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Theoretical reasons for rapid heating of vegetable oils by microwaves

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ABSTRACT

Water and high-moisture foods are readily heated in microwaves due to their relatively high dielectric loss factors. Vegetable oil, on the other hand, has a much smaller loss factor (about 1/100th that of water), and is generally believed to be unsuitable for microwave heating. In this study, we conducted experiments to compare heating rates between vegetable oil and pure water in a 2450 MHz microwave oven. We found that the vegetable oil samples were heated rapidly in microwaves, and even faster (1.4–2.0 times) than the water samples. To provide a theoretical explanation, we developed a 3-D computer simulation model. The simulation revealed an approximately 10-fold stronger electric field in oil compared to water, resulting in a similar amount of microwave power being absorbed by the oil and water samples. As the absorbed microwave power was converted into thermal energy, the oil samples were heated faster due to their smaller specific heat (1/2 that of water). But we also found that when the dimensions of oil are smaller than half the microwave wavelength, oil is heated slower than water due to the absence of hot spot areas. This study provides a theoretical explanation for microwave heating of vegetable oils and demonstrates opportunities for utilizing microwave energy to electrify industrial heating of vegetable oils.

1. Introduction

Many countries, including the United States and the European Union, have set a goal of achieving net-zero greenhouse gas (GHG) emssions by 2050 (Huang and Zhai, 2021). Traditional heating technologies used in the food industry, such as steam boilers, contribute significantly to carbon emissions due to their reliance on fossil fuels such as coal and natural gas. Electrification of industrial heating is considered as a crucial step to reduce CO_2 emissions (U.S. Department of Energy, 2022). On October 7th, 2022, PepsiCo announced its plan to replace natural gas-fired steam boilers with resistance heaters in production of deep-fried snacks, such as Lay's chips and Cheetos (Sterling, 2022). However, the relatively high viscosity and low thermal conductivity of oil (compared to water) may hinder heat transfer and restrict the applicability of resistance heaters in industrial operations. Therefore, it is necessary to explore other effective alternatives for oil heating.

Microwave heating has gained popularity in households and the food industry due to its ability to penetrate and directly interact with dielectric materials, providing rapid and volumetric heating (Tang, 2015; Zhou and Wang, 2019). During microwave heating, the absorption of microwave power by a dielectric material can be determined by (Metaxas and Meredith, 1993):

$$P_v = 2\pi f \varepsilon_0 \varepsilon_r^{''} \mathbf{E}^2 \tag{1}$$

where P_v = converted thermal energy per unit volume (W/m^3).
f = microwave frequency (Hz).
ε_0 = permittivity of free space (constant value, 8.854×10^{-12} F/m).
$\varepsilon_r^{''}$ = loss factor of the dielectric material (relative to free space).
$\mathbf{E}$ = electric field strength (root mean square) in the material (V/m).

Vegetable oils, which are esters of long-chain fatty acids, have very small loss factors, $\varepsilon_r^{''}$. For example, at 2450 MHz corn oil has $\varepsilon_r^{''}$ of 0.14, which is about ~1/100th that of tap water ($\varepsilon_r^{''} = 14$) (Gezahegn et al., 2021; Tang, 2015). Eq. (1) shows that the larger the loss factor, the easier the material absorbs the microwave energy (Metaxas and Meredith, 1993). Therefore, it has been generally believed that low-loss vegetable oils are not readily heated in microwaves. However, contrary to this belief, our preliminary tests with vegetable oils showed

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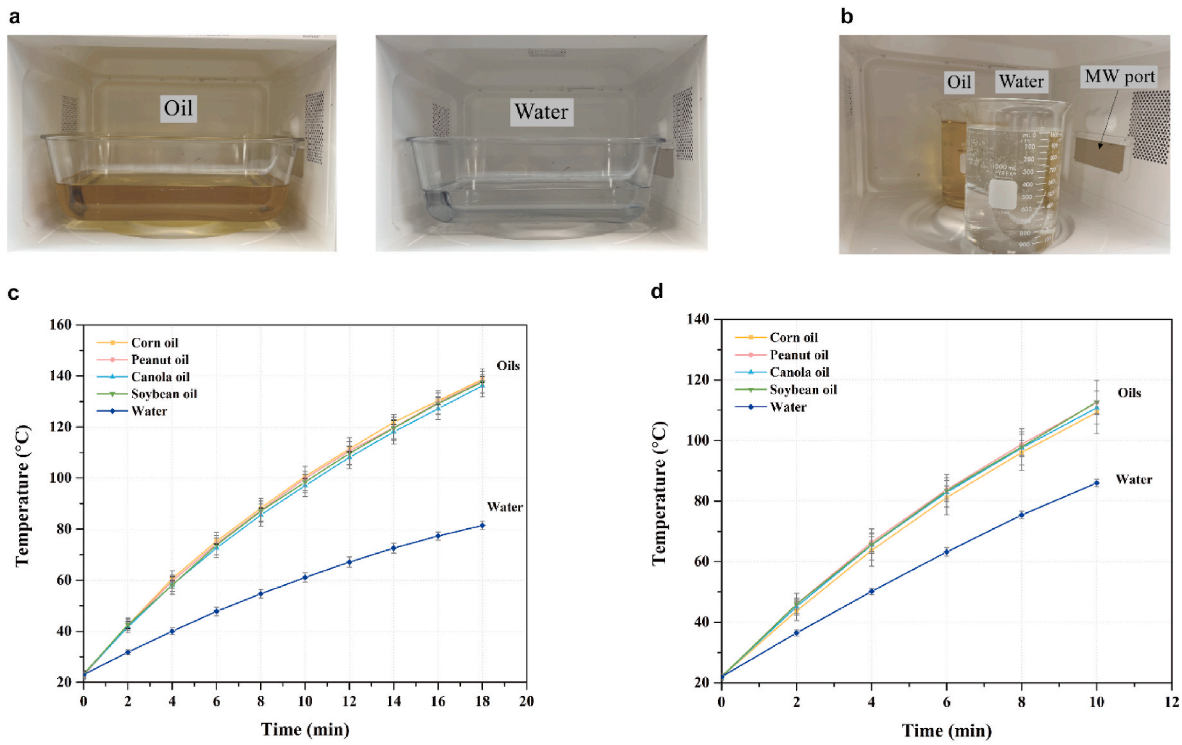

