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Microwave frying and post-frying of French fries

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ABSTRACT

French fries are popular items in the diets of many countries, but the high oil content is a major health concern for consumers. Numerous novel frying techniques have been explored by the fast food service industry and the research community to address such concern. This research aimed to study the influence of microwave heating at two frequencies (2.45 and 5.85 GHz), both individually or in combination, in frying and post-frying on oil reduction in French fries. Results showed that microwave frying reduced the frying time by 30 – 40%, with equivalent product quality attributes in terms of oil content, color, and texture, as compared to deep-oil frying. Oil intake increased with increasing moisture loss during frying, regardless of the frying methods. Post-frying condition was the key to oil reduction. Specifically, a 60 s microwave heating after frying reduced the oil content by 18 – 23%. Compared to 2.45 GHz, microwaves at 5.85 GHz could produce French fries with significantly lower oil content ($p \leq 0.05$) and better quality attributes such as color and texture. This study demosnstrated the potential of microwave heating in production of deep-fried French fries with lower oil content and better quality.

1. Introduction

Deep-oil frying is a popular culinary method used worldwide to provide unique flavor, texture, and overall taste to food products (Liberty, Dehghannya, & Ngadi, 2019). One of the most favorite fried foods in USA and many other countries is French fries, which have the same nutrition composition as fresh potatoes but with characteristic taste and texture (i.e., crispy crust and soft interior). The United States produced 42.4 billion pounds of potatoes in 2019, 44% of which were manufactured into French fries (USDA, 2020). The global French fries market continues to grow due to continued expansion of fast food restaurants, such as McDonald's and Burger King in the world. However, a major concern associated with French fries is their high oil content (Bingol et al., 2012). A large serving of French fries provides 520 calories, 43% of which come from oil (USDA, 2019). Human consumption of high-oil affordable foods such as French fries without adequate physical exercise can contribute to obesity and overweight. McGuire (2016) estimated that >70% of Americans are overweight or obese. Obesity and overweight are major causes of prevalent chronic diseases, such as hypertension, type 2 diabetes, and cancer metastasis (CDC, 2022).

The food service industry has been actively seeking new frying techniques to produce healthy and nutritious French fries without compromising texture, taste, and flavor (Liberty et al., 2019; Parikh & Takhar, 2016) that can be readily integrated into the current manufacturing operations. Three general methods have been considered for oil reduction in French fries, namely, modifying potatoes surface (e.g., coating with hydrocolloids and blanching), optimizing frying temperature and selecting the best types of oil, and changing frying methods (e.g., air frying and vacuum frying) (Asokapandian, Swamy, & Hajjul, 2020; Liberty et al., 2019; Li et al., 2020). For example, 25% oil content reduction was observed in French fries coated with whey protein and pectin films due to their desirable barrier properties (Liberty et al., 2019). Water vapor created in the coating prevents oil from penetrating foods, but meanwhile slows down heat transfer. Dry blanching by infrared heating could reduce the amount of oil uptake in French fries as compared to unblanched samples (Bingol et al., 2012). However, wet blanching by water or steam is still the prefered blanching method as it leaches out reducing sugars in potatoes to avoid severe Maillard reactions during frying. The mathematical models based on unsaturated fluid transport theory of Takhar (2014) show that hydrophilic food matrix has oil suction potential due to negative pore pressure. This negative pore pressure cannot be avoided by merely changing the frying parameters such as oil temperature and type. Optimizing frying oil parameters in deep-oil frying is tedious for the food service industry. Air

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frying is a relatively new method designed to simulate deep-oil frying without submerging the food in oil. However, it is only used to a limited extent in the catering industry due to slow heat transfer, high energy consumption, and undesirable product quality (Liberty et al., 2019).

Microwaves are electromagnetic (EM) waves with frequencies between 0.3 GHz and 300 GHz (Tang, 2015; Zhou & Wang, 2019). Unlike conventional heating in which heat transfers from high-temperature medium to low-temperature medium, microwaves heat foods volumetrically by converting EM energy to thermal energy within the food matrix (Tang, 2005). Microwave heating can thus sharply reduce heating time. However, microwave heating is rarely used in the frying industry (Schiffmann, 2017). To date, microwave-assisted doughnut frying is the only successful industrial application in which microwave heating serves the purpose of preventing the doughs to form 'core' — the unexpanded interior portion where the density is twice as that in expanded portion (Schiffmann, 2017). Several studies combined microwave heating and heated-oil frying for oil reduction in fried foods. Recently, Parikh & Takhar (2016) reported that oil contents of French fries can be reduced by up to 8% when combining microwave heating with conventional heated-oil frying. This reduction was attributed to a shift in the gage pore pressure in French fries, from negative to positive (compared to the atmospheric pressure) when turning on microwave power in a commercial microwave fryer. The studies of Parikh & Takhar (2016) and Sandhu, Bansal, & Takhar (2013) revealed steep drops in pore pressure during the final frying stage and persistent negative gage pressures during the entire post-frying stage. This explains why most of the oil of French fries is absorbed during post-frying (cooling) than during frying.

Thus, we hypothesize that microwave energy has more potential to reduce oil intake if it is utilized in post-frying. However, there is little understanding on the role of microwaves on the oil reduction during post-frying. Commercial microwave fryers available in the market do not allow post-frying and they all operate at one single frequency (i.e., 2.45 GHz) (Parikh & Takhar, 2016; Schiffmann, 2017). Microwaves at 5.8 GHz have shallower penetration depth in high-moisture products, which is approximately 1/3 that of 2.45 GHz (Tang, 2005). We also hypothesize that microwaves at 5.8 GHz might be more applicable to post-frying treatments for French fries, as the microwave energy might be directed more intensely at the interface between the crust and the interior of French fries to expel the oil out. Although 5.8 GHz is allocated by US Federal Communications Commission (FCC) for industrial, scientific, and medical (ISM) applications, there are no reported food applications using this frequency (Tang, 2015).

To prove the above hypotheses, a dual-frequency (2.45 and 5.85 GHz) microwave frying test unit (Fig. 1) was designed and fabricated at Washington State University (WSU) (Pullman, WA, USA). The developed unit can be operated at each of the two frequencies (2.45 or 5.85 GHz) or in combination. In addition, microwave sources can be turned on after food materials are removed from oil while still in the fryer. This option allows for the tests to investigate the role of microwave energy in post-

