

MATHEMATICAL MODELLING AND OPTIMIZATION OF MELON SLICE DRYING WITH RESPONSE SURFACE METHODOLOGY IN A HEAT PUMP DRYING SYSTEM

C. TUNCKAL[†], A. OZKAN-KARABACAK[‡], C.E. TAMER[‡], P. YOLCI-OMEROGLU^{‡,§} and Z. GOKSEL^{*}

[†]Yalova University, Electric and Energy Department, Air Conditioning and Refrigeration Technology Program, Yalova Community College, 77100, Yalova, Turkey

[‡]Bursa Uludag University, Faculty of Agriculture, Department of Food Engineering, 16059, Gorukle, Bursa–Turkey

[§]Bursa Uludag University, Science and Technology Application and Research Center, 16059, Gorukle, Bursa–Turkey

^{*}Atatürk Horticultural Research Institute, Food Technology Department, 77100, Yalova, Turkey

Corresponding author e-mail: etamer@uludag.edu.tr

Abstract— The objective of this study was to optimize the process conditions (in terms of air temperature, air velocity and thickness of the slices) using response surface methodology (RSM) to achieve minimum specific energy consumption and maximum moisture diffusivity during drying of melon slices with a closed loop heat pump drying (HPD) system. An optimum drying temperature of 45 °C, air velocity of 1 m/s and slice thickness of 5.04 mm were recommended with following predicted responses close to experimental values: drying time 216.58 min, total energy consumption 2.94 kWh, coefficient of performance heat pump (COP_{hp}) 3.08, coefficient of performance system (COP_{ws}) 2.75, specific moisture extraction rate (SMER) 0.22 kg/kWh, drying rate 2.53, *L** value 82.53, *a** value -1.83 and *b** value 25.82. The most suitable models to represent the drying behavior of optimum melon slices was chosen Wang & Sing. Effective moisture diffusivities (*D*_{eff}) of the melon slices were ranging from 7.075E-10 - 1.843E-07 m²s⁻¹ and increasing drying air temperature, drying air velocity and slice thickness led to an increment of *D*_{eff}.

Keywords— Heat pump drying, Melon, Response surface methodology, Drying characteristics, Mathematical modelling

I. INTRODUCTION

Dried fruits function as the concentrated form of their fresh properties in terms of energy, nutrients, dietary fiber and antioxidants (Bennett *et al.*, 2011). Melon (*Cucumis melo* L.) is a popular fruit grown in European, Asian and African countries (Dias da Silva *et al.*, 2016). In addition to its rich nutritional composition and bioactive substances, melon has excellent flavour properties (Petkova and Antova, 2015). Since melons are highly perishable and rapidly get decomposed, they can easily deteriorate after harvesting (Welti-Chanes *et al.*, 2002). For this reason, drying is a useful process to extend the shelf life of melons (Azuara *et al.*, 2009; Dias da Silva *et al.*, 2016) and to increase their added value by transforming them in to a healthy snack, especially in over production seasons. On the other hand, drying can cause adverse effects on melon by reducing its quality in terms of colour, texture and bioactive compounds (Dias da Silva *et al.*, 2016). It is very important to select a proper drying

method in terms of its technology, energy consumption, and frequency of requirements to maintenance (Kırbaş *et al.*, 2019). Due to the prolonged exposure to high temperature and/or heat and oxygen, traditional drying processes adversely affect typical fresh fruit colour, aroma, and overall flavour (Zanoni *et al.*, 1999; Abano *et al.*, 2011). Therefore, there is a need to establish a proper drying method to increase the amount of vitamins and flavour in the final dried product in addition to decreasing the rate of pigment deterioration (Perera and Rahman, 1997). The studies in the literature prevailed that Heat Pump Drying (HPD) system played an important method to retain the colour, vitamins, and other heat sensible components of agricultural products (Prasertsan, 2010; Jeyaprakash *et al.*, 2016; Coskun *et al.*, 2017). Moreover, it was proven that HPD consumes the lowest energy among the other drying methods (Tunçkal and Doymaz, 2020). The objective of this study was to optimize the process conditions (in terms of air temperature, air velocity and thickness of the slices) using the response surface methodology to achieve minimum specific energy consumption and maximum moisture diffusivity during drying of melon slices with a closed loop HPD system.