Fig. 1. **(a)** Oil or water samples in a rectangular glass container (250 mm × 250 mm × 50 mm) were heated separately in a microwave oven; **(b)** oil and water samples in cylindrical glass containers (sample diameter = 100 mm, sample height = 120 mm) were heated side-by-side in a microwave oven, symmetrically facing the microwave (MW) port from the waveguide (right side of the oven). The temperature rises of the water and four oil samples when heated **(c)** separately, and **(d)** side-by-side (n = 3).

different results. In the tests, we observed a rapid temperature increase in 3000 mL of soybean oil samples from 20 to 180 °C in just 30 min when heated in a 1200 W microwave oven (resulting in a heating rate of 5 °C/min) (Zhou et al., 2022). The result is consistent with earlier studies that reported significant temperature increases in corn oil when heated in microwave ovens (Barringer et al., 1994; Prosetya and Datta, 1991). Prosetya and Datta (1991) hypothesized that the electric field in corn oil differs from that in water, but this hypothesis has not been validated. The reasons why low-loss vegetable oils heat rapidly in microwaves are not fully understood. This study aims to understand this phenomenon based on physics principles.

It is well understood that pure water (deionized water) heats well in microwave ovens due to the dipole structure of water molecules (Gezahegn et al., 2021). So it is of interest to study microwave heating of vegetable oils in comparison with pure water. Thus, the objectives of this study were to: (1) experimentally compare the rates of temperature increases between vegetable oils and pure water when subjected to the same microwave heating conditions, (2) develop a theoretical explanation for the observed experimental results, (3) establish criteria for microwave heating of vegetable oils, and (4) discuss potential applications in the food industry.

2. Material and methods

2.1. Samples

Four types of vegetable oils (corn oil, canola oil, soybean oil, and peanut oil) (Great Value brand, Walmart Inc., Bentonville, AR, USA) were purchased from a local Walmart store (Pullman, WA, USA). These oils were selected because of their wide usage in food frying and cooking applications. Pure water (deionized water) was collected from a Milli-Q purification system (Millipore Co., Billerica, MA, USA). Pure water was chosen as the tested water because Gezahegn et al. (2021) reported that at 2450 MHz, the loss factor of pure water was not significantly different from that of tap water within the temperature range of 20–70 °C. Therefore, microwave heating rates for pure water would not be different from those of tap water in this temperature range. Before microwave heating, both the oil and water samples were allowed to equilibrate to room temperature, 21 ± 1 °C for 12 h.

2.2. Microwave heating tests

Two sets of microwave heating experiments were conducted using a 1200 W 2450 MHz domestic microwave oven (Model: NN-SD681S, Panasonic, Tokyo, Japan). To maintain stationary load conditions, the turntable was removed.

(1) In the first set of experiments, a rectangular glass container (250 mm × 250 mm × 50 mm) was centrally placed on the base of the microwave cavity, as shown in Fig. 1a. A 3 L sample of either water or oil was heated for 18 min.
(2) In the second set of experiments, two cylindrical beakers (diameter: 100 mm; height: 120 mm) filled with 1.0 L of oil or water were placed side-by-side in the microwave cavity. The oil and water samples were symmetrically faced toward the waveguide port, as illustrated in Fig. 1b. Preliminary tests were conducted by interchanging the positions of the oil and water samples, and it was found that the difference in the temperature rise was less than 5% for the same samples at different locations. That is, the relative position of the samples in the cavity did not significantly affect the overall heating result. The samples were heated for 10 min. Both experiments were repeated three times. Rectangular and cylindrical containers (3 L and 1 L) were used to represent common food container sizes and geometries in domestic heating.

The temperatures of the samples during the tests were measured

Table 1
Thermal properties of oil and water at the average temperature [a].

	Pure water [b]	Vegetable oil [c]
Density, ρ, kg/m^3	988	882
Thermal conductivity, k, W/m·K	0.644	0.158
Specific heat, C_p, J/kg·K	4180	2128

[a] Average temperature during the microwave heating period. For water, the average temperature was about (20 + 80)/2 = 50 °C. For oil, the average temperature was about (20 + 140)/2 = 80 °C.
[b] Data from Çengel and Ghajar (2015).
[c] Data from Hoffmann et al. (2018).

using fiber optic sensors (Model MAN-00075 R5, FISO, Quebec, Canada) with an accuracy of ±0.5 °C and short response times (0.05–2 s). In cylindrical containers, three fiber optic sensors were positioned at the radial center but different depths in the sample: one near the top, the second at the center, and the third near the bottom of the container. In rectangular containers, three fiber optic sensors were placed: one at the geometry center, the second near the bottom corner close to the waveguide, and the third near the bottom corner far from the waveguide. Fiber optic sensor cables are flexible. To hold the sensors in their respective positions within liquid samples, the cables (diameter: 1.8 mm) of fiber optic sensors were threaded through Teflon tubes (inner diameter: 2.0 mm). The rigid Teflon tubes served as guide sleeves to maintain the position of the sensors. After the tips of sensors were placed at the desired locations, the Teflon tubes with the cables were securely fixed to the ceiling of the microwave cavity via thru-holes.

