Journal of Food Science

ORIGINAL ARTICLE OPEN ACCESS

Food Engineering, Materials Science, and Nanotechnology

The Effect of Conventional and Microwave Frying on the Quality Characteristics of French Fries

Yash Shah[1] | Xu Zhou[2,3] | Juming Tang[2,3] | Pawan Singh Takhar[1]

[1]Department of Food Science and Human Nutrition, University of Illinois, Urbana-Champaign, Urbana, Illinois, USA | [2]Department of Industrial & Systems Engineering, University of Washington, Seattle, Washington, USA | [3]Department of Biological Systems Engineering, Washington State University, Pullman, Washington, USA

Correspondence: Pawan Singh Takhar (ptakhar@illinois.edu)

Received: 21 February 2025 | **Revised:** 9 June 2025 | **Accepted:** 8 July 2025

Funding: Financial support was provided by USDA National Institute of Food and Agriculture (NIFA) (Awards 2020-67017-31194, ILLU-698-308, and ILLU-698-926).

Keywords: frequency-dependent heating | microwaves | moisture loss | oil uptake | penetration depth | stress relaxation

ABSTRACT: Fried foods have a widespread appeal worldwide, but consumers are cautious about their high-calorie density and oil content. We evaluated microwave frying (MF) at 2.45 and 5.8 GHz frequencies as potential alternatives to conventional frying (CF) to produce fried foods containing less oil. MF is expected to lead to higher magnitudes of pressure in the food matrix than CF, which can provide higher resistance to oil penetration into the food. Real-time temperature and pressure measured using fiber optic sensors showed that MF resulted in faster sample heating and generated higher internal pressure than CF. The peak sample temperature and internal gauge pressure were the highest for MF at 2.45 GHz (107.3°C, 24.9 kPa), followed by MF at 5.8 GHz (104.1°C, 20.8 kPa) and CF (100.5°C, 13.8 kPa). The results indicated that the microwaves were not completely attenuated while traveling through the bulk oil and could penetrate the French fries. Below a sample moisture content of 3 g/g solids, the oil content increased rapidly with reducing moisture content for CF; the increase in oil content was relatively slower for MF at 5.8 GHz and negligible for MF at 2.45 GHz. This indicated that MF is an effective substitute for CF to produce lower oil content French fries with similar endpoint moisture content. The stress relaxation data showed that MF at 5.8 GHz produced stiffer (crunchier) French fries, which could be due to the intense crust heating.

Practical Applications

The current study showed that microwave frying can reduce frying times and produce French fries with lower oil content than conventional frying. This can help the food industry reduce processing times and offer consumers healthier fried foods. The insights generated from this work can help design process optimization studies and guide the physics-based modeling of microwave frying.

1 | Introduction

Deep-fried foods are popular across different cuisines. Fried foods like French fries and chips have a global consumer base and generate significant revenues for the food industry. For example, the North American market for French fries, estimated to be $8.22 billion in 2022, is expected to grow at a compounded annual growth rate (CAGR) of 4.3% between 2022 and 2027

Author has previously published as Pawan P. Singh

(Anonymoys 2023). The widespread appeal of fried foods is driven by their characteristic color, flavor, and texture. Physicochemical changes in foods during frying, including crust formation, protein denaturation, starch gelatinization, the Maillard reactions, and caramelization (Dash et al. 2022), are responsible for the desirable traits of fried foods. These physicochemical changes are driven by the multiphase (liquid water, gas, oil, and solid phases) transport processes occurring at high temperatures during frying.

Today's consumers are more health-conscious about food choices. Despite their appeal, fried foods are calorie-dense and abundant in oil (Dangal et al. 2024). Eating fried foods is linked with an increased risk of obesity and hypertension (Qin et al. 2022). More than 890 million adults worldwide were obese in 2022 (OECD/WHO 2024). Obesity may contribute to diseases like diabetes, cancer, and cardiovascular disease (Bray et al. 2017; Okunogbe et al. 2021). Therefore, there is a growing need to produce healthier fried foods with lower oil content.

Food companies have explored alternatives to conventional deep-oil frying, such as vacuum frying and hot air frying, to reduce the oil content of fried foods. However, these methods have ultimately fallen short of replacing conventional frying (CF). For example, vacuum frying is hindered by high initial investment (Zhang et al. 2020), and air frying is limited by its inability to replicate the texture and sensory characteristics of deep-fried foods (Teruel et al. 2015).

1.1 | Microwave Frying (MF) as an Alternative to CF

Pressure changes inside foods during frying are expected to affect the oil uptake behavior of foods (Vitrac et al. 2000). Combining microwave heating with CF, referred to as MF, has the potential to cause higher pressure development inside foods due to volumetric heating by microwaves. The higher pressure in foods during MF than CF can help reduce the oil content of fried foods by resisting oil penetration.

During frying, food is rapidly heated in hot oil, which causes the evaporation of liquid water and an increase in gas volume. The expanding gas trapped in the porous food pushes against the pore walls (Shah and Takhar 2024). Consequently, the average pressure exerted on the solid pore walls by the fluids occupying the pores, referred to as the pore pressure (p_{pore}), increases. The pore pressure is given by (Ehlers and Bluhm 2002)

$$p_{\text{pore}} = S^w p^w + S^g p^g + S^o p^o \tag{1}$$

where S^α and p^α are the degree of saturation and pressure of phase α, respectively, where α represents liquid water (w), gas (g), and oil (o) phases. Positive gauge pore pressures can resist oil infiltration into the food (Figure 1A) (Shah and Takhar 2024). However, as the material loses water, higher magnitudes of water phase capillary pressure (p^{cw}) develop in the porous matrix (Takhar 2014). The water pressure (p^w) is given by

$$p^w = p^g - p^{cw} \tag{2}$$

Consequently, the water pressure (p^w) and pore pressure (p_{pore}) decrease and can become negative during frying (Sandhu et al. 2013; Takhar 2014). Negative gauge pore pressures can cause a "suction" potential in the food, leading to faster oil uptake (Figure 1B). The pore pressure remains negative after removing the sample from the oil, which is expected to cause the surface oil to penetrate the sample.

Parikh and Takhar (2016) compared the MF and CF of French fries at three frying temperatures (177°C, 185°C, and 193°C). They found that MF led to higher positive gauge pressures than CF, and the gauge pressures tended to stay positive for longer times during MF. In addition, lower magnitudes of negative gauge pressures were developed in the food during MF than CF. Parikh and Takhar (2016) also measured the oil content of microwave-fried and conventionally fried French fry samples. They reported that MF led to lower French fry oil content at 185°C (lower by 0.08 g/g solids) and 193°C (lower by 0.07 g/g solids) compared to CF for a frying time of 2 min. The difference in oil content between microwave-fried and conventionally fried samples was not significant at 177°C. The samples are expected to have developed a higher resistance to oil penetration during MF because of the higher positive gauge pressures. Additionally, the suction potential is expected to be lower in microwave-fried samples than conventionally fried samples because of the lower magnitude of negative gauge pressures. The above two reasons could explain the lower oil content of the microwave-fried samples.

The industrial application of MF is also expected to be relatively less challenging than other alternatives to CF, like vacuum frying. Continuous fryers, which are typically utilized for industrial-scale production of fried foods (Bou et al. 2012), could be modified to conduct MF by incorporating microwave generators (e.g., magnetrons) along the length of the fryer. Magnetrons are inexpensive, and their availability is unlikely to be a concern. Therefore, MF is expected to be economically feasible for industrial use.

1.2 | Previous Works on MF in the Food Literature

Past MF studies in the food literature include those of Aydınkaptan and Barutçu Mazı (2017), Barutcu et al. (2009), Chen et al. (2009), Gharachorloo et al. (2010), Oztop et al. (2007), Parikh and Takhar (2016), Sahin et al. (2007), Sensoy et al. (2013), and Zhou et al. (2022). Oztop et al. (2007) studied the effect of microwave power (400, 550, and 700 W), frying time (2.0, 2.5, and 3.0 min), and frying oil (corn, hazelnut, and sunflower) on the quality characteristics of fried potato slices. Oztop et al. (2007) found that the moisture content of the fried slices decreased with an increase in microwave power and frying time, whereas the effect of oil type was insignificant. The authors hypothesized that the reason for the insignificant effect of oil type on the moisture content was the similarity of the dielectric properties of the oils used in their study. The oil content of the fried potato slices increased with microwave power and frying time, with the highest oil content observed for hazelnut oil (Oztop et al. 2007).

Sensoy et al. (2013) conducted CF and MF experiments for chicken breast samples. The temperature at the center of the

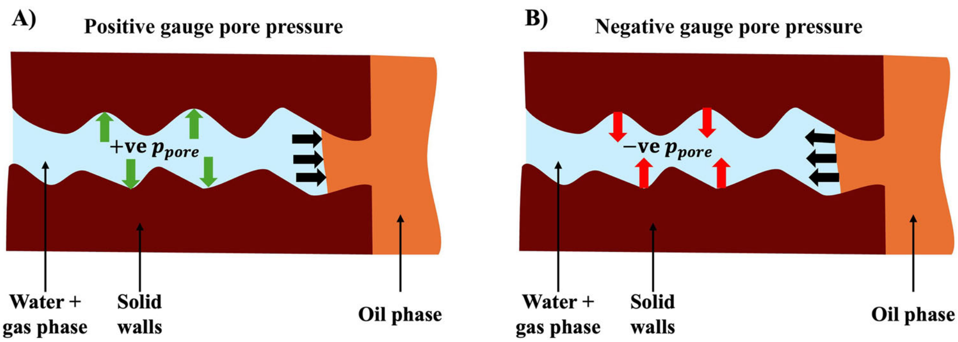

FIGURE 1 | Schematic diagram illustrating the effect of (A) positive and (B) negative gauge pore pressure (p_{pore}) on oil penetration in the food matrix during frying.

chicken breast sample reached 100°C in approximately 30 s during MF and took more than 160 s during CF (Sensoy et al. 2013). The moisture content profile for the chicken breast samples as a function of frying time showed that MF led to faster moisture loss compared to CF.

Barutcu et al. (2009) analyzed the impact of MF on acrylamide formation in fried chicken coating for samples prepared using batters formulated with different flour types (chickpea, rice, and soy). The acrylamide contents for different flour types were similar for samples microwave-fried for 1.5 min. The authors also conducted CF of the samples for 5 min and found that microwave-fried samples had a lower acrylamide content than conventionally fried samples, regardless of the flour type.

1.3 | Novelty and Objectives of This Study

There are two key aspects of this study that make it novel. First, we conducted MF experiments at two frequencies, 2.45 and 5.8 GHz. Second, we measured pressure and volume changes during frying, which enabled us to generate more insights about the transport mechanisms involved in MF and CF.