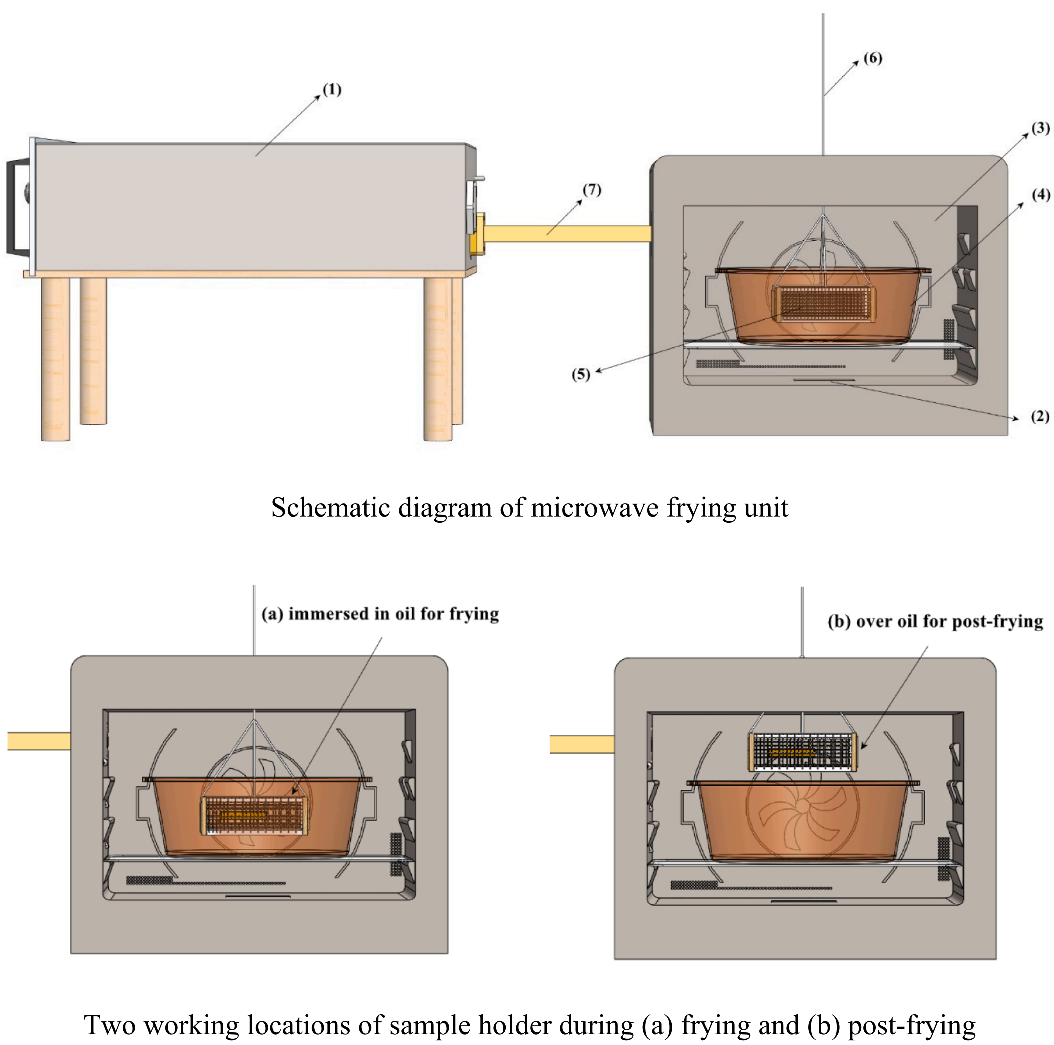


Fig. 1. Schematic diagram of a dual-frequency microwave fryer consisting of (1) 5.85 GHz solid-state microwave generator, (2) 2.45 GHz magnetron and its entry port, (3) microwave cavity, (4) glass oil container, (5) nylon sample holder, (6) nylon wire, (7) waveguide, and two working locations [(a), (b)] of the sample holder.

frying. The design will be discussed in detail later (See *Section 2.2*).

The objectives of this study were to: (1) study the effectiveness of microwaves on oil reduction in French fries during frying and post-frying, and to (2) compare different microwave treatments affecting final quality attributes of French fries.

2. Material and methods

2.1. Material and sample preparation

Fresh potatoes (Russet Burbank variety) were purchased from a local grocery store (Walmart, Pullman, WA, USA). The potatoes were packaged in perforated plastic bags and stored in a refrigerator at 9 ± 1 °C (Parikh & Takhar, 2016) prior to experiments. French fries prepared from fresh potatoes closely simulated industrial procedures (Pederson, Braich, Samoray, & Sloan, 2003; Strong, 1968) with some modifications to suit the lab-scale testing. Specifically, the washed potatoes were hand peeled and cut into elongated strips (9.5 mm × 9.5 mm × 60 mm) with a French fry cutter (B00DVXLGHO, New Star Foodservice Co., Chino, CA, USA). The cut stirps were washed free of surface starch to reduce adhesion of the potatoes to each other. The potato strips were blanched in a water bath (Model 260, Thermo Fisher Scientific Inc., Marietta, OH): the samples were first blanched at 80 °C for 2 min to inactivate polyphenol oxidase (PPO) (Bingol et al., 2012), and then held in water at 65 °C for 20 min to leach out reducing sugars and starches (Aguilar, AnzalduaMorales, Talamas, & Gastelum, 1997). The two-step blanching not only avoided over-cooking of potato tissue, but also improved the texture by reinforcing potato cell wall structure due to the activation of the pectin methyl esterase (PME) (Aguilar, AnzalduaMorales, Talamas, & Gastelum, 1997). The surface water on the blanched strips was removed by adsorbent paper.

2.2. Microwave fryer test unit

Fig. 1 shows a schematic view of the microwave fryer test unit. It was modified from a commercial domestic microwave oven (NN-CF876S, Panasonic, Tokyo, Japan). The unit consisted of seven main components: (1) 5.85 GHz solid-state microwave generator (RIU58800-20, RFHIC Co., Anyang, South Korea), (2) 2.45 GHz magnetron (2 M261, Panasonic, Tokyo, Japan) and its entry port, (3) microwave cavity, (4) glass oil container, (5) nylon sample holder, (6) nylon wire, and (7) waveguide. The microwave frying unit can operate at a single frequency (2.45 or 5.85 GHz) or as a combination of the two frequencies. The sample holder was used for holding potato strips at two locations: (a) immersed in oil for frying, and (b) over oil for post-frying (Fig. 1). The sample holder was raised or lowered manually using a nylon wire.

2.3. Microwave frying

The microwave heating was combined with heated oil frying ("microwave frying" was used synonymously). Four different frying treatments were studied: (1) oil frying served as control, (2) oil plus microwave frying at 2.45 GHz, (3) oil plus microwave frying at 5.85 GHz, and (4) oil plus microwave frying at the dual-frequency (2.45 + 5.85 GHz). All the experiments were conducted using the unit depicted in Fig. 1. The power settings for microwave generators for the frying experiments are shown in Table 1. Industrial frying temperatures for French fries vary from 170 to 190 °C (Pederson, Braich, Samoray, & Sloan, 2003; Strong, 1968; Bouchon, 2009), so we selected 180 °C as the temperature for the oil.

Before frying, 3.0 L soybean oil (Great Value brand, Walmart, WA, USA) was loaded in the oil container. The oil was heated by microwave (1200 W for 30 min) to 180 ± 1 °C. Pre-blanched potato strips (30 ± 3 g) were immersed in the oil and fried by one of the four methods described above. The frying times were 1, 3 and 5 min. After frying, the sample holder was removed from the oil container and allowed to cool to room temperature (∼22 ± 3 °C).