To obtain average temperatures of the samples, the microwave power was turned off every 2 min. The oil and water samples inside the microwave oven were stirred by hand (no need to move the containers). The stirring was considered complete when the temperature difference among the three sensor readings was less than 2 °C. It took approximately 3–4 s to stir the water samples, and 6–9 s to stir the oil samples which had a much higher viscosity and lower thermal conductivity than

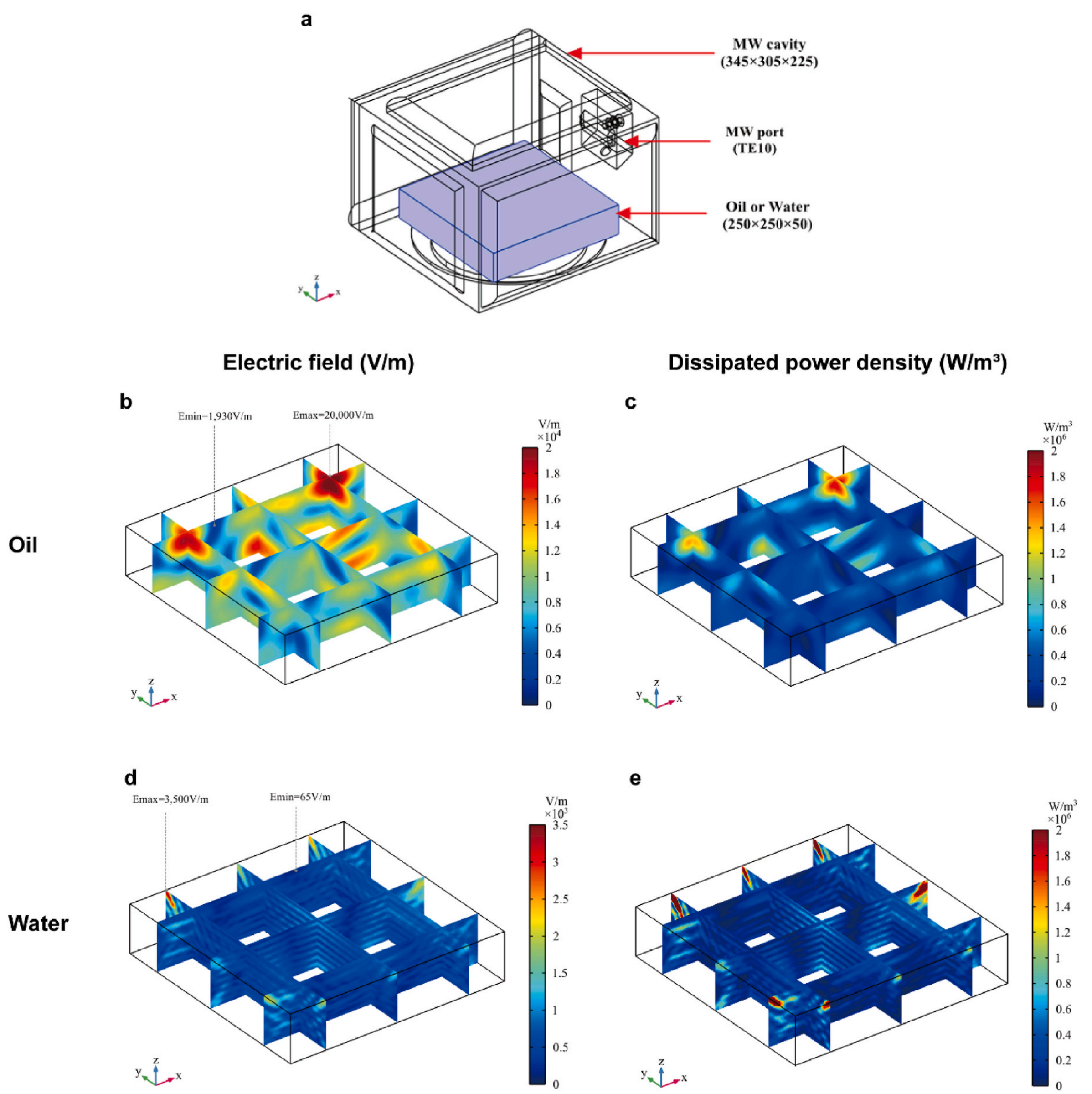

Fig. 2. **(a)** Sample placement in the microwave oven and related dimensions (in mm) used in the computer simulation model, **(b-c)** electric field intensity (V/m) and dissipated microwave power density (W/m^3) in oil, **(d-e)** electric field intensity (V/m) and dissipated microwave power density (W/m^3) in water. Please note that a larger scale of the electric field (× 10^4 V/m) was used for oil, about ten times of the scale for water (× 10^3 V/m), whereas the same power density scale (× 10^6 W/m^3) was used for oil and water.

