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Impact of novel far-infrared frying technique on quality aspects of chicken nuggets and frying medium

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Abstract

The impact of far-infrared and conventional heaters on heat distribution and physicochemical qualities of chicken nuggets and frying medium were investigated. For chicken nuggets, moisture content, fat content, color (L^*, a^*, and b^*), and texture characteristics were determined, while free fatty acid (FFA), peroxide value (PV), total polar materials (TPMs), and color were used to measure the quality of frying oil. A higher heating rate and more uniform heat distribution were observed in the far-infrared frying. Physicochemical qualities of chicken nugget were not significantly influenced by type of heater, except the fat content in the crust was significantly higher ($p < 0.05$) in far-infrared fried samples. The FFA, TPM, and color values of frying oil were better in far-infrared frying. Far-infrared frying can be used for about 56 and 115 more cycles than conventional frying when using FFA of 0.8% and TPM of 25%, respectively as an indicator to discard the oil.

Practical application

These results present a novel technology for using far-infrared radiation in deep-fat frying process. The far-infrared radiation provides a way of uniform heating of food. In addition, it therefore shortens frying time, saves energy, and prolong the shelf life of frying medium.

1 | INTRODUCTION

Deep-fat frying is a complex process of heat and mass transfer which involves immersing food in hot oil at a temperature above the boiling point of water (Rocío Teruel, García-Segovía, Martínez-Monzó, Belén Linares, & Dolores Garrído, 2014; Vitrac, Trystram, & Raoultwack, 2015). Simultaneously, physicochemical and structural changes, such as water loss, oil uptake, protein denaturation, crust formation, starch gelatinization, and color formation occur in fried foods, resulting in a unique flavor, appearance, and taste (Adedeji, Liu, & Ngadi, 2011; Karimi, Wawire, & Mathooko, 2017; Mir-Bel, Oria, & Salvador, 2012). The frying process can also substantially reduce weight and volume, minimizing packing, storage, and transportation costs in some products. However, frying is accompanied by many chemical reactions such as lipid oxidation, hydrolysis, polymerization, and fission of the frying medium (Li et al., 2019). These reactions lead to by-products such as aldehydes, ketones, peroxides, esters, etc., which are absorbed by the finished products (Nayak et al., 2016) and many of these compounds have been shown to have adverse effects on human health (Venkata & Subramanyam, 2016). Recently, many studies have proposed new techniques to improve the frying process by either reducing the oil uptake in fried products and/or increasing the stability of the frying medium by, for example, vacuum frying (Belkova et al., 2018; Pan, Ji, Liu, & He, 2015), ultrasonic microwave-assisted vacuum frying (Devi, Zhang, & Law, 2018; Su, Zhang, Zhang, Liu, & Adhikari, 2018), pressure frying (Das, Pawar, & Modi, 2013; Pawar, Boomathi, Hathwar, Rai, & Modi, 2013), microwave frying (Parikh & Takhar, 2016), and radiant frying (Nelson et al., 2013; Lloyd, Farkas, & Keener, 2004).

Infrared (IR) is one of the promising technologies that has been introduced in the food processing industry, especially in baking, roasting, drying, thawing, and pasteurization (Melito & Farkas, 2013; Sakai & Hanzawa, 1994). In general, IR radiation is electromagnetic radiation transmitted as a wave and converted into heat when it touches the food surface (water molecules and ions) (Bingol, Wang, Zhang, Pan, & McHugh, 2014; Cullen, Tiwari, & Valdramidis, 2011). Based on the wavelength, IR can be divided into three regions including near-IR (0.78–1.4 μm), mid-IR (1.4–3.0 μm), and far-IR (3.0–1,000 μm). Far-IR radiation is advantageous for food processing because most food components can absorb radiative energy in far-IR region (Rastogi, 2012). In comparison with convective and conductive heating mechanisms, IR heating provides less degradation of nutritional components as well as higher thermal efficiency and more uniform heating (Sandu, 1986), which reduces processing time and energy costs.

Although the integration of far-IR with other processing operations, such as blanching (Chen et al., 2018; Jamali, Kashanunejad, Amirabadi, Aalami, & Khomeiri., 2018), convective-drying (Adak, Heybeli, & Ertekin, 2017; Ding et al., 2018; Savas & Basman, 2016), freeze-drying (Song, Hu, & Zhang, 2018; Wang, Zhang, & Adhikari, 2015), thawing (Reis et al., 2017), roasting (Yang et al., 2010; Bagheri et al., 2016), and baking (Nicolas, Glouannec, Ploteau, Salagnac, & Jury, 2017; Ploteau, Glouannec, Nicolas, & Magueresse, 2015) has been shown to be a new processing option, it does not extensively apply as a replacement method for deep-fat frying. Thus, the objective of this study was to investigate the effects of far-IR and conventional heat on the heat distribution and physicochemical characteristics of chicken nuggets and frying medium.

2 | MATERIALS AND METHODS

2.1 | Frying experiments

Pre-cooked chicken nuggets with a size of 3.5 × 5 × 1.2 cm and an average weight of 21 ± 1.5 g were purchased from CP Interfood (Thailand) Co. Ltd., Bangkok, Thailand and frozen at −10°C before use and brought to refrigerator temperature at 4°C for 24 hr before frying experiment. The coating layer thickness was approximately 0.15 cm and it was comprised of wheat flour, salt, spices, bicarbonate, yeast, and xanthan gum, while the core part composed of chicken breast, salt, phosphate, and albumin. Refined palm oil was obtained from Morakot Industry Co. Ltd., Bangkok, Thailand.

The frying process was performed in a commercial dual-unit electric batch fryer (Sripipat Engineering, Bangkok, Thailand) with a size of 40 × 30 × 20 cm and a capacity of 12 L of frying oil (Figure 1). The control consisted of the conventional heater with a power of 2000 W and output of 200 V, while the far-IR heater with similar power and output was used in the infrared frying treatment. The materials in the far-IR heater were mainly composed of magnesium oxide (MgO), silicon dioxide (SiO_2), and aluminum oxide (Al_2O_3). The oil was set at the temperature 180°C using a programmable temperature controller prior frying. Each batch of 500 g (about 25 pieces) chicken nuggets was fried at a set temperature of 180°C in 7.5 L of heated oil for 3.5 min. To monitor the core temperature of chicken nugget which should be 75°C for at least 30 s, the temperature of each sample was recorded by inserting a T-type thermocouple in a core point connected to a data logger (TC-08, Pichotechnology Co, UK). The core temperature was immediately measured after chicken nuggets were placed into the fryer. The fried samples were then allowed to cool at ambient temperature (25°C). Five samples were randomly collected from every eighteenth cycle of frying process and kept in desiccators prior physicochemical analyses. The process was conducted for 324 cycles/type of heater. One cycle of frying started from loading sample to the fryer, frying, and withdrawing samples, preparing the sample for the next cycle, and waiting for the temperature of the frying oil to build back up. Each cycle was carried out for 5.5 min.

