p = specific heat of the sample (J/kg·K)

Based on Eq. (18), the absorbed microwave power was about 1000 W for the vegetable oil sample and 80 W for the mineral oil sample (the microwave oven output power was 1200 W). This considerable difference in heating rates and power absorption between vegetable oil and mineral oil highlights the presence of specific components in vegetable oils (i.e., water or glycerol which are absent in mineral oils) that caused microwave heating. To further investigate this observation, we analyzed the dielectric properties of the oils.

3.2. *Influence of dielectric properties on microwave heating*

3.2.1. *Dielectric properties of oils*

Fig. 6 shows the dielectric constant and loss factor values of vegetable and mineral oil at temperatures from 20 to 80 °C. The temperature within the tested range had very little influence on the dielectric properties of oils. The dielectric constant (ε') for both oils had a similar value: 2.6 for vegetable oil and 2.2 for mineral oil. But a large difference was observed in the loss factor (ε''): 0.15 for vegetable oil, which was 30 times higher than that of mineral oil ($\varepsilon'' = 0.005$). According to Eq. (2), the microwave power absorption (P_V) is proportional to $\varepsilon''|\mathbf{E}|^2$ (Metaxas and Meredith, 1983). Based on the analysis of Zhou et al. (2023a), the electric field strength in oil (E) is proportional to $1/\varepsilon'$. Given the similar ε' values, it can be inferred that both peanut oil ($\varepsilon' = 2.6$) and mineral oil ($\varepsilon' = 2.2$) should be exposed to similar E field strengths when placed in the same microwave oven. Consequently, a material with a higher loss factor (ε'') will absorb more microwave energy (P_V). This explains why the vegetable oil sample, with its higher ε'' of 0.15 was able to convert more microwave energy into heat, as compared to the mineral oil sample with a much lower ε'' of 0.005.

Previous research on the dielectric properties of vegetable oil at 2450 MHz is very limited. Pace et al. (1968) measured dielectric properties of vegetable oil at 25 °C and 3000 MHz, obtaining values of $\varepsilon' = 2.506$, $\varepsilon'' = 0.138$. These data are very similar to our measurement at 20 °C and 2450 MHz ($\varepsilon' = 2.6$, $\varepsilon'' = 0.14$). The small variances can be explained by the slight differences in measurement frequencies (3000 vs. 2450 MHz) and temperatures (25 vs. 20 °C). However, there is no published dielectric property data of mineral oil at 2450 MHz, so no comparisons can be made.

3.2.2. *Penetration depth of oils*

The value of microwave penetration depth is another good indicator for the ability of the material to convert microwave energy to heat. As shown in Table 2, microwaves at 2450 MHz have larger penetration depth values in mineral oil compared to in vegetable oil. For example, at 20 °C, the penetration depth in mineral oil was 6027 mm, whereas in vegetable oil, it was 222 mm. Given that the 1 L oil container used in the experiments had dimensions of approximately 120 mm in height and 100 mm in diameter, the calculated penetration depths in Table 2 suggest that the vegetable oil samples could convert most of the microwave

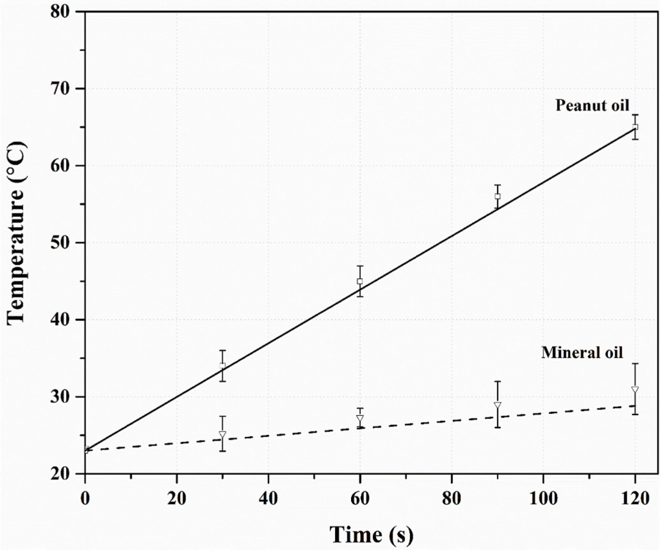


Fig. 7. Comparison of experimental (symbols) and simulated (lines) average temperature-time histories of 1L peanut oil and mineral oil samples when heated in a 1200 W, 2450 MHz microwave oven.