Household microwave ovens utilize the 2.45 GHz frequency, and some industrial microwave processing systems operate at 915 MHz (Guzik et al. 2022; Tang 2015). The Federal Communications Commission (FCC) has allocated the 5.8 GHz frequency for industrial, scientific, and medical (ISM) applications (Guzik et al. 2022). However, there is a lack of use of this frequency for food heating applications. There are only a handful of studies in the food literature that used the 5.8 GHz frequency (Zhou et al. 2022; Zhou, Pedrow, et al. 2023; Zhou, Tang, et al. 2023).

The power penetration depth (d_p) in a material is defined as the distance over which the power of an electromagnetic wave attenuates to 36.8% of its original value (Tang and Resurreccion 2009). The penetration depth is given by (Metaxas and Meredith 1983)

$$d_p = \frac{1}{2\alpha} \tag{3}$$

where α is the attenuation factor given by (von Hippel 1995)

$$\alpha = \frac{2\pi f}{c}\sqrt{\frac{\epsilon'}{2}\left(\sqrt{1+\left(\frac{\epsilon''}{\epsilon'}\right)^2}-1\right)} \tag{4}$$

where c, f, ϵ', and ϵ'' are the speed of light in vacuum, wave frequency, relative dielectric constant, and relative dielectric loss factor, respectively. Combining Equations (3) and (4), we get

$$d_p = \frac{c}{2\pi f\sqrt{2\epsilon'\left(\sqrt{1+\left(\frac{\epsilon''}{\epsilon'}\right)^2}-1\right)}} \tag{5}$$

The penetration depth is inversely proportional to the frequency of the microwaves. As a result, the penetration depth of microwaves in foods at 5.8 GHz is shorter than that at 2.45 GHz. The shorter penetration depth at 5.8 GHz is expected to cause power dissipation to be concentrated near the crust of fried foods (Zhou et al. 2022), which can help impede oil penetration in food by increasing the pore pressure. Therefore, we hypothesize that using 5.8 GHz microwaves for MF applications can help produce lower oil content fried foods.

The advantage of using 5.8 GHz microwaves has also been shown for post-frying applications. Zhou et al. (2022) showed that 1 min of post-frying microwave heating at 5.85 and 2.45 GHz reduced the oil content of French fries by 23% and 18%, respectively, compared to the samples held at room temperature. This further established the benefits of using 5.8 GHz microwaves. However, studying the effect of post-frying microwave heat treatment was not an objective for this study.

The previous works on MF in the food literature were focused on studying the variations in moisture content, oil content, temperature, and color during frying. Oil penetration during frying is affected by the changes in the food's internal pressure. The direct measurement of the internal pressure and sample volume during frying should provide critical insight into comparing the transport mechanisms involved in MF and CF. Zhou et al. (2022) conducted MF experiments at two frequencies (2.45 and 5.85 GHz) but did not measure the internal pressure and sample volume during frying. Parikh and Takhar (2016) measured the internal pressure during MF but conducted experiments only at 2.45 GHz frequency and did not measure the sample volume.

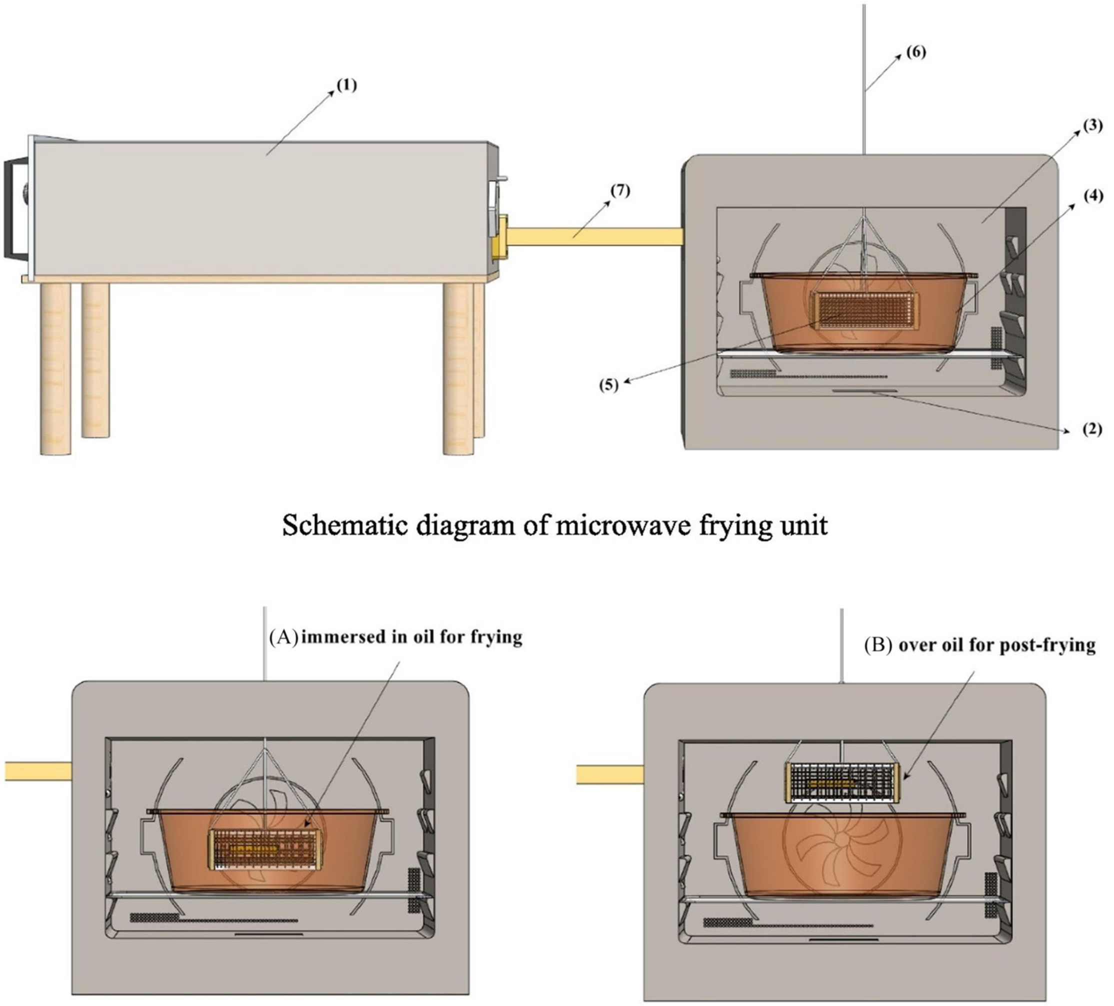

FIGURE 2 | Schematic diagram of the microwave fryer prototype ((1)–(7): 5.8 GHz solid-state [SS] generator, 2.45 GHz magnetron and its entry port [86.36 mm × 43.18 mm], oven cavity, oil container [250 mm × 250 mm × 100 mm], sample holder, rope for lifting/lowering the sample holder, and rectangular waveguide [40.38 mm × 20.2 mm]), and the sample holder locations during and after frying. *Source*: Figure adapted from Zhou et al. (2022) with permission from Elsevier. A) Positive gauge pore pressure; B) Negative gauge pore pressure.

The objectives for this study were to (1) conduct frying experiments using a special prototype fabricated to operate at two microwave frequencies (2.45 and 5.8 GHz) and record the real-time internal temperature and pressure of foods, (2) measure the quality characteristics of the fried samples (moisture content, oil content, volume, and texture), and (3) gain insights about the multiphase transport phenomena involved in MF. Comparing the sensory attributes of foods fried using CF and MF was not a focus for this study but can be a future study by itself.

2 | Materials and Methods

2.1 | Microwave Fryer Prototype

The microwave fryer prototype of Zhou et al. (2022) was used for conducting the frying experiments (Figure 2). A domestic microwave oven (Panasonic, Newark, New Jersey, USA, model no. NN-CF876S) was modified to include a source for 5.8 GHz microwaves. A gallium nitride (GaN)-based solid-state (SS) generator (RFHIC Co., Gwacheon, South Korea, model no. RIU58800-20) was used for producing microwaves at 5.8 GHz frequency. A rectangular waveguide (WR-159) was installed on the left wall of the microwave oven, based on electric field simulation results (data not shown), to guide the microwaves from the SS generator into the oven cavity (Figure 2). The manufacturer-installed magnetron for generating 2.45 GHz frequency microwaves is present near the bottom of the cavity (Zhou et al. 2022).

A ceramic container filled with 3 L of soybean oil (Great Value, Walmart, Bentonville, Arkansas, USA) was used as an oil bath for frying French fries. A special nylon-based sample holder was fabricated to immerse the samples in the oil during frying and hold the samples above the oil container after frying (Zhou et al. 2022). The relative dielectric constant and loss factor for nylon at 2.45 GHz are 2.4 and 0.02, respectively (Buffler 1993). Nylon is not expected to cause any significant disturbance to the electromagnetic waves due to its low dielectric loss factor. A rope made from fiber optic material was used to lift/lower the sample holder. Fiber optic material, like nylon, is not expected to cause much impact on the electric field distribution in the cavity (Kalinke et al. 2022). The oil container was kept stationary during frying by removing the turntable prior to the experiments. A difference between the setup shown in Figure 2 and the setup used in our study was that the oil container was placed directly on the bottom face of the cavity instead of placing it on an elevated glass plate.

2.2 | Preheating of Oil

The frying oil was preheated to 180°C using 2.45 GHz microwaves at an operating power of 1000 W, and the oil temperature was measured using fiber optic temperature sensors (FISO Technologies Inc., Quebec, Canada). It took 30–40 min to heat the oil to 180°C. Heating oil to the frying temperature is expected to take less time using 2.45 GHz microwaves than 5.8 GHz microwaves due to the greater penetration depth in oil for the former.

Zhou, Gezahegn, et al. (2023) studied the microwave heating capabilities of vegetable oils and found the heating rate of oils to be higher than that of water. The microwave power dissipation density (Q_{mh}) is given by (Stratton 2007)

$$Q_{\mathrm{mh}} = \frac{1}{2}\omega\epsilon_0\epsilon''|E|^2 \tag{6}$$

where ω, ϵ_0, and E stand for angular frequency, the permittivity of vacuum, and electric field, respectively. The relative dielectric loss factor of vegetable oils (ϵ'') is approximately 1/100th that of tap water, but the electric field inside oil was about 10 times stronger than water (Zhou, Gezahegn, et al. 2023). As microwave power dissipation is directly proportional to the loss factor and the square of the magnitude of the electric field, the power dissipation in oil and water was similar (Zhou, Gezahegn, et al. 2023). For similar power dissipation densities, the heating rate for vegetable oil was higher than water because of its lower specific heat capacity, which is approximately half that of water.

