

## Integrating Microwave Heating with Foam-Mat Drying: Drying Kinetics and Optimization for Thick Foamed Mango Pulp

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### Abstract

This study addresses the challenge of processing undersized or overripe mangoes by integrating microwave heating with traditional foam-mat drying technique. The study aims at investigating drying kinetics coupled with thin-layer drying modeling and influences of microwave power (300 - 600 W) and hot-air temperature (55 - 75 °C). Among ten drying models, the so-called Midilli equation fitted well with experimental data. Results showed enhanced drying process associated with microwave heating, providing reduced drying time from 600 - 700 min (for conventional hot-air mode) to 30 - 100 min (for microwave-assisted mode). Standard deviations of moisture content and dried foam thickness measured at various points revealed uneven heat distribution when using high microwave energy, evidenced by burnt spots at 600 W. Additionally, foam collapse was observed under the mild process with low microwave powers, possibly due to prolonged drying periods. Response surface methodology demonstrated that microwave power was more important factor, positively affecting effective diffusivity coefficient ( $D_{eff}$ ) while inversely influencing specific energy consumption (SEC) and color difference ( $\Delta E$ ).  $D_{eff}$  value increased from  $5.41 \times 10^{-6} \text{ m}^2 \cdot \text{s}^{-1}$  at 300 W and 55 °C to  $18.43 \times 10^{-6} \text{ m}^2 \cdot \text{s}^{-1}$  at 600 W and 75 °C, confirming enhance drying performance. As assisted with microwave heating, drying foamed mango sample consumed less energy up to 92 %. Optimal drying parameters were determined based on balancing the enhancement of drying performance and color alteration, suggesting drying the thick foamed mango pulp at temperature of 55 °C combined with microwave heating at 520 W, which can be served as a basis for further industrial scale-up.

**Keywords:** Microwave-assisted drying, Foam-mat drying, Mango pulp, Drying kinetics, Effective diffusivity, Specific energy consumption, Color difference

## Introduction

The cultivation of Mahachanok or Rainbow mangoes (*Mangifera indica* L.), a well-known fruit for its rich nutritional and bioactive profile [1], in the northeast of Thailand, has been drastically affected. The farmers in the region need help with market fluctuation and the abundance of undersized or overripe fruits, resulting in low pricing. Therefore, this research proposes a sustainable solution by processing these fruits into dried foamed mango pulp snacks as an alternative choice for consumers.

Foam-mat drying is an effective technique to convert food liquid or semi-liquid to dry foamed materials with retention of nutritive values [2]. Its efficacy in moisture removal by traditional convective hot-air drying is advantageous for thin-layered foams. Chaux-Gutiérrez *et al.* [3], Rajkumar *et al.* [4,5] and Sansomchai *et al.* [2] successfully applied the foam-mat drying process to produce the powdered mango pulp. Their results of the drying kinetics study and optimization for foamed mango pulps highlighted the importance of adjusting drying parameters to maintain product quality. However problematic prolonged drying in thick foamed materials is still a challenge due to energy-intensive and foam structure collapse. Microwave energy generating high volumetric heating can be beneficial as its direct interaction with water molecules facilitates rapid and uniform heat distribution, enhancing drying rates, reducing energy consumption, and minimizing physical deformation of the foamed materials.

Dry crisp foods, particularly snacks, possess the good qualities in terms of minimal moisture content, high retention of nutritional values, color, porous microstructure. Among several factors drying temperature or drying method plays important role, as high water evaporation and diffusion rate can produce crisp products which consist of pores with cell walls formed by a brittle matrix [6].

Recent developments in drying technology have shed light on the combination of microwave heating technique with conventional foam-mat drying; this is expected to be one of the breakthrough points in energy efficiency and product quality. Findings reported by Qadri and Srivastava [7,8] have confirmed that microwave-assisted foam-mat drying can minimize drying time of tomato and guava pulps while remaining their nutritional values. Theoretical and experimental investigations conducted by Gao *et al.* [9], Yüksel and Pandiselvam [10], and Süfer *et al.* [11] provided insights of drying kinetics as affected by operational parameters in microwave-assisted drying for blueberry pulp, kefir and bitter orange, respectively. Furthermore, experimental research by Varol *et al.* [12] and the energy source analyses by Yüksel [13] and Zheng *et al.* [14] prove that operational parameters require forms of tuning for optimal results.

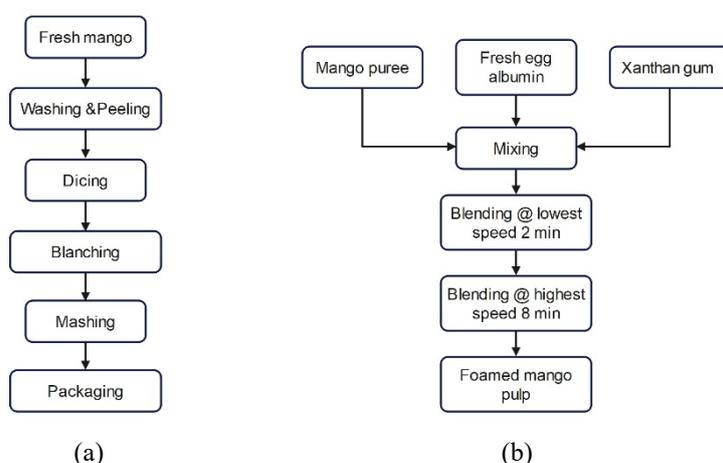
Microwave-assisted foam-mat drying appears promising, but its effectiveness for thick foamed fruit pulp still needs to be explored. Therefore, this research aims to propose foam-mat drying combined with microwave heating as a process for producing a foamed mango pulp snack. The study systematically investigates the drying kinetics, effective diffusivity, specific energy consumption, and physical properties affected by drying parameters. Response Surface Methodology (RSM) is employed to identify the optimal conditions that balance moisture removal, energy saving, and minimal color alteration. By analyzing the drying behavior of thick foamed mango pulp under various conditions, the research focuses on the influence of different drying parameters. Comparing traditional and microwave-assisted drying techniques, the study highlights the advantages of microwave-assisted foam-mat drying, such as reduced drying time, lower energy consumption, and better preservation of physical properties. The findings are expected to provide valuable insights for the food processing industry, particularly for small and medium-sized enterprises aiming to produce high-quality dried mango products efficiently.

## Materials and methods

### Raw materials and foamed mango pulp preparation

Ripe Mahachanok mangoes (*Mangifera indica* L.) with  $12.7 \pm 0.4$  °Brix were obtained from Kalasin Province located in the northeast of Thailand. First, the mangoes were peeled and cut into 1-cm diced pulp. The pulp cubes were blanched in boiling water for 1 min to inactivate any enzymes present, subsequently crushed into puree. The mango puree was packed into the aluminum foil bags and then stored in a freezer until use.