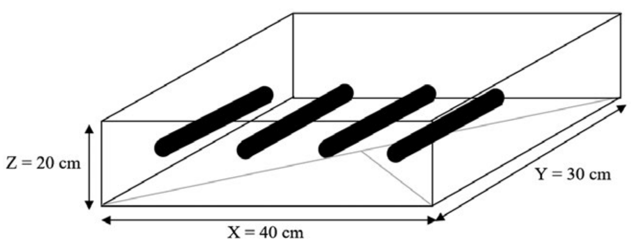

FIGURE 1 The position of heaters in the batch fryer

To evaluate the quality of frying oil, the temperature was continuously maintained at 180°C for the rest of the cycle even if food materials were being unloaded. After every ninth cycle, 50 ml of the frying oil sample was individually collected into closed containers, sealed off with caps to prevent oxidation, air-cooled at room temperature in a dark room for 1 hr, and then kept at 7°C until further analyses. In order to maintain the same volume of oil throughout (Hao, Li, & Yao, 2016), a small amount of fresh oil (about 50 ml) was added to the fryer. Each treatment had three replications. The free fatty acid (FFA), peroxide value (PV), total polar material (TPM), and color (L^*, a^*, and b^*) parameters were measured to determine the rate of deterioration.

2.2 | Evaluation of heat distribution from heaters to frying medium

Without frying, 7.5 L of palm oil was added into a bath fryer and the oil was heated by conventional and far-IR heaters to a temperature of 100 and 180°C for 40 min. An increase in temperature was recorded by a T-type thermocouple with a diameter of 1 mm connected to a data logger (TC-08, Pichotechnology Co, UK). A recorded temperature from seven different positions as shown in Figure 2 was used to analyze heat distribution from heater to frying medium at 10 and 40 min using the finite element method. In addition, heating rate was also calculated and presented as °C/min. The temperature measurement at each position was performed in ten replications.

2.3 | Analysis of fried chicken nuggets

In the physicochemical analyses, 95 pieces of fried chicken nuggets which were randomly collected from every 18th cycle of frying process were used. The moisture content of the chicken meat and its crust was individually determined using the AOAC method (1990). The sample was dried at 105°C for 16 hr in a hot air oven (model UF55, Memmert Oven, Germany). The loss in weight was recorded as moisture and the test was repeated three times for each frying treatment.

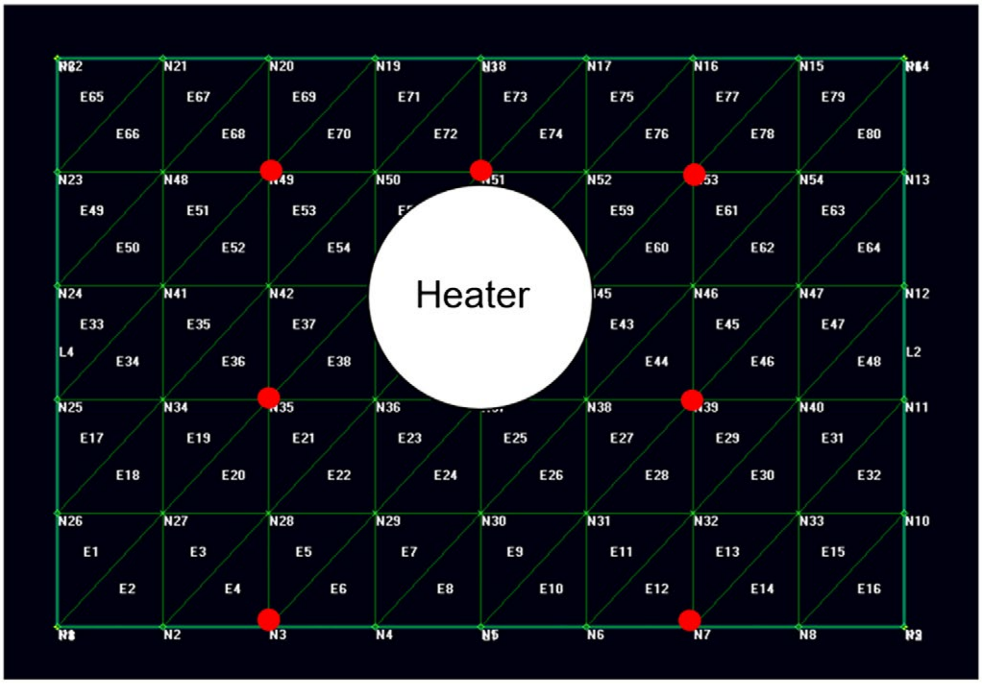

FIGURE 2 The cross-sectioned model of batch fryer and the positions for temperature measurement (•)

Total oil content of meat mass and crust was also individually analyzed using the Soxhlet extraction technique (model HT6, Soxtec™ extraction, Denmark) with hexane (AOAC, 1990). Analysis determinations were performed for each frying treatment in triplicate.

The surface color of the nuggets including crust was measured using a colorimeter (Color-view™ spectrophotometer, model 9000, Gardner, USA). Before the test measurement, the colorimeter was calibrated to a white plate (CIE L^* = 98.76, a^* = −0.19, b^* = −0.06). The L^*, a^*, and b^* values were recorded to present the color development of fried products and the test was repeated five times for each frying treatment.

The method of Rahimi, Kashaninejad, Ziaiifar, and Mahoonak (2018) was modified to determine the texture characteristics of fried chicken nugget. A texture analyzer (model TA-XT2i, Stable Micro System Co. Ltd, UK) was applied to measure index of firmness, hardness, and breaking distance of the nuggets including crust. Each nugget was cut into dimensions of 20 × 20 × 20 mm. The speed of the blade set with compression probe (5 mm diameter) was set up for the pretest at 5 mm/sec, test 2 mm/sec, and posttest speed at 5 mm/sec. The probe was set 10 mm above the sample. The maximum force value was considered as an indicator of the hardness, while the curve slope was used as an indicator of index of firmness, and the distance from the initial point to the maximum force point as an indicator of displacement (breaking distance). The measurement was done at room temperature and each treatment was tested in ten replications.