2.3 | Sample Preparation

The sample preparation and frying procedures used in this study closely resemble those of Zhou et al. (2022). Russet potatoes were bought from a Walmart Supercenter in Pullman, Washington, USA. The potatoes were kept refrigerated (<10°C) prior to experiments, and bruised potatoes were discarded. Potatoes were rinsed with water, and their skin was removed with a peeler. The peeled potatoes were cut into cuboidal strips (9.5 mm × 9.5 mm × 60 mm) using a French fry cutter and immersed in room temperature water until further processing.

Six potato strips were blanched and fried per batch. The cut potato strips were blanched in two stages to reduce the browning of samples (Zhou et al. 2022). In stage one, the strips were immersed in 80°C water for 2 min. In stage two, the strips were immersed in 65°C water for 20 min. The two blanching steps were performed in two separate water baths (Thermo Fisher Scientific Inc., Waltham, Massachusetts, USA, and Laboratory Devices Inc., USA). A two-step blanching procedure comprising high-temperature (for shorter time) and low-temperature (for longer time) treatment steps can lead to foods with better texture and color traits compared to a single high-temperature treatment step (Agblor and Scanlon 1998, 2000; Richter Reis 2017). The blanched samples were laid on paper towels that absorbed the surface water, and the samples were allowed to cool for 3 min before frying.

2.4 | Microwave and CF

Before frying, the blanched samples were placed inside the sample holder, which was held above the oil container using a rope. Three frying methods were used: CF, MF at 2.45 GHz (800 W), and MF at 5.8 GHz (800 W). Experiments were conducted for four frying times, $t = 0$, 1, 3, and 5 min, where $t = 0$ min referred to the blanched samples.

To begin frying, the sample holder was lowered into the heated oil. For MF, the sample holder was immersed in the oil, and microwave power from the 2.45 GHz magnetron or the 5.8 GHz SS generator was turned on. At the end of the desired frying time, the microwave power was turned off, and the sample holder was removed from the oil and placed over the oil container. The French fries were carefully taken out of the sample holder and submerged in liquid nitrogen for 10 s to stop further cooking.

2.5 | Real-Time Temperature and Pressure Measurement

Fiber optic temperature and pressure sensors (FOP-MH-NS-556A, FISO Technologies Inc., Quebec, Canada) recorded the temperature and pressure, respectively, at the geometric center of the sample during frying. Before the experiments, the sensors were introduced into the oven cavity through holes created in the microwave oven's top wall (ceiling). After inserting a sensor into the sample, the sample was gently squeezed near the entrance of the sensor to close the air gap and prevent oil entry. The sensors could pop out of a sample during frying because of the large pressures generated inside the sample. Data from the experiments where the sensor had popped out of the sample were discarded.

2.6 | Moisture and Oil Content Measurement

The moisture content of the fried samples was determined gravimetrically, and the oil content was determined using the Soxhlet extraction method. An electronic balance (OHAUS Corporation, Parsippany, New Jersey, USA, model no. AP110-0) was utilized for weight measurements. For moisture content measurement, the samples were dried in a convection oven (BINDER Inc., Bohemia, New York, USA, model no. ED 56-UL) at 105°C for a minimum of 24 h. The dried samples were allowed to cool in a desiccator before measuring their weight.

For oil content measurement, the dried samples were ground into a fine powder using a coffee grinder to improve the oil extraction efficiency. Whatman filter paper ($\phi = 90$ mm) was used to create pouches to hold the sample during oil extraction. An amount of 0.4–0.8 g of powdered sample was filled into a weighted, dried, empty pouch. The pouch was sealed from the top by folding the

Whatman filter paper, and a paper clip was used to ensure that the pouch remained shut during oil extraction experiments.

Petroleum ether was used for oil extraction, and 12 h of extraction was performed for each sample pouch. After oil extraction, the sample-filled pouches were dried under the fume hood for 12 h, followed by drying in a convection oven for 24 h (Pinto and Takhar 2023). The dried sample pouches were cooled in a desiccator, and their weights were subsequently recorded. The difference in weights of a sample pouch before and after oil extraction is equal to the oil content of the sample in grams. The oil and moisture content values of the samples were calculated on a dry basis (g/g solids).

2.7 | Volume Measurement

The volume of the fried samples was measured using a liquid displacement technique with n-heptane as the solvent. The procedure of Shah and Takhar (2022) was followed. A clear, flat-bottom glass tube was used as the sample holder. A 50 mL burette was utilized to measure the volume of n-heptane needed to fill the glass tube. A Whatman filter paper was used to check if the glass tube was completely filled by placing it over the mouth of the glass tube. A circular wet spot on the filter paper confirms that the glass tube is completely filled (Shah and Takhar 2022). The difference in the volume of n-heptane required to fill an empty glass tube and a sample-loaded glass tube is equal to the sample volume. Measurements were made rapidly to ensure minimal uptake of n-heptane by the samples. The volume change of the fried samples was calculated relative to the volume of the blanched samples.

2.8 | Stress Relaxation Experiments

The objective for conducting French fry texture analysis was to compare the end products of the three frying methods (CF, MF at 2.45 GHz, and MF at 5.8 GHz). In the food industry, the endpoint for frying is typically determined on the basis of the moisture content of the fried samples. Zhou et al. (2022) found that CF for 5 min, MF at 2.45 GHz for 3 min, and MF at 5.8 GHz for 3.5 min led to fried samples with similar moisture contents. Therefore, frying experiments were conducted for the abovementioned conditions, and the fried samples were used for the stress relaxation study.

Potatoes exhibit viscoelastic behavior (Alvarez et al. 1998; Krokida et al. 1998; Pinto and Takhar 2023); that is, they display a mix of fluid- and solid-like traits when they are deformed. For viscoelastic materials, the relationship between stress and strain is time-dependent (Banks et al. 2011). In a stress relaxation study, the test sample is strained to a certain amount, and the stress required to maintain the strain is measured as a function of time (Steffe 1996). Viscoelastic materials relax gradually (Steffe 1996); that is, the stress decays with time. Stress relaxation data are typically presented in terms of a stress relaxation modulus ($G(t)$) (Steffe 1996), which is the ratio of the time-varying stress and the constant strain applied to the material. Stress relaxation experiments were performed using a TA-XT2 texture analyzer (Stable Micro Systems, Surrey, UK). A 2″ diameter cylindrical probe was used for the stress relaxation experiments. A load cell of 25 kg was used, and measurements were performed at room

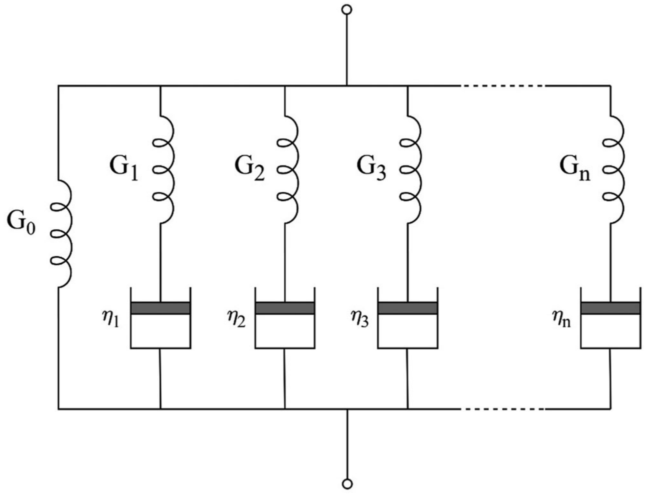

FIGURE 3 | A representation of the generalized Maxwell's model.

temperature. The pretest, test, and posttest speeds were set as 2, 2.8, and 5 mm/s. The trigger force was set as 8 g. A 10 mm section was cut from a fried potato strip along its length. The face dimensions of the separated section were measured using a vernier caliper before placing it on the texture analyzer platform.

The stress and strain are proportional when a material is tested in the linear viscoelastic range (Steffe 1996). Preliminary experiments at different strain levels indicated that a strain of 4% was within the linear range. Therefore, a 4% strain was chosen for conducting the stress relaxation experiments. Each stress relaxation run was conducted for 300 s, and 4–6 runs were performed for samples prepared using each frying method.

Force versus time data were recorded during the stress relaxation experiments. Force was converted to stress by dividing the force by the area of contact, which was calculated using the dimensions of the sample surface in contact with the probe. The stress versus time data were then converted to stress relaxation modulus versus time data by dividing the stress by the strain (4%). The stress relaxation modulus versus time data were smoothed in Python using the Savitzky–Golay filter (savgol_filter) from the SciPy library. This was followed by removing the outlier runs and averaging the stress relaxation modulus data.

Generalized Maxwell's models (depicted in Figure 3) given by (Ferry 1980)

$$G(t) = G_0 + \sum_{i=1}^{n} G_i e^{-\frac{t}{\lambda_i}} \tag{7}$$

with two to five elements were fitted to the stress relaxation modulus data, and the R^2 and RMSE (root mean square error) were calculated to evaluate the fit. In Equation (7), $G(t)$ is the stress relaxation modulus, and G_0 is the elastic modulus of the free spring. G_i, η_i, and λ_i $(= \eta_i / G_i)$ are the spring elastic modulus, dashpot viscosity, and relaxation time for the ith Maxwell element, respectively. The generalized Maxwell's model assumes a linear viscoelastic nature but has the advantage of being simple and robust (Jalocha et al. 2015). On the basis of the fit analysis results (data not shown), the four-element

TABLE 1 | Moisture content, oil content, and relative volume change for different frying methods and frying times (n = 3–6).

Frying method	Frying time (min)	Moisture content (g/g solids)	Oil content (g/g solids)	Relative volume change
CF	0	7.42±0.91[a]	−0.001 ± 0.002[a]	0.000±0.017[a]
MF at 2.45 GHz	0	7.42±0.91[a]	−0.001±0.002[a]	0.000±0.017[a]
MF at 5.8 GHz	0	7.42±0.91[a]	−0.001±0.002[a]	0.000±0.017[a]
CF	1	2.75±0.33[bc]	0.050±0.005[b]	−0.257±0.039[bc]
MF at 2.45 GHz	1	3.05±0.30[b]	0.058±0.006[bc]	−0.304±0.028[cd]
MF at 5.8 GHz	1	2.82±0.31[bc]	0.054±0.004[b]	−0.236±0.018[b]
CF	3	1.91±0.22[cd]	0.068±0.002[c]	−0.330±0.024[de]
MF at 2.45 GHz	3	1.01±0.09[de]	0.060±0.003[bc]	−0.379±0.012[e]
MF at 5.8 GHz	3	1.41±0.33[de]	0.067±0.004[c]	−0.325±0.033[de]
CF	5	1.83±0.24[cd]	0.085±0.007[d]	−0.319±0.065
MF at 2.45 GHz	5	0.71±0.23[e]	0.125±0.007[e]	No data
MF at 5.8 GHz	5	0.67±0.14[e]	0.096±0.003[d]	No data

Note: Different letters in a column indicate a significant difference between means ($p \leq 0.05$).

generalized Maxwell's model, that is, a free spring in parallel with three spring-dashpots (Figure 3), was found to be optimum for representing the material.

