

# Enhancing the drying efficiency of okra using innovative microwave energy technology

*Sawapon Tap tong*<sup>1</sup>, *Kittichai Chaihirunkarn*<sup>1</sup>, *Phadungsak Rattanadecho*<sup>2</sup>, and *Pornthip Keangin*<sup>1</sup>

<sup>1</sup>Department of Mechanical Engineering, Faculty of Engineering, Mahidol University, Nakhon Pathom, Thailand

<sup>2</sup>Department of Mechanical Engineering, Faculty of Engineering, Thammasat University, Pathumthani, Thailand

**Abstract.** Okra is widely consumed in many countries and is commonly used in various culinary applications, such as boiling, stir-frying, or consumed fresh. It can also be dried and ground into powder for medicinal purposes, such as treating diarrhea and acute inflammation. Traditional methods of preserving okra include hot air drying and sun drying. However, these methods are time-consuming, energy-intensive, and can result in the loss of nutritional value due to heat being concentrated only at the surface of the okra. Microwave energy heating is a promising alternative that can address these issues, as microwaves are capable of penetrating the surface and heating the interior of the okra before the exterior. This research developed a three-dimensional model of microwave drying applied to okra using the finite element method (FEM). Maxwell's equations and heat transfer equations are employed to study the effects of different positions of the waveguide port and different okra arrangement patterns. The study used microwave power of 1,600 W at a frequency of 2.45 GHz and a duration of 60 s to analyze the distributions of absorbed energy, electric field, and temperature within the okra. The results indicated that positioning both waveguides on the same side of the microwave oven and arranging the okra in a double-row zigzag pattern without alternating orientations produced the most uniform distributions of absorbed energy, electric field, and temperature. These results can be applied to the microwave drying of other herbs or fruits, serving as a foundation for the future design of microwave ovens for drying.

## 1 Introduction

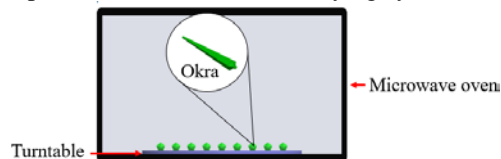
Currently, okra has gained widespread popularity as a food ingredient in various countries, especially in the East Asian region. Okra is an annual herbaceous plant in the Malvaceae family. Okra grows rapidly and is highly nutritious. It contains natural mucilage and dietary fiber that aid digestion. One hundred grams of okra provides approximately 55 kcal of energy [1]. It is commonly consumed in various culinary forms, such as boiling, stir-frying, or as dried fresh produce. A traditional method of preserving okra is hot air drying, which allows for its use either directly or in powdered form. This dried form is employed for medicinal purposes to alleviate diarrhea, acute inflammation, gastrointestinal irritation, respiratory

infections, gonorrhoea, and difficult urination [2]. However, hot air drying has disadvantages, such as being time-consuming and energy-intensive, which can lead to the loss of certain nutritional components. As a result, microwave drying has attracted increasing interest in research as a potential solution to these issues. In 2018, Song, C. et al. [3] studied vacuum microwave drying of blackberries using heat transfer simulations. The results found that drying at 400 W and -80 kPa resulted in a temperature of 60 °C, which was suitable for industrial drying. In 2019, Thuto W. and Banjong K. [4] investigated heat and moisture transfer during microwave drying of bananas using a computer program. Tomas-Egea J. A. et al. [5] studied hybrid microwave and hot air drying of potatoes. The results indicated that hot air mainly caused surface moisture evaporation with minimal heat transfer inward, while microwave energy was primarily converted into internal thermal energy. In 2021, Bozkir H. et al. [6] examined the temperature distribution during hybrid microwave-hot air drying of dragon fruit using a three-dimensional model. Moreover, a systematic study of the degradation of anthocyanins due to non-uniformity of microwave heating in blueberry puree is presented by Xue, L. et al. [7].