II. METHODS

A. Materials

Fresh melons (Futuro F1) were purchased from local producers in Yalova, Turkey. Following washing under tap water, melons were peeled and sliced into 5 mm, 7 mm and 9 mm-thick slices. 5 g of melon slices were weighted to measure moisture content in an oven at 105±3 °C. Moisture analysis was ceased once the two successive weights of the sample less than 1% (Koşan *et al.*, 2020). It was obtained that the initial moisture content of fresh melon slices ranged between 5.337 g water/g dry matter and 9.967 g water/g dry matter.

B. Drying system procedure

Melon slices were dried with a heat pump dryer whose technical properties and detailed figure were given before by Coskun *et al.* (2017). Before starting the drying process, the dryer was operated for about 30 min. to reach steady state conditions. The process input variables included drying air temperature, velocity and slice thickness ranging by 35 - 45 °C, 0.5 - 1.0 m/s and 5 - 9 mm, respectively. Following weighing of 635 g of melon

slices, they were distributed homogeneously on the drying tray, and consequently the drying process was started. During drying process, the mass loss of samples was measured by using the load cell at every four min. and all data were recorded by a computer connected to the system. The temperature and relative humidity of air within the drying system were measured every one minute by a data collector. When the moisture content of the melon slices decreased about 8 ± 0.5 % (wet basis), the drying procedure was finished. Energy consumption of the compressor was measured by a digital wattmeter (Makel, Turkey) every one hour followed by recording the data. Drying system operates with ± 0.8 °C sensitivity by a digital thermostatic control.

C. HPD system analyses

The performance of HPD system is expressed in terms of specific moisture extracted ratio (SMER) and the coefficient of performance (COP). SMER is defined as the water extracted from the product per consumed energy; and COP is the ratio between the heat delivered to the drying air through the condenser ($\dot{Q}_{cd}$) and energy consumed at the compressor ($\dot{W}_{comp}$) (Jia *et al.*, 1990). COP for HPD system was calculated by Eq. 1.

$$COP_{hp} = \frac{\dot{Q}_{cd}}{\dot{W}_{comp}} \quad (1)$$

where COP_{hp} represents coefficient of performance of heat pump.

The COP of the overall system (COP_{sys}) was based on Eq. 2:

$$COP_{sys} = \frac{\dot{Q}_{cd}}{\dot{W}_{comp} + \dot{W}_{fan,i} + \dot{W}_{fan,e}} \quad (2)$$

where $\dot{W}_{fan,i}$ and $\dot{W}_{fan,e}$ represents power consumption (kJ/s) of the internal and external condenser fan, respectively.

Heat transfer rate (kJ/s) of the internal condenser was used to increase the enthalpy of the drying air as given in Eq. 3.

$$\dot{Q}_{cd} = \dot{m}_a(h_A - h_E) \quad (3)$$

where $\dot{m}_a$, h_A and h_E represents mass flow rate of air (kg/s), specific enthalpy of air at the exit and at the inlet (kJ/kg) of the condenser, respectively.

SMER (specific moisture added ratio) represents the total amount of energy consumed per the moisture absorbed from the product and calculated using the following equation (Jia *et al.*, 1990).

$$SMER = \frac{\dot{m}_w}{\dot{W}_{comp} + \dot{W}_{fan,i} + \dot{W}_{fan,e}} \quad (4)$$

where $\dot{m}_w$ represents amount of water evaporated from the melon during drying process (kg/s).

D. Mathematical modelling of drying kinetics

Seven drying models were applied to determine the best model for drying characteristics of melon slices. These models were given as following equations (Özkan Karabacak *et al.*, 2020):

$$\text{Page: } MR = \exp(-kt^n) \quad (5)$$

$$\text{Modified Page: } MR = \exp[(-kt)^n] \quad (6)$$

$$\text{Logarithmic: } MR = a \exp(-kt) + c \quad (7)$$

$$\text{Lewis: } MR = \exp(-kt) \quad (8)$$

$$\text{Henderson \& Pabis: } MR = a \exp(-kt) \quad (9)$$

$$\text{Two Term Exponential: } MR = a \exp(-kt) + (1 - a) \exp(-kat) \quad (10)$$

$$\text{Wang \& Singh: } MR = 1 + at + bt^2 \quad (11)$$

where a , b , and n represent model constant, k is the coefficient in the drying model (1/s) and t is the drying period (s).