2.9 | Data Analysis

Separate frying trials were conducted to measure temperature, pressure, moisture and oil content, and sample volume. The temperature and pressure profiles were recorded at the sample center, and only one sensor was inserted into a sample at a time. The average of temperature and pressure profiles for n = 3–4 samples was calculated. For moisture and oil content measurement, frying was performed once for each frying method-frying time combination (Table 1). The moisture content results are an average of n = 6 samples fried in a batch. The oil content results are an average of n = 3 samples. Another set of frying trials was conducted to measure the volume of fried samples for each frying method-frying time combination. The volume change results are an average of n = 3–4 samples fried in a batch.

Data analysis was performed using the Python programming language, Microsoft Excel, and OriginPro (v. 2024b, OriginLab Corporation, Northampton, Massachusetts, USA). The standard deviations in the data were calculated to construct error bars. A two-way analysis of variance (ANOVA) was performed using OriginPro software to evaluate the effect of the frying method and frying time on the moisture content, oil content, and volume changes of fried samples. The results of the two-way ANOVA analysis are included in Table A1. Post hoc Tukey tests were performed for means comparison.

3 | Results and Discussion

3.1 | Temperature

Figure 4 shows the temperature profiles at the sample center and of the bulk oil during CF, MF at 2.45 GHz, and MF at 5.8 GHz. For all three frying methods, the sample temperature rose rapidly and plateaued around 100°C within 100 s of frying. The temperature rise was the fastest for MF at 2.45 GHz, followed by MF at 5.8 GHz, and lastly, CF. The peak temperatures attained during frying for MF at 2.45 GHz, MF at 5.8 GHz, and CF were 107.3°C, 104.1°C, and 100.5°C, respectively. Faster heating of samples is expected during MF because of the additional heat source (microwaves). Microwave heating is volumetric and is independent of the temperature gradient, unlike convection heating. The faster heating of the samples during MF can be advantageous in reducing the processing times for the food industry. This will be discussed further in the text.

The differences in the temperature profiles for MF at 2.45 and 5.8 GHz (Figure 4) are likely because of two factors: (1) the frequency-dependence of penetration depth and (2) the location of the waveguides. The penetration depth of electromagnetic waves is inversely proportional to the wave frequency (Equation 5). Therefore, the penetration depth of 5.8 GHz microwaves in the bulk oil and French fries is expected to be shorter than that of 2.45 GHz microwaves.

For vegetable oil at 2.45 GHz microwave frequency, $\epsilon' = 2.6$ and $\epsilon'' = 0.14$ (Zhou et al. 2024). Dielectric properties of vegetable oil are not expected to be sensitive to relatively small frequency changes (e.g., between 2.45 and 5.8 GHz), primarily due to the long carbon chains in the molecular structure of vegetable oils. Assuming the dielectric properties of oil to be equal at both frequencies, the penetration depth in vegetable oil at 2.45 GHz is 224.5 mm, and at 5.8 GHz is 94.8 mm. Three liter of oil fills the oil container to a height of approximately 48 mm. As the penetration depth in oil at both frequencies is longer than 48 mm, we can expect the electric field not to be completely attenuated at either frequency. However, there might be more attenuation of 5.8 GHz microwaves in the oil before reaching the French fries than 2.45 GHz microwaves.

The following dielectric properties of potatoes (moisture content of 5.02 g/g solids) were estimated using the data of Luo et al. (2019)

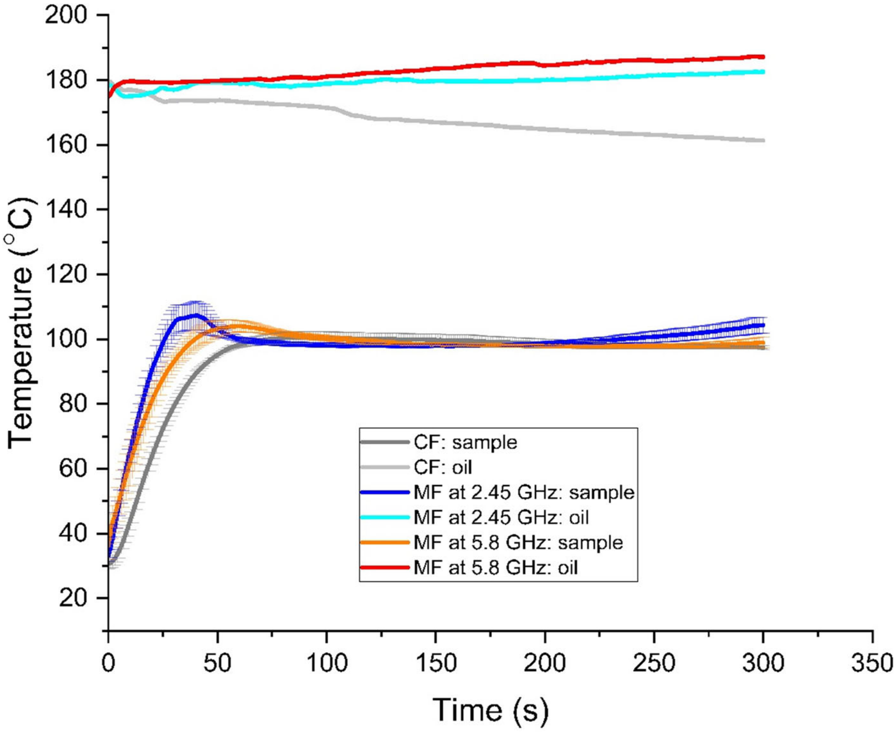

FIGURE 4 | The temperature profiles at the geometric center of the samples and of the oil during conventional frying (CF) and microwave frying (MF) (n = 3–4).

and Nelson et al. (1994): $\epsilon' = 60.4$ and $\epsilon'' = 16.2$ at 2.45 GHz, and $\epsilon' = 47.6$ and $\epsilon'' = 15.1$ at 5.8 GHz. A detailed explanation about the estimation of the dielectric properties can be found in Shah and Takhar (In review). Using Equation (5), the penetration depths in the French fries at 2.45 and 5.8 GHz are 9.4 and 3.8 mm, respectively. The 2.45 GHz microwaves likely penetrated deeper into the French fries (dimensions: 9.5 mm × 9.5 mm × 60 mm) than 5.8 GHz microwaves. The lower attenuation of 2.45 GHz microwaves in the oil and their deeper penetration in the French fries can explain the faster heating of samples during MF at 2.45 GHz than 5.8 GHz.

The second factor that can explain the differences between the temperature profiles for MF at 2.45 and 5.8 GHz is the proximity of the waveguides to the oil container (Figure 2). The waveguide connecting the 5.8 GHz SS generator and the cavity was installed on the left wall of the oven, approximately at two-thirds of the cavity height from the bottom. The entry port for the manufacturer-installed 2.45 GHz magnetron lies on the bottom face of the cavity. As the oil container was placed on the bottom face of the cavity, it is much closer to the source of 2.45 GHz microwaves than of 5.8 GHz microwaves. This can cause the electric field in the oil to be stronger for MF at 2.45 GHz than at 5.8 GHz.

We also conducted microwave heating experiments with samples immersed in oil initially at room temperature ($T \approx 18°$C). The measured temperature profiles at the center of the samples and of the oil are shown in Figure 5. Microwave heating at 2.45 GHz caused rapid heating of the samples, with the temperature at the sample center increasing beyond 100°C within 75 s, whereas the oil temperature remained close to the room temperature. The temperature profile for microwave heating at 2.45 GHz peaked at $T = 110.8°$C and then plateaued around $T = 98°$C.

Microwave heating at 5.8 GHz also led to the heating of the samples, albeit at a slower rate compared to 2.45 GHz (Figure 5). These observations confirmed that during MF, (1) French fries are heated not only by convection due to the hot oil but also volumetrically by microwaves, that is, microwaves are not completely attenuated while traveling through the bulk oil and are able to penetrate the samples, and (2) there are differences in the heating rates at 2.45 and 5.8 GHz, likely due to differences in penetration depth of microwaves in oil and French fries at the two frequencies.

3.2 | Pressure

The gauge pressure profiles at the geometric center of the samples were recorded during CF and MF (Figure 6). The initial pressure in the samples before frying varied slightly from sample to sample. For all samples, the measured pressure profiles were shifted to start from 0 kPa, which enabled the comparison between different pressure profiles.

Like temperature, the pressure at the center rose rapidly for all three frying methods. The peak gauge pressure for MF at 2.45 GHz was the highest (24.9 kPa), followed by MF at 5.8 GHz (20.8 kPa) and CF (13.8 kPa). The higher pressures generated during MF are expected to provide a stronger resistance to oil penetration.

The gauge pressure at the sample center became negative within a frying time of 75 s for all three frying methods and stayed negative for the remaining frying duration (Figure 6). The large

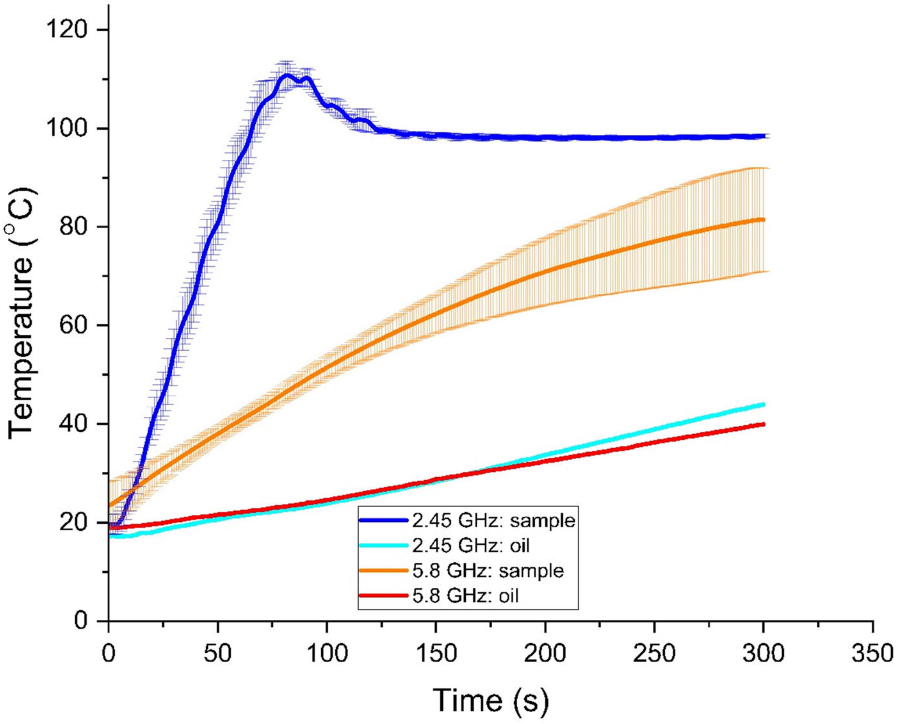

FIGURE 5 | The temperature profiles at the geometric center of the samples and of the oil during microwave heating at 2.45 and 5.8 GHz (both at 800 W) when the samples were immersed in 18°C oil ($n = 3$–4).