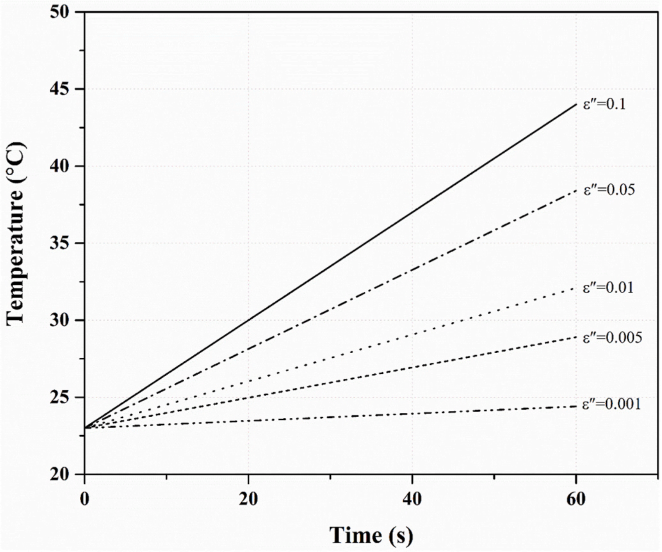
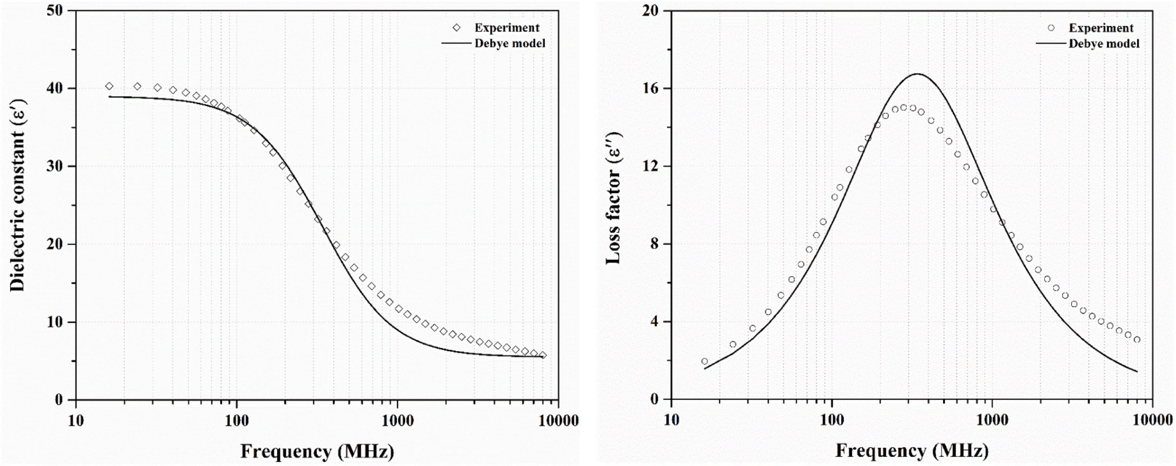


Fig. 8. Sensitivity analysis: simulated average heating rates of 1L sample with different loss factor (ε'') values heated in a 1200 W, 2450 MHz microwave oven. Assuming that the sample has a constant dielectric constant (ε' = 2.4) and specific heat (C_p = 2000 J/kg·K).



(a) (b)

Fig. 9. (a) Dielectric constant and (b) loss factor of glycerol at 40 °C between frequencies of 10 MHz and 8000 MHz. Experimental data (open symbols) were fitted to Debye model (solid lines). The open-ended coaxial probe method was used for measurements ($n = 3$).

power within the container volume. In contrast, most of the incoming microwaves passed through the mineral oil samples without causing significant heating. That is, mineral oil samples were nearly transparent to microwaves.

3.2.3. *Computer simulation*

Fig. 7 compares average temperature-time histories of vegetable oil and mineral oil samples between experiments and simulations. The simulated results by using the measured dielectric properties matched well with the experimental results, which validated the computer model. This also demonstrated that our measured dielectric property values are reliable.

To further illustrate the influence of the loss factor values on average microwave heating rates, a sensitivity analysis was conducted using the validated computer simulation model. The result are illustrated in Fig. 8. The simulation showed that microwave heating rate decreased as the loss factor decreased. When the loss factor was below 0.005, dielectric materials (such as mineral oil) were extremely difficult to heat using microwaves.