The moisture ratio (MR) and drying rate of the samples (DR) (g/s) were estimated from the following equations:

$$MR = \frac{M - M_e}{M_i - M_e} \quad (12)$$

In Eq. 12, MR , M , M_i , M_e are the moisture ratio, the moisture content at a specific time (g water/g dm.), moisture content (g water/g dm.) of the sample prior to drying, moisture content (g water/g dm.) at equilibrium state, respectively (Tüfekçi and Özkal, 2017). Equilibrium moisture content was accepted as zero since M_e is much lower than M and M_i values.

$$DR = \frac{M_0 - M_t}{\Delta t} \quad (13)$$

where M_0 and M_t represent the weight (g) of the melon before drying and after drying, respectively. Δt refers to the duration of the drying process (s).

The highest correlation coefficient (R^2) and lowest root mean square error (RMSE), Chi square (χ^2) were used as the statistical parameters to identify the integrity of the fit models describing the drying kinetics of melon slices (Gamli *et al.*, 2018). Subsequent equations were used for the calculation of these values:

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2 \right]^{1/2} \quad (14)$$

$$\chi^2 = \frac{(MR_{exp,i} - MR_{pre,i})^2}{N - n} \quad (15)$$

Here, $MR_{exp,i}$ and $MR_{pre,i}$ are the experimental and dimensionless moisture ratios, respectively for the test i . N is the number of observations and n is the constant number for the models.

E. Effective moisture diffusivity (D_{eff})

Fick's second diffusion law is broadly utilized for the estimation of effective moisture diffusivities of agricultural products (Süfer and Palazoğlu, 2019). The mathematical explanation of Fick's law is given in Eq. 16, based on the assumptions including uniform initial moisture diffusion, negligible shrinkage, constant diffusion coefficient throughout the process and symmetric mass transfer in an infinite slab,

$$MR = \frac{8}{\pi^2} \sum_{i=1}^N \frac{1}{(2n-1)^2} \exp\left(-\frac{(2n-1)^2 \pi^2 D_{eff} t}{4L^2}\right) \quad (16)$$

In Eq. (16) MR , D_{eff} , L and n represents dimensionless moisture ratio, effective moisture diffusivity (m^2/s), half thickness of the slab in the melon slices (m) and positive integer, respectively. For sufficiently extended drying periods, Eq. (17) can be abbreviated to the first term in the series by using a logarithmic form as follows:

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff} t}{4L^2}\right) \quad (17)$$

D_{eff} was computed through the slope of a straight line which was plotted $\ln MR$ versus time in drying experiments. The equation was expressed as follows:

Table 1. Box–Behnken matrix of independent variables used in the RSM design

Values	Parameter	Levels		
		-1	0	1
X_1	Drying air temperature (°C)	35	40	45
X_2	Slice thickness (mm)	5	7	9
X_3	Drying air velocity (m/s)	0.5	0.75	1

Table 2. Experimental Design

Run	Coded Values			Uncoded values		
				X_1	X_2	X_3
1	-1	-1	0	35	5	0.75
2	+1	-1	0	45	5	0.75
3	-1	+1	0	35	9	0.75
4	+1	+1	0	45	9	0.75
5	-1	0	-1	35	7	0.5
6	+1	0	-1	45	7	0.5
7	-1	0	+1	35	7	1
8	+1	0	-1	45	7	1
9	0	-1	-1	40	5	0.5
10	0	+1	-1	40	9	0.5
11	0	-1	+1	40	5	1
12	0	+1	+1	40	9	1
13	0	0	0	40	7	0.75
14	0	0	0	40	7	0.75
15	0	0	0	40	7	0.75
16	0	0	0	40	7	0.75
17	0	0	0	40	7	0.75

$$D_{eff} = -\frac{slope \ 4L^2}{\pi^2} \quad (18)$$

F. Colour analysis

Colour measurements were carried out with a chroma meter (CR-5, Konica Minolta, Osaka-Japan). L^* value indicates the change from vertical luminous intensity to darkness, ($+a^*$) redness, ($-a^*$) greenness, ($+b^*$) yellowness, ($-b^*$) blueness. Measurements were performed in triplicate, and the average was used for further calculations.