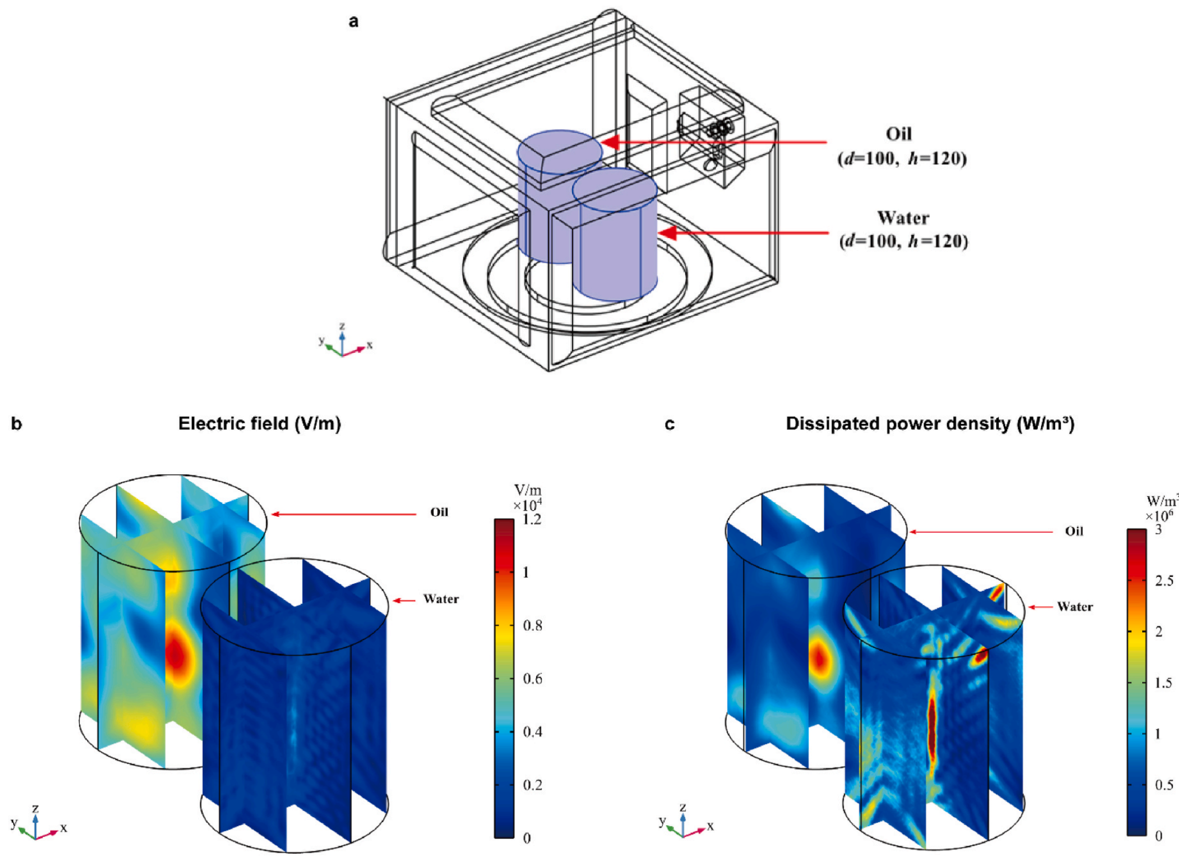

Fig. 3. **(a)** Sample placement in the microwave oven and related dimensions (in mm) used in the computer simulation model, d = sample diameter, h = sample height, **(b)** electric field intensity (V/m) in oil and water, **(c)** dissipated microwave power density (W/m^3) in oil and water. Please note that the same electric field intensity scale ($\times$ 10^4 V/m) and power density scale ($\times$ 10^6 W/m^3) were used for oil and water.

water. The fiber optic sensors, secured in rigid Teflon tubes, remained in their designated positions during stirring. After each stirring, the average temperatures based on the three sensor readings were recorded. The microwave power was then immediately turned on for another 2 min. This was repeated until the completion of the microwave heating processes.

2.3. Microwave power absorption calculation

Based on the measured temperature-time history of the oil and water samples, the microwave power P (W) absorbed by the samples was calculated by the energy balance equation (Çengel and Ghajar, 2015):

$$P = mC_p\frac{\Delta T}{\Delta t} \tag{2}$$

where P is absorbed microwave power (W), m is the sample mass (kg), C_p is the specific heat of the samples (J/kg°C) (Table 1), and $\Delta T/\Delta t$ is the average heating rate of the sample (°C/s). To minimize the influence of heat loss, the temperature data in the first 2-min period were used in Eq. (2), as suggested by the IMPI 2-L test procedure for domestic microwave ovens (Buffler, 1993).

2.4. Computer simulation

2.4.1. Governing equations and boundary conditions

To complement the above experiments, a three-dimensional computer simulation was developed using COMSOL Multiphysics 5.5 (COMSOL Inc., Boston, MA, USA). Two models were built, each corresponding to one of the experimental conditions described above (Figs. 2a and 3a).

The microwave fields inside the cavity and within samples are governed by Maxwell's equations (Sadiku, 2018):

$$\nabla \cdot (\varepsilon \mathbf{E}) = \rho_v \tag{3-a}$$

$$\nabla \cdot (\mu \mathbf{H}) = 0 \tag{3-b}$$

$$\nabla \times \mathbf{E} = -\frac{\partial(\mu \mathbf{H})}{\partial t} \tag{3-c}$$

$$\nabla \times \mathbf{H} = \frac{\partial(\varepsilon \mathbf{E})}{\partial t} + \mathbf{J}_v \tag{3-d}$$

where $\mathbf{E}$ is the electric field intensity (V/m), $\mathbf{H}$ is the magnetic field intensity (A/m), $\mathbf{J}_v$ is the volume current density (A), ρ_v is the free charge density (C/m^3), ε is the complex permittivity (F/m): $\varepsilon = \varepsilon_0(\varepsilon_r{'} - j\varepsilon_r{''})$, μ is the permeability (H/m), and ω is the angular frequency (rad/s).

The transient heat transfer in microwave heating is (Metaxas and Meredith, 1993):

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right) + P = \rho C_p\frac{\partial T}{\partial t} \tag{4}$$

where T is the temperature (°C) of the oil or water sample, $k_{(x,\,y,\,z)}$ is the thermal conductivity (W/m·K), and ρ is the density (kg/m^3) (Table 1). The P is the thermal energy converted from microwave energy (W), which can be calculated using Eq. (1).

We assumed that the oil and water were isotropic materials with constant thermal conductivity within the tested temperature range. Thus, Eq. (4) reduced to:

Table 2
Dielectric constant (ε_r') and loss factor (ε_r") of water and oil at temperature 20–90 °C and 2450 MHz.

Temperature (°C)	Pure water [a]		Vegetable oil [b]	
	ε_r'	ε_r''	ε_r'	ε_r''
20	78.0	9.3	2.57	0.14
40	73.5	5.9	2.60	0.16
60	67.8	3.6	2.64	0.16
80	62.2	2.4	2.66	0.15
90	59.7	2.0	2.66	0.15

[a] Data from Gezahegn et al. (2021).
[b] Data measured by the dielectric resonator cavity (average value, $n = 3$).

$$\nabla^2 T + \frac{P}{k} = \frac{\rho C_p}{k}\frac{\partial T}{\partial t} \tag{5}$$

The boundary condition at the food surface due to natural convection was (Çengel and Ghajar, 2015):

$$-k\nabla T = h(T_s - T_{air}) \tag{6}$$

where T_s is the surface temperature of samples (°C), T_{air} is air temperature (21 °C), and h is the convection coefficient (W/m^2·K) which is assumed to be 10 W/m^2·K (Pitchai et al., 2016).

Computer simulation was conducted for the two separated cases shown in Figs. 2a and 3a, for the total microwave heating time of 18 and 10 min, respectively, at a time step of 1 min. After each 2-min heating (between stirring), the volume-average temperatures of oil and water samples were calculated from those of the simulated sample elements. The calculated average temperatures were then used as the initial temperature condition for the next step simulation, until the end of the total heating time. This procedure was implemented using the MATLAB (R2021b, MathWorks Ltd, Natick, MA, USA) LiveLink interface with COMSOL.