Prior to the experiments, four fiber optical sensors (Model MAN-00075 R5, FISO, Quebec, Canada) were carefully inserted into the geometric center of four different potato strips. The center temperatures were continuously measured and recorded during frying. Fresh soybean oil was added after each frying experiment to maintain a constant oil level, and the oil was discarded after 12 h of frying to avoid oil degradation (Asokapandian, Swamy, & Hajjul, 2020; Bingol et al., 2012).

2.4. Microwave post-frying

Microwave post-frying in this study refers to microwave heating between frying and cooling. Prior to each post-frying treatment, blanched potato strips were fried in 180 °C oil for 5 min. After the fried potatoes were lifted out of the oil (Fig. 1), three different post-frying treatments were evaluated: (1) no microwaves (control), (2) microwave heating at 2.45 GHz, and (3) microwave heating at 5.85 GHz. The heating times were 30, 60, 90 and 120 s. After heating, the French fries were removed from the microwave oven and allowed to cool to room temperature. The power settings for microwave generators for the post-frying experiments are shown in Table 1. To study the post-frying holding temperature on oil reduction, the control group for post-frying experiments was divided into two sub-groups: 1) the control samples were held inside the microwave cavity in which the air temperature was high (90 ± 4 °C, measured by the fiber optic sensors); 2) the control samples were taken out of the microwave cavity and held at the room temperature (22 ± 3 °C).

2.5. Quality evaluation

The quality of French fries was analyzed 3 min after the samples were removed from the fryer. Three minutes is the normal French fry holding time before serving customers in fast food restaurants (Pederson, Braich, Samoray, & Sloan, 2003). The quality analysis was performed in order of color, texture, moisture content and oil content.

2.5.1. Color

The color of French fries was determined using CIE LAB Color System where L^* (0–100) represents dark vs. light, a^* (-50 to 50) represents green vs. red, and b^* (-50 to 50) represents blue vs. yellow. The color values were captured by a computer vision system, which included illuminant D_{65} light produced by incandescent bulbs, a Canon EOS 60D

Table 1
Power settings for microwave generators (magnetron and solid-state generators) used in frying and post-frying.

	Control group	2.45 GHz microwaves	5.85 GHz microwaves	2.45 GHz + 5.85 GHz microwaves
	No generator was turned on	Magnetron[†]	Solid-state[*]	Both generators were turned on
Frying	0 W	800 W[**]	800 W	400 + 400 W (in total 800 W)
Post-frying	0 W	400 W[***]	400 W	–

[†] Magnetron [(2) in Fig. 1] produced microwaves at 2.45 GHz.
[*] Solid-state microwave generator [(1) in Fig. 1] produced microwaves at 5.85 GHz.
[**] 800 W is normal working power of a domestic microwave oven.
[***] 400 W was determined in preliminary tests to avoid over-cooking of French fries.

digital camera (exposure time of 0.01 s, aperture of f/5.6 and ISO 640) and a computer. Details about the computer vision system can be found in Qu et al. (2021). The RGB color images of samples were first calibrated using a standard color reference card (QPcard 203, QPcard AB, Helsingborg, Sweden), and then analyzed with Adobe Photoshop CC (San Jose, CA, USA) to obtain L^*, a^* and b^* values. The total color difference (ΔE) was calculated by Eq. (1):

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \tag{1}$$

where L_0^*, a_0^* and b_0^* correspond to the color values of French fries from the control groups, and L^*, a^* and b^* correspond to color values of samples from microwave treatments.

2.5.2. Texture

The crust of French fries gets soggier when held for too long after frying (Sanz, Primo-Martin, & van Vliet, 2007). The crispness of French fries was measured immediately after color analysis. A puncture test of French fries was performed with a TA-XT Plus Texture Analyzer (Stable Micro Systems, Surrey, UK) which included a TA-52 puncture probe (2 mm diameter) and a customized aluminum plate with a 4 mm thru-hole. The French fries were carefully positioned so that the probe penetration occurred at the location of 1/3rd length (~20 mm) from the end of potato strips. Based on preliminary results, the positioning was standardized to avoid puncturing too close to the sample ends (with the highest fracturability) and to avoid puncturing directly in the center (with the lowest fracturability).

After calibration, a French fry strip was placed on the aluminum plate. The puncture test was conducted with the following parameters: pre-traveling speed of 3.0 mm/s, detection force of 10 g, travel speed of 1.0 mm/s, travel distance of 10 mm, and probe withdraw speed of 10 mm/s. Two puncture tests for each French fry sample and three samples from one batch were applied to obtain an average force–deformation curve. A Texture Expert Exceed software (Stable Micro Systems, v. 2.64, Surrey, UK) was used to obtain the peak force (the maximum force required to puncture into a sample), and the work (area under the curve from the original point to the first peak force point).

2.5.3. Moisture content

The moisture content of French fry samples was determined by the vacuum oven method according to the AOAC Official Method 926.12 (AOAC, 2005). The samples (5.0 ± 0.2 g) were placed on an aluminum dish and dried in a vacuum oven at 60 °C and 13.3 kPa for 24 h. The moisture contents were calculated based on the weight loss and expressed on dry basis.

2.5.4. Oil content

After the moisture measurement, the dehydrated samples were transferred to Soxhlet apparatus for oil analysis based on AOAC Official Method 948.22 (AOAC, 2013). The vacuum oven dehydration makes the French fries easier to grind and break lipid-water emulsion for better oil extraction. The ground samples (2 ~ 3 g) were weighed and placed into a thimble, loaded in the Soxhlet extractor, and extracted with petroleum ether for 6 hrs. The oil content of French fries was expressed on dry basis.

2.6. Statistical analysis

Three replications were conducted for frying and post-frying tests, and data were expressed as mean ± standard deviations (SDs). One-way Analysis of Variance (ANOVA) was conducted to perform multiple comparisons by Tukey's procedure using $\alpha = 0.05$ in SAS® (Cary, NC, USA) and RStudio (Boston, MA, USA).

3. Results and discussion

3.1. Microwave frying

3.1.1. Temperature profiles

The temperature profiles of potato strips during four frying methods are shown in Fig. 2. The center temperature increased rapidly and reached approximately 100 °C within 1 min, due to the fast convection in oil. Compared with control (heated oil frying without microwaves), microwave frying increased the heating rates by 40 – 58% in the heating period. The 2.45 GHz microwave frying had a faster heating rate than 5.85 GHz microwave frying. First, the potato strips were closer to 2.45 GHz microwave source than 5.85 GHz source upon immersing in the oil (Fig. 1). The strong electric field generally occurs in the vicinity of the microwave source. Second, the higher the microwave frequency, the less deep microwave energy can penetrate the food materials (Tang, 2015). 2.45 GHz microwaves have a larger penetration depth (7 mm) than 5.85 GHz microwaves (2 mm) in potatoes (Tang, 2005). Therefore, more microwave energy was likely to be absorbed in the center of potato strips during the 2.45 GHz microwave heating.

After 1 min of heating, the center temperatures remained fairly constant, and the majority of energy was used for latent heat of vaporization.