3.2.4. *Chemical structures*

The extremely small loss factor of mineral oil can be explained by its nonpolar carbon chain structure. Mineral oils consist mainly of hydrocarbons. Hydrocarbons range from linear (alkanes) to cyclic (cycloalkanes) structures. Fig. 1b shows a typical straight-chain hydrocarbon chain ($C_{12}H_{26}$). Carbon chains of mineral oils are nonpolar due to the symmetric structure and the equal sharing of electrons between carbon and hydrogen atoms (Damodaran et al., 2007). As a result, the orientational polarization in mineral oils under microwave fields should be very weak, leading to the low loss factor value. The reasons for the relatively high loss factor of vegetable oil will be discussed later.

3.3. *Contribution of dissolved moisture*

Using Eq. (8), the moisture contents of the peanut oil samples conditioned to a_w of 0.16 and 1.00 were calculated to be 0.015% and 0.090% on a wet basis (w.b.), respectively. Fig. 5 shows no difference in the temperature rises of the peanut oil samples with the two different moisture contents. To further understand the microwave heating phenomenon, we measured the dielectric properties of the peanut oil samples. Fig. 6 shows no significant difference ($p > 0.05$) in the dielectric constant or loss factor between the peanut oil samples with different moisture contents. That means the water dissolved in peanut oils had negligible influence on dielectric properties and microwave heating, which refutes our first hypothesis. A likely reason is that vegetable oils can only hold a very small amount of water. Even after prolonged exposure to high RH air for four days, peanut oil was only conditioned to a saturated moisture content of 0.090% (w.b.) at room temperature. Such a low concentration of water in the vegetable oil sample does not contribute to microwave heating.

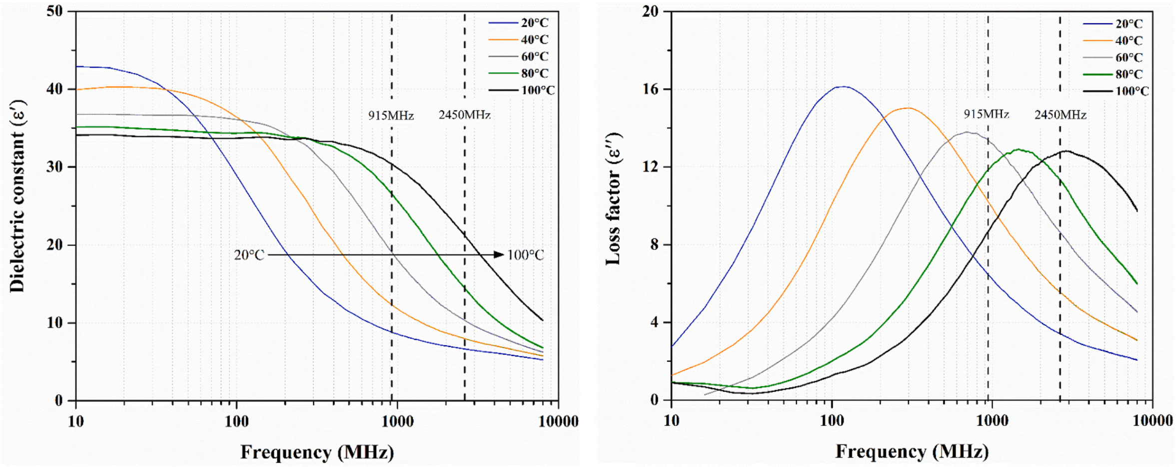
Table 3
The parameters of glycerol for fitting the Debye model (Eqs. (9)–(11)).

T (°C)	ε_s	ε_∞	τ ($\times 10^{-9}$ s)	f_c (MHz)
20	38.4	6.0	4.80	33.1
40	37.1	6.3	2.21	72.0
60	34.8	6.3	1.05	151.5
80	33.0	6.6	0.61	262.4
100	33.4	6.4	0.33	486.9

where T = temperature (°C).
ε_s = static permittivity (permittivity at zero frequency).
ε_∞ = permittivity at infinite frequency.
τ = relaxation time (s).
f_c = critical frequency (MHz).

3.4. *Dielectric properties of glycerol*

Triglyceride is a glycerol molecule bound to three fatty acid chains (Fig. 1). We measured dielectric properties of pure glycerol solution to provide possible explanation to the contribution of glycerol component to dielectric properties of vegetable oil. Fig. 9 shows the dielectric constant and loss factor of pure glycerol over the frequency range of 10 MHz to 8000 MHz. At lower frequencies, the glycerol dipoles have enough time to orient themselves with the applied electric field (E-field). The polarization remains in phase with the E-field, resulting in a stable dielectric constant and minimal energy loss (and thus a low loss factor). As the frequency increases, the glycerol dipoles are no longer able to follow the rapidly oscillating E-field due to short excitation periods and internal viscosity. This leads to a decline in the dielectric constant. Concurrently, the phase lag between the dipoles and E-field causes an increase in energy dissipation, seen as a peak in the loss factor (Fig. 9b). This peak occurred at the critical frequency f_c (calculated from Eq. (11)) at which the relaxation of glycerol dipoles was out of phase with the applied electric field. Beyond this peak, at even higher frequencies, both the dielectric constant and the loss factor decline due to the great misalignment between the dipoles and the E-field (Metaxas and



(a) (b)

Fig. 10. (a) Dielectric constant and (b) loss factor of glycerol at different temperatures between frequencies of 10 MHz and 8000 MHz.