Two hundred and fifty g of foamed mango pulp was prepared using 96.43 g of puree (38.57 % w/w), 128.57 g of fresh egg albumin as a foaming agent (51.43 % w/w), and 25 g of 1 % xanthan gum solution as a stabilizer (10 % w/w). The mixture was initially blended gently at the lowest speed using (Electrolux, model EHM3407, Thailand) for 2 min to ensure even mixing, and then for 8 min at its maximum rotation speed to create a strong foam, as shown in **Figure 1**.

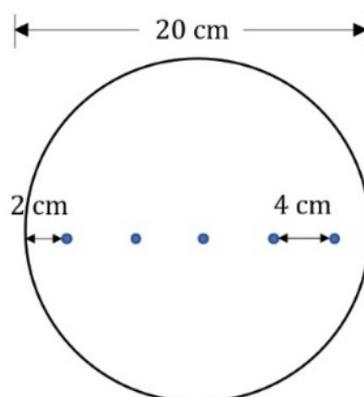


**Figure 1** flow chart as an illustration of raw materials (a) and foamed mango pulp (b) preparation.

### Quality measurement

#### Moisture content and dried foam thickness

Analysis of the moisture content was carried out according to the standard protocol [15]. Uniformity of moisture content in the dried foamed mango pulp was also determined by measuring the values at 5 points, as shown in **Figure 2**. Moreover, in the same points, the thickness of the dried foams was measured to evaluate the homogeneity of the foam structure.



**Figure 2** Measuring points for analyzing uniformity of moisture content and foam thickness.

### ***Morphology of dried foamed mango pulp***

The dried foamed mango pulp morphology was examined using a scanning electron microscope (SEM) (Tabletop Microscope, TM4000Plus, Hitachi, Hitachi High-Tech Ltd.) operated at magnifications of 30× under a voltage of 10 kV.

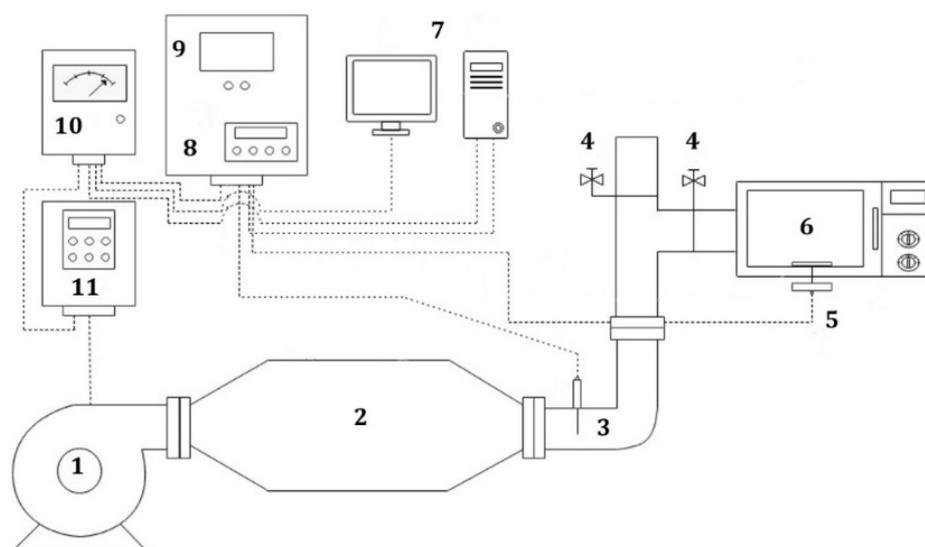
### ***Color difference***

In this study, microwave power was kept constant throughout drying process, resulting in higher intensity due to progressively reduced material mass. The resulting uneven heating may cause non-enzymatic browning or even charring, leading to color alteration. The color difference ( $\Delta E$ ), expressed in Eq. (1), of the foamed mango pulp dried under various drying conditions was evaluated using the values of lightness ( $L^*$ ), redness ( $a^*$ ) and yellowness ( $b^*$ ) measured by a color meter (HunterLab, Reston, VA, USA). All color values of the foamed samples dried under various conditions were compared with those of the samples dried by freeze drying method, known as the best drying technique for preserving original color.

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

### **Drying procedure**

**Figure 3** shows a modified domestic microwave oven (model MS23F300EEK, Samsung, Thailand) (number 6) allowing hot air flowing into the drying system. Ambient air was drawn by a blower (number 1) through a 10-kW electric heater (number 2). Drying air temperature was controlled using a PID temperature controller (Model MAC-3D, Shimax Co., Ltd., Japan) (number 8) incorporated with a thermocouple type K (number 3). The air velocity was maintained at  $0.5 \text{ m}\cdot\text{s}^{-1}$  using an inverter (number 11), and the air flow direction was controlled by a butterfly valve (number 4), ensuring the air was heated to the desired temperature before being introduced into the oven. A microcontroller connected to a step-down ZK-D60 module (number 9) was used to regulate microwave power output. During the process, sample weight was monitored using a load cell (number 5) and recorded in a computer (number 7). Furthermore, an electricity meter (number 10) was used to record energy consumption during the process.



**Figure 3** Schematic diagram of lab-scale combined microwave/hot-air dryer.

The foamed mango pulp (250 g) was spread homogeneously in a 20-cm microwaveable plate, and an excess foamed mass was removed using a stainless-steel bar, resulting in flat-surface foam with a thickness of 2 cm. 3 drying air temperatures of 55, 65, and 75 °C and 3 microwave powers of 300, 450, and 600 W were considered as primary variables; however, the drying air velocity was kept constant at 0.5 m·s<sup>-1</sup>. The impact of these variable factors and their optimal values were systematically examined by means of response surface methodology with full factorial design.

### Drying kinetics and model analysis

The present work examined several drying scenarios to evaluate the influence of microwave-assisted foam-mat drying on drying behavior of foamed mango pulp. Each experimental run was conducted until reaching equilibrium or 10 % on a dry basis (db) of moisture content. A simplified moisture ratio (MR) equation, as expressed in Eq. 2, was employed to capture the change in MR as a function of time (t, in min), where  $M_t$  and  $M_0$  denote moisture content at a certain time and at the onset of drying period, respectively. The MR data observed from all experimental runs were consequently fitted to 10 semi-empirical drying models as summarized in **Table 1**.

$$MR = \frac{M_t}{M_0} \quad (2)$$

**Table 1** Semi-empirical drying models summarized in [16-18].

Model	Equation
Lewis	$MR = e^{-kt}$
Page	$MR = e^{-kt^n}$
Henderson and Pabis	$MR = ae^{(-kt)}$
Two term (exponential)	$MR = ae^{(-kt)} + (1-a)e^{(-kat)}$
Wang and Singh	$MR = 1 + at + bt^2$
Logarithmic	$MR = ae^{(-kt)} + c$
Approximate of diffusion	$MR = ae^{(-kt)} + (1-a)e^{(-kt)}$
Verma <i>et al.</i> [18]	$MR = ae^{(-kt)} + (1-a)e^{(-gt)}$
Two term (4 parameters)	$MR = ae^{(-k_0t)} + be^{(-k_1t)}$
Midilli <i>et al.</i> [16]	$MR = ae^{(-kt^n)} + bt$

Model parameters of all drying models were analyzed by means of nonlinear regression. The suitable models were evaluated using the coefficient of determination ( $R^2$ ), root mean square error (RMSE) (Eq. (3)) and chi square ( $\chi^2$ ) (Eq. (4)). The best choice of drying model was selected based on highest  $R^2$  and lowest RMSE and  $\chi^2$ .