3.1.2. Moisture and oil content

As expected, an increase of frying time led to lower moisture and higher oil contents of French fries (Fig. 3). For control, a great amount of oil was absorbed within the first 1 min of frying, and then the oil uptake rate was steadily reduced (Fig. 3b). The 50% of moisture loss occurred in the first 1 min, and the drying rate began to decline as frying progressed (Fig. 3a). The reductions in the moisture loss rate and oil intake rate were mainly because of the starch gelatinization of outer surface and the formation of crust (Bouchon, 2009), which together slowed down heat and mass transfer.

Microwave frying yielded faster drying and oil-intake rates, particularly at 2.45 GHz. For example, at frying time of 5 min, 2.45 GHz microwaves resulted in the lowest moisture content and highest oil content in French fries, followed by dual-frequency microwaves, 5.85 GHz microwaves, and the control. More pores could be formed in the crust upon water removal with the addition of microwave energy (Bouchon, 2009; Liberty et al., 2019). Such pores determine maximum volumes available for oil pickups. Under the test conditions in this study, microwave frying increased not only water loss but also oil uptake. Parikh & Takhar (2016) found that French fries with lower oil contents were produced by microwave frying (7% less oil compared with conventional frying at 2 min). In their study, the moisture contents of French fries from microwave frying and conventional frying were similar, while in this study the moisture content of microwave fried samples were significantly lower than that of conventional fried samples at the same frying time ($p \leq 0.05$) (for example, 0.45 ± 0.01 db of microwave frying vs. 1.09 ± 0.20 db of conventional frying at 5 min). Moreover, other differences in blanching conditions, microwave cavity, and geometry of potato strips between two study cases may contribute to this disparity.

The moisture contents of French fries were plotted vs. the corresponding oil contents (Fig. 4). Regardless of frying methods, an approximate linear correlation was observed between moisture and oil contents. This suggests that when more water was lost, more oil was likely to be absorbed by the samples. Similar results were observed by Bingol et al. (2012) and Li et al. (2020). Thus, further comparison between microwave frying and heated-oil frying should be made with the identical moisture content of French fries (see *Section 3.1.4*).

3.1.3. Color pattern

Consumers expect French fries of a light and golden color without any brown, dark spots and traces (Strong, 1968). The French fries produced by different frying methods in this study underwent different

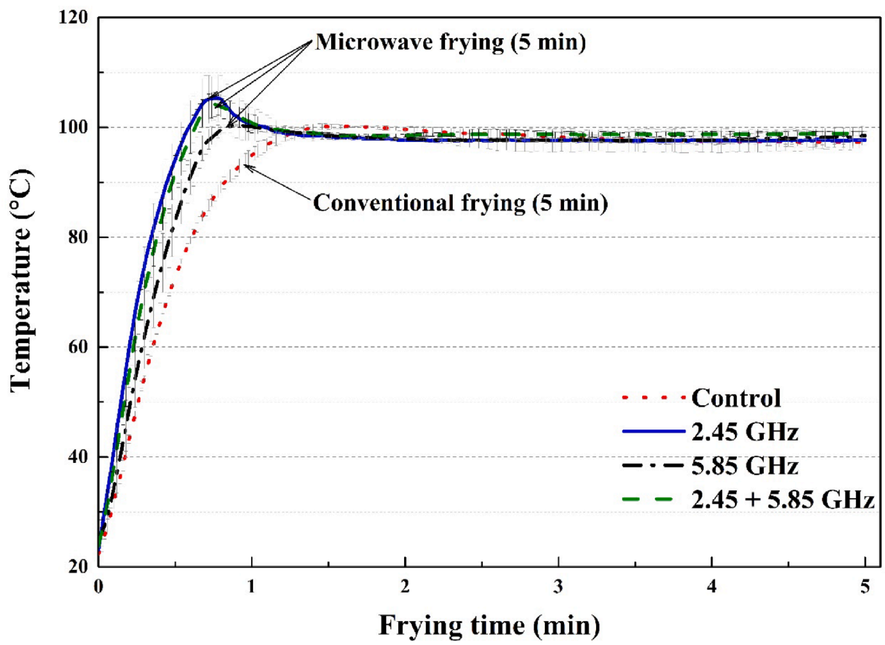


Fig. 2. Temperature profiles (mean ± standard deviations) at potato strip centers during conventional frying (control), and oil plus microwave frying at different microwave frequencies (2.45 GHz, 5.85 GHz, and combination of 2.45 and 5.85 GHz), n = 3.

levels of discoloration (Table 2). Overall, the a^* and b^* values, representing redness and yellowness, increased with increasing frying times, due to the Maillard reaction (data not shown). Blanching prior to frying can partially leach out reducing sugar from fresh potato fleshes and lead to relatively uniform reducing sugar distribution on the potato surface (Aguilar, AnzalduaMorales, Talamas, & Gastelum, 1997). Therefore, this browning reaction on the potato surface could help to visualize the heating pattern of frying.

As expected, the heated oil frying resulted in even surface color distribution, since potato strips were fully immersed in the hot oil. Localized dark/brown color of French fries was observed during microwave frying, particularly at 2.45 GHz (Table 2). This phenomenon could be explained by the standing waves in the microwave cavity: antinodes (high electric field intensity) and nodes (low electric field intensity) of microwaves are alternatively ¼ wavelength apart (Tang, 2015). For a simple case of one travelling wave, the two adjacent antinodes (hot spots) in a potato strip during 2.45 GHz microwave heating is estimated to be 11.5 mm from each other (wavelength of 23 mm in the potato (Tang, 2005)), while this distance is reduced to 4.5 mm for 5.85 GHz microwaves (wavelength of 9 mm in the potato). Three-dimensional standing waves were generated in the microwave oven, and the localized brown colors of French fries were developed due to accumulative time–temperature effects in these antinodes. Overall, 5.85 GHz microwaves had more uniform heating in potatoes than 2.45 GHz.

Moreover, the lengthy exposure of French fries to microwave heating at both 2.45 GHz and 5.85 GHz resulted in edge heating (Table 2), due to the large difference between the impedance of oil (242 Ω) and that of potatoes (50 Ω) when heated in a domestic microwave oven (Tang, 2015). Under the test conditions in this study, therefore, ≥ 5 min microwave frying is not recommended.

3.1.4. End-point of frying

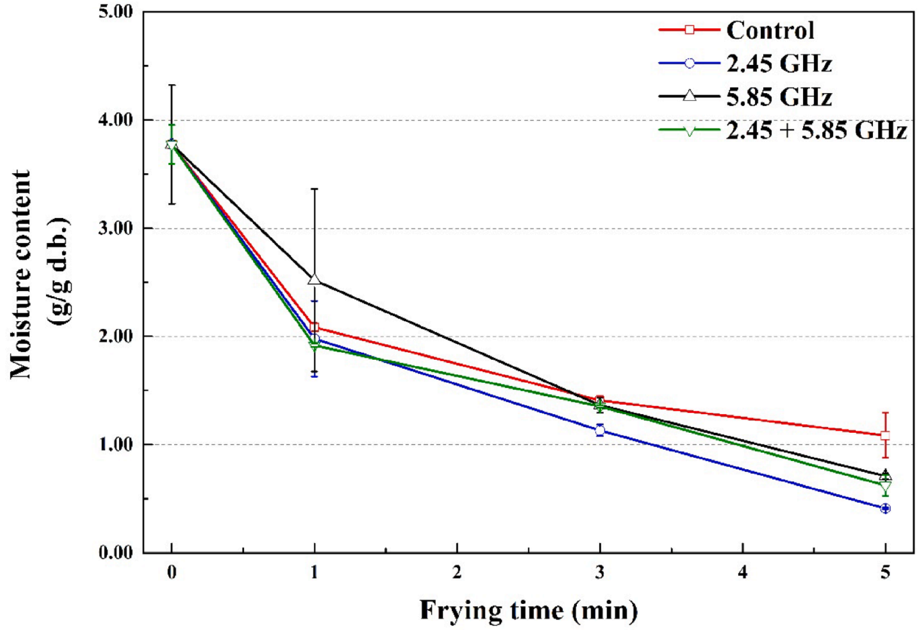
In industrial operations, the moisture content of French fries is used as a quantitative measure to terminate a frying process (Bouchon, 2009; Strong, 1968). To better compare different frying methods, an end point of frying was standardized based on final moisture content of French fries (0.52 ~ 0.55 on wet basis or 1.08 ~ 1.22 on dry basis).