From previous studies, microwave heating of fruits and foods has been extensively investigated using finite element modeling (FEM) to analyze the effects of power and frequency levels. However, the study of enhancing the drying efficiency of okra using microwave energy for industrial applications still reveals some limitations, particularly in examining the influence of different positions of the waveguide port and different okra arrangement patterns. Therefore, this research aims to examine microwave drying of okra utilizing a power of 1,600 W, frequency of 2.45 GHz, and duration of 60 s through three-dimensional (3D) model simulation using FEM. The propagation of electromagnetic waves within the oven and the okra is described using Maxwell's equations, while microwave-induced heating is analyzed using heat transfer equations. This study focuses on the effects of different waveguide positions and okra arrangement patterns during microwave heating. The findings from this study highlight the significance of heat transfer characteristics during okra microwave drying to apply drying to other herbs or fruits.

## 2 Formulation of the Problem

In this study, a 3D simulation of okra subjected to microwave heating inside a microwave oven is conducted. The components of the microwave drying system are illustrated in Fig. 1.



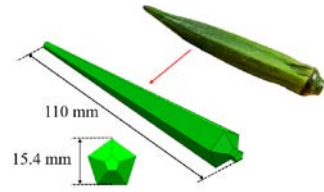
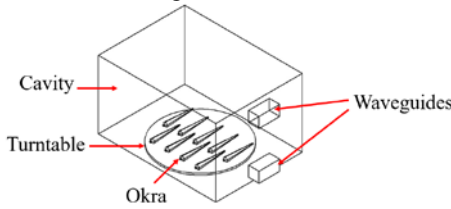
**Fig. 1.** The schematic of microwave heating.

## 3 Methods and Models

### 3.1 Physical Model

The simulation model comprises four main components: the microwave cavity, the waveguide, the turntable, and the okra pod. The dimensions of the microwave oven are 450 × 330 × 260 mm (width × depth × height) [8], while the waveguide measures 80 × 40 × 40 mm (width × depth × height) [9]. The diameter of the turntable is 300 mm [8], as illustrated in Fig. 2. Due to the inherently asymmetrical shape of actual okra pods, a model

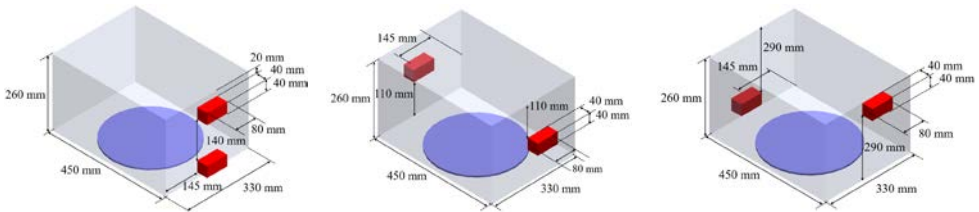
approximating the natural geometry of okra was constructed, as depicted in Fig. 3. The modeled okra has a length of 110 mm [10].



**Fig. 2.** The components of the 3D model.

**Fig. 3.** Shape of okra.

In this research, the influence of waveguide positioning at three different locations is investigated, namely, both waveguides positioned on the same side of the microwave oven (Model I), waveguides located at the center of the microwave oven on opposite sides (Model II), and waveguides installed on the top and bottom sides of the microwave oven on opposite sides (Model III), as shown in Fig. 4. Additionally, two different okra arrangement patterns on the turntable during microwave drying are examined, namely a single-row arrangement (Arrangement I), and a double-row zigzag arrangement (Arrangement II) as displayed in Fig. 5. Table 1 lists the properties of the okra used in the simulations.



**Fig. 4.** The waveguide positioning at three different locations: (a) Model I, (b) Model II, and (c) Model III.



**Fig. 5.** The arrangement of the okra in the turntable for microwave drying (a) Arrangement I, and (b) Arrangement II.

**Table 1.** The thermal and dielectric properties of the okra.

Parameters		Values	Unit
Thermal properties	Density, $\rho$	1714.9 [11]	kg/m <sup>3</sup>
	Specific heat capacity, $c_p$	1802 [11]	J/kg · K
	Thermal conductivity, $k$	0.184 [11]	W/m · K
Dielectric properties	Relative permittivity, $\epsilon_r$	2.938-0.188j <sup>a</sup>	-
	Electric conductivity, $\sigma$	0	S/m