Meredith, 1983). The peak loss factor values and the corresponding relaxation time are summarized in Table 3.

The dielectric properties of glycerol also changed with temperature (Fig. 10). Increasing temperature depressed the height of the plateau in dielectric constant and shifted the peak of the loss factor to higher frequencies. This shift corresponded to a reduction of the relaxation times of the glycerol samples in microwave fields, as shown in Table 3. This is because at elevated temperatures, the viscosity of glycerol molecules decreases and the molecule mobility increases, which allows quicker realignment of polar molecules in a changing electric field. Von Hippel (1954) developed a mathematical equation to describe how temperature and viscosity of the liquid affect the relaxation time:

$$\tau = V\frac{3\eta}{kT} \tag{19}$$

where τ = relaxation time (s)
V = volume of a molecule (m^3)
η = viscosity (kg/m·s)
k = Boltzmann constant (1.38×10^{23} J/K)
T = absolute temperature (K)

According to Eq. (19), an increase in temperature (T) results in a decrease in the relaxation time (τ). Also, according to Arrhenius law (Eq. (20)), the viscosity (η) of fluid decreases as temperature increases, which further reduces the relaxation time and increases the critical frequency.

$$\eta = \eta_0 e^{\frac{E_a}{RT}} \tag{20}$$

where η_0 = initial viscosity (kg/m·s)
E_a = activation energy (J/mol)
R = universal gas constant (8.3 J/K·mol)

Compared to water which has a relaxation time that changes from 8.5×10^{-12} s at 23 °C to 2.1×10^{-12} s at 100 °C (Gezahegn et al., 2021) with the corresponding resonance frequency changing from 19,000 MHz to 75,000 MHz (calculated from Eq. (11)), glycerol has a relaxation time about 2 – 3 orders of magnitudes larger, varying from 4.8×10^{-9} s at 20 °C to 0.3×10^{-9} s at 100 °C. The corresponding resonance frequency of glycerol increases from 33 MHz at 20 °C to 487 MHz at 100 °C. The much larger molecular weight (92 Da) and consequently bulkier size of glycerol, compared to water (18 Da), sharply increases relaxation time and reduces resonance frequency of glycerol at a given temperature.

3.5. *Contribution of glycerol*

Fig. 9 shows that the dielectric behavior of glycerol matched well with the predictions of the Debye model (Eqs. (9) and (10)), which suggests that glycerol is a solution comprised of polar molecules (Von Hippel, 1954). Polar glycerol might be the major component in vegetable oil contributing to microwave heating. Here, we summarized the dielectric properties of vegetable oil, pure glycerol, and free fatty acids at around 2450 MHz at room tenperature.

- For vegetable oil, $\varepsilon^{'} = 2.6$ and $\varepsilon^{''} = 0.14$ (Table 2).
- For glycerol, $\varepsilon^{'} = 7.0$ and $\varepsilon^{''} = 4.1$(Table 2).
- For fatty acids, such as capric, palmitic, and stearic acids, $\varepsilon^{'} = 2.3$ and $\varepsilon^{''} = 0.03$ (data from Buchanan, 1954).

The above data suggests that the fatty acid components (90% by weight) reduce the loss factor of vegetable oils, whereas the glycerol components (10% by weight) greatly increase the loss factor and facilitate interactions with microwave fields. The measured dielectric property data can be explained by examining the molecular structure of vegetable oil (Fig. 1). In vegetable oil molecules, the bulky structure and the long carbon chains in fatty acids greatly restrict the mobility of glycerol, resulting in slower reorientation, or large relaxation time in response to electromagnetic fields. As a result, vegetable oil has a lower loss factor, compared to pure glycerol. Yet, the loss factor of vegetable oil is still higher than that of free fatty acids, due to the glycerol component in the oil. This supports our second hypothesis that the glycerol component in vegetable oil molecule is a major contributor to microwave heating.