Based on above results and preliminary tests, to achieve this moisture level, the required frying time was 5.0 min for control (heated oil frying without microwaves), 3.5 min for both 5.85 GHz microwave frying and dual-frequency microwave frying, and 3.0 min for 2.45 GHz microwave frying (Table 3). The ANOVA revealed no significant difference in the moisture content and oil content among French fries produced by the conventional heated-oil frying and microwave frying methods ($p > 0.05$). It was confirmed that the oil content of French fries was dependent on the moisture content. The color values, including L^*, a^*, and b^*, of the samples treated by microwave frying were comparable to those of samples fried by the conventional frying method. For example, $\Delta E = 1.2$ of French fries from 5.85 GHz microwave frying indicates a very small color difference as compared to the conventional frying. It is interesting to note that the microwaves at 5.85 GHz yielded higher crispness than other frying methods ($p \leq 0.05$). A more detailed texture profiles of French fries treated by four frying methods are shown in Fig. 5.

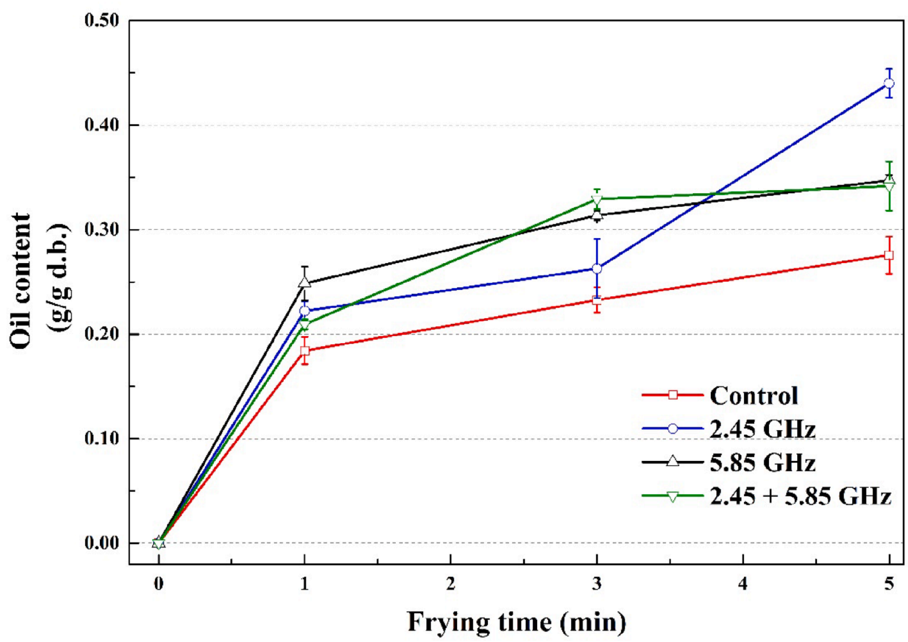
Each curve showed a 1st peak, a 2nd peak, and a trough (Fig. 5) which represents the forces required to puncture into the samples, puncture out through the bottom side of the samples, and travel through the center, respectively. The peak forces required to initially puncture into fries was used to evaluate crust harnesses. 5.85 GHz microwave frying resulted in the highest crust hardness, followed by dual-frequency frying, 2.45 GHz microwave frying, and deep-oil frying, although the overall moisture contents of French fry samples were similar. It may be possible that 5.85 GHz microwave energy was focused on the crust of a French fry due to its shallow penetrate depth (Tang, 2015), resulting in the lower moisture content in the crust area. Sanz, Primo-Martin, & van Vliet (2007) found that the crust hardness was better correlated with the moisture content of outer layer (i.e., crust), not the whole moisture content of French fries.

It can be concluded from the above results that microwave frying could shorten frying time by 30% – 40%, while producing French fries with equivalent quality in terms of color and texture (or even better, if using 5.85 GHz microwaves) as compared to the deep-oil frying.

Several studies demonstrated that oil intake toward inner layers of French fries mostly takes place during post-frying, rather than during frying (Bouchon, 2009; Liberty et al., 2019; Asokapandian, Swamy, & Hajjul, 2020). For example, Bouchon (2009) reported that 20% of oil in tortilla chips is absorbed during frying, whereas 64% of oil is absorbed during post-frying. The pressure development is an important factor



(a)



(b)

Fig. 3. Changes of (a) moisture content (mean ± standard deviations) and (b) oil content (mean ± standard deviations) of potato strips during deep-oil frying (control) and oil plus microwave frying at different microwave frequencies (2.45 GHz, 5.85 GHz, andcombination of 2.45 and 5.85 GHz), n = 3.

afftecting oil absorption of foods (Sandhu, Bansal, & Takhar, 2013). During frying, positive pore pressure due to vigorous water evaporation precludes oil penetration deeper into the food. As frying proceeds, the gage pressure starts decreasing and remains negative throughout the cooling (Parikh & Takhar, 2016;). When French fries are taken outside the oil, surface oil migrates into the porous crust of French fries due to the negative pressure (Takhar, 2014). So, we propose a microwave heating treatment between frying and cooling for oil reduction (it is referred as "microwave post-frying").