2.4.2. Assumptions

To simplify the computer simulation, the following assumptions were made:

1) The study focused on the general microwave heating effect on oil or water rather than the temperature distribution in the samples. Therefore, internal fluid flow and convective heat transfer inside the samples were not considered.
2) The electromagnetic fields were time-harmonic (fields varied sinusoidally with time).
3) The samples were linear, isotropic, and homogenous.
4) The metal walls of the cavity and the waveguide were perfect electric conductors (PECs).
5) The thermal properties of oil and water were assumed to be constant within the tested temperature range.

2.4.3. Thermal and dielectric properties of oil and water

In the computer simulation, soybean oil and pure water were used as test samples. To simplify calculations, the thermal conductivity (k), specific heat (C_p), and density (ρ) were assumed to remainconstant at the average temperature. For example, the oil sample was heated from 20 to 140 °C, so the average temperature was (20 + 140)/2 = 80 °C. This simplification can significantly reduce computational time while achieving an acceptable level of accuracy (Çengel and Ghajar, 2015). Table 1 shows thermal property values of water and oil obtained from Çengel and Ghajar (2015) and Hoffmann et al. (2018). Dielectric properties of pure water within the temperature range of 20–90 °C were obtained from Gezahegn et al. (2021). Dielectric properties of vegetable oil were measured using a 2450 MHz dielectric resonator ($TE_{01\delta}$ mode, QWED, Warsaw, Poland) within 20–90 °C. The dielectric constant and loss factor of the vegetable oil sample were not sensitive in response to temperature (see results in Table 2). Therefore, the dielectric property values at 90 °C were extrapolated for temperatures beyond this range. The dielectric properties of water and oil used in the computer simulation are summarized in Table 2.

2.4.4. Input parameters and meshing

The microwave frequency used in the computer simulation greatly influences the simulated results, such as microwave field distribution and energy absorption of foods (Zhou et al., 2023a, b). Magnetrons in household microwave ovens do not generate microwaves exactly at 2450 MHz. Instead, the operating frequency varies between 2400 and 2500 MHz, depending on food loads in the oven and the specific oven used (Luan et al., 2017; Zhou et al., 2023a). Measuring exact microwave frequency of the oven is necessary to get reliable and accurate simulation results (Zhou et al., 2023a, b). A spectrum analyzer (SPA-6G, LATNEX, Toronto, Canada) was used to measure the operating microwave frequency of the microwave oven, following the method described by Zhou et al. (2023a). The peak frequencies were measured as 2466, 2458, and 2470 MHz, when heating individual water samples, individual oil samples, and water & oil together in the oven, respectively. These frequencies were then used in the simulations. The dominant mode, TE_{10}, was used for excitation of the waveguide (Zhou et al., 2023b).

The accuracy of simulation results also depends on mesh resolution. Preliminary convergence tests were conducted with various mesh sizes ranging from extremely fine to extremely coarse (data not shown). The final simulations for the individual oil sample (Fig. 2a), individual water sample (Fig. 2a), and oil & water samples heated side-by-side (Fig. 3a) utilized 230,211, 770,464, and 141,332 elements, respectively. These simulation programs ran for about 5, 9, and 2 h, respectively, on a high-performance workstation equipped with an Intel Xeon X5680 CPU @ 3.33 GHz and 96 GB RAM.

2.5. Influence of sample dimensions on microwave heating of oil

To study the influence of oil dimensions on microwave heating, we conducted experiments using cylindrical beakers with different heights (H) and diameters (D) for both oil and water samples. The dimensions were chosen based on the wavelength of the 2450 MHz microwave in oil ($L = 7.6$ cm), which will be discussed in more detail later. The selected dimensions for the samples were as follows: $H = D = ¼\,L$, $½\,L$, and L. The vegetable oil and pure water samples were placed in the center of the cavity base and heated separately.

2.6. Statistical analysis

The Analysis of Variance (ANOVA) was conducted using $\alpha = 0.05$ by the statistics software, R Studio (Posit Software, Boston, MA, USA). The experimental and simulated results were statistically compared with the coefficient of determination (R^2) and root mean square error (RMSE).

3. Results and discussion

3.1. Microwave heating of oil in comparison with water

Fig. 1a and b illustrate the placement of the samples in two sets of microwave heating experiments, namely heating oil or water separately, and heating oil and water simultaneously. In both cases, the vegetable oil samples were heated at higher rates compared to the water samples (Fig. 1c and d). Specifically, when separately heating the 3 L oil or water sample, the heating rates for the oil samples (6 °C/min) were twice as that of the water sample (3 °C/min) (Fig. 1c). When heating the 1 L oil and water samples side-by-side, the average heating rate of the oil samples was about 9.0 °C/min, which was about 1.4 times that of water (6.4 °C/min) (Fig. 1d). These experimental results demonstrate that vegetable oils heat readily in microwaves, and even faster than water. It is interesting to note that no significant difference ($p \geq 0.05$) in the