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2} \quad (3)$$

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{N - z} \quad (4)$$

In Eqs. (3) - (4), subscripts 'exp' and 'pre' denote the moisture ratio obtained by experiment and prediction, respectively. N is the number of observations, and z is the number of model parameters.

Effective diffusivity coefficient ( $D_{eff}$ ) was determined to evaluate drying performance as high  $D_{eff}$  indicating high speed of moisture migration. The  $D_{eff}$  value was estimated based on the Fick's second law of diffusion for a slab with thickness of L (m), as expressed in Eq. (5). The  $D_{eff}$  value ( $m^2 \cdot s^{-1}$ ) was obtained from a slope of natural logarithm function of Eq. (5).

$$MR = \frac{8}{\pi^2} \exp\left(-\pi^2 \frac{D_{eff}}{4L^2} t\right) \quad (5)$$

Additionally, the drying performance was evaluated based on specific energy consumption (SEC), calculated by Eq. 6, representing the total energy (E) provided as electricity (KWh) consumed for evaporating 1 kg of water ( $W_{evap}$ ). Lower values imply higher efficiency.

$$SEC = \frac{E}{W_{evap}} \times 1000 \quad (6)$$

### Response surface methodology

Response surface methodology (RSM), a robust statistical technique for describing the relationship between input factors and resultant outputs [19], was employed to analyze how independent variables of hot air temperature (T) and microwave power (MW) influence the effective diffusivity coefficient ( $D_{eff}$ ), specific energy consumption (SEC), and color difference ( $\Delta E$ ). Utilizing RSM with a quadratic equation (Eq. (7)), the study aimed to optimize drying parameters. The experimental setup included 2 main operating variables ( $X_1$  and  $X_2$ ), each at 3 levels, which were used to establish quadratic relationships with the 3 response variables ( $Y_1$ ,  $Y_2$ , and  $Y_3$ ) as part of a comprehensive full factorial design represented by Eq. (7). Here,  $X_1$  and  $X_2$  were identified as the control variables for drying temperature ( $^{\circ}C$ ) and microwave power (W), respectively, and  $Y_1$ ,  $Y_2$ , and  $Y_3$  corresponded to the responses of effective diffusivity coefficient ( $m^2 \cdot s^{-1}$ ), specific energy consumption ( $kWh \cdot kg^{-1}$ ), and color difference, respectively.

$$Y_i = a_0 + a_1 X_1 + a_2 X_2 + a_3 X_1 X_2 + a_4 X_1^2 + a_5 X_2^2 \quad (7)$$

The desirability function,  $d_i(Y_i)$ , was employed to determine the best drying conditions, focusing on achieving the highest  $D_{eff}$  while reducing SEC and  $\Delta E$ , as expressed in Eqs. (8) - (9), respectively [20];

$$d_i(y_i(x)) = \begin{cases} 0 & \text{if } y_i(x) < L_i \\ \left(\frac{y_i(x) - L_i}{U_i - L_i}\right)^s & \text{if } L_i \leq y_i(x) \leq U_i \\ 1 & \text{if } y_i(x) > U_i \end{cases} \quad (8)$$

$$d_i(y_i(x)) = \begin{cases} 1 & \text{if } y_i(x) < L_i \\ \left(\frac{U_i - y_i(x)}{U_i - L_i}\right)^t & \text{if } L_i \leq y_i(x) \leq U_i \\ 0 & \text{if } y_i(x) > U_i \end{cases} \tag{9}$$

In Eqs. (8) - (9),  $L_i$  and  $U_i$  are the lower and upper acceptable limits for each response, respectively, while the parameters ‘s’ and ‘t’ are weights calculating the range of maximization and minimization levels for each response. Thus, the investigated method can result in the optimization of several process responses at the same time, with each receiving a desirability score from 0 to 1, where 1 means maximum desirability, and 0 — undesirability. The established desirability functions for maximizing and minimizing each response were used to calculate the developed desirability defined in Eq. (10), where ‘m’ is the number of responses to optimize. The solution with the maximum D shows the best combination of drying conditions in the current study [20].

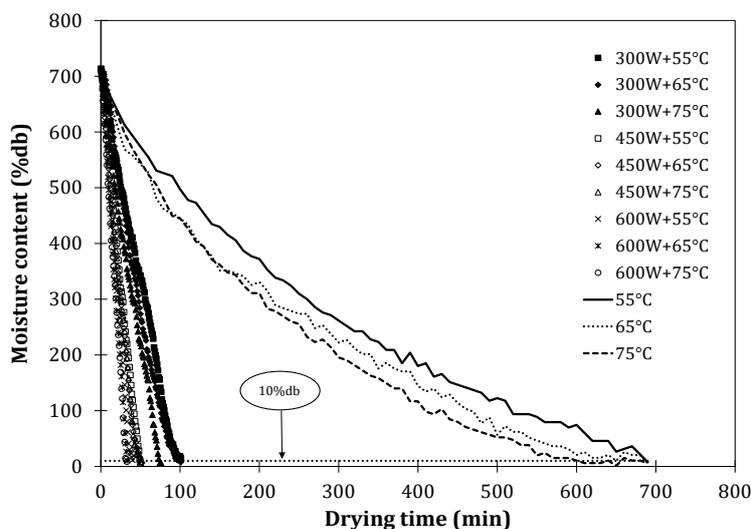
$$D = (d_1 \cdot d_2 \cdot d_3)^{1/3} \tag{10}$$