2.4 | Analysis of frying oil

The percentages of FFA were analyzed by the titration method as described in AOCS official method Ca 5a-40 (AOCS, 1990). Briefly, 1 g of oil sample was precisely weighed into an Erlenmeyer flask. Ten milliliters of 95 ml/L ethanol and a phenolphthalein indicator were added to the flask with volumetric dispensers and shaken vigorously. The mixture was then titrated against 0.1 mol/L sodium hydroxide solution until a consistent pink color persisted for at least 30 s. Weight percentage of FFA was calculated based on oleic acid and the test was repeated three times.

The PV was determined according to the standard AOCS official method Cd 8-53 (AOCS, 1990). About 2 g of frying sample was dissolved in 30 ml of a mixture of 2 L chloroform /3L acetic acid and then 1 ml of freshly prepared saturated potassium iodide solution was added to react in darkness for 3 min. Subsequently, 30 ml of distilled water and 1–2 drops of 1 g/100 g starch solution were added and the liberated iodine was titrated with a 0.1 mol/L sodium thiosulfate solution. The PV was expressed as milli-equivalents of active oxygen per kg of oil (meq O_2/kg) and the test was repeated three times.

The content of TPMs in the oil sample was analyzed using the AOCS official method Cd 20–91 (AOCS, 1990). A glass column (length 35 cm, diameter 2.1 cm) was used for chromatography and a mixture of 870 ml petroleum/130 ml diethyl ether was prepared as an eluent. About 2.5 g of sample was loaded into the packed column and the nonpolar fraction was eluted. The content of TPMs (%) was calculated as the mass fraction of the total polar compounds in the oil sample. The test was repeated three times.

A Tintometer (model PFX190, Lovibond, England) was used to determine oil color. Three color readings were taken from each sample with the average used for analysis. The L^*, a^*, and b^* values of the frying oil were measured.

2.5 | Data analysis

The effect of different heaters on the heat distribution and qualities of fried chicken nugget and frying oil samples was subjected to statistical analyses using the General Linear Model Program (GLM). Least Significant Difference (LSD) estimated the differences among the means of each treatment at 5% of the probability level using the SAS program (SAS, 2000). The heat distribution by finite element method was evaluated using the EasyFEM mathematical software (Dechaumphai & Phongthanapanich, 2009).

3 | RESULTS AND DISCUSSION

3.1 | Heat distribution from heaters to frying medium

The results showed that far-IR heater significantly reduced ($p < 0.05$) heating time to reach a temperature of 100 and 180°C (Table 1). This resulted in a significant increase of heating rate. For example, the heating rate of far-IR increased by 52% at 100°C and 45% at 180°C when compared to the conventional heater. In addition, the effect of heaters on the heat distribution in the frying chamber was simulated during heating as shown in Figure 3. A faster heat distribution was observed for the far-IR heater at both 10 and 40 min. Since current information about heat distribution under frying with far-IR radiation is very limited in the literature, this can most likely be explained by the properties of far-IR as it can transmit as a wave and be converted into heat when it touches the surface of materials through changes in the molecular vibrational state (Ginzburg, 1969; Rastogi, 2012). This might be confirmed by a study of Rahimi et al. (2018) who reported that the infrared system can increase the effective moisture diffusivity value during cooking of chicken nuggets and the value increased greatly with increasing power of infrared heat.

3.2 | Physicochemical characteristics of fried chicken nuggets

There was no significant difference in all chemical and physical attributes of fried samples obtained from far-IR frying and conventional frying, except the fat content in the crust (Table 2). Due to more heat distribution of far-IR, the sample fried under far-IR resulted in significantly higher ($p < 0.05$) fat content in the crust compared with conventional frying. It could be seen that lower moisture content led to higher oil uptake in the fried products. This is in an agreement of Krokida, Oreopoulou, and Maroulis (2000) and Southern, Chen, Farid, Howard, and Eyres (2000) who reported a linear relationship between oil uptake and moisture loss. As capillary pores increase at initial steps of the frying, Bouchon, Aguilera, and Pyle (2003) stated that the vigorous escape of water vapor and related high inner pressure impede oil penetration into the products. Therefore, oil uptake would be essentially a surface-related phenomenon that involves equilibrium between surface drainage and suction during post-frying cooling (Baumann & Escher, 1995; Bouchon et al., 2003; Krokida et al., 2000; Pan et al., 2015). In particular, once the chicken nuggets were removed from the fryer, their temperature slowly dropped, subsequently the interfacial tension between oil and gas vapor declined and the surface oil rapidly started diffusing to the porous surface, leading to an increase in oil uptake. A higher heating rate of far-IR heater might be related to a higher increase in temperature of the samples, leading to higher thermal denaturation and contraction of proteins on the chicken nuggets (Oroszvári et al., 2006). Hughes et al. (2014) indicated that these alteration in the structure of myofibrillar proteins caused the loss of water in the chicken nuggets. However, Pankaj and Keener (2017) stated that radiant frying relies on a constant heat flux from an emission source to maintain a set point temperature of the product's environment. Rahimi et al. (2018) reported that a higher IR cooking intensity resulted in lower oil content in partially fried chicken nuggets. This observation was in agreement with a study of Melito and Farkas (2013) during IR cooking of donut.

3.3 | Changes of frying medium

As hydrolysis produces mono- and di-acylglycerols, glycerol, and FFAs and these substances increase with increased frying cycles (Chung, Lee, & Choe, 2004), the FFA value is used by many fried food industries as an indicator to monitor the degree of hydrolysis of frying oil (Choe & Min, 2007). In this study, the results showed that FFA content in both far-IR and conventional frying gradually increased from 0 to 324 cycles of frying (Figure 4). This can be ascribed to the effect of hydrolysis reaction in which water vapor released from the inside and surfaces of the chicken nuggets consequently reacted with triglycerides and formed FFA. Also, Kun (1990) indicated that the change of FFA content could be caused by further oxidation of secondary products made during frying. In particular, FFA in the conventional frying was 0.20% and reached 1.46% after the 324th cycle of frying, whereas FFA content in far-IR frying was lower by 38.4% when compared with the control at the last cycle

TABLE 1 Heating time and heating rate of heaters to frying medium

	Heating time (min)[A]		Heating rate (°C/min)	
Type of heaters[B]	100°C	180°C	100°C	180°C
Far-IR	8.4[a] (0.3)	28.0[a] (0.7)	11.9[b] (0.4)	6.4[b] (0.2)
Conventional	17.8[b] (0.4)	51.5[b] (1.2)	5.7[a] (0.1)	3.5[a] (0.1)

[A]Numerical number in the table presented $\bar{x}$ (*SD*)
[B]The average data obtained from seven measurement positions/replication.
[a,b]Means within a row with different letters are significantly different ($p \le 0.05$).