G. Experimental design

Response Surface Methodology (RSM) was applied to evaluate the effect of independent variables including air temperature (X_1), slice thickness (X_2) and drying air velocity (X_3) on depended variables which include drying time (Y_1), total energy consumption (Y_2), COP_{hp} (Y_3), COP_{ws} (Y_4), $SMER$ (Y_5), drying rate (Y_6), and colour parameters (L^* , a^* , b^*) (Y_6 , Y_7 , Y_8). A three level of Box–Behnken design was used for RSM study. Three factors and their levels (-1, 0, 1) were determined based on the preliminary experimental trials. 1, 0, and -1 represent high, optimal and low value. This experimental design involved 17 experimental trials carried out in a randomized order. Factors, their levels and experimental design including coded and uncoded values were illustrated in Table 1 and Table 2.

All experiments were performed in triplicate, and each sample was analyzed in duplicate. Average analysis results of each trial were used to draw three dimensional contour plots and consequently were evaluated to establish an optimization model. The contour surface as a bi-

dimensional projection of RSM was a proper tool to determine a relationship between drying parameters of the process and the studied variables.

A second order polynomial equation (Eq. 19) was fitted to model each responses, i.e. depended variables as a function of independent variables.

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_1X_2 + b_5X_1X_3 + b_6X_2X_3 + b_7X_1^2 + b_8X_2^2 + b_9X_3^2 \quad (19)$$

In this equation, coefficients of the model were b_0 (constant), b_1 , b_2 , b_3 (linear), b_4 , b_5 , b_6 (interaction), b_7 , b_8 , b_9 (quadratic).

Second-order coefficients of model equations were generated by regression analysis with Minitab statistical software (version 17, Minitab Inc., Pennsylvania, USA). The goodness of fit of the model was evaluated by the coefficient determination (R^2). The significance of the estimated regression coefficient for each response variable was assessed by using a 5% test of significance at a probability (p) of 0.05. Moreover, optimum levels were determined by optimizing the responses.

III. RESULTS AND DISCUSSION

A. Analysis the Response Surface Models

The analytical results obtained from all the experiments designed based on Box–Behnken model for drying of melon slices were given in Table 3. Those experimental data were used to determine the coefficients of the quadratic polynomial equations given Eq. 19. The resulting model parameters were demonstrated in Table 4 providing regression coefficients for each dependent variable. The determination coefficient (R^2) for most of the responses except colour ranged from 0.9772 and 0.9928, indicating a high correlation between predicted and observed values. The alterations in moisture content of melon slices over time were illustrated in Fig. 3. Drying time of the melon samples changed between 244 - 792 min.

Drying time:

Drying time (Y_1) of the melon samples changed between 244 and 792 min. The quadratic model for drying time can be expressed by the following equation.

$$Y_1 = 0.432 - 68.00X_1 + 170.00X_2 - 28.00X_3 - 32.0X_1X_2 + 14.0X_1X_3 + 10.0X_2X_3 + 8.4X_1^2 + 70.4X_2^2 - 55.6X_3^2 \quad (20)$$

From the Eq. (20), it can be observed that while linear terms of drying air temperature (X_1) and drying air velocity (X_3) had negative impact on drying time, slice thickness (X_2) had positive effect on it. Quadratic term of slice thickness (X_2^2) had the highest positive effect. However, drying time significantly negative influenced by the quadratic terms of drying air velocity (X_3^2) ($p < 0.05$). Maximum drying time was determined for in Run 11. However, minimum drying time was found in Run 3. It was prevailed that drying time decreased by reducing the slice thickness and increasing the drying air velocity and temperature (Fig. 1a). Those results were in line with the previous studies reported in the literature in which increasing air temperature (Phahom *et al.*, 2021) and drying

air velocity (Ndukwu, 2009) and reduced slice thickness (Sadin *et al.*, 2014) led to a reduction on drying time.

Total energy consumption

Total energy consumption (Y_2) in kWh changed between 3.008 - 9.258 kWh. The quadratic model for total energy consumption can be expressed by the following Eq. (21):

$$Y_2 = 5.294 - 0.4196X_1 + 2.1585X_2 - 0.3119X_3 - 0.514X_1X_2 + 0.293X_1X_3 + 0.298X_2X_3 + 0.191X_1^2 + 1.760X_2^2 - 1.391X_3^2 \quad (21)$$