## Results and discussion

### Drying characteristics

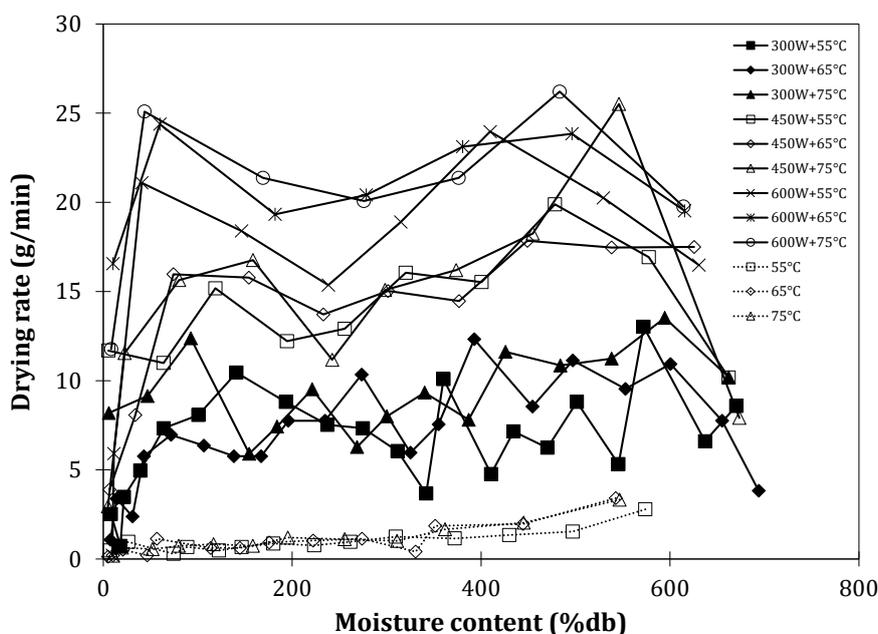
#### Drying curves

The results of drying kinetics of foamed mango pulp dried under various conditions are presented in this section. Initially, the drying kinetics of the proposed method using the combination of convective hot-air drying and microwave heating was compared with those obtained from conventional convective hot-air drying, as shown in **Figure 4**. It was observed that, as is typical, the moisture ratio decreased with drying time in all conditions tested. The time spent on decreasing moisture from 700 % db to the targeted level of 10 % db using only hot air was in the range of 600 - 700 min, while the time for obtaining the same moisture content with the combined method was in the range of 30 - 100 min. The extremely shorter time obtained from the proposed method was attributed to the enhanced volumetric heating effect of microwave facilitating quicker internal moisture migration from the foam internal structure to the surface.



**Figure 4** Drying curves at various conditions.

The enhancement of drying kinetics of the foamed mango pulp using the microwave-assisted foam-mat drying process was in line with the findings reported in several studies focusing on different materials and conditions. For instance, Qadri and Srivastava [7] revealed that volumetric heating promoted by microwave heating shortens the drying time of tomato and tomato pulp while maintaining essential nutritional and sensory characteristics. These authors later reached similar conclusions when studying guava pulp, indicating that microwave-assisted drying was efficient. Similarly, Gao *et al.* [9] optimized the conditions of microwave power and foaming agents to show that microwave significantly improved the physical and chemical properties of food, considering the specific case of dried blueberry fruit. These findings agreed with our results since microwave setting correlates with the drying rate. In addition, microwave-assisted drying has been studied in other fruit pulps, including mango pulp in Chau-Gutiérrez *et al.* [3] exploring the influences of operational parameters on drying kinetics and the nutritional values. It was noted that microwave energy contributed to reduced drying time. Varol *et al.* [12] and Süfer *et al.* [11] additionally considered kumquat and bitter orange, respectively. These 2 studies showed that the drying process took shorter time and enhanced energy efficiency while conserving color and textural properties. Yüksel [13] also applied this combined drying method to yogurt, suggesting the proposed method is potential application in diverse matrices beyond fruit pulps.



**Figure 5** Drying rate curves at various drying conditions.

The improved drying rates by the combined foam-mat and microwave drying are further depicted by the drying rate curves presented in **Figure 5**. The graph clearly shows the higher drying rate of the combined method as opposed to dependence on the hot air method alone. As such, the microwave has the ability to provide volumetric heat, which penetrates the mango pulp foam and reaches it uniformly and faster. This rapid heating process leads to more efficient water evaporation on the inner structure of the foam, accelerating moisture migration to its surface. The improved drying rates indicated the effectiveness of microwave technology in drying foam-mat systems. Our findings on the high enhancement of drying rates achieved through the microwave with foam-mat drying were similar to those reported by Yüksel and Pandiselvam [10], Qadri and Srivastava [7], and Islam *et al.* [21]. Qadri and Srivastava [7] reported that the

use of microwave-assisted foam-mat drying for tomato pulp significantly enhanced drying rate compared to traditional methods. They found that increasing microwave power levels accelerated dehydration, reducing drying time by approximately 15 - 16 times compared to simple foam-mat drying. Similarly, Yüksel and Pandiselvam [10] found that microwave power levels had a significant impact on drying rates, with higher power levels resulting in faster drying times and improved moisture diffusivity for kefir foam. Furthermore, Islam *et al.* [21] investigated the drying kinetics of microwave-assisted foam-mat drying for jackfruit juice. Their study emphasized the advantages of microwave drying in terms of energy efficiency and product quality. Therefore, the enhanced drying rate revealed the effectiveness of microwave-assisted foam-mat drying for the thick foamed mango pulp in this study.

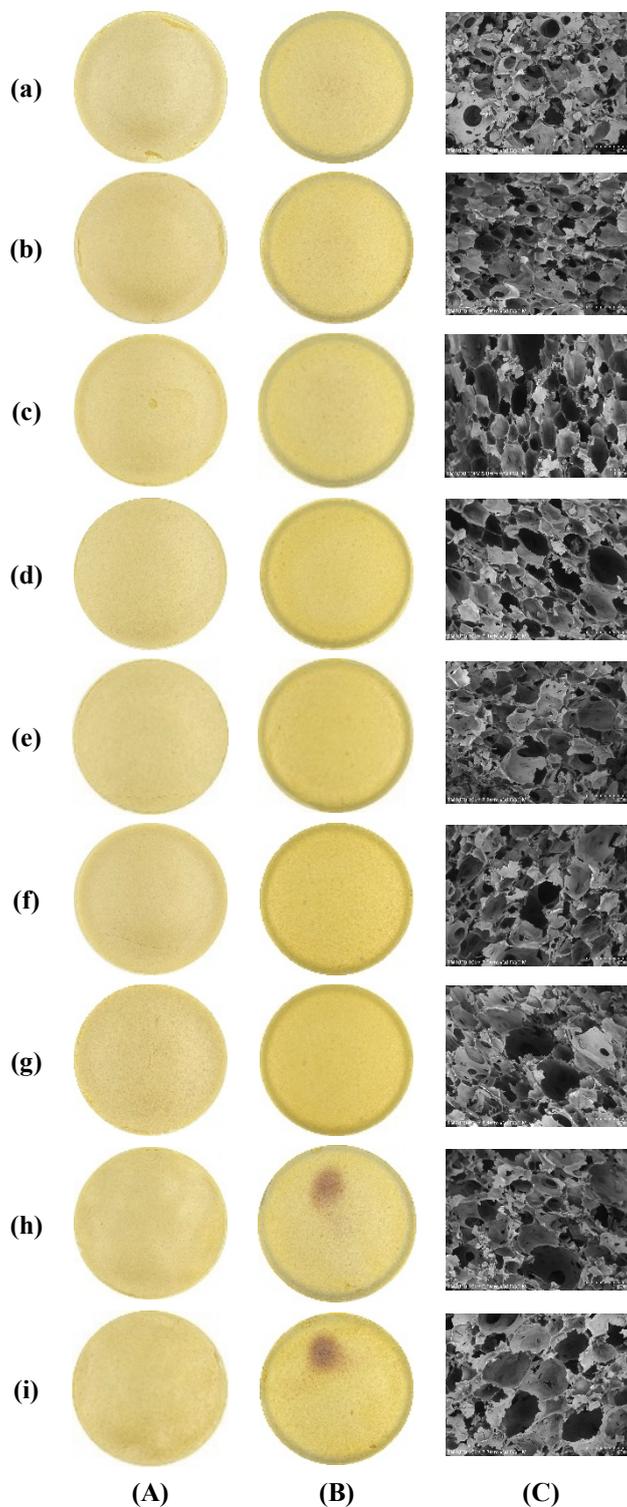
**Table 2** Deviations of moisture content and dried foam thickness at various drying conditions.