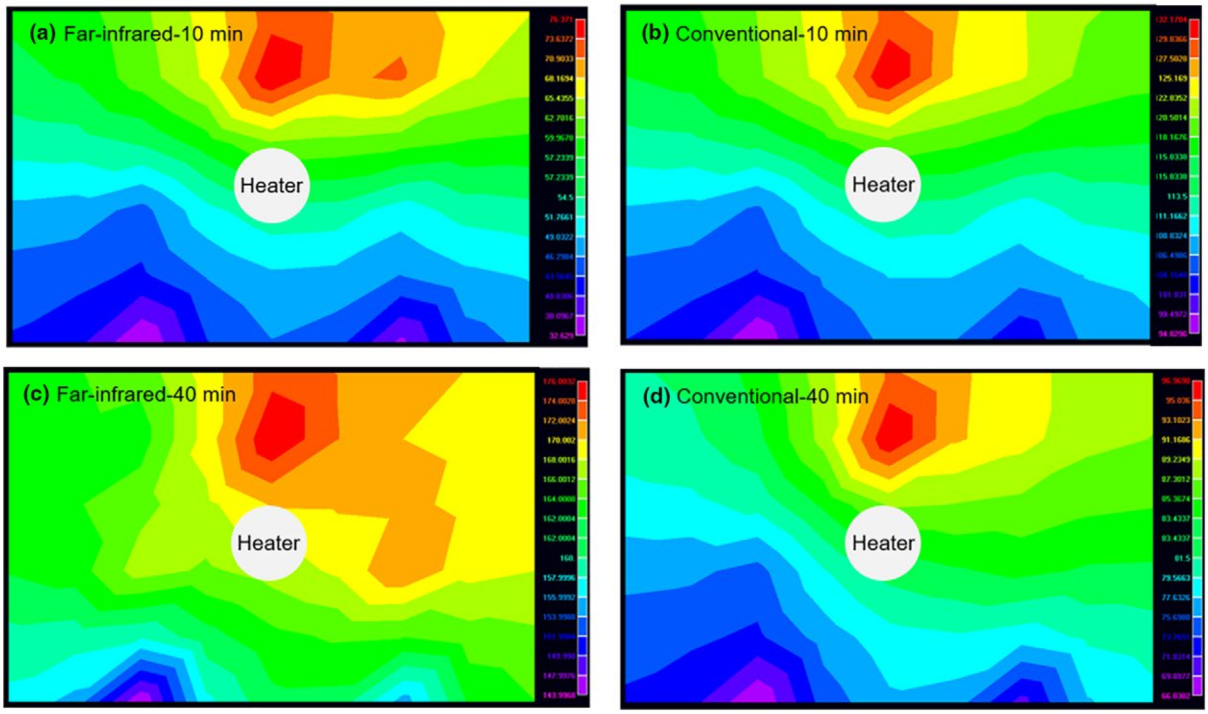

FIGURE 3 Heat distribution inside the batch fryer during heating frying medium at 180°C with (a, c) far-IR and (b, d) conventional heaters for 10 and 40 min. Colors indicate temperature

TABLE 2 Physicochemical characteristics of fried chicken nuggets obtained from far-IR and conventional heaters

	Type of heaters	
Characteristics[B]	Far-IR[A]	Conventional
Moisture content (g water/100 g) (*N* = 9)		
Crust	25.1[a] (1.9)	27.2[a] (3.6)
Core	61.8[a] (1.0)	62.5[a] (1.6)
Fat content (g/100 g) (*N* = 9)		
Crust	29.5[a] (1.6)	26.1[b] (2.6)
Core	13.3[a] (1.9)	11.9[a] (2.2)
Color (*N* = 15)		
*L**	57.0[a] (1.3)	56.4[a] (1.3)
*a**	10.0[a] (10.0)	9.7[a] (0.8)
*b**	31.0[a] (3.0)	29.4[a] (2.6)
Texture (*N* = 30)		
Hardness (*N*)	0.8[a] (0.1)	0.9[a] (0.1)
Index of firmness (*N*/s)	93.7[a] (10.9)	116.2[a] (6.2)
Displacement (mm)	10.1[a] (0.0)	10.0[a] (0.0)

[A]Numerical number in the table presented $\bar{x}$ (*SD*)
[B]The average data obtained from 19 cycles of frying process/replication.
[a,b]Means within a column with different letters are significantly different ($p \le 0.05$).

of frying. When using FFA of 0.8% as an indicator to discard frying medium, it could be seen that far-IR frying can be used for about 56 more cycles than conventional frying. This result might be explained by the fact that when a material is exposed to radiation by far-IR, it is heated intensely and the temperature gradient in the material reduces within a short period (Rastogi, 2012), therefore reducing the oil deterioration rate when compared to conventional heating.

Thermal oxidation continuously leads to formation of hydroperoxides (primary oxidation products) (Che Man & Jaswir, 2000), thus the PV value is used to assess the oxidative state of frying oils. The initial PV was 4.82 meq O_2/kg and it was increased to 15.12 meq O_2/kg for far-IR and 19.25 meq O_2/kg for conventional frying after 324 cycles of frying (Figure 5). As the frying time increased, the level of PV obviously fluctuated in both far-IR and conventional frying. However, it should be noted that these primary oxidation products rapidly break down into secondary or tertiary oxidation products such as unsaturated aldehydes, conjugated dienoic acids, epoxides, hydroxides, and ketones (Bansal et al., 2010; Innawong, Mallikarjunan, & Marcy, 2004). Therefore, the total accumulation of PV in frying medium can be greatly underestimated.