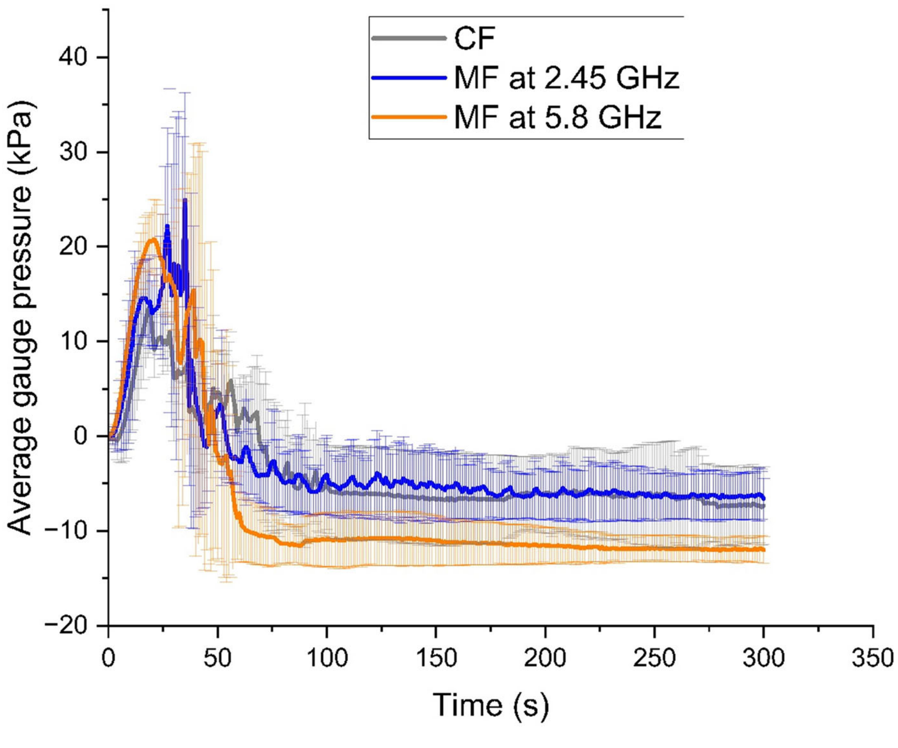

FIGURE 6 | The gauge pressure profiles at the geometric center of the samples during conventional frying (CF) and microwave frying (MF) ($n = 3$).

pressure magnitudes during frying are expected to cause outward movement of water from the core of the sample. As the moisture content in the sample core decreases, the capillary pressure is expected to increase above the gas pressure, which will make the water pressure negative ($p^w = p^g - p^{cw}$). As a result, the gauge pore pressure (the effective pressure experienced by the pore walls) is expected to decrease and become negative for longer frying times. Negative gauge pore pressure is expected to cause a "suction" potential to develop in the porous matrix and facilitate oil penetration into the food.

Interestingly, the pressure stayed positive the longest for CF (68 s), followed by MF at 2.45 GHz (53 s) and 5.8 GHz (48 s) (Figure 6). In the case of CF, the direction of heating is from the food surface to the core, whereas microwaves heat food internally. The higher temperatures and pressures generated in the sample core during MF are expected to cause faster water loss from the sample core than CF. This could explain why the gauge pressure became negative sooner in the case of MF. From these observations, we can conclude that although MF is effective in increasing the pressure generated in foods, the duration of positive gauge pressures may depend on the drying rate.

The food matrix developed a suction potential (due to negative gauge pressure) in a shorter frying time during MF than CF, which may lead to an increase in the sample oil content. However, the endpoint for frying is determined on the basis of the moisture content of the food instead of the frying time. So, the sample oil content for the same endpoint moisture content should be compared. This is discussed in more detail in Section 3.3.

Although the current work used a continuous application of microwaves during frying, future works could study the effect of turning on microwaves when the pressure in the core starts decreasing. Modeling the unsaturated (presence of gas and liquid phases in pores) transport during MF, for example, by utilizing the hybrid mixture theory (HMT)-based equations of Takhar (2014), can generate deeper insights into the mechanisms involved in MF (Shah and Takhar In review).

3.3 | Moisture Content and Oil Content

The changes in moisture content of the French fry samples during CF and MF are presented in Figure 7. The moisture content decreased rapidly in the first minute of frying for all three frying methods. This is expected because of the fast evaporation and loss of the surface water, referred to as surface or superficial boiling in the frying literature (Farkas et al. 1996; Vitrac et al. 2000). The vapor bubbles escaping the food surface cause oil movement and enhance the rate of convective heat transfer. The external heat flux controls the drying rate in the initial frying stages (Vitrac et al. 2000).

For the remaining frying duration (t = 1–5 min), the moisture loss continued, albeit at a slower rate. The formation and thickening of the crust layer during frying is expected to reduce the heat transfer owing to the low thermal conductivity of the crust (Farkas et al. 1996) and also decrease the moisture loss rate. The differences between the moisture contents of samples fried using the three frying methods were not statistically significant for 1 and 3 min of frying (Table 1). After 5 min of frying, there were statistically significant differences between the moisture contents of samples fried using CF and MF, with the latter leading to higher moisture loss (Figure 7). The difference between the moisture contents of samples fried for 5 min at 2.45 and 5.8 GHz microwave frequencies was not statistically significant.

MF caused faster moisture removal from the samples than CF because of the additional volumetric heat source (microwaves). MF is expected to generate larger pressure gradients in the core of the sample (Figure 6), which drives out moisture from the core faster than in the case of CF. Therefore, as the moisture content profile for CF plateaued (Figure 7), there was further moisture loss during MF. This result implies that the endpoint for frying (determined based on moisture content) can be reached faster with MF than with CF. For example, Zhou et al. (2022) found that it took 5, 3, and 3.5 min to reach similar endpoint moisture contents for CF, MF at 2.45 GHz, and MF at 5.8 GHz, respectively. Therefore, MF can enable the food industry to make substantial time savings during frying operations.

The oil content profiles for the three frying methods (Figure 8) showed a general increasing trend of oil content with decreasing moisture content. This agrees with previous frying studies in the food literature (Pinto and Takhar 2023; Zhou et al. 2022; Ziaiifar et al. 2010). The oil content versus moisture content trends for the three frying methods appeared to be similar till a moisture content of about 3 g/g solids. The oil content increased rapidly in the first minute of frying for all three frying methods (Table 1). This is expected because of the loss of surface water, which leaves behind empty spaces (pores) for the oil phase to occupy. Additionally, the surface of the raw potato samples is not perfectly smooth and may have cracks/abrasions that allow the oil to seep in during frying. During the nascent stages of frying, the food's internal pressure is low (Figure 6), and there is not much resistance to oil penetration.

Differences between the oil contents for the three frying methods started to emerge when the moisture content became lower than 3 g/g solids. The oil content of samples fried at 2.45 GHz microwave frequency changed negligibly when the moisture content reduced from 3 to 1 g/g solids. This is expected due to the high magnitude of pressure in the food matrix during MF at 2.45 GHz, which can help impede oil penetration. On the other hand, the oil content increased rapidly as a function of moisture content for CF and relatively slowly for MF at 5.8 GHz (Figure 8). This indicated the potential of MF to produce French fries with lower oil content at lower endpoint moisture content.

Mesias et al. (2019) measured the moisture content of French fries collected from thirty food service establishments and found that the moisture content ranged from 0.29 to 0.66 g/g total, with a mean of 0.46 g/g total. A sample fried at 2.45 GHz microwave frequency with a dry basis moisture content of approximately 1 g/g solids and oil content of 0.06 g/g solids (Figure 8) would have a moisture content of 0.48 g/g total. This is within the range of moisture contents observed for commercial French fry samples by Mesias et al. (2019). On the basis of the oil content trends in Figure 8, for the same endpoint moisture content of 1 g/g solids, CF is expected to result in samples with a significantly higher oil content than MF. The oil content of samples fried at 5.8 GHz microwave frequency is expected to be higher than those fried at 2.45 GHz frequency, for an endpoint moisture content of 1 g/g solids (Figure 8). However, below a moisture content of 1 g/g solids, the oil content increased rapidly as a function of moisture content for MF at 2.45 GHz. Therefore, if even lower moisture content French fries are desired for increased crispiness, MF at 5.8 GHz may produce French fries containing less oil.

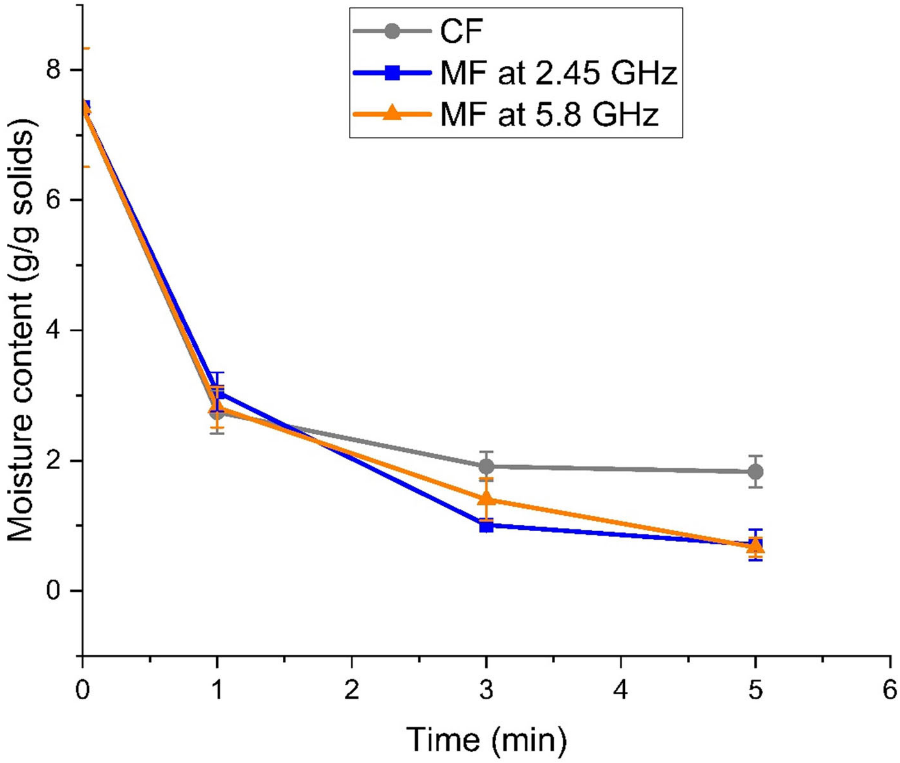

FIGURE 7 | The moisture content of samples fried using conventional frying (CF) and microwave frying (MF) ($n = 6$).