<sup>a</sup> Measured by a E5063A ENA Vector Network Analyzer

### 3.2 Equations and boundary conditions for electromagnetic wave propagation analysis

The analysis of the propagation of electromagnetic waves in all domains can be performed using Maxwell's equation as shown in Equation (1). The dielectric properties of the cavity, waveguide, and turntable are equal to those of air. In addition, the rectangular waveguide is considered in TE<sub>01</sub> mode.

$$\nabla \times \mu_r^{-1} (\nabla \times \mathbf{E}) - k_0^2 \left( \epsilon_r - \frac{j\sigma}{\omega\epsilon_0} \right) \mathbf{E} = 0 \quad (1)$$

where  $\mu_r$  refers to the relative permeability (-),  $\mathbf{E}$  denotes the electric field (V/m),  $k_0$  indicates the wave number of free space (m<sup>-1</sup>),  $\epsilon_r$  represents the relative permittivity (-),  $\sigma$  refers to the electric conductivity (S/m),  $\epsilon_0 = 8.854 \times 10^{-12}$  F/m denotes the free space permittivity and  $\omega = 2\pi f$  indicates the angular frequency (rad/s).

The boundary condition for electromagnetic wave propagation analysis, the perfect electric conductors is analyzed at the waveguide and cavity.

$$\vec{n} \times \mathbf{E} = 0 \quad (2)$$

### 3.3 Equations and boundary conditions for heat transfer analysis

The temperature distribution during microwave heating within the okra domain is analyzed by the Fourier heat transfer equation, as shown in Equation (3). The initial temperature of the okra model is set to 27 °C. The heat transfers in the cavity and the turntable are not considered. There is no phase change in the okra domain.

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \cdot \nabla T) + Q_{MW} \quad (3)$$

where  $\rho$  refers to the density (kg/m<sup>3</sup>),  $c_p$  denotes the specific heat capacity (J/kg · K),  $k$  indicates the thermal conductivity (W/m · K), and  $T$  represents the temperature (°C), The heat source from the microwave ( $Q_{MW}$ ) is equal to the microwave power absorbed in the material is depends on the dielectric factor ( $\epsilon''$ ), which can be calculated from:

$$Q_{MW} = 2\pi f \epsilon_0 \epsilon'' |\mathbf{E}| \quad (4)$$

The outer surface of the okra exchanges heat with the air inside the cavity, which will be considered using a heat flux boundary condition, which can be calculated from

$$-\vec{n} \cdot k \nabla T = h_{air} (T - T_{air}) \quad (5)$$

Where  $h_{air} = 10$  W/m<sup>2</sup> · K represents the convective heat transfer coefficient of air and  $T_{air} = 25$  °C refers to the air temperature.

### 3.4 Calculation Procedure

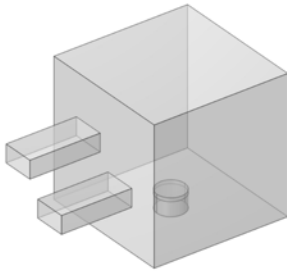
This research simulated microwave drying using FEM via COMSOL™ Multiphysics

program by developing a three-dimensional model of microwave heating applied to okra. Mesh independence analysis, a critical step due to its direct impact on simulation accuracy, is performed for various waveguide placements and okra arrangement patterns. The number of elements obtained from the analysis of independence of elements are Model I and Arrangement I is 468,689 elements, Model II and Arrangement I is 446,696 elements, Model III and Arrangement I is 446,641 elements, Model I and Arrangement II is 449,981 elements, Model II and Arrangement II is 450,604 elements, Model III and Arrangement II is 450,243 elements, respectively.

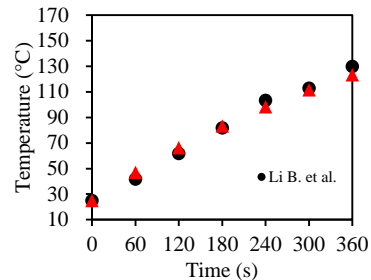
## 4 Results and Discussion

### 4.1 Validation of the Computational Model

To perform verification of the present numerical study, the present numerical model is validated by the results obtained by Li B. et al. [12]. In the validation, tobacco stem (TS) biomass was subjected to microwave energy using the geometry model shown in Fig. 6. The condition for simulation is microwave power of 500 W at a frequency of 2.45 GHz for 6 min, which same conditions obtained by Li B. et al. [12]. The result of the validation, as displayed in Fig. 7. The temperature from the simulation closely matches that of Li B. et al. [12], with an average error of 4.36%.