The presence of TPMs indicates degradation of oils and the breakdown of triglycerides, mainly resulting in the formation of oligomeric triacylglycerols, dimeric triacylglycerols, oxidized triacylglycerols, diacylglycerols, and free fatty acids (Aniołowska & Kita, 2015, 2016). Blumenthal (1991) referred TPMs to all oxidized and dimerized triglycerides, FFAs, mono- and di-glycerides, sterols, carotenoids, antioxidants, anti-foamers, crystal inhibitors, bleaching earth, filter-aid, hydrogenation catalyst residues, soaps, residues of chlorophyll, and phospholipids, and other materials that are soluble, emulsified, or present as suspended particulates in the frying oil as polar materials (Romano, Giordano, Vitiello, Grottaglie, & Musso,

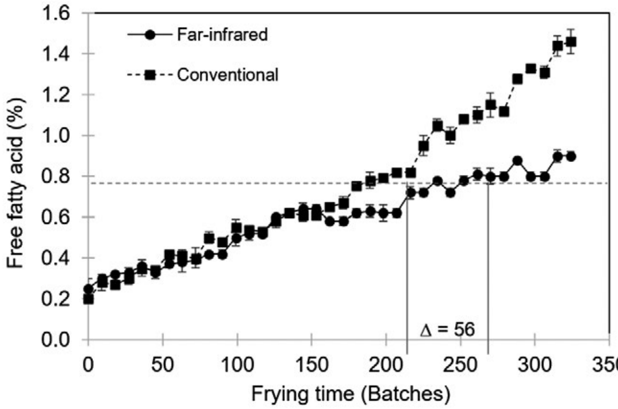

FIGURE 4 Changes of free fatty acid (%FFA) during frying with far-IR and conventional heaters

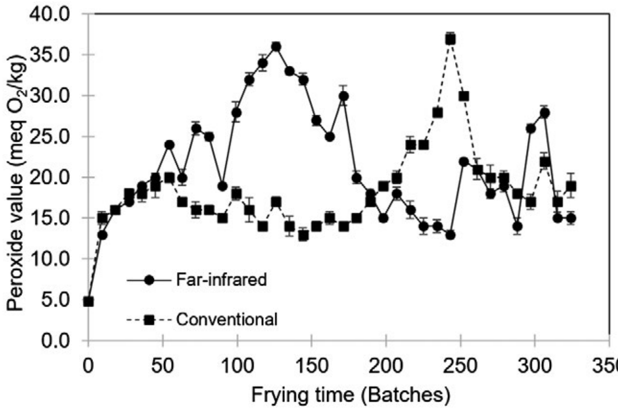

FIGURE 5 Changes of peroxide value (meq O_2/kg) during frying with far-IR and conventional heaters

2012). TPMs are commonly considered as the most reliable method to measure oil degradation during the frying process (Melton, Jafar, Sykes, & Trigiano, 1994). In this study, TPMs gradually increased in both far-IR and conventional frying over time during the 324 cycles of frying. The TPMs of conventional frying increased from 10.25% to 34.12% at the end of frying operations (Figure 6). The TPM was lower by 7.4% in far-IR frying when compared to conventional frying. Gertz and Stier (2011) indicated that the maximum level of TPMs above which oil should be discarded is 25–27%. This is similar to Thailand where the maximum level of TPMs in frying oil have been set at 25%. The result could be observed that far-IR frying can be used for 280 cycles, while conventional frying was discarded at 165 cycles of frying. Because the far-IR system required less time to heat the oil and constantly maintained the temperature during frying, less TPMs were accumulated in far-IR frying.

Color is another indicator of frying oil quality (Bheemreddy, Chinnan, Pannu, & Reynolds, 2002; Karimi et al., 2017). The color change of frying oil can occur by Maillard reaction due to the interaction between sugar and amino acids (Lin, Akoh, & Reynolds, 2001). The intensity of browning by the Maillard reaction is mainly linked to

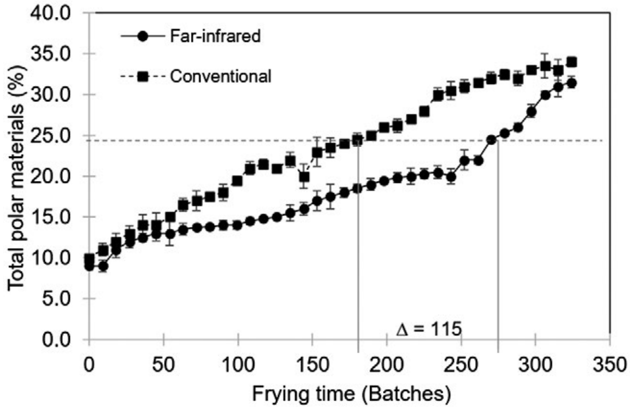

FIGURE 6 Changes of total polar materials (%TPM) during frying with far-IR and conventional heaters

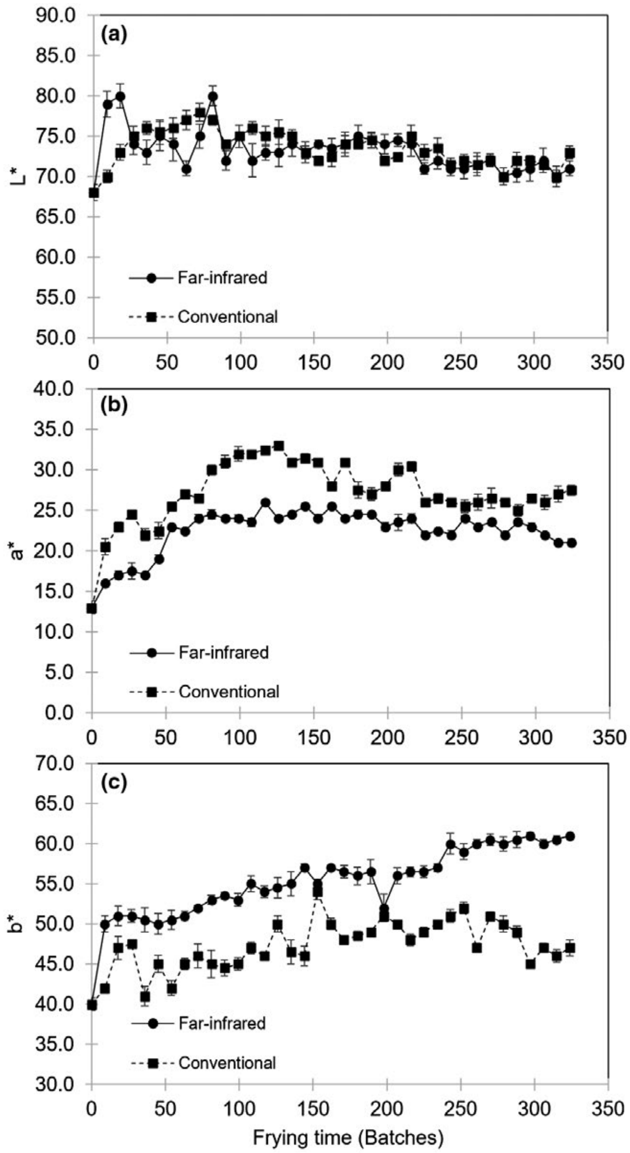

FIGURE 7 Changes of colors during frying with far-IR and conventional heaters: (a) L^*, (b) a^*, and (c) b^* values