MW (W)	T (°C)	MC (%db)		Thickness (mm)	
		Mean value	Deviation	Mean value	Deviation
300	55	6.00	0.59	11.8	0.6
300	65	7.03	0.14	11.7	0.8
300	75	9.59	0.53	12.6	1.3
450	55	7.79	0.66	13.4	1.0
450	65	6.48	0.64	15.0	0.8
450	75	6.45	1.00	19.8	0.9
600	55	6.94	1.50	20.2	1.6
600	65	6.84	1.12	20.9	1.4
600	75	6.55	0.47	21.7	2.4

The uniformity of moisture content and volumetric structural characteristics in dried foamed mango pulp was also investigated in this study. As shown in **Table 2**, the standard deviations of moisture content and thickness were obtained from 5 measurement points (see **Figure 2**); low standard deviations indicating high uniformity, implying that the microwave heat generated across the pulp achieving consistency. Our findings align with those reported by Chen *et al.* [22], who conducted an experimental study on the high-power microwave drying of apples. They observed that microwave drying significantly improved the uniformity of moisture distribution due to the volumetric heating effect, which provides rapid and even heat penetration throughout the material. This uniform heating led to consistent moisture content across the dried apple slices. Additionally, the results of Chen *et al.* [22] highlighted the efficiency of microwave drying in achieving uniform drying and structural consistency.

Regarding the standard deviations of moisture content presented in **Table 2**, uniformity tended to decrease with microwave power, but not obviously observed with respect to temperature effect. For instance, the deviation of 0.14 % db from 300 W and 65 °C indicated highly uniform drying process while the deviation of 1.50 % db from 600 W and 55 °C indicated less uniform drying process. Such fluctuations may be attributed to uneven heating distribution when using high microwave energy, resulting in moisture gradient across the foamed pulp. Thickness measurement in **Table 2** reveals foam deformation affected by drying conditions. The foamed pulp dried from 600 W and 75 °C gave this highest thickness of 21.7 mm, higher than initial value of 20 mm. This could be attributed to puffing effect caused by high microwave energy. On the contrary, the lowest average thickness of about 12 mm was obtained from low microwave settings, mostly 300 W. In this case, less puffing took places due to lower heat levels, and more foam collapse may occur due to prolonged drying periods. Variations of moisture content and thickness across the foamed mango pulp dried under various conditions demonstrated higher microwave power levels increased heat transfer and, thereby, drying performance significantly, while the non-uniformity of the drying process was also pronounced. A comparison with Chauz-Gutiérrez *et al.* [3] and Yüksel [13]

confirms the uneven heating distribution when using high microwave energy. These observations suggested that microwave-assisted foam-mat drying required precise control over microwave intensity and material temperature to prevent such product degradation.



**Figure 6** Images of dried mango pulp foam at various drying conditions: (a) 300 + 55, ( b) 300 + 65, (c) 300 + 75, (d) 450 + 55, 450 +65, 450 + 75, 600 + 55, 600 + 65 and 600 W + 75 °C ; (A) front side, (B) bottom side and (C) SEM images ( $\times 30$  magnification at 10 kV).

The effects of different combined microwave powers and air temperatures on appearance and morphology of dried foams are visually demonstrated in **Figure 6**. Images of the front and bottom sides are depicted in columns A and B, respectively, while SEM images are shown in column C. Both front and bottom sides of dried foams were important as they contributed to understanding the physical alterations induced by certain drying conditions.

The front side images displayed minimal color variations, while the bottom images showed significant difference, especially at high microwave powers. At 600 W, the burnt spots were present. This occurrence confirmed non-uniform heat distribution or localized overheating at high microwave energy, consistent with the quantitative data discussed earlier in **Table 2**. Raj and Dash [23] reported that the highest color change of dragon fruit sample was found at high microwave power of 600 W, due to non-enzymatic browning. The findings of Poogungploy *et al.* [24] also demonstrated that using high microwave power resulted in overheated surface of macadamia nuts, confirming that microwave assisted drying with material temperature control led to better product quality. Therefore, microwave-assisted drying with pulse strategies and material temperature monitoring could enhance the uniformity and even minimize charring.

**Figure 6(C)** also demonstrates the dried foam morphology as affected by drying conditions. It was observed from this figure that the pore size of the dried foam tended to increase at higher microwave power. When using high microwave power with a high evaporation rate, the moisture in the foam could move to the surface through capillary action more quickly that it could collapse, thereby preserving the foam structure. Conversely, at low microwave levels, foam collapse may result in intense structure with small pore size, as seen in **Figures 6(C)** and **(a)**. This observation was consistent with the reduced thickness at 300 W presented in **Table 2**.

#### **Drying models**

The goodness of fit of different drying models was examined to ascertain the suitable model for describing the drying characteristics of foamed mango pulp under various conditions. **Table 3** summarizes all statistical parameters including  $R^2$ , RMSE and  $\chi^2$  averaged for each drying scenario. It can be observed that  $R^2$  obtained from all drying models were consistently higher than 90 %, ranging from 91.54 to 99.92 % , demonstrating high accuracy in predicting moisture content of the materials. Among semi-empirical drying models tested, the so-called Midilli model was considered as the best choice as it gave the highest  $R^2$  and lowest errors of RMSE and  $\chi^2$ . Therefore, the Midilli drying model coupled with all parameters for each drying condition, as summarized in **Table 4**, suitably describes drying behavior of the foamed mango pulp in microwave-assisted foam-mat drying process in this work.