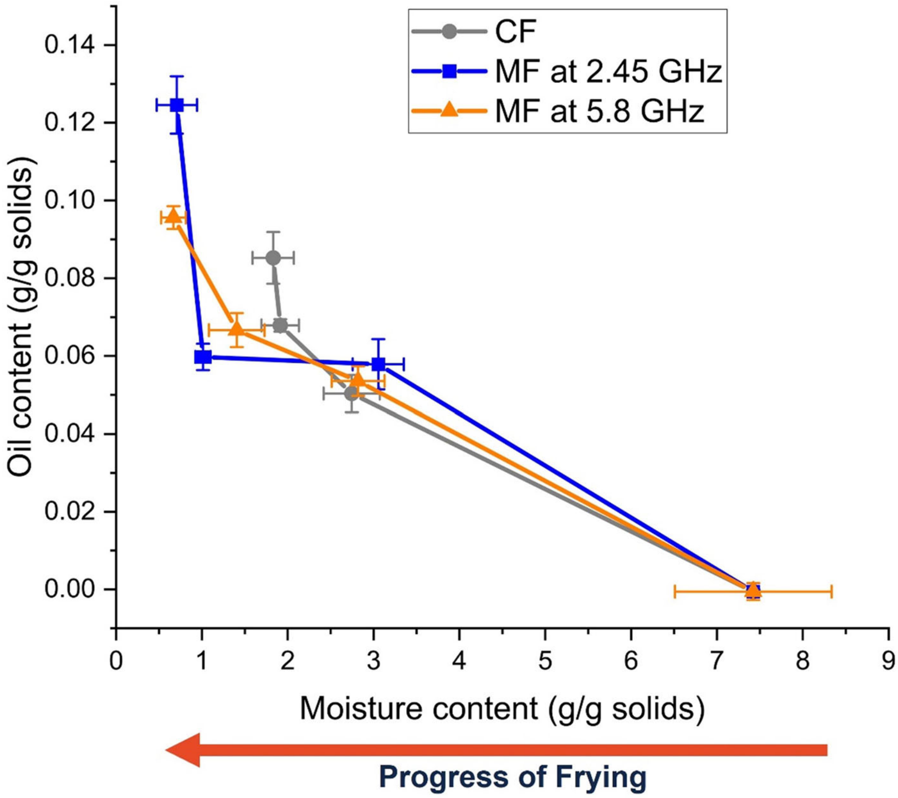

FIGURE 8 | The oil content of samples fried using conventional frying (CF) and microwave frying (MF) plotted against their moisture content ($n = 3$–6).

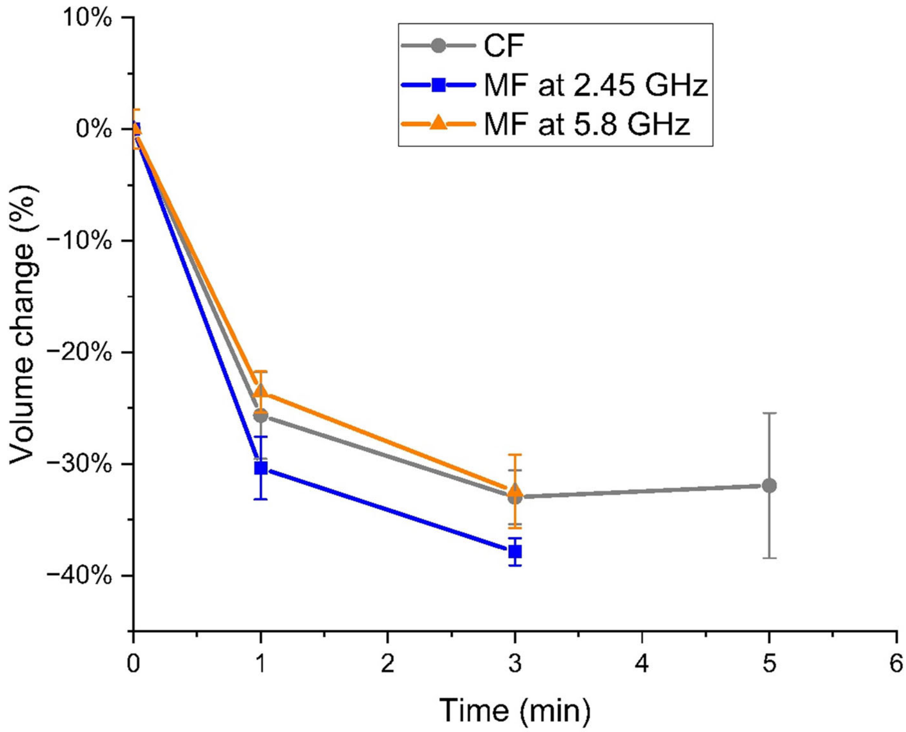

FIGURE 9 | Sample volume changes with frying time for conventional frying (CF) and microwave frying (MF) (n = 3–4).

Although the observations from our study indicate that MF can produce French fries containing less oil than CF, further work is needed to strengthen our conclusions. Process optimization studies are also needed to find the optimum set of processing parameters (e.g., microwave power and on-off times) for MF. Purely experimental approaches might be tedious. Physics-based models like the one mentioned in Section 3.2 can help increase the effectiveness of MF in reducing the oil content of fried foods.

3.4 | Volume Change

The sample volume changes for the three frying methods are shown in Figure 9. A negative volume change implied sample shrinkage during frying. This is in agreement with previous frying studies in the food literature (Shah and Takhar 2022; Ziaiifar et al. 2010). The samples shrank rapidly during the first minute for all three frying methods.

For t = 1 min, the sample volume changes for MF at 2.45 and 5.8 GHz were significantly different (Table 1). However, the sample volume change for CF was not significantly different from that of either MF method. After 3 min of frying, though the sample volume change for MF at 2.45 GHz was higher than CF and MF at 5.8 GHz, the differences were not statistically significant for the three frying methods (Table 1).

After 5 min of frying, there was only a slight change in the sample volume for CF (Figure 9). In comparison, samples fried for 5 min at 2.45 and 5.8 GHz microwave frequencies floated in n-heptane. As a result, their volumes could not be measured. The density of n-heptane at 25°C is 679.5 kg/m^3 (Haynes 2014). Thus, the density of the microwave-fried samples became lower than 679.5 kg/m^3. The density of the microwave-fried samples was expected to be lower than that of the conventionally fried samples because of the significantly higher moisture loss during MF (Figure 7).

During frying, foods undergo deformation driven by phenomena like moisture loss and gas expansion. Shah and Takhar (2024) predicted the deformation of potato cylinders during CF by utilizing pore pressure as the driving force governing deformation. Similarly, pore pressure was utilized to predict the expansion of a starch matrix undergoing extrusion in the work of Ditudompo and Takhar (2015). Therefore, pressure changes in a food matrix during frying are expected to impact the oil content as well as the deformation of the fried food.

3.5 | Stress Relaxation

The stress relaxation modulus profiles of conventionally and microwave-fried samples, obtained after smoothing, removing outliers, and averaging, are shown in Figure 10. The fitted parameters for the four-element generalized Maxwell's model for the three frying methods are given in Table 2. The spring elastic moduli (G_0, G_1, G_2, and G_3) for MF at 5.8 GHz were the highest, followed by CF and MF at 2.45 GHz. This indicated that in comparison to CF, MF at 5.8 GHz produced stiffer French fries, and MF at 2.45 GHz produced softer French fries. We hypothesize that the shorter penetration depth of 5.8 GHz microwaves in French fries caused heating to be focused near the crust (Zhou et al. 2022). This could lead to increased stiffness due to the faster drying of the crust.

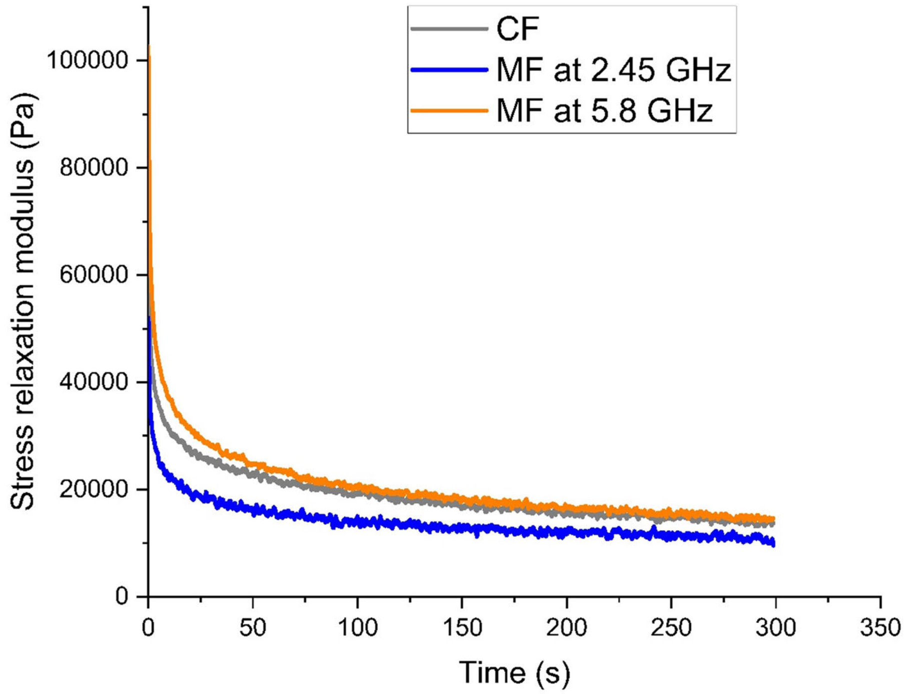

FIGURE 10 | The average stress relaxation modulus profiles of samples fried using conventional frying (CF) and microwave frying (MF) (n = 3–5).

TABLE 2 | The four-element generalized Maxwell's model parameters for samples fried using conventional frying (CF) and microwave frying (MF).

Sample	G_0 (Pa)	G_1 (Pa)	G_2 (Pa)	G_3 (Pa)	λ_1 (s)	λ_2 (s)	λ_3 (s)	R^2	RMSE (Pa)
CF	12,805.02	15,071.85	14,517.31	29,200.43	118.66	9.26	0.76	0.99	344.83
MF at 2.45 GHz	10,380.30	8841.97	10,534.44	21,851.19	114.63	10.95	0.91	0.99	437.99
MF at 5.8 GHz	13,853.85	17,396.26	22,274.24	49,607.00	105.69	9.60	0.77	0.99	372.53

Abbreviation: RMSE, root mean square error.