**Fig. 6.** The geometry model for validated results between the present study and Li B. et al. [12].

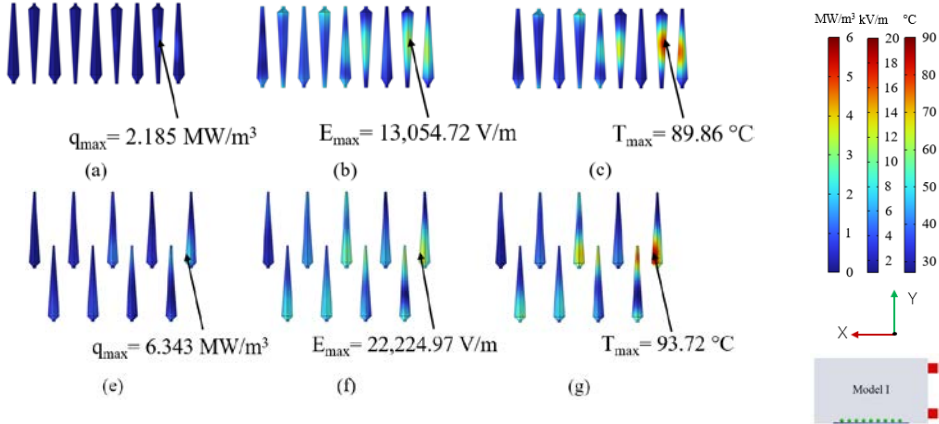


**Fig. 7.** The validation results of the temperature between the present study and Li B. et al. [12].

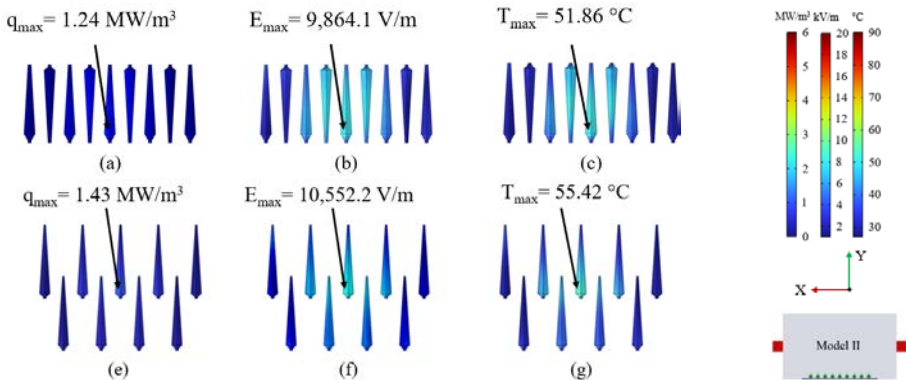
### 4.2 A Study on the Influence of Waveguide Positioning and Different Arrangements of Okra in the Microwave Oven

This study aims to analyze the influence of varying waveguide installation positions and different okra arrangements to determine the optimal configuration for microwave heating. The microwave heating process of okra was analyzed using an input microwave power of 1,600 W at a frequency of 2.45 GHz and a heating duration of 60 s. Fig. 8 shows the distributions of absorbed energy, electric field, and temperature within the okra in the case of Model I. The distributions of absorbed energy, electric field, and temperature within the okra in the case of Model II is presented in Fig. 9. Moreover, Fig. 10 displays the distributions of absorbed energy, electric field, and temperature within the okra in the case of Model III. The findings indicate that the waveguide positioning and okra arrangement significantly affect the distributions of absorbed energy, electric field, and temperature within the okra. The configuration with both waveguides positioned on the same side of the microwave oven (Model I) and Arrangement II yielded the highest absorbed energy, electric field, and temperature values within the okra. The electric field distribution corresponds to the