The Midilli model is robust and can accurately capture the complex kinetics involved in the heat and mass transfer processes and is thus most suited for the current analysis. Qadri [25] also concluded that the Midilli model was the most appropriate in describing drying characteristics of guava pulp subjected to processes with variation of microwave power. Additionally, Yüksel and Pandiselvam [10] demonstrated that the Midilli model suitably described drying behavior of kefir in microwave-assisted foam-mat drying.

**Table 3** Statistical parameters of different drying models obtained from all drying conditions.

Models	Statistical parameters		
	$R^2$	RMSE	$\chi^2$
Lewis	91.54 - 94.84	0.0646 - 0.0918	0.0042 - 0.0087
Page	97.81 - 99.55	0.0211 - 0.0449	0.0005 - 0.0021
Henderson & Pabis	93.76 - 96.20	0.0570 - 0.0788	0.0033 - 0.0066

Models	Statistical parameters		
	R <sup>2</sup>	RMSE	$\chi^2$
Two term (2 parameters)	92.20 - 98.13	0.0536 - 0.0917	0.0030 - 0.0088
Wang and Singh	98.78 - 99.85	0.0109 - 0.0368	0.0001 - 0.0014
Logarithmic	98.95 - 99.90	0.0087 - 0.0341	0.0001 - 0.0012
Approximate of diffusion	91.54 - 94.87	0.0646 - 0.0918	0.0043 - 0.0089
Verma <i>et al.</i> [18]	91.54 - 99.88	0.0095 - 0.0918	0.0001 - 0.0092
Two term (4 parameters)	93.76 - 96.20	0.0570 - 0.0788	0.0034 - 0.0070
Midilli <i>et al.</i> [16]	99.43 - 99.92	0.0085 - 0.0241	0.0001 - 0.0006

**Table 4** Midilli Model parameters at various drying conditions.

MW (W)	T (°C)	Model parameters			
		a	b	k	n
300	55	0.992697	0.005263	1.127763	-0.003755
300	65	1.012998	0.004127	1.352223	-0.001305
300	75	1.020146	0.022428	0.704980	-0.008242
450	55	1.015223	0.009677	1.242391	-0.005613
450	65	0.990529	0.012610	1.213454	-0.004710
450	75	1.018591	0.012005	1.245101	-0.004494
600	55	0.978851	0.006426	1.585083	-0.001564
600	65	1.014010	0.011681	1.113584	-0.016906
600	75	1.002476	0.013643	1.196749	-0.011965

### Response surface methodology and optimization

In addition to the analysis of the drying kinetics, the following study employed response surface methodology (RSM) to optimize the microwave-assisted foam-mat drying for the foamed mango pulp. Two drying factors (drying temperature, T and microwave power, MW) and their responses including effective diffusivity coefficient ( $D_{\text{eff}}$ ), specific energy consumption (SEC) and color difference ( $\Delta E$ ) are presented in **Table 5**.

**Table 5** Drying factors and their responses.

Factors		Responses		
MW	T	$D_{\text{eff}}$	SEC	$\Delta E$
300	55	5.41	13.14	3.73
300	65	6.21	17.21	4.14
300	75	6.99	18.99	4.37
450	55	10.54	8.96	4.34
450	65	12.47	11.82	4.44
450	75	12.63	12.28	6.78
600	55	15.03	5.83	6.89
600	65	16.19	8.42	7.37
600	75	18.43	8.95	7.94

MW – microwave power (W); T – drying temperature (°C);  $D_{\text{eff}}$  – effective diffusivity coefficient expressed in  $\times 10^{-6} \text{ m}^2 \cdot \text{s}^{-1}$ ; SEC – specific energy consumption ( $\text{kWh} \cdot \text{kg}^{-1}$ );  $\Delta E$  – color difference.

**Table 5** reveals that  $D_{\text{eff}}$  value increases with increasing microwave powers at all temperature tested, indicating enhanced moisture removal at higher microwave energy. At hot-air temperature of 55 °C,  $D_{\text{eff}}$  increased from  $5.41 \times 10^{-6} \text{ m}^2 \cdot \text{s}^{-1}$  (at 300 W) to  $15.03 \times 10^{-6} \text{ m}^2 \cdot \text{s}^{-1}$  (at 600 W). The increased  $D_{\text{eff}}$  at higher microwave power was attributed to a greater amount of microwave energy absorbed by the foam sample, accelerating moisture diffusion from the inside to the surface of the foam. This observation was confirmed by the results reported by Yüksel and Pandiselvam [10], stating that the increased microwave power resulted in greater effective moisture diffusivity values of kefir foam. Similar results were observed in other microwave-assisted drying techniques and various food materials; for instance, convective hot air drying for apple slices [26] and vacuum-assisted microwave drying for pomelo albedo [27]. However, influence of hot-air temperature on  $D_{\text{eff}}$  is less substantial. Conversely, SEC value decreased considerably as the microwave power increased, inferring that using a higher power setting increased energy efficiency. For instance, at 55 °C, SEC decreased from 5.83 kWh·kg<sup>-1</sup> at 600 W to 13.14 kWh·kg<sup>-1</sup> at 300 W. Regarding color difference ( $\Delta E$ ), the positive trend was found when using higher microwave power, especially at 600 W at which uneven heat distribution and overheating took place, as described earlier. This color alteration could be linked to nonenzymatic browning or even charring of the product, which was evidenced by the burnt spots shown in **Figure 6**. These observations aligned with those obtained by Taşova *et al.* [28], Kumar *et al.* [29] and Jiang *et al.* [30], suggesting that while moisture removal was improved and energy consumption is reduced at high microwave power, color alteration needed to be taken into account to maintain product appearance.

**Table 6** ANOVA results of fitted models for all responses.

Source	Estimate coefficients		
	$D_e$	SEC	$\Delta E$
Model ( <i>p</i> -value)	0.001 <sup>b</sup>	0.0006 <sup>b</sup>	0.0542 <sup>ns</sup>
Intercept			
( <i>a</i> <sub>0</sub> )	11.96	11.77	4.95 <sup>b</sup>
Linear terms			
( <i>a</i> <sub>1</sub> ) MW	5.17 <sup>b</sup>	-4.36 <sup>b</sup>	1.66 <sup>ns</sup>
( <i>a</i> <sub>2</sub> ) T	1.18 <sup>a</sup>	2.05 <sup>b</sup>	0.69 <sup>ns</sup>
Interaction terms			
( <i>a</i> <sub>12</sub> ) (MW*T)	0.45 <sup>ns</sup>	-0.68 <sup>a</sup>	0.10 <sup>ns</sup>
Quadratic terms			
( <i>a</i> <sub>11</sub> ) MW <sup>2</sup>	-0.50 <sup>ns</sup>	1.07 <sup>a</sup>	0.55 <sup>ns</sup>
( <i>a</i> <sub>22</sub> ) T <sup>2</sup>	-0.12 <sup>ns</sup>	-1.12 <sup>a</sup>	0.36 <sup>ns</sup>
F value			
Model	137.70	189.09	8.49
MW	649.29	738.80	34.58
T	33.69	163.31	5.95
MW*T	3.35	12.09	0.088
MW <sup>2</sup>	2.05	14.85	1.28
T <sup>2</sup>	0.11	16.42	0.54