3.2. *Microwave post-frying*

3.2.1. *Moisture and oil contents*

The moisture contents of the potato strips continued to decrease during post-frying, except for the control samples held at the room temperature (Fig. 6a). Fig. 6b shows the changes of oil content of French fries during post-frying. For the control samples that were taken out of the oil/microwave cavity and cooled at the room temperature (22 ± 3 °C), the oil content remained mostly unchanged during the post-frying period. However, for the control samples held in the microwave cavity where the air temperature was high (90 ± 4 °C), the oil content initially

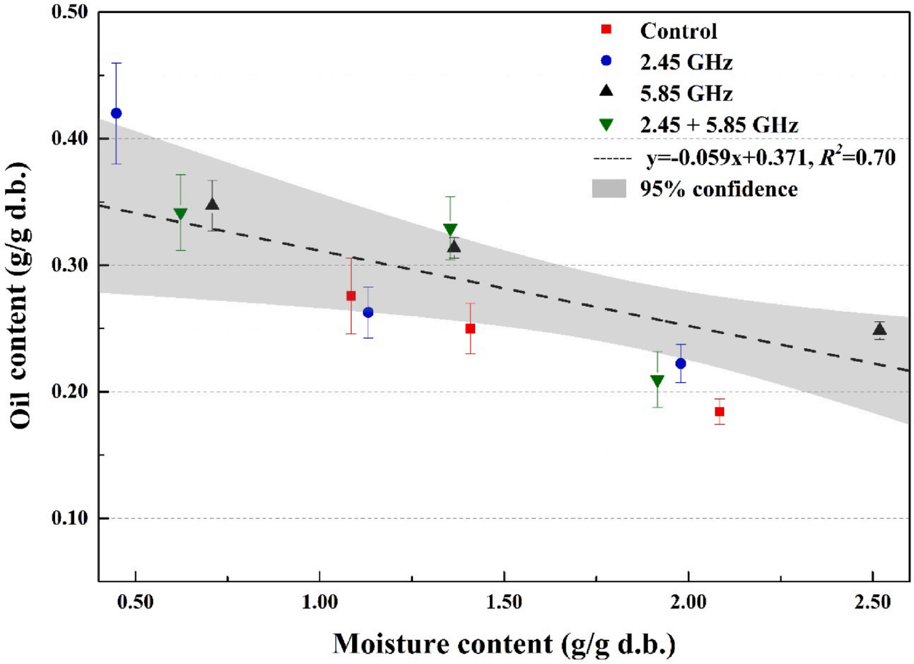
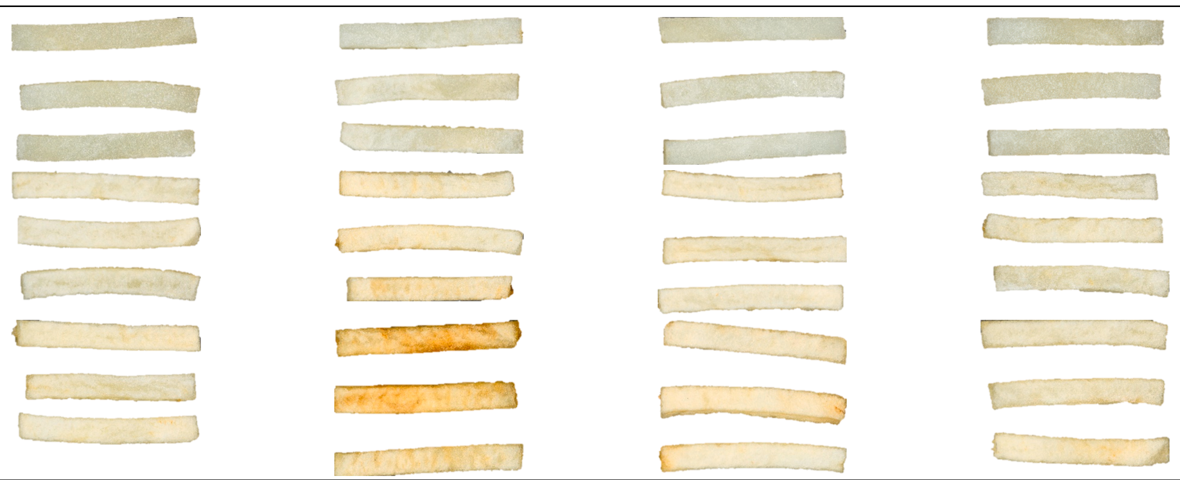


Fig. 4. The correlation between moisture content and oil content (mean ± standard deviations) of potato strips produced by deep-oil frying (control) and oil plus microwave frying at different microwave frequencies (2.45 GHz, 5.85 GHz, and combination of 2.45 and 5.85 GHz), n = 3.

Table 2
Effect of frying methods on color of French fries.

Time (min)	Frying methods[†]			
	Control	2.45 GHz microwaves	5.85 GHz microwaves	Dual-frequency microwaves
1				
3				
5				



[†] Control: deep-oil frying; 2.45 GHz microwaves: oil plus microwave frying at 2.45 GHz; 5.85 GHz microwaves: oil plus microwave frying at 5.85 GHz; Dual-frequency microwaves: oil plus microwave frying at both 2.45 GHz and 5.85 GHz.

increased and then decreased. As a result, after 30 s of the post-frying the oil content of French fries held at 90 °C was significantly lower than that of control samples held at 22 °C (p-value < 0.05, statistical data not shown), suggesting that air temperature at which the samples are held could be one contributor to the oil reduction in this study. The reduced oil content might be due to the decreased oil viscosity at the high temperature (Liberty et al., 2019; Yang et al., 2019). Liu, Tian, Duan, Li, & Fan (2021) reported that the viscosity of soybean oil decreased from 0.05 to 0.01 Pa × s when the oil temperature increased from 30 to 90 °C. The surface oil with lower viscosity could more easily drain from the French fries, resulting in less oil absorption (Liberty et al., 2019).

In addition to the high holding temperature, microwave heating could further help to reduce the oil content of French fries. For example, the oil content of French fries heated by 5.85 GHz microwaves for 60 s (0.251 ± 0.005 d.b.) was significantly lower than that of samples without microwave heating (0.303 ± 0.013 d.b. at 90 °C, 0.336 ± 0.015 d.b. at 22 °C) (p-value < 0.001), and significantly lower than that of French fries treated by 2.45 GHz microwaves (0.277 ± 0.009 d.b.) (p-value = 0.027). Eighteen percent and twenty-three percent oil reductions in French fries were achieved by the 60 s microwave heating at 2.45 GHz and 5.85 GHz, respectively, as compared with the control held at the room temperature.

The oil reduction during the post-frying microwave heating was most likely due to two factors (oil viscosity and pore pressure of foods): (1) the

Table 3
Quality attributes of French fries produced by different frying methods based on the same end-point of frying.

Quality attributes		Frying methods[†]			
		Control	2.45 GHz microwaves	5.85 GHz microwaves	Dual-frequency microwaves
Images					
Frying time (min)		5.0	3.0	3.5	3.5
Moisture content (d.b.)		1.22 ± 0.02a[*]	1.08 ± 0.05a	1.10 ± 0.03a	1.09 ± 0.03a
Oil content (d.b.)		0.31 ± 0.02a	0.28 ± 0.03a	0.31 ± 0.01a	0.30 ± 0.01a
Color	L^*	85.5 ± 4.5a	83.4 ± 5.4a	84.7 ± 5.6a	84.3 ± 5.7a
	a^*	−1.1 ± 0.6a	−0.9 ± 0.7a	−0.9 ± 0.7a	−0.4 ± 0.8a
	b^*	18.0 ± 3.6a	19.7 ± 4.3a	18.8 ± 4.7a	22.4 ± 6.1a
	ΔE	–	2.8	1.2	4.7
Texture	Peak force (g)	140.9 ± 11.2b	173.2 ± 23.4b	219.8 ± 12.4a	195.7 ± 12.0a
	Work (g × mm)	250.6 ± 20.8b	268.3 ± 31.1b	368.6 ± 35.9a	347.7 ± 30.9a

[†] Control: deep-oil frying; 2.45 GHz microwaves: oil plus microwave frying at 2.45 GHz; 5.85 GHz microwaves: oil plus microwave frying at 5.85 GHz; Dual-frequency microwaves: oil plus microwave frying at both 2.45 GHz and 5.85 GHz.
[*] Values within a row followed by the same lowercase letter are not significantly different at $p > 0.05$, n = 3.