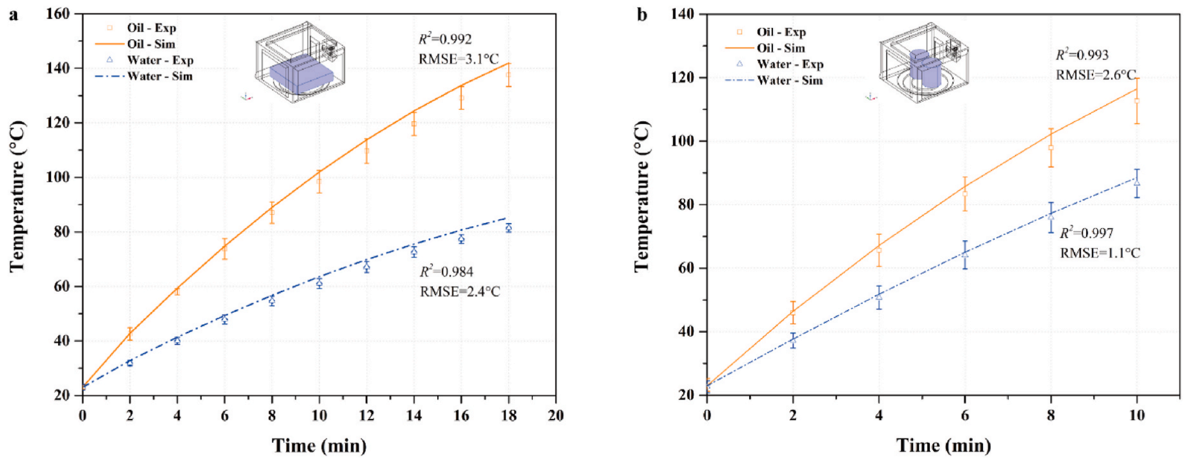

Fig. 4. Comparison of temperature-time profile between computer simulated and experimental results ($n = 3$) when heating oil and water samples **(a)** separately and **(b)** side-by-side.

Table 3
Measured and simulated microwave power absorption (W) by vegetable oil and pure water samples heated in a microwave oven (1200 W).

	Samples	Absorbed microwave power (W)	
		Simulation [a]	Experiment ($n = 3$) [b]
Samples heated separately	Water (3 L)	912	888 ± 84
	Oil (3 L)	843	807 ± 32
Samples heated side-by-side	Water (1 L)	513	492 ± 37
	Oil (1 L)	352	342 ± 33

[a] From Eq. (1).
[b] From Eq. (2).

average heating rates was observed among the four different vegetable oil samples (see Appendix). This could be attributed to the similar values of dielectric properties and thermal properties (particularly specific heat) of the four selected vegetable oils (Pace et al., 1968; Hoffmann et al., 2018).

3.2. Theoretical explanation

To provide a theoretical explanation for the above experimental results, a 3-D computer simulation model was developed. To validate the model, the temperature data of oil and water samples were compared between the experimental and simulated results. Fig. 4 demonstrates good agreement between the simulated and experimental data, as indicated by the high R^2 ($\geq$0.98) and the low RMSE ($\leq$3 °C). We also observed slight discrepancies (maximum temperature difference <5 °C) at elevated sample temperatures (that is, above 80 °C for water and 130 °C for oil). These discrepancies can be attributed to heat losses from stirring, thermal radiation, and conduction through containers during experiments. Such heat losses were not considered in the simulation models. Our models were further validated by comparing the microwave power absorption in oil and water between the experimental and simulated results (Table 3). The simulated results agree with the experimental data, falling within the range of average ± standard deviation from the experimental data ($n = 3$) (Table 3).

Then, the validated simulation model was used to calculate the electric fields (E-field) in the vegetable oils and water samples heated in the microwave oven. The simulation revealed a much higher E-field in oil compared to water (Figs. 2 and 3). For example, when heating oil and water separately, the maximum E-field intensity (E_{max}) in the oil sample was 20,000 V/m, while the minimum E-field intensity (E_{min}) was 1930 V/m (Fig. 2b). These values were several orders of magnitude greater than those in the water sample (E_{max} = 3500 V/m; E_{min} = 65 V/m) (Fig. 2d). The average E-field intensity in the oil sample ranged from 6000 to 12,000 V/m, which was approximately ten times higher than that in the water sample (500–1000 V/m). Similarly, when 1 L oil and water were heated side-by-side, much higher E-field intensities were observed in the oil sample, approximately ten times higher than that in the water sample (Fig. 3b and d).

According to Eq. (1), thermal energy, P_v converted from electric energy in a microwave field is proportional to the loss factor (ε_r'') of the sample and the square of E-field intensity (E^2) inside the sample. As illustrated in Table 4, vegetable oil has a smaller dielectric loss factor than water (i.e., about 1 vs 100), but it has about 10 times the electric field in water. As a result, the high value of E^2 (about 100 times that in water) compensated for the small ε_r'' of oil, leading to a comparable amount of microwave power absorption (P_v) generated in the oil and water samples. Oil, however, has a smaller specific heat than water, so it heats faster.

The stronger E-field in oil can be attributed to the small dielectric permittivity (ε_r) of vegetable oil:

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \tag{7}$$

where ε_r = complex permittivity of oil (relative to free space).
ε_r' = dielectric constant
ε_r'' = dielectric loss factor

When a plane wave travels from air to a dielectric material (such as oil or water), the E-field intensity of the wave is reduced to $1/\varepsilon_r$ of its original value(Sadiku, 2018). At 2450 MHz, water has higher permittivity (ε_r of 60–80), while oil has much lower permittivity (ε_r of 2–3) (Table 2). Consequently, the reduction in E-field intensity in oil is much smaller than in water.

The values of E-field intensity obtained from the computer simulation were used in Eq. (1) to calculate the dissipated microwave power, P_v, within the oil and water samples (Fig. 2c, e & Fig. 3c, e). Regardless of whether oil and water were heated separately or side-by-side, the dissipated microwave power density (P_v, W/m^3) in most regions of the oil and water was found to be in a similar range. That means oil and water of the same volume would absorb a comparable amount of microwave energy. This simulated result was further confirmed by the experimental calculations presented in Table 3. The experimental data showed that the amount of microwave power absorbed by oil was 70–90% of that absorbed by water under the identical experimental conditions.

After microwave power is converted into thermal energy in samples, the heating rate ($\frac{\Delta T}{\Delta t}$, °C/s) is mainly dependent on the specific heat of

Table 4
Approximate values and ratios of the parameters used in Eqs. (1) and (8) in calculating microwave heating rates of pure water and vegetable oils

	Water	Oil	Ratio (water/oil)
Loss factor at 20°C, ε''	10	0.1	100:1
Average E-field intensity, E (V/m)	1000	10000	1:10
Microwave power (P) ~ $\varepsilon''\cdot E^2$	1×10^7	1×10^7	1:1
Specific heat, C_p (J/kg·K)	4200	2100	2:1
Microwave heating rate ($\Delta T/\Delta t$) ~ $1/C_p$	1/4200	1/2100	1:2

samples, C_p:

$$\frac{\Delta T}{\Delta t} = \frac{P}{mC_p} \tag{8}$$

where C_p = 2128 J/kg·K for soybean oil, which is about 50% that of water (C_p = 4180 J/kg·K) (Table 1). Thus, the heating rate of the oil sample was higher compared to the water sample (Table 4).