Source	Estimate coefficients		
	D <sub>e</sub>	SEC	ΔE
R <sup>2</sup>	0.9957	0.9968	0.9340
Adjusted R <sup>2</sup>	0.9884	0.9916	0.8239
Predicted R <sup>2</sup>	0.9634	0.9616	0.3220
Adequate Precision	31.28	39.96	8.32
C.V. (%)	4.31	3.35	12.45
Std. Dev.	0.50	0.39	0.69

The ANOVA results for the fitted models presented in **Table 6** show the statistical validation of the models to describe the relationships between drying parameters and responses. The notable significance of D<sub>eff</sub> model with an F-value of 137.70 was evidenced by a *p*-value below 0.05. All monomial values (T and MW) were significant, while interaction (T\*MW) and quadratic terms (T<sup>2</sup> and MW<sup>2</sup>) were insignificant. With closely matching predicted R<sup>2</sup> (0.9634) and adjusted R<sup>2</sup> (0.9884) values, and the adequate precisions of 31.28 (higher than desired threshold of 4), the D<sub>eff</sub> model effectively directed toward the target design. Moreover, microwave power with F-value of 649.29 was dominant, whereas hot-air temperature at 33.69 was less influential. Regarding the SEC value, the quadratic model was significant with a *p*-value < 0.01 and F-value of 189.09. All model terms were significant with both close predicted and adjusted R<sup>2</sup> and high adequate precision of 39.96. Higher F-value of 738.80 reveals that microwave power was more important than hot-air temperature with respect to SEC value. Additionally, **Table 6** shows that the color difference (ΔE) model and all model terms were insignificant with *p*-value higher than 0.05. The adjusted R<sup>2</sup> of 0.8239 did not align well with predicted value of 0.3220, implying the model fit or potential overfitting issues. However, the model reliability could be affirmed with an adequate precision value of 8.32 was higher than the desired threshold. The primary influence of microwave power on ΔE was confirmed by higher F-value of 34.58. In conclusion, the data presented in **Table 6** indicated that the quadratic model could sufficiently be served as a tool for navigating design space and optimization.

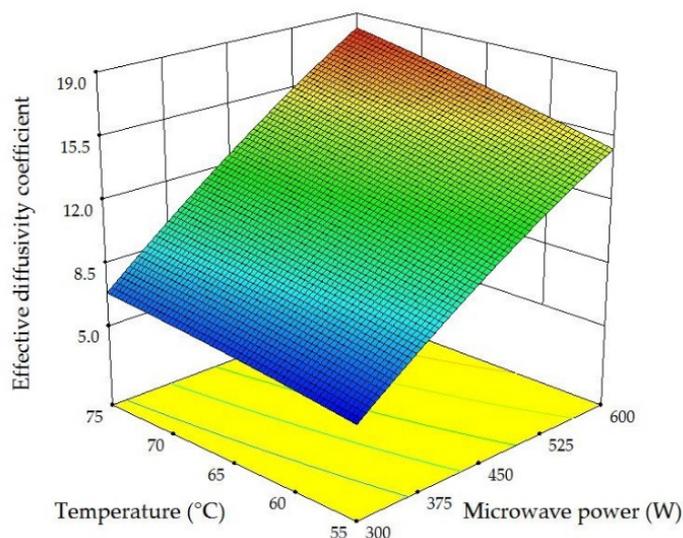
The optimization analysis using response surface methodology yielded quadratic models that effectively described the relationships between the drying factors and their responses. The models are presented as follows:

$$D_{\text{eff}} = -11.88 + 0.035(\text{MW}) + 0.135(\text{T}) + 3.03 \times 10^{-4}(\text{MW})(\text{T}) - 2.24 \times 10^{-5}(\text{MW})^2 - 0.0012(\text{T})^2 \quad (11)$$

$$\text{SEC} = -39.68 - 0.042(\text{MW}) + 1.87(\text{T}) - 4.55 \times 10^{-4}(\text{MW})(\text{T}) + 4.76 \times 10^{-5}(\text{MW})^2 - 0.0112(\text{T})^2 \quad (12)$$

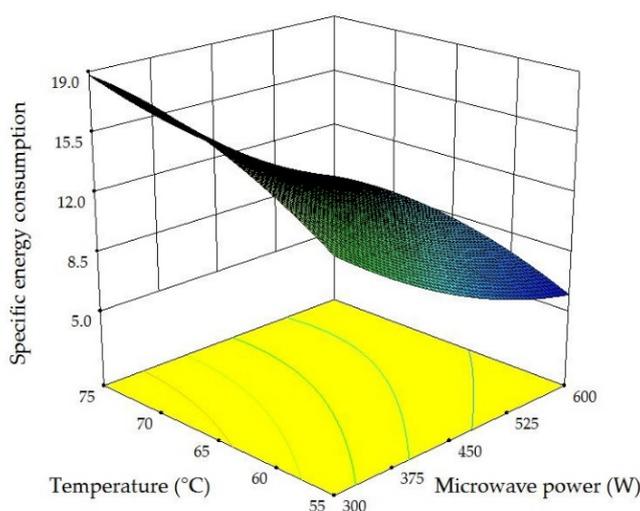
$$\Delta E = 17.61 - 0.016(\text{MW}) - 0.428(\text{T}) + 6.83 \times 10^{-5}(\text{MW})(\text{T}) + 2.46 \times 10^{-5}(\text{MW})^2 + 0.0036(\text{T})^2 \quad (13)$$

Using all these equations, influences of microwave power (MW) and hot-air temperature (T) on effective diffusivity coefficient (D<sub>eff</sub>), specific energy consumption (SEC) and color difference (ΔE) were presented via contour plots, as shown in **Figures 7 - 9**, respectively.