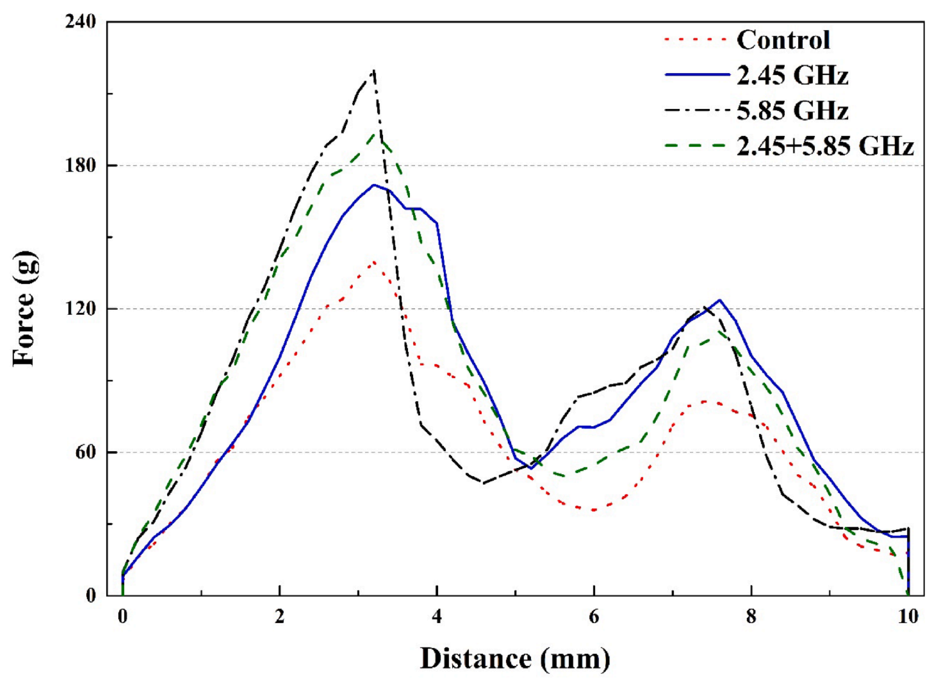


Fig. 5. The force–deformation curves of French fries produced by deep-oil frying (control) and oil plus microwave frying at different microwave frequencies (2.45 GHz, 5.85 GHz, and combination of 2.45 and 5.85 GHz). The curves were average of measurements (n = 3). The moisture contents of French fries were comparable as shown in Table 3.

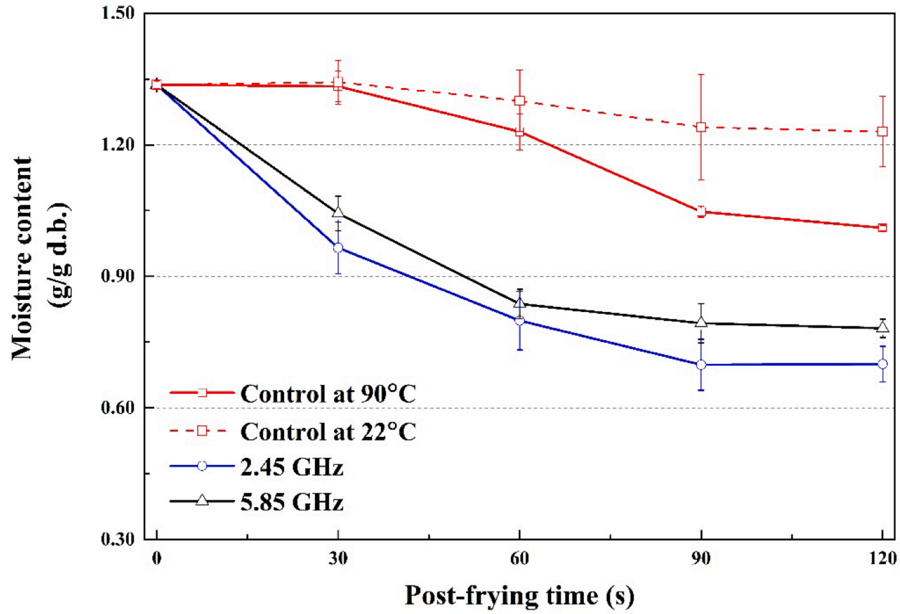
oil on the food surface continued to be heated by microwaves and more easily drained off from the surface due to reduced viscosity (Liu, Tian, Duan, Li, & Fan, 2021). During the subsequent cooling, there was little surface oil available for pickup by the French fries. As described above, oil viscosity has been considered as one of the key factors in determining oil absorption (Bouchon, 2009; Yang et al., 2019). In many frying applications, oil reduction of foods can be achieved by decreasing the oil viscosity or using frying oil with low viscosity (Liberty et al., 2019; Yang et al., 2019); (2) a great amount of vapor pressure was generated in French fries and increased the pore pressure of the samples. It could help to resist oil penetration. The investigation of the gage pore pressure during microwave heating needs further detailed research.

It is interesting to note that microwaves at 5.85 GHz reduced more oil contents than microwaves at 2.45 GHz. Most oil is retained in the crust region of a French fry (Bouchon, 2009). 2.45 GHz microwaves have a larger penetration depth (7 mm) than 5.85 GHz microwaves (2 mm) in potatoes (Tang, 2005). Given that the geometry of a potato strip was 9.5 mm × 9.5 mm × 60 mm in this study, it was most likely that microwaves at 5.85 GHz could focus on the crust and increase the pore pressure in the crust region to expel the oil out.

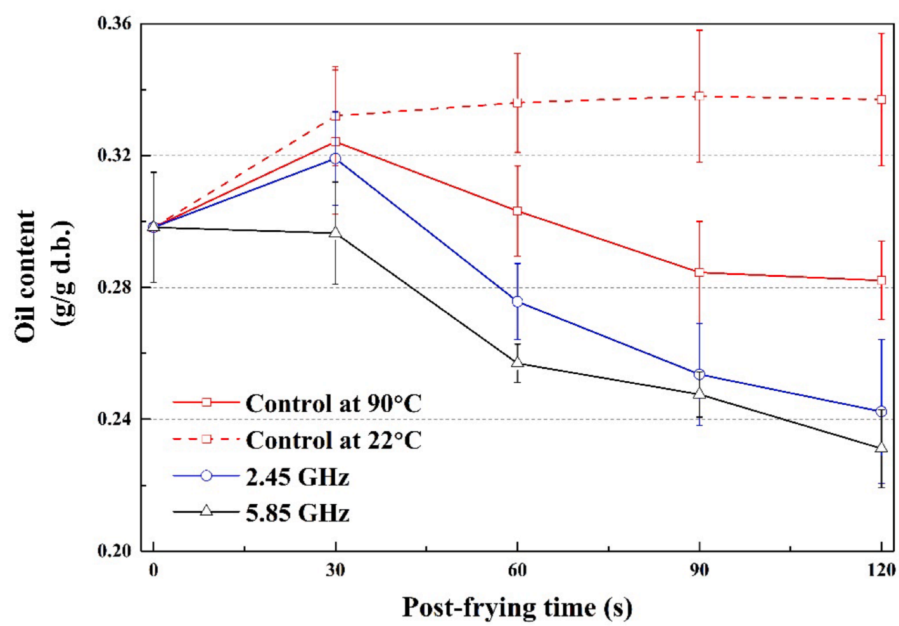
In practice, after frying food baskets are shaken to remove excessive surface oil (Bingol et al., 2012). Such de-oiling could be utilized with our microwave post-frying method for further oil reduction.