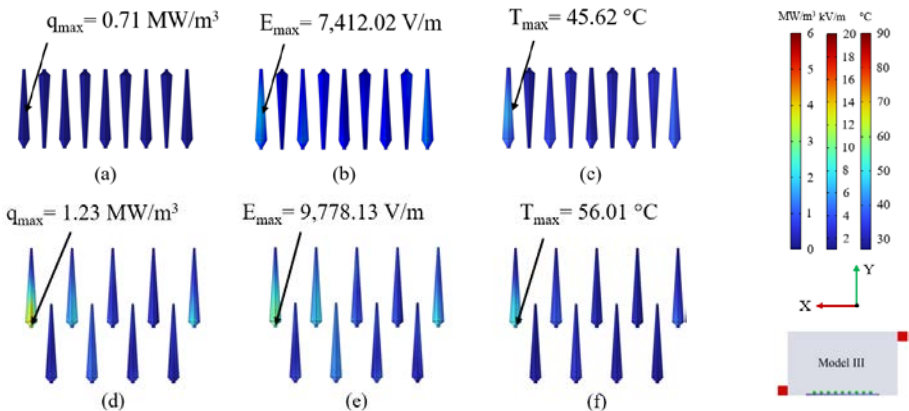
temperature distribution, demonstrating a direct relationship between electric field intensity and heating performance. As microwave energy passes through the waveguides and is absorbed by the okra, it is converted into heat through dielectric heating.



**Fig. 8.** The distributions of absorbed energy, electric field, and temperature within the okra in the case of Model I.



**Fig. 9.** The distributions of absorbed energy, electric field, and temperature within the okra in the case of Model II.



**Fig. 10.** The distributions of absorbed energy, electric field, and temperature within the okra in the case of Model III.

## 5 Conclusion

In this research, a three-dimensional simulation of okra and a microwave heating oven is conducted during the microwave heating process to investigate the behavior of the distributions of absorbed energy, electric field, and temperature inside the okra. The results of the study showed the recommended design of the waveguide installation position in the appropriate position for microwave heating. It is found that the installation of both waveguides on the same side of the microwave oven, along with a double-row zigzag arrangement of okra without alternating orientations, resulted in a more uniform distribution of absorbed energy, electric field, and temperature inside the okra. The findings from this research can be applied to the drying of other herbs or fruits and can serve as a foundation for the design of microwave ovens for drying applications.

This research project is supported by Mahidol University (Fundamental Fund: fiscal year 2024 by National Science Research and Innovation Fund (NSRF))

## References

1. M. H. Romdhane, H. Chahdoura, L. Barros, M. I. Dias, R. C. G. Corrêa, P. Morales, M. Ciudad-Mulero, G. Flamini, H. Majdoub, I. C. F. R. Ferreira, *Molecules* **25**, 4739 (2020)
2. S. Habtemariam, *Medicinal Foods as Potential Therapies for Type-2 Diabetes and Associated Diseases* (Elsevier, Amsterdam, 2019), p. 307–332
3. C. Song, T. Wu, Z. Li, J. Li, H. Chen, *J. Food Eng.* **223**, 70 (2018)
4. W. Thuto, K. Banjong, *Processes* **7**, 545 (2019)
5. J. A. Tomas-Egea, M. V. Traffano-Schiffo, M. Castro-Giraldez, P. J. Fito, *Appl. Sci.* **11**, 1730 (2021)
6. H. Bozkir, A. Rayman Ergün, S. Serdar, S. Y. Özdemir, *J. Food Process. Eng.* **44**, e13775 (2021)
7. L. Xue, R. Gao, L. Shen, X. Zheng, M. Gao, *Food Bioprod. Process.* **139**, 129 (2023)
8. C. Song, Y. Chen, H. Pu, Z. Li, H. Chen, L. Meng, Y. Wang, *Int. J. Food Eng.* **14**, 20180169 (2018)
9. S. Jumrat, T. Punvichai, S. Karrila, M. Nisosa, Y. Pianroj, *J. Aquat. Food Prod. Technol.* **30**, 968 (2021)
10. M. Saifullah, M. G. Rabbani, *SAARC J. Agric.* **7**, 92 (2009)
11. U. E. Ekpunobi, S. C. Ukatu, B. O. Ngene, C. T. Onyema, P. U. Ofora, *Am. J. Sci. Technol.* **1**, 293 (2014)
12. B. Li, X. Fan, S. Yu, H. Xia, Y. Nong, J. Bian, M. Sun, W. Zi, *J. Clean. Prod.* **274**, 127347 (2023)