Conversely, for MF at 2.45 GHz, power dissipation is expected to be distributed across the French fry due to the longer penetration depth of 2.45 GHz microwaves. X-ray micro-computed tomography images of Parikh and Takhar (2016) showed that MF at 2.45 GHz led to a less compact crust than CF. This was likely due to more uniform moisture removal during MF at 2.45 GHz than CF (Parikh and Takhar 2016). Therefore, we can expect the stiffness of French fries to be lower for MF at 2.45 GHz than for CF. Textural characteristics of fried foods are crucial for consumer acceptability. The data from the stress relaxation experiments indicated that MF at 5.8 GHz can produce stiffer (crunchier) French fries due to the intense heating of the crust.

Although using 5.8 GHz microwaves for frying is advantageous, there may be some challenges in their application at the industrial scale. The SS generator for 5.8 GHz microwaves is costlier than the magnetron for 2.45 GHz microwaves, and the SS generator may not be as abundantly available. Further research is needed to determine the feasibility of using 5.8 GHz microwaves in the food industry.

The relaxation times (λ_1, λ_2, and λ_3) for the three frying methods were found to be similar, and no clear trend was observed (Table 2). Reiner (1964) introduced a nondimensional number called the Deborah number (De), which is the ratio of the relaxation and observation times. As Steffe (1996) explained, the Deborah number can be utilized to estimate the extent of the viscoelastic nature of a material. Materials with $De \gg 1$ tend to exhibit elastic behavior, and materials with $De \ll 1$ show viscous behavior (Steffe 1996). Viscoelastic materials tend to have De of the order of 1. The average De values for the second, third, and fourth Maxwell elements were 0.377, 0.033, and 0.003. Therefore, the second Maxwell element demonstrated the viscoelastic behavior of French fries, whereas the third and fourth elements displayed viscous behavior (Ozturk and Takhar 2017).

The Maxwell's model parameters determined in this study can be utilized in mechanistic models to predict the deformation of French fries during frying. For example, Ditudompo and Takhar (2015) modeled the deformation of a starch extrudate by using the generalized Maxwell's model. Maxwell's model parameters were provided as inputs to solve the deformation equations.

4 | Conclusions

MF at two frequencies, 2.45 and 5.8 GHz (both at 800 W), was tested as an alternative to CF. Results showed that MF at both frequencies led to a faster increase in temperature inside French fry samples. MF at 2.45 GHz led to the highest peak temperature (107.3°C) during frying, followed by MF at 5.8 GHz (104.1°C) and CF (100.5°C). Microwaves enabled the faster heating of the French fry samples due to volumetric heating. The faster heating of the samples during MF at 2.45 GHz than 5.8 GHz could be because of the longer penetration depths in oil and French fries at 2.45 GHz than at 5.8 GHz, and the closer proximity of the oil container to the 2.45 GHz source than the 5.8 GHz source. The temperature profiles recorded during the microwave heating of samples immersed in room temperature oil confirmed that the electric field was not completely attenuated while traveling through the bulk oil phase and could penetrate the samples. MF led to higher pressures in the samples compared to CF. Higher positive gauge pressures are expected to help the porous matrix resist oil penetration more strongly. Therefore, MF can potentially increase the resistance of food to oil penetration.

MF led to faster moisture loss from the samples, which can reduce frying times and help the food industry make substantial time savings. The oil content versus moisture trends showed that below a moisture content of 3 g/g solids, the oil content increased rapidly with decreasing moisture content for CF, relatively slowly for MF at 5.8 GHz, and negligibly for MF at 2.45 GHz. This indicated that MF can produce French fries with lower oil content, and thus lower calorie density, than CF. Below a moisture content of 1 g/g solids, there was a rapid increase in oil content as a function of moisture content for MF at 2.45 GHz. Therefore, MF at 5.8 GHz can be used when French fries with a lower moisture and oil content are desired. The stress relaxation data of French fries showed that MF at 5.8 GHz can produce stiffer (crunchier) fries, which are liked by consumers. This is expected due to the shorter penetration depth of 5.8 GHz microwaves in foods than 2.45 GHz microwaves, which can lead to crust-focused heating. However, a sensory study is needed to validate the differences in texture between samples fried using CF and MF. The parameters for the four-element generalized Maxwell's model, determined based on the stress relaxation data, can be utilized in physics-based models to predict the deformation of French fries during frying. The high cost of SS generators for 5.8 GHz microwaves can be a barrier to their application in the food industry, and SS generators may be less readily available than magnetrons for 2.45 GHz microwaves. Further studies are needed to optimize the processing parameters in MF, such as microwave power and on-off time. The insights generated from this study can help design new experimental studies and guide the physics-based modeling of MF.

Author Contributions

Yash Shah: investigation, writing–original draft, methodology, validation, writing–review and editing, software, data curation, formal analysis, visualization. **Xu Zhou**: investigation, methodology, validation, writing–review and editing. **Juming Tang**: methodology, supervision, writing–review and editing, funding acquisition, resources, project administration. **Pawan Singh Takhar**: conceptualization, investigation, funding acquisition, methodology, writing–review and editing, project administration, supervision, resources.

Acknowledgments

The authors thank Brian Nyquist, Huimin Lin, Stewart Bohnet, and Zhongwei Tang at Washington State University for their help in conducting the experiments.

Conflicts of Interest

The authors declare no conflicts of interest.

References

Agblor, A., and M. G. Scanlon. 1998. "Effects of Blanching Conditions on the Mechanical Properties of French Fry Strips." *American Journal of Potato Research* 75, no. 6: 245–255. https://doi.org/10.1007/BF02853603.

Agblor, A., and M. G. Scanlon. 2000. "Processing Conditions Influencing the Physical Properties of French Fried Potatoes." *Potato Research* 43, no. 2: 163–177. https://doi.org/10.1007/BF02357957.

Alvarez, M. D., W. Canet, F. Cuesta, and M. Lamua. 1998. "Viscoelastic Characterization of Solid Foods From Creep Compliance Data: Application to Potato Tissues." *Zeitschrift Für Lebensmitteluntersuchung Und -Forschung A* 207, no. 5: 356–362. https://doi.org/10.1007/s002170050345.

Aydınkaptan, E., and I. Barutçu Mazı. 2017. "Monitoring the Physicochemical Features of Sunflower Oil and French Fries During Repeated Microwave Frying and Deep-Fat Frying." *Grasas y Aceites* 68, no. 3: 202. https://doi.org/10.3989/gya.1162162.

Anonymoys. 2023. "North America French Fries Market by Product and End-User—Forecast and Analysis (2023-2027)." A Market Research Report by Technavio. Retrieved from https://www.technavio.com.

Banks, H. T., S. Hu, and Z. R. Kenz. 2011. "A Brief Review of Elasticity and Viscoelasticity for Solids." *Advances in Applied Mathematics and Mechanics* 3, no. 1: 1–51. https://doi.org/10.4208/aamm.10-m1030.

Barutcu, I., S. Sahin, and G. Sumnu. 2009. "Acrylamide Formation in Different Batter Formulations During Microwave Frying." *LWT—Food Science and Technology* 42, no. 1: 17–22. https://doi.org/10.1016/j.lwt.2008.07.004.

Bou, R., J. A. Navas, A. Tres, R. Codony, and F. Guardiola. 2012. "Quality Assessment of Frying Fats and Fried Snacks During Continuous Deep-Fat Frying at Different Large-Scale Producers." *Food Control* 27, no. 1: 254–267. https://doi.org/10.1016/j.foodcont.2012.03.026.

Bray, G. A., K. K. Kim, J. P. H. Wilding, and World Obesity Federation. 2017. "Obesity: A Chronic Relapsing Progressive Disease Process. A Position Statement of the World Obesity Federation." *Obesity Reviews* 18, no. 7: 715–723. https://doi.org/10.1111/obr.12551.

Buffler, C. R. 1993. *Microwave Cooking and Processing: Engineering Fundamentals for the Food Scientist*. Van Nostrand Reinhold.

Chen, S.-D., H.-H. Chen, Y.-C. Chao, and R.-S. Lin. 2009. "Effect of Batter Formula on Qualities of Deep-Fat and Microwave Fried Fish Nuggets." *Journal of Food Engineering* 95, no. 2: 359–364. https://doi.org/10.1016/j.jfoodeng.2009.05.016.

Dangal, A., R. Tahergorabi, D. R. Acharya, et al. 2024. "Review on Deep-Fat Fried Foods: Physical and Chemical Attributes, and Consequences of High Consumption." *European Food Research and Technology* 250: 1537–1550. https://doi.org/10.1007/s00217-024-04482-3.

Dash, K. K., M. Sharma, and A. Tiwari. 2022. "Heat and Mass Transfer Modeling and Quality Changes During Deep Fat Frying: A Comprehensive Review." *Journal of Food Process Engineering* 45, no. 4: e13999. https://doi.org/10.1111/jfpe.13999.

Ditudompo, S., and P. S. Takhar. 2015. "Hybrid Mixture Theory Based Modeling of Transport Mechanisms and Expansion-Thermomechanics of Starch During Extrusion." *AIChE Journal* 61, no. 12: 4517–4532. https://doi.org/10.1002/aic.14936.

Ehlers, W., and J. Bluhm. 2002. *Porous Media: Theory, Experiments and Numerical Applications*. Springer. https://doi.org/10.1007/978-3-662-04999-0.

Farkas, B. E., R. P. Singh, and T. R. Rumsey. 1996. "Modeling Heat and Mass Transfer in Immersion Frying. I, Model Development." *Journal of Food Engineering* 29, no. 2: 211–226. https://doi.org/10.1016/0260-8774(95)00072-0.

Ferry, J. D. 1980. *Viscoelastic Properties of Polymers*. 3rd ed. John Wiley & Sons.

Gharachorloo, M., M. Ghavami, M. Mahdiani, and R. Azizinezhad. 2010. "The Effects of Microwave Frying on Physicochemical Properties of Frying and Sunflower Oils." *Journal of the American Oil Chemists' Society* 87, no. 4: 355–360. https://doi.org/10.1007/s11746-009-1508-y.

Guzik, P., P. Kulawik, M. Zając, and W. Migdał. 2022. "Microwave Applications in the Food Industry: An Overview of Recent Developments." *Critical Reviews in Food Science and Nutrition* 62, no. 29: 7989–8008. https://doi.org/10.1080/10408398.2021.1922871.

Haynes, W. M., ed. 2014. *CRC Handbook of Chemistry and Physics: A Ready-Reference Book of Chemical and Physical Data*. 95th ed. CRC Press.

Jalocha, D., A. Constantinescu, and R. Neviere. 2015. "Revisiting the Identification of Generalized Maxwell Models From Experimental Results." *International Journal of Solids and Structures* 67–68: 169–181. https://doi.org/10.1016/j.ijsolstr.2015.04.018.