3.3. Criteria for microwave heating of oil

Previous research suggested that for samples smaller than 100 g, water heats faster than oil (Barringer et al., 1994). However, our observations revealed some exceptions to this generalization. For example, we observed that oil (heating rate: 2.2 °C/min) was heated faster than water (heating rate: 1.2 °C/min) for 80 g samples in a cylindrical beaker (Diameter = 4.6 cm, height = 4.6 cm) (data not shown). This observation highlighted the need for a more reliable criterion to evaluate oil heating in comparison to water. Here, we investigated the influence of oil dimensions and incorporated the concept of *microwave wavelength*.

As microwaves propagate from air to a dielectric material, microwave wavelength is shortened. The wavelength (L) in the material can be determined using the following equation (Tang and Resurreccion, 2009):

$$L = \frac{2\pi}{2\pi f\sqrt{\frac{\mu_o\varepsilon_o\varepsilon'}{2}\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}+1\right]}} = \frac{L_0}{\sqrt{\frac{\varepsilon'}{2}\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}+1\right]}} \tag{9}$$

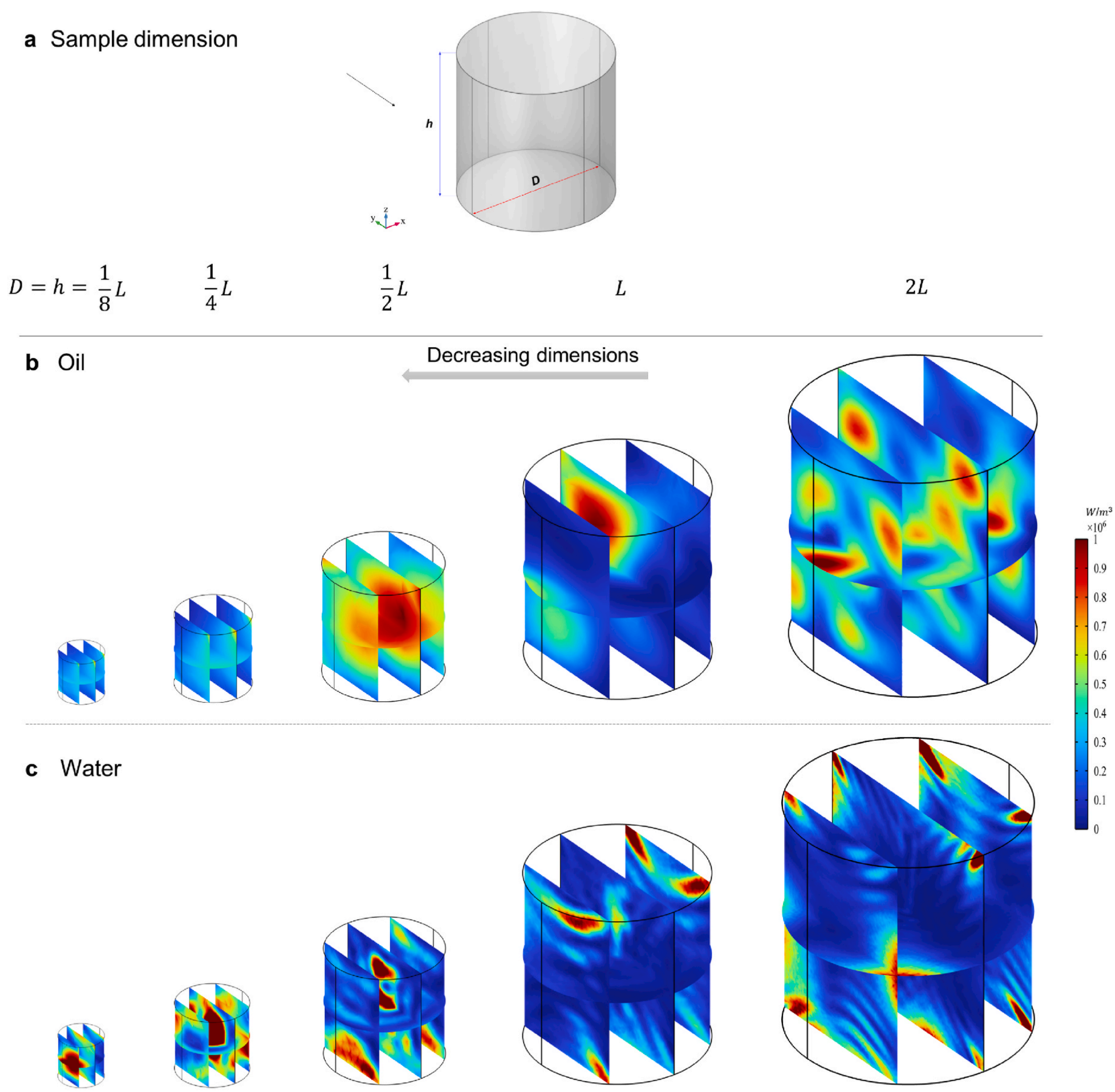

Fig. 5. Influence of sample dimensions on microwave fields: **(a)** oil and water samples in cylindrical containers with equal diameter and height ($h = D$) were heated separately in microwaves. Simulated microwave energy fields (W/m^3) in **(b)** oil and **(c)** water. L represents the microwave wavelength in oil at 2450 MHz (L = 7.6 cm).