From Eq. (21), it can be monitored that while linear terms of drying air temperature (X_1) and drying air velocity (X_3) had negative impact on total energy consumption, slice thickness (X_2) had positive effect on it. Similar to drying time, quadratic term of slice thickness (X_2^2) had the highest positive effect on total energy consumption. However, total energy consumption was significantly influenced by the quadratic terms of drying air velocity (X_3^2) in a negative manner ($p < 0.05$). Maximum total energy consumption was determined for in Run 3. In contrast, the lowest total energy consumption was found in Run 11. The graphical representation of the influence of slice thickness (X_2) and drying air temperature (X_1) on total energy consumption (Fig. 1b) revealed that when drying air temperature increased to 40 – 45 °C and minimum slice thickness was applied, total energy consumption was the lowest. Also it can be observed that lower drying air velocity (< 0.8 m/s) and lower drying air temperature (35 °C) had negative influence on total energy consumption. The effect of slice thickness (X_2) and drying air velocity (X_3) at center point of drying air temperature (40°C) demonstrated that increase of slice thickness resulted in higher total energy consumption.

HPD system analyses

COP_{hp}

COP_{hp} (Y_3) changed between 1.430 and 3.074. The quadratic model for COP_{hp} can be expressed by the following Eq. (22):

$$Y_3 = 2.2234 + 0.1452X_1 - 0.0028X_2 + 0.6765X_3 + 0.0005X_1X_2 + 0.0260X_1X_3 - 0.0060X_2X_3 - 0.0074X_1^2 - 0.0069X_2^2 + 0.0100X_3^2 \quad (22)$$

From the Eq. (22), it can be monitored that while linear terms of drying air temperature (X_1) and drying air velocity (X_3) had positive impact on COP_{hp} , slice thickness (X_2) had negative effect on it. Quadratic term of drying air temperature and slice thickness (X_1^2 and X_2^2) had negative effect on COP_{hp} . However, COP_{hp} positive influenced by the quadratic terms of drying air velocity (X_3^2) ($p < 0.05$). Maximum COP_{hp} determined for in Run 8. However, minimum COP_{hp} was found in Run 5. Factorial plots for COP_{hp} demonstrated that when drying air temperature increased, COP_{hp} was also increased (Fig. 1c). It can be also observed that lower drying air velocity (< 0.8 m/s) had negative influence on COP_{hp} . The effect of slice thickness (X_2) and drying air velocity (X_3) at center point of drying air temperature (40 °C) was represented in Figure 1c, demonstrated that increase of drying air velocity (> 0.75 m/s) resulted in higher COP_{hp} .

COP_{ws}

COP_{ws} (Y_4) changed between 1.359 and 2.749. The quadratic model for COP_{hp} can be expressed by the following Eq. (23):

$$Y_4 = 1.9756 + 0.1440X_1 - 0.0015X_2 + 0.5600X_3 - 0.0002X_1X_2 + 0.0597X_1X_3 - 0.0063X_2X_3 + 0.0058X_1^2 - 0.0232X_2^2 + 0.0233X_3^2 \quad (23)$$

From the Eq. (23), it can be determined that both linear and quadratic terms of slice thickness (X_2 and X_2^2) had negative effect on COP_{ws} ($p < 0.05$). Although maximum COP_{ws} determined for in Run 8, minimum COP_{ws} was found in Run 9.

Those results were consistent with previous studies performed with HPD in which 2.72 COP value was obtained for banana at 48 – 52 °C drying air temperature and 0.4 m/s drying air velocity conditions (Kuan *et al.*, 2019) and COP values between 2.11-2.96 were obtained for grated carrots at 56 °C drying air temperature (Aktaş *et al.*, 2019). On the other hand COP values of the melon slices were found lower than mint leaves were dried by heat pump dryer at 40 °C drying air temperature and 1.8 m/s drying air velocity conditions. Factorial plots for COP_{ws} showed that when drying air temperature (X_1) was increased, COP_{ws} was also increased (Fig. 1d). It can be seen that drying air velocity (X_3) (> 0.8 m/s) had positive influence on COP_{ws} . The effect of slice thickness (X_2) and drying air velocity (X_3) at center point of drying air temperature (40°C) was showed in Fig. 1d, demonstrated that increase of drying air velocity (> 0.75 m/s) resulted in higher COP_{ws} .