losses of lysine, histidine, and methionine. The interaction between epoxyalkenals and proteins produces polypyrrolic polymers and volatile heterocyclic compounds (Hidalgo & Zamora, 2000). In addition, the accumulation of highly conjugated oxidation products caused by oxidation, pyrolysis, and polymerization can also lead to color change in the frying medium (Sebastian, Ghazani, & Marangoni, 2014). In this study, the initial frying medium exhibited a color of 68.15 for *L**, 13.06 for *a**, and 40.23 for *b** (Figure 7). After 324 cycles of frying, the color values of the far-IR frying increased by 4.4% for *L**, 61.5% for *a**, and 52.5% for *b**, while the values were increased by 7.4% for *L**, 111.5% for *a**, and 17.5% for *b** in conventional frying. This indicated that far-IR frying tends to reduce the color change of frying oil.

4 | CONCLUSIONS

Far-IR frying had a more favorable impact on heating rate and heat distribution when compared with conventional frying. The physicochemical qualities of finished products were not affected by type of heat, except fat content in the crust was significantly higher when far-IR heat was applied. In addition, far-IR heat proved to be a promising technology to slow down the oil deterioration rate as could be observed from lower values of FFA, TPMs, and *a**. Based on this study, it can be concluded that far-IR heat was the most effective way than conventional heat in preserving the quality of fried products and frying medium. To understand the interaction between far-IR frying and the food matrix system, further research is still required to process optimal frying times for a wide range of products.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

ETHICAL STATEMENT

This study does not involve any human or animal testing.

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REFERENCES

Adak, N., Heybeli, N., & Ertekin, C. (2017). Infrared drying of strawberry. *Food Chemistry*, *219*, 109–116. https://doi.org/10.1016/j.foodchem.2016.09.103

Adedeji, A. A., Liu, L., & Ngadi, M. O. (2011). Microstructural evaluation of deep-fat fried chicken nugget batter coating using confocal laser scanning microscopy. *Journal of Food Engineering*, *102*(1), 49–57. https://doi.org/10.1016/j.jfoodeng.2010.08.002

Aniołowska, M., & Kita, A. (2015). The effect of type of oil and degree of degradation on glycidyl esters content during the frying of French fries. *Journal of the American Oil Chemists' Society*, *92*(11–12), 1621–1631. https://doi.org/10.1007/s11746-015-2715-3

Aniołowska, M., & Kita, A. (2016). The effect of frying on glycidyl esters content in palm oil. *Food Chemistry*, *203*, 95–103. https://doi.org/10.1016/j.foodchem.2016.02.028

AOAC. (1990). *Official methods of analysis* (15th ed). Arlington, VA: Author.

AOCS. (1990). *Official methods and recommended practice of the American Oil Chemist Society* (5th ed.). Champaign, IL: AOAC Press.

Bagheri, H., Kashaninejad, M., Ziaiifar, A. M., & Aalami, M. (2016). Novel hybridized infrared-hot air method for roasting of peanut kernels. *Innovative Food Science and Emerging Technologies*, *37*(Part A), 106–114. https://doi.org/10.1016/j.ifset.2016.08.014.

Bansal, G., Zhou, W., Barlow, P. J., Joshi, P., Neo, P. L., & Lo, H. L. (2010). Evaluation of commercially available rapid tests kits for the determination of oil quality in deep frying operations. *Food Chemistry*, *12*, 621–626. https://doi.org/10.1016/j.foodchem.2009.12.076

Baumann, B., & Escher, F. (1995). Mass and heat transfer during deep-fat frying of potato slices, rate of drying and oil uptake. *LWT-Food Science and Technology*, *28*, 395–403. https://doi.org/10.1016/0023-6438(95)90023-3

Belkova, B., Hradecky, J., Hurkova, K., Forstova, V., Vaclavik, L., & Hajslova, J. (2018). Impact of vacuum frying on quality of potato crisps and frying oil. *Food Chemistry*, *241*, 51–59. https://doi.org/10.1016/j.foodchem.2017.08.062

Bheemreddy, R. M., Chinnan, M. S., Pannu, K. S., & Reynolds, A. E. (2002). Active treatment of frying oil for enhanced fry-life. *Journal of the American Oil Chemists' Society*, *67*(4), 1478–1484. https://doi.org/10.1111/j.1365-2621.2002.tb10309.x

Bingol, G., Wang, B., Zhang, A., Pan, Z., & McHugh, T. H. (2014). Comparison of water and infrared blanching methods for processing performance and final product quality of French fries. *Journal of Food Engineering*, *121*, 135–142. https://doi.org/10.1016/j.jfoodeng.2013.08.001

Blumenthal, M. M. (1991). A new look at the chemistry and physics of deep-fat frying. *Food Technology*, *45(2)*, *68–71*, 94.

Bouchon, P., Aguilera, J. M., & Pyle, D. L. (2003). Structure oil-absorption relationships during deep-fat frying. *Journal of Food Science*, *68*, 2711–2716. https://doi.org/10.1111/j.1365-2621.2003.tb05793.x

Che Man, Y. B., & Jaswir, I. (2000). Effect of rosemary and sage extracts on frying performance of refined, bleached and deodorized (RBD) palm olein during deep-fat frying. *Food Chemistry*, *69*, 301–307. https://doi.org/10.1016/S0308-8146(99)00270-8

Chen, J., Venkitasamy, C., Shen, Q., McHugh, T. H., Zhang, R., & Pan, Z. (2018). Development of healthy crispy carrot snacks using sequential infrared blanching and hot air drying method. *LWT-Food Science and Technology*, *97*, 469–475. https://doi.org/10.1016/j.lwt.2018.07.026

Choe, E., & Min, D. B. (2007). Chemistry of deep-fat frying oils. *Journal of Food Science*, *72*(5), R77–R86. https://doi.org/10.1111/j.1750-3841.2007.00352.x

Chung, J., Lee, J., & Choe, E. (2004). Oxidative stability of soybean and sesame oil mixture during frying of flour dough. *Journal of Food Science*, *69*, 574–578. https://doi.org/10.1111/j.1365-2621.2004.tb13652.x

Cullen, P. J., Tiwari, B. K., & Valdramidis, V. (2011). *Novel thermal and non-thermal technologies for fluid foods*. London: Academic Press.