3.2.2. Texture and color

The two control groups (held at 22 or 90 °C) showed the similar values of color and texture properties (data not shown), so only the control samples held at 90 °C (~in the microwave cavity) during the



(a)



(b)

Fig. 6. Changes of (a) moisture content (mean ± standard deviations) and (b) oil content (mean ± standard deviations) during control at 90 °C (held inside the microwave cavity), control at 22 °C (held at room temperature) and microwave post-frying at two frequencies (2.45 GHz and 5.85 GHz), n = 3.

post-frying will be discussed and compared with the microwave treatments in the following manuscript.

Fig. 7 shows the changes of textural properties, including peak force and work (work input to puncture samples), of French fries during post-frying treatments. For control samples, both the peak force and work values remained almost constant. For French fries treated by post-frying microwave heating, the peak forces and work increased steadily with treatment time, up to 90 s, due to an increase in dehydration by microwave heating. The values decreased as microwave heating progressed. It was likely due to the "moisture leveling effect" of microwaves (Zhou & Wang, 2019). The portion of food with higher moisture would absorb more microwave energy than that with lower moisture content (Zhou & Wang, 2019). The crust regions of French fries are usually more dehydrated than the interior. Water molecules in the interior of French fries might be heated more during post-frying microwave heating and migrate to the surface crust. Since the crispness of French fries is directly correlated with the moisture content of the crust (Sanz, Primo-Martin, & van Vliet, 2007), the surface hardness of French fries decreased with the water migration. Further research is needed to analyze the water distribution in French fries by using nuclear magnetic resonance or confocal laser scanning method.

Table 4 shows the color of samples treated by different post-frying methods. L^* values became constant as post-frying proceeded, which indicated that post-frying did not influence the brightness of French fries. At 60 s after frying, the ΔE values of microwave processed samples were < 7, in particular for the sample produced by 5.85 GHz microwave

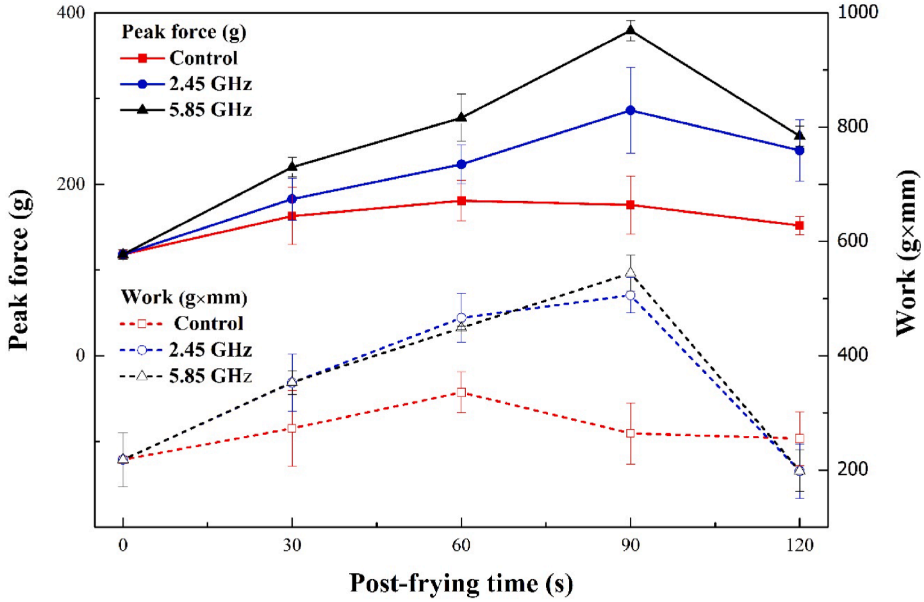
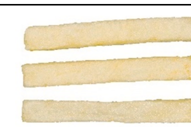
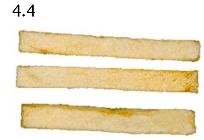


Fig. 7. Changes of textural properties (mean ± standard deviations) of French fries during control (no microwave energy) and microwave post-frying at two frequencies (2.45 GHz and 5.85 GHz), n = 3.

Table 4
Effect of post-frying methods on color changes of French fries.

Time (s)	Color	Post-frying methods[†]		
		Control	2.45 GHz microwaves	5.85 GHz microwaves
60	Images			
	L^*	86.4 ± 4.1a*	85.4 ± 4.4a	86.6 ± 3.8a
	a^*	−0.2 ± 0.8a	0.2 ± 0.9a	0.0 ± 0.8a
	b^*	19.5 ± 5.4a	26.4 ± 9.1a	23.9 ± 6.9a
	ΔE	–	6.9	4.4
90	Images			
	L^*	88.4 ± 6.6a	78.1 ± 6.7a	80.5 ± 6.6a
	a^*	−1.8 ± 1.0b	1.4 ± 1.5ab	1.9 ± 1.6a
	b^*	19.3 ± 5.0a	29.1 ± 7.4a	33.7 ± 9.8a
	ΔE	–	13.2	15.9

[†] Control: no microwaves; 2.45 GHz microwaves: microwave heating at 2.45 GHz; 5.85 GHz microwaves: microwave heating at 5.85 GHz.
[*] Values within a row followed by the same lowercase letter are not significantly different at $p > 0.05$, n = 3.

heating (ΔE = 4.4), which indicated that there was not a strong color difference between controls and microwave treated samples (Qu et al., 2021). However, higher b^* and a^* values for microwave treated samples were observed at longer heating times, which suggested that dark-color compounds were produced. Localized dark color was observed at 90 s and 120 s of microwave heating, and such color patterns were similar to those during frying (as discussed in *Section 3.1.3*). Therefore, 60 s of microwave heating in post-frying was recommended to minimize oil uptake without compromising texture and color.

4. Conclusions

As compared to the heated-oil frying, microwave frying reduced total frying times of French fries with equivalent product quality attributes in terms of oil content, moisture content, color, and texture. It was not microwave frying but rather the microwave post-frying which was the key factor for oil reduction of French fries. Additional 60 s microwave heating after frying reduced oil content by 18 – 23%. This study also demonstrated that microwaves at 5.85 GHz would be more suitable for French fries than 2.45 GHz microwaves regarding oil reduction and texture improvement.

CRediT authorship contribution statement

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

Declaration of Competing Interest

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

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