Kalinke, I., P. Kubbutat, S. Taghian Dinani, S. Ambros, M. Ozcelik, and U. Kulozik. 2022. "Critical Assessment of Methods for Measurement of Temperature Profiles and Heat Load History in Microwave Heating Processes—A Review." *Comprehensive Reviews in Food Science and Food Safety* 21, no. 3: 2118–2148. https://doi.org/10.1111/1541-4337.12940.

Krokida, M. K., Z. B. Maroulis, and D. Marinos-Kouris. 1998. "Viscoelastic Behavior of Dehydrated Carrot and Potato." *Drying Technology* 16, no. 3–5: 687–703. https://doi.org/10.1080/07373939808917430.

Luo, G., C. Song, P. Hongjie, et al. 2019. "Optimization of the Microwave Drying Process for Potato Chips Based on the Measurement of Dielectric Properties." *Drying Technology* 37, no. 11: 1329–1339. https://doi.org/10.1080/07373937.2018.1500482.

Mesias, M., C. Delgado-Andrade, F. Holgado, and F. J. Morales. 2019. "Acrylamide Content in French Fries Prepared in Food Service Establishments." *LWT—Food Science and Technology* 100: 83–91. https://doi.org/10.1016/j.lwt.2018.10.050.

Metaxas, A. C., and R. J. Meredith. 1983. *Industrial Microwave Heating*. P. Peregrinus on behalf of the Institution of Electrical Engineers.

Nelson, S., W. Forbus, and K. Lawrence. 1994. "Permittivities of Fresh Fruits and Vegetables at 0.2 to 20 GHz." *Journal of Microwave Power and Electromagnetic Energy* 29, no. 2: 81–93. https://doi.org/10.1080/08327823.1994.11688235.

OECD/WHO. 2024. *Health at a Glance: Asia/Pacific 2024*. OECD Publishing. https://doi.org/10.1787/51fed7e9-en.

Okunogbe, A., R. Nugent, G. Spencer, J. Ralston, and J. Wilding. 2021. "Economic Impacts of Overweight and Obesity: Current and Future Estimates for Eight Countries." *BMJ Global Health* 6, no. 10: e006351. https://doi.org/10.1136/bmjgh-2021-006351.

Oztop, M. H., S. Sahin, and G. Sumnu. 2007. "Optimization of Microwave Frying of Potato Slices by Using Taguchi Technique." *Journal of Food Engineering* 79, no. 1: 83–91. https://doi.org/10.1016/j.jfoodeng.2006.01.031.

Ozturk, O. K., and P. S. Takhar. 2017. "Stress Relaxation Behavior of Oat Flakes." *Journal of Cereal Science* 77: 84–89. https://doi.org/10.1016/j.jcs.2017.08.005.

Parikh, A., and P. S. Takhar. 2016. "Comparison of Microwave and Conventional Frying on Quality Attributes and Fat Content of Potatoes." *Journal of Food Science* 81, no. 11: E2743–E2755. https://doi.org/10.1111/1750-3841.13498.

Pinto, G. S. A., and P. S. Takhar. 2023. "Stress-Relaxation Properties of French Fries as a Function of Moisture Content, Oil Content, Frying Temperature, and Testing Temperature." *Journal of Texture Studies* 54, no. 4: 521–531. https://doi.org/10.1111/jtxs.12781.

Qin, P., D. Liu, X. Wu, et al. 2022. "Fried-Food Consumption and Risk of Overweight/Obesity, Type 2 Diabetes Mellitus, and Hypertension in Adults: A Meta-Analysis of Observational Studies." *Critical Reviews in Food Science and Nutrition* 62, no. 24: 6809–6820. https://doi.org/10.1080/10408398.2021.1906626.

Reiner, M. 1964. "The Deborah Number." *Physics Today* 17, no. 1: 62. https://doi.org/10.1063/1.3051374.

Richter Reis, F. 2017. "Effect of Blanching on Food Physical, Chemical, and Sensory Quality." In *New Perspectives on Food Blanching*. Springer International Publishing. https://doi.org/10.1007/978-3-319-48665-9.

Sahin, S., G. Sumnu, and M. H. Oztop. 2007. "Effect of Osmotic Pretreatment and Microwave Frying on Acrylamide Formation in Potato Strips." *Journal of the Science of Food and Agriculture* 87, no. 15: 2830–2836. https://doi.org/10.1002/jsfa.3034.

Sandhu, J. S., H. Bansal, and P. S. Takhar. 2013. "Experimental Measurement of Physical Pressure in Foods During Frying." *Journal of Food Engineering* 115, no. 2: 272–277. https://doi.org/10.1016/j.jfoodeng.2012.10.016.

Sensoy, I., S. Sahin, and G. Sumnu. 2013. "Microwave Frying Compared With Conventional Frying via Numerical Simulation." *Food and Bioprocess Technology* 6, no. 6: 1414–1419. https://doi.org/10.1007/s11947-012-0805-x.

Shah, Y., and P. Takhar. 2024. "Hybrid Mixture Theory-Based Modeling of Unsaturated Transport in a Deforming Porous Food Matrix During Frying." *InterPore Journal* 1, no. 2: ipj240824–6. https://doi.org/10.69631/ipj.v1i2nr25.

Shah, Y., and P. S. Takhar. In review. "Predicting the Quality Changes During Microwave Frying of Food Biopolymers by Solving the Hybrid Mixture Theory-Based Unsaturated Transport and Electromagnetics Equations." *Current Research in Food Science*.

Shah, Y., and P. S. Takhar. 2022. "Pressure Development and Volume Changes During Frying and Post-Frying of Potatoes." *LWT—Food Science and Technology* 172: 114243. https://doi.org/10.1016/j.lwt.2022.114243.

Steffe, J. F. 1996. *Rheological Methods in Food Process Engineering*. Freeman Press.

Stratton, J. A. 2007. *Electromagnetic Theory*. IEEE Press. https://doi.org/10.1002/9781119134640.

Takhar, P. S. 2014. "Unsaturated Fluid Transport in Swelling Poroviscoelastic Biopolymers." *Chemical Engineering Science* 109: 98–110. https://doi.org/10.1016/j.ces.2014.01.016.

Tang, J. 2015. "Unlocking Potentials of Microwaves for Food Safety and Quality." *Journal of Food Science* 80, no. 8: E1776–E1793. https://doi.org/10.1111/1750-3841.12959.

Tang, J., and F. P. Resurreccion. 2009. "Electromagnetic Basis of Microwave Heating." In *Development of Packaging and Products for Use in Microwave Ovens*. Elsevier. https://doi.org/10.1533/9781845696573.1.3.

Teruel, M. D. R., M. Gordon, M. B. Linares, M. D. Garrido, A. Ahromrit, and K. Niranjan. 2015. "A Comparative Study of the Characteristics of French Fries Produced by Deep Fat Frying and Air Frying." *Journal of Food Science* 80, no. 2: E349–E358. https://doi.org/10.1111/1750-3841.12753.

Vitrac, O., G. Trystram, and A.-L. Raoult-Wack. 2000. "Deep-Fat Frying of Food: Heat and Mass Transfer, Transformations and Reactions Inside the Frying Material." *European Journal of Lipid Science and Technology* 102, no. 8–9: 529–538. https://doi.org/10.1002/1438-9312(200009)102:8/9⟨529::AID-EJLT529⟩3.0.CO;2-F.

von Hippel, A. R. (with Labounsky, A. S.). 1995. *Dielectrics and Waves* (Republication). Artech House.

Zhang, X., M. Zhang, and B. Adhikari. 2020. "Recent Developments in Frying Technologies Applied to Fresh Foods." *Trends in Food Science & Technology* 98: 68–81. https://doi.org/10.1016/j.tifs.2020.02.007.

Zhou, X., P. Czekala, M. Olszewska-Placha, et al. 2024. "Understanding Microwave Heating of Oils." *Journal of Food Engineering* 375: 112039. https://doi.org/10.1016/j.jfoodeng.2024.112039.

Zhou, X., Y. Gezahegn, S. Zhang, et al. 2023. "Theoretical Reasons for Rapid Heating of Vegetable Oils by Microwaves." *Current Research in Food Science* 7: 100641. https://doi.org/10.1016/j.crfs.2023.100641.

Zhou, X., P. D. Pedrow, Z. Tang, S. Bohnet, S. S. Sablani, and J. Tang. 2023. "Heating Performance of Microwave Ovens Powered by Magnetron and Solid-State Generators." *Innovative Food Science & Emerging Technologies* 83: 103240. https://doi.org/10.1016/j.ifset.2022.103240.

Zhou, X., Z. Tang, P. D. Pedrow, S. S. Sablani, and J. Tang. 2023. "Microwave Heating Based on Solid-State Generators: New Insights Into Heating Pattern, Uniformity, and Energy Absorption in Foods." *Journal of Food Engineering* 357: 111650. https://doi.org/10.1016/j.jfoodeng.2023.111650.

Zhou, X., S. Zhang, Z. Tang, J. Tang, and P. S. Takhar. 2022. "Microwave Frying and Post-Frying of French Fries." *Food Research International* 159: 111663. https://doi.org/10.1016/j.foodres.2022.111663.

Ziaiifar, A. M., F. Courtois, and G. Trystram. 2010. "Porosity Development and Its Effect on Oil Uptake During Frying Process." *Journal of Food Process Engineering* 33, no. 2: 191–212. https://doi.org/10.1111/j.1745-4530.2008.00267.x.

Appendix

TABLE A1 | Results of the two-way analysis of variance (ANOVA) performed to evaluate the effect of the frying method and frying time on the moisture content, oil content, and volume changes of fried samples.

Moisture content	**Degrees of freedom**	**Sum of squares**	**Mean square**	***F* value**	***p* value**
Frying method	2	2.74584	1.37292	5.33413	0.00738
Frying time	3	460.19038	153.39679	595.98348	<0.0001
Interaction	6	5.23579	0.87263	3.39039	0.00603
Model	11	468.17201	42.56109	165.36009	<0.0001
Error	60	15.44306	0.25738		
Total	71	483.61507			
Oil content					
Frying method	2	5.88889E – 4	2.94444E - 4	15.10264	<0.0001
Frying time	3	0.04838	0.01613	827.20022	<0.0001
Interaction	6	0.00211	3.51503E - 4	18.02928	<0.0001
Model	11	0.05108	0.00464	238.18015	<0.0001
Error	24	4.67909E - 4	1.94962E - 5		
Total	35	0.05155			
Volume change					
Frying method	2	0.0103	0.00515	8.38594	0.00155
Frying time	2	0.75618	0.37809	615.48173	<0.0001
Interaction	4	0.00569	0.00142	2.31749	0.08385
Model	8	0.76609	0.09576	155.88632	<0.0001
Error	26	0.01597	6.14299E - 4		
Total	34	0.78206			