Das, R., Pawar, D. P., & Modi, V. K. (2013). Quality characteristics of battered and fried chicken: Comparison of pressure frying and conventional frying. *Journal of Food Science and Technology*, *50*, 284–292. https://doi.org/10.1007/s13197-011-0350-z

Dechaumphai, P., & Phongthanapanich, S. (2009). *Easy finite element method with software (CD-ROM)* (361 p.). New Delhi: Narosa Publishing House; Oxford Alpha Science International.

Devi, S., Zhang, M., & Law, C. L. (2018). Effect of ultrasound and microwave assisted vacuum frying on mushroom (*Agaricus Bisporus*) chips quality. *Food Bioscience*, *25*, 111–117. https://doi.org/10.1016/j.fbio.2018.08.004

Ding, C., Khir, R., Pan, Z., Wood, D. F., Venkitasamy, C., Tu, K., … Berrios, J. (2018). Influence of infrared drying on storage characteristics of brown rice. *Food Chemistry*, *264*, 149–156. https://doi.org/10.1016/j.foodchem.2018.05.042

Gertz, C., & Stier, R. (2011, May). *Recommendations for used frying oils and fats*. Presentation at the 6th International Symposium on Deep Frying-Errors and Myths of Industrial and Catering Frying: German Society for Fat Research (DFG), Hagen.

Ginzburg, A. S. (1969). *Application of infrared radiation in food processing*. London: Leonard Hill Books.

Hao, X., Li, J., & Yao, Z. (2016). Changes in PAHs levels in edible oils during deep-frying process. *Food Control*, *66*, 233–240. https://doi.org/10.1016/j.foodcont.2016.02.012

Hidalgo, F. J., & Zamora, R. (2000). The role of lipids in non-enzymatic browning. *Grasas Aceites*, *51*, 37–51. https://doi.org/10.3989/gya.2000.v51.i1-2.405

Hughes, J., Oiseth, S., Purslow, P., & Warner, A. (2014). A structural approach to understanding the interactions between colour, water-holding capacity and tenderness. *Meat Science*, *98*(3), 520–532.

Innawong, B., Mallikarjunan, P., & Marcy, J. E. (2004). The determination of frying oil quality using a chemosensory system. *LWT-Food Science and Technology*, *37*, 35–41. https://doi.org/10.1016/S0023-6438(03)00122-1

Jamali, S. N., Kashanunejad, M., Amirabadi, A. A., Aalami, M., & Khomeiri, M. (2018). Kinetics of peroxidase inactivation, color and temperature changes during pumpkin (*Cucurbita moschata*) blanching using infrared heating. *LWT-Food Science and Technology*, *93*, 456–462. https://doi.org/10.1016/j.lwt.2018.03.074

Karimi, S., Wawire, M., & Mathooko, F. (2017). Impact of frying practices and frying conditions on the quality and safety of frying oils used by street vendors and restaurants in Nairobi, Kenya. *Journal of Food Composition and Analysis*, *62*, 239–244. https://doi.org/10.1016/j.jfca.2017.07.004

Krokida, M. K., Oreopoulou, V., & Maroulis, Z. B. (2000). Water loss and oil uptake as a function of frying time. *Journal of Food Engineering*, *44*, 39–46. https://doi.org/10.1016/S0260-8774(99)00163-6

Kun, T. Y. (1990). *Improvements in the frying quality of vegetable oil by blending with palm olein* (Palm oil development No. 15). Bangi: Palm Oil Research Institute of Malaysia (PORIM).

Lin, S., Akoh, C. C., & Reynolds, A. E. (2001). Recovery of used frying oils with adsorbent combinations: Refrying and frequent oil replenishment. *Food Research International*, *34*, 159–166. https://doi.org/10.1016/S0963-9969(00)00147-2

Li, X., Wu, G., Yang, F., Meng, L., Huang, J., Zhang, H., … Wang, X. (2019). Influence of fried food and oil type on the distribution of polar compounds in discarded oil during restaurant deep frying. *Food Chemistry*, *272*, 12–17.

Lloyd, B. J., Farkas, B. E., & Keener, K. M. (2004). Quality comparison of French fry style potatoes produced by oven heating, immersion frying and controlled dynamic radiant heating. *Journal of Food Processing and Preservation*, *28*, 460–472. https://doi.org/10.1111/j.1745-4549.2004.23075.x

Melito, H. S., & Farkas, B. E. (2013). Physical properties of gluten-free donuts. *Journal of Food Quality*, *36*, 32–40. https://doi.org/10.1111/jfq.12008

Melton, S. L., Jafar, S., Sykes, D., & Trigiano, M. K. (1994). Review of stability measurements for frying oils and fried food flavor. *Journal of the American Oil Chemists' Society*, *71*, 1301–1308. https://doi.org/10.1007/BF02541345

Mir-Bel, J., Oria, R., & Salvador, M. L. (2012). Influence of temperature on heat transfer coefficient during moderate vacuum deep-fat frying. *Journal of Food Engineering*, *113*(2), 167–176. https://doi.org/10.1016/j.jfoodeng.2012.06.009

Nayak, P. K., Dash, U., Rayaguru, K., & Krishnan, K. R. (2016). Physiochemical changes during repeated frying of cooked oil: A review. *Journal of Food Biochemistry*, *40*(3), 371–390.

Nelson, L. V., Keener, K. M., Kaczay, K. R., Banerjee, P., Jensen, J. L., & Liceaga, A. (2013). Comparison of the FryLess 100K Padiant Fryer to oil immersion frying. *LWT-Food Science and Technology*, *53*, 473–479. https://doi.org/10.1016/j.lwt.2013.03.009

Nicolas, V., Glouannec, P., Ploteau, J. P., Salagnac, P., & Jury, V. (2017). Experiment and multiphysic simulation of dough baking by convention, infrared radiation and direct conduction. *International Journal of Thermal Sciences*, *115*, 65–78. https://doi.org/10.1016/j.ijthermalsci.2017.01.018.