In addition, our microwave heating experiments showed that pure glycerol samples heat rapidly in the microwave oven, even faster than water (Fig. S1). The rapid heating of glycerol samples can be attributed to the relatively high loss factor ($\varepsilon^{''}$ ranging from 4.4 to 12.2) (Table 2). Another contributing factor is the relative shallow microwave penetration depths in glycerol. Table 2 shows that the penetration depths of glycerol (dp ranging from 6.8 to 13.0 mm) were much less than the dimensions of the sample container (Fig. 4b), meaning that most of microwave energy can be absorbed and converted into heat within the glycerol volume. The faster heating rate of glycerol compared to water was due to the lower specific heat of glycerol. Glycerol has a specific heat of ~2300 J/kg·K, which is about ½ that of water (~4186 J/kg·K). The lower specific heat means glycerol requires less thermal energy to increase the temperature.

3.6. *Influence of double bonds on microwave heating*

Unsaturated fatty acids in triglycerides contain double bonds while saturated fatty acids have only single bonds (Damodaran et al., 2007).

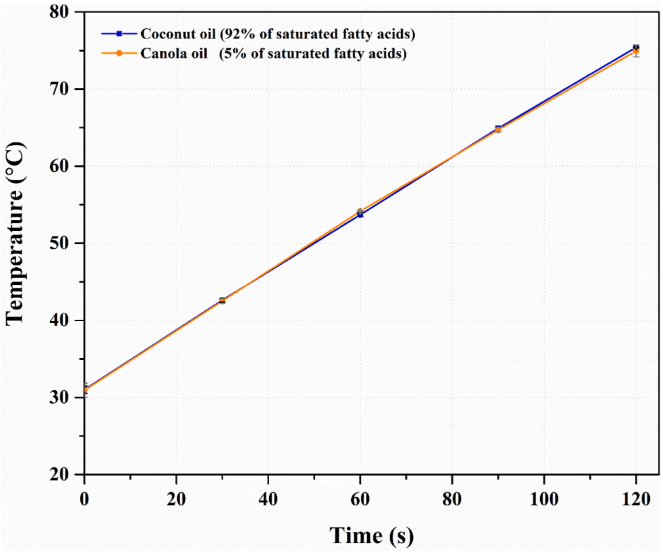


Fig. 11. Average temperature increases of 1L coconut and canola oil samples when heated in a 1200 W, 2450 MHz microwave oven ($n = 3$).

Single and double bonds have different characteristics, including variations in electron distribution, bond length, bond strength, and the ability to rotate (Damodaran et al., 2007). It is not clear if double bonds influence microwave heating of vegetable oils. To address this question, we compared two natural vegetable oils: canola oil and coconut oil. Canola oil has 95% unsaturated fatty acids, while coconut oil has only 8% unsaturated fatty acids (Damodaran et al., 2007). That means canola oil has more double bonds than coconut oil. Fig. 11 shows the temperature increases of canola oil and coconut oil samples during microwave heating under the same experimental conditions. The heating rates between the two oils were not significantly different ($p > 0.05$), suggesting that double bonds of the fatty acids have negligible influence on microwave heating.

4. Conclusions

We found that 1) water dissolved in vegetable oils does not contribute to microwave heating. A likely reason is that vegetable oils can only hold a very small amount of water (0.09%, w.b.); 2) Glycerol component (10% by weight) in vegetable oil molecules is a major contributor to microwave heating. Glycerol-present vegetable oil had a loss factor (~ 0.15), 30 times higher than glycerol-absent mineral oil (~ 0.005). This explains why vegetable oil heats well in the microwave oven whereas mineral oil does not. Computer simulations were also utilized to demonstrate the influence of loss factor values on microwave heating rates. We also found that double bonds in vegetable oils have negligible influence on microwave heating. In summary, this study offers new fundamental understanding about microwave heating of vegetable oils and provides reliable dielectric property data of oils for future computer simulation of related industrial microwave heating operations.

CRediT authorship contribution statement

Xu Zhou: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Piotr Czekala:** Writing – review & editing, Methodology, Investigation. **Marzena Olszewska–Placha:** Writing – review & editing, Methodology, Investigation. **Bartlomiej Salski:** Writing – review & editing, Methodology, Investigation. **Shuang Zhang:** Writing – review & editing, Methodology, Investigation. **Patrick D. Pedrow:** Writing – review & editing, Methodology. **Shyam S. Sablani:** Writing – review & editing, Methodology. **Juming Tang:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

To the best of our knowledge, the named authors have no conflict of interest, financial or otherwise.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jfoodeng.2024.112039.

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