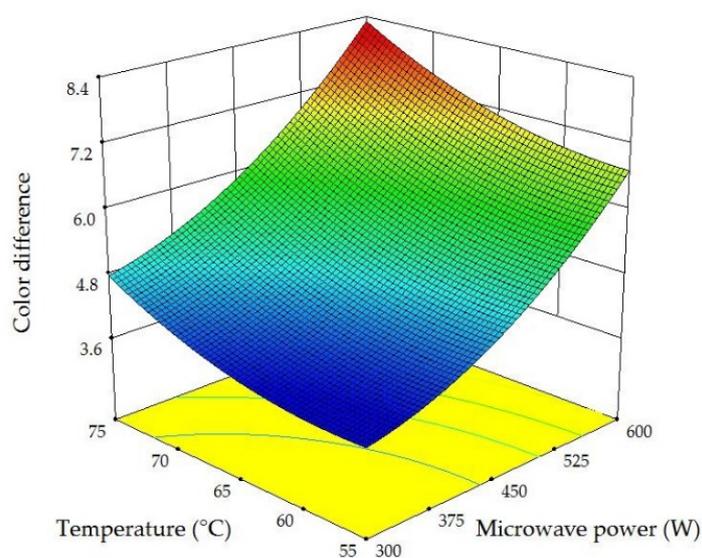
**Figure 7** Contour plot of effective diffusivity coefficient ( $D_{eff}$ ) as functions of temperature and microwave power.

**Figure 7** clearly reveals positive influence of microwave power on  $D_{eff}$  value, demonstrating that faster moisture migration from inside foamed material toward its surface was observed at higher microwave levels. This enhanced drying performance was attributed to increased internal heat generation in the foamed mango pulp with increasing microwave energy. This observation was supported by Poogungploy *et al.* [24], Jiang *et al.* [30], and Kumar *et al.* [29]. However, optimal adjustment of microwave settings should be concerned as excess energy may degrade the product quality. Raj and Dash [23] suggested that moderated or intermittent power might balance drying performance while avoiding overheating, resulting in promising quality. However, as shown in **Figure 7**, hot-air temperature slightly affected  $D_{eff}$  value as it gradually inclined with increasing temperature. The explanation of this positive trend was explained by the role of higher thermal energy in accelerating moisture migration [29,31,32].



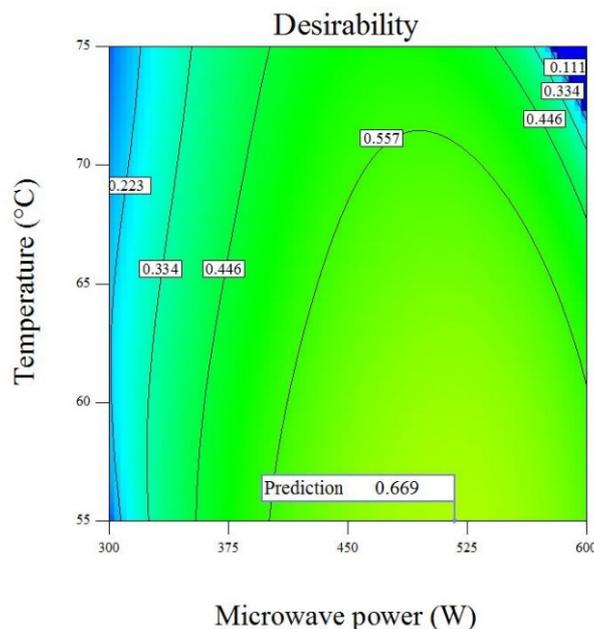
**Figure 8** Contour plot of specific energy consumption (SEC) as functions of temperature and microwave power.

**Figure 8** shows the 3D contour plot of SEC value as functions of microwave powers and hot-air temperature. Among these two drying factors, microwave power was a pronounced effect on SEC as seen by steeper plot. Microwave power inversely influenced SEC value; decreasing SEC with higher microwave levels. The minimum SEC value was found at hot-air temperature of 55 °C combined with microwave power of 600 W, suggesting the most energy efficiency at this condition. This result was responsible for more electromagnetic energy absorbed by moist foamed material, resulting in shortened drying period and subsequently less total energy consumed. This result agreed well with those obtained by Zaki and Ismail [33] and Kumar *et al.* [29]. Considering the effect of hot-air temperature, **Figure 8** also shows inverse trend as SEC value slightly decreased with increasing temperature. Higher thermal energy not only resulted in shorter drying time, but also contributed to less energy consumption [29,32].



**Figure 9** Contour plot of color difference ( $\Delta E$ ) as functions of temperature and microwave power.

Color alteration ( $\Delta E$ ) is also important response, reflecting how drying parameters affecting product quality. Contour plot in **Figure 9** also displays inverse trend of all factors, demonstrating that color of the foamed mango pulp degraded with higher microwave power and hot-air temperature. With using higher microwave energy levels, more internal heat may result in non-enzymatic browning reactions or even charring caused by overheating. This color degradation was also observed by Zaki *et al.* [34] and Taşova *et al.* [28]. Additionally, Poogungploy *et al.* [24] reported that higher electromagnetic energy with increased microwave power seriously reduced product lightness. Using the process with precise temperature control [35] or alternative methods such as ultrasonic-assisted drying [32] could improve this problem. However, **Figure 8** shows less influential factor with respect to hot-air temperature. Color difference slightly increased with higher temperature possibly due to Maillard reaction or caramelization resulting from higher thermal energy [29,30]. Biswas *et al.* [35] and Sarpong *et al.* [36] explained that sugar-rich fruits were prone to browning.



**Figure 10** Contour plot of desirability function

RSM results revealed that microwave power and hot-air temperature affected effective diffusivity coefficient, specific energy consumption and color difference in different ways. Here, the best combination of these two independent variables was determined for process optimization. **Figure 10** shows contour plot of desirability function. Based on the criteria of maximized  $D_{\text{eff}}$ , and minimized SEC and  $\Delta E$ , corresponding to highest desirability value of 0.669, foam-mat drying under temperature of 55 °C combined with an intermediate microwave power of 520 W for the thick foamed mango pulp was optimal. At this condition, a dried foamed mango pulp snack can effectively produce with regard to drying performance, while minimizing color alteration.

### Conclusions

This study confirmed the possibility of using a combination of microwave heating and foam-mat drying to produce the foamed mango pulp snack. With microwave-assisted method, drying performance in terms of moisture diffusivity and energy consumption was enhanced, resulting in drying time reduced by up to 20 times, while saving energy up to 92 %. Among ten semi-empirical drying models tested, the Midilli model suitably described drying behavior of the foamed mango pulp, evidenced by highest  $R^2$  and lowest error parameters.

Images of dried foams and their morphology indicated non-uniform heat distribution and overheating when applying excess microwave energy. Additionally, RSM results reveal that microwave power was more pronounced, influencing effective diffusivity coefficient, specific energy consumption and color difference. Based on maximum  $D_{\text{eff}}$ , and minimum SEC and  $\Delta E$ , the highest desirability value was 0.669 corresponding to microwave power of 520 W and drying temperature of 55 °C, meaning that this combination of these independent drying parameters was globally optimal.

Future research should focus on improving the uniformity of heat distribution by exploring pulsed microwave energy. Attention should also be given to maintaining and enhancing the nutritional values and textural properties of the final product, ensuring that the drying process preserves these essential quality

attributes. Scale-up studies are essential to transition from laboratory to industrial scale, optimizing parameters for larger batches and assessing economic feasibility.

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