Oroszvári, B. K., Ingegerd, E. B., & Tornberg, S. E. (2006). The mechanisms controlling heat and mass transfer on frying of beefburgers. III. Mass transfer evolution during frying. *Journal of Food Engineering*, *76*(2), 169–178.

Pan, G., Ji, H., Liu, S., & He, X. (2015). Vacuum frying of breaded shrimps. *LWT-Food Science and Technology*, *62*, 734–739. https://doi.org/10.1016/j.lwt.2015.01.007

Pankaj, S. K., & Keener, K. M. (2017). A review and research trends in alternate frying technologies. *Current Opinion in Food Science*, *16*, 74–79. https://doi.org/10.1016/j.cofs.2017.09.001

Parikh, A., & Takhar, P. S. (2016). Comparison of microwave and conventional frying on quality attributes and fat content of potatoes. *Journal of Food Science*, *81*, E2743–E2755. https://doi.org/10.1111/1750-3841.13498

Pawar, D. P., Boomathi, S., Hathwar, S. C., Rai, A. K., & Modi, V. K. (2013). Effect of conventional and pressure frying on lipids and fatty acid composition of fried chicken and oil. *Journal of Food Science and Technology*, *50*, 381–386. https://doi.org/10.1007/s13197-011-0331-2

Ploteau, J. P., Glouannec, P., Nicolas, V., & Magueresse, A. (2015). Experimental investigation of French bread baking under conventional conditions or short infrared emitters. *Applied Thermal Engineering*, *75*, 461–467. https://doi.org/10.1016/j.applthermaleng.2014.09.034

Rahimi, D., Kashaninejad, K., Ziaiifar, A. M., & Mahoonak, A. S. (2018). Effect of infrared final cooking on some physico-chemical and engineering properties of partially fried chicken nugget. *Innovative Food Science and Emerging Technologies*, *47*, 1–8. https://doi.org/10.1016/j.ifset.2018.01.004

Rastogi, N. K. (2012). Recent trends and developments in infrared heating in food processing. *Critical Reviews in Food Science and Nutrition*, *52*(9), 737–760. https://doi.org/10.1080/10408398.2010.508138

Reis, M. M., Martínez, E., Saitua, E., Rodríguez, R., Pérez, I., & Olabarrieta, I. (2017). Non-invasive differentiation between fresh and frozen/thawed tuna fillets using near infrared spectroscopy (VIS-NIRS). *LWT-Food Science and Technology*, *78*, 129–137. https://doi.org/10.1016/j.lwt.2016.12.014

Rocío Teruel, M., García-Segovía, P., Martínez-Monzó, J., Belén Linares, M., & Dolores Garrído, M. (2014). Use of vacuum-frying in chicken nugget processing. *Innovative Food Science and Emerging Technologies*, *26*, 482–489. https://doi.org/10.1016/j.ifset.2014.06.005

Romano, R., Giordano, A., Vitiello, S., Le Grottaglie, L., & Musso, S. S. (2012). Comparison of the frying performance of olive oil and palm superolein. *Journal of Food Science*, *77*(5), C519–C531. https://doi.org/10.1111/j.1750-3841.2012.02663.x

Sakai, N., & Hanzawa, T. (1994). Applications and advances in far-infrared heating in Japan. *Trends in Food Science and Technology*, *51*, 357–362. https://doi.org/10.1016/0924-2244(94)90213-5

Sandu, C. (1986). Infrared radiative drying in food engineering: A process analysis. *Biotechnology Progress*, *2*, 109–119. https://doi.org/10.1002/btpr.5420020305

Savas, K., & Basman, A. (2016). Infrared drying: A promising technique for bulgur production. *Journal of Cereal Science*, *68*, 31–37. https://doi.org/10.1016/j.jcs.2015.11.001

Sebastian, A., Ghazani, S. M., & Marangoni, A. G. (2014). Quality and safety of frying oils used in restaurants. *Food Research International*, *64*, 420–423. https://doi.org/10.1016/j.foodres.2014.07.033

Song, X., Hu, H., & Zhang, B. (2018). Drying characteristics of Chinese Yam (*Dioscorea opposite* Thunb.) by far-infrared radiation and heat pump. *Journal of the Saudi Society of Agricultural Sciences*, *17*(3), 290–296. https://doi.org/10.1016/j.jssas.2016.05.008

Southern, C. R., Chen, X. D., Farid, M. M., Howard, B., & Eyres, L. (2000). Determining internal oil uptake and water content of fried thin potato crisps. *Transactions of the Institution of Chemical Engineers Part C*, *78*, 119–125. https://doi.org/10.1205/096030800532851

Su, Y., Zhang, M., Zhang, W., Liu, C., & Adhikari, B. (2018). Ultrasonic microwave-assisted vacuum frying technique as a novel frying method for potato chips at low frying temperature. *Food and Bioproducts Processing*, *108*, 95–104. https://doi.org/10.1016/j.fbp.2018.02.001

Venkata, R. P., & Subramanyam, R. (2016). Evaluation of the deleterious health effects of consumption of repeatedly heated vegetable oil. *Toxicology Reports*, *3*, 636–643. https://doi.org/10.1016/j.toxrep.2016.08.003

Vitrac, O., Trystram, G., & Raoultwack, A. L. (2015). Deep-fat frying of food: Heat and mass transfer, transformations and reactions inside the frying material. *European Journal of Lipid Science and Technology*, *102*(8–9), 529–538. https://doi.org/10.1002/1438-9312(200009)102:8/9<529::AID-EJLT529>3.0.CO;2-F

Wang, H., Zhang, M., & Adhikari, B. (2015). Drying of shiitake mushroom by combining freeze-drying and mid-infrared radiation. *Food and Bioproducts Processing*, *94*, 507–517. https://doi.org/10.1016/j.fbp.2014.07.008

Yang, J., Bingol, G., Pan, Z., Brandl, M. T., McHugh, T. H., & Wang, H. (2010). Infrared heating for dry-roasting pasteurization of almonds. *Journal of Food Engineering*, *101*(3), 273–280. https://doi.org/10.1016/j.jfoodeng.2010.07.007

SUPPORTING INFORMATION

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