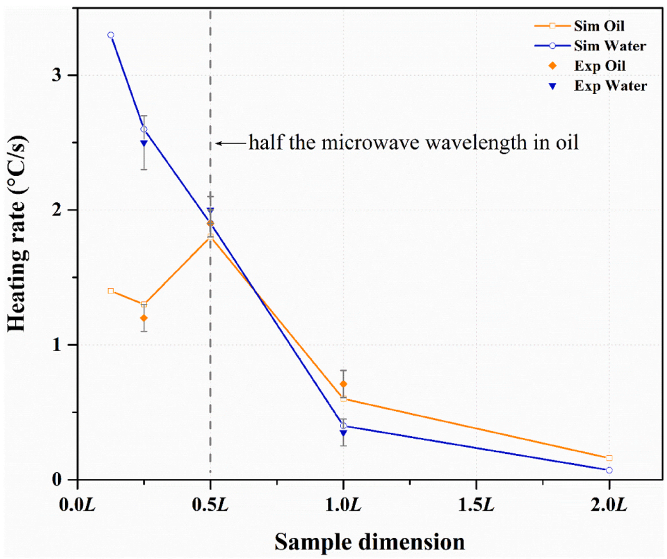

Fig. 6. Influence of sample dimension on the heating rate of water and oil samples, including both experiment ($n = 3$) and simulation results. Oil and water samples in cylindrical containers with equal diameter and height ($h = D$) were heated separately in microwaves. L represents the microwave wavelength in oil at 2450 MHz ($L = 7.6$ cm).

where L_0 is the wavelength of microwaves in air (e.g., 12.2 cm at 2450 MHz). The value of L depends on the dielectric properties of the heated subject. At 2450 MHz, the wavelength in oil is approximately 7.6 cm, whereas in water, it is approximately 1.3 cm (calculated using the averaged dielectric property data in Table 2). The distance between two adjacent anti-nodes, representing maximum microwave strength or hot spots, is about *half microwave wavelength* in the material (Tang, 2015). Based on this fundamental law of physics, we hypothesized that oil may not effectively absorb microwave energy when the dimensions of oil body are smaller than *half microwave wavelength*.

To validate this hypothesis, we first used simulation to analyze the microwave fields in oil and water with different sample dimensions. Fig. 5 illustrates the simulated microwave energy fields, showing that when the dimensions of the oil were smaller than half wavelength (~ 3.8 cm), oil cannot accommodate a single hot spot area. In contrast, when the oil dimension exceeded half wavelength, multiple hot spots were created within oil. In the case of water, even very small dimensions of the water body (~ 1.9 cm) can generate multiple hot spot areas due to the smaller wavelength of microwaves in water (~ 1.3 cm).

We further conducted microwave heating experiments and measured the heating rates in oil and water samples under three different dimension conditions. Fig. 6 shows that (1) when the dimensions of the oil samples were smaller than half wavelength in oil, oil was heated slower than water. This was due to the absence of hot spot areas, as shown earlier in Fig. 5; (2) when the oil sample dimensions were larger than half wavelength in oil, the oil heated faster than water; (3) when the oil sample dimensions were equal to half wavelength in oil, the heating rates of oil and water samples were similar. These criteria, which have not been previously reported, provide valuable insights for optimizing microwave heating of vegetable oil.

3.4. Potential applications

Microwave heating offers an alternative to traditional heating methods for vegetable oils in the food industry. In traditional heating methods, such as steam boilers, energy from fossil fuels (coal or natural gas) is first converted into heat by combustion. The heat is then used to boil water to produce steam, which subsequently transfers thermal energy to vegetable oils. Each of these steps introduces potential energy losses. In contrast, microwaves from electric energy directly interact with oils and generate thermal energy within the oils. Thus, microwave heating of oils is more energy efficient. Moreover, microwave heating can be directly powered by renewable electric sources such as solar, wind, and hydro power, offering the opportunity to sharply reduce CO_2 emissions. Recent studies also demonstrated that microwave frying is a promising technology for reducing oil content in fried foods without compromising product quality (Zhou et al., 2022). An entire frying operation line (oil heating and food frying) can be powered by microwaves, leading to more efficient, sustainable, and environmentally friendly processing.

Moreover, this study is helpful for the development of microwavable food products, particularly those containing oil-rich components. Recent research (Chen et al., 2023) and consumers reported that fatty food components, such as the fat in lean meat and cheese in sauce, heated up faster than other components when exposed to electromagnetic fields. The underlying reason for this was not well understood until now. Our findings may suggest that components rich in oil or fat could absorb substantial microwave energy due to the strong electric field intensity. However, it should be noted that our findings were established for microwave heating of oil and water in liquid states. Solid foods containing both components (such as fat in lean meat) might experience more uneven microwave heating in the absence of internal convection. Due to the slow heat conduction in solid foods, the fat-rich component might become localized hotspots. Also, the heating pattern of these foods might be influenced by the spatial arrangement and proportions of the fat-rich component to the high-moisture component (Chen et al., 2023). Future studies are needed to understand the heating behavior of solid foods with mixed fat and water components.

4. Conclusions

This study demonstrates that vegetable oils can be effectively heated using microwaves, often even faster than water. This can be explained through computer simulation that the electric field in vegetable oils is much stronger than in water. The strong electric field intensity compensated for the small loss factor of oil, resulting in a significant absorption of microwave power in oil. In addition, we established criteria for oil heating: when the dimensions of the oil are smaller than half wavelength in oil, the oil will be heated slower than water due to the absence of hot spot areas, whereas larger dimensions (relative to the half wavelength) can lead to faster microwave heating in oil. This study provides a theoretical basis for microwave heating of vegetable oils and suggests potential applications for carbon-neutral industrial heating processes. The fundamental mechanism of microwave heating of vegetable oils at the molecular level is still not fully understood. Further studies on the chemical structures of oils in response to microwave fields are recommended.

CRediT authorship contribution statement

Xu Zhou: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Project administration. **Yonas Gezahegn:** Data curation, Writing – review & editing. **Shuang Zhang:** Methodology, Investigation. **Zhongwei Tang:** Writing – review & editing. **Pawan S. Takhar:** Methodology, Writing – review & editing, Funding acquisition. **Patrick D. Pedrow:** Conceptualization, Methodology, Writing – review & editing. **Shyam S. Sablani:** Conceptualization, Methodology, Writing – review & editing. **Juming Tang:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.

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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