SMER

$SMER$ (Y_5) changed between 0.125 and 0.215 kg/kWh. The quadratic model for $SMER$ can be expressed by the following Eq. (24):

$$Y_5 = 0.1642 + 0.00738X_1 - 0.027X_2 + 0.00762X_3 + 0.00100X_1X_2 - 0.00075X_1X_3 - 0.0060X_2X_3 + 0.00423X_1^2 + 0.00402X_2^2 + 0.00977X_3^2 \quad (24)$$

According to Eq. (24), both drying air temperature (X_1) and drying air velocity (X_3) had positive correlation, but slice thickness (X_2) had negative correlation on $SMER$ value. Moreover, it was significantly negative influenced by the quadratic term of drying air temperature (X_1^2). Quadratic terms of slice thickness (X_2^2) and drying air velocity (X_3^2) had highest positive effect on it ($p < 0.05$). Similar to drying time and total energy consumption, maximum $SMER$ was determined for in Run 11. However, minimum $SMER$ was found in Run 3. In previous studies $SMER$ values were obtained as 2.05 kg/kWh for mango by Wang *et al.* (2019), 0.6 kg/kWh for banana by Kuan *et al.* (2019), 1.64 kg/kWh for red jujube by Yuan *et al.* (2019) and 0.06 kg/kWh for ginger by Chapchaimoh *et al.* (2016).

The graphical representation of the influence of slice thickness (X_2) and drying air temperature (X_1) on $SMER$ value (Fig. 1e) revealed that when both drying air temperature decreased and slice thickness increased (> 6 mm), $SMER$ value was reduced. From Fig. 1e it can be seen that lower drying air velocity (< 0.8 m/s) and lower

Table 3. The results of analyzed responses for dried melon slices

Run	Drying air temperature (°C)	Slice thickness (mm)	Drying air velocity (m/s)	Drying time (min)	Total energy consumption (kWh)	COP _{hp}	COP _{ws}	SMER (kg/kWh)	Drying rate (kg/s)	D _{eff} (m ² /s)	L*	a*	b*
1	35	5	0.75	352	4.016	2.108	1.848	0.182	1.543	7.075E-10	76.35	2.64	29.52
2	45	5	0.75	276	3.795	2.314	2.072	0.201	1.989	9.996E-10	81.92	1.46	27.33
3	35	9	0.75	792	9.258	2.103	1.845	0.125	0.718	1.272E-07	68.38	4.04	27.78
4	45	9	0.75	588	8.008	2.311	2.068	0.148	0.895	1.636E-07	73.32	5.46	33.20
5	35	7	0.5	480	5.568	1.430	1.380	0.154	1.152	8.520E-10	74.29	5.18	29.16
6	45	7	0.5	320	4.332	1.752	1.613	0.164	1.734	1.146E-09	69.70	1.77	26.27
7	35	7	1	404	4.763	2.648	2.277	0.177	1.396	9.737E-10	59.30	-2.48	18.51
8	45	7	1	300	4.113	3.074	2.749	0.184	1.907	1.258E-09	71.59	-2.95	28.64
9	40	5	0.5	328	4.042	1.506	1.359	0.194	1.695	8.698E-10	78.00	0.68	26.96
10	40	9	0.5	612	7.650	1.511	1.369	0.153	0.922	1.843E-07	82.62	1.30	25.83
11	40	5	1	244	3.008	2.954	2.595	0.215	2.295	1.071E-09	81.18	1.37	25.69
12	40	9	1	568	7.213	2.935	2.580	0.150	0.991	1.818E-07	81.85	4.25	30.06
13	40	7	0.75	400	5.007	2.231	1.983	0.166	1.355	9.635E-10	67.22	5.09	30.69
14	40	7	0.75	424	5.336	2.222	1.976	0.165	1.283	9.432E-10	74.08	3.30	29.17
15	40	7	0.75	424	5.321	2.224	1.975	0.165	1.290	9.230E-10	75.51	-0.73	32.87
16	40	7	0.75	428	5.384	2.221	1.974	0.164	1.266	8.824E-10	73.74	6.73	32.01
17	40	7	0.75	440	5.420	2.219	1.970	0.161	1.280	9.432E-10	81.38	1.02	25.90

Table 4. Summary of regression analysis response

Regression coefficient	Drying time (min)	Total energy consumption (kWh)	COP _{hp}	COP _{ws}	SMER (kg/kWh)	Drying rate (g/s)	L*	a*	b*
b ₀	0.432	5.294	2.2234	1.9756	0.16420	1.2948	74.39	3.08	30.13
b ₁ (for X ₁ - Drying air temperature)	-68.00	-0.4196	0.1452	0.1440	0.00738	0.2145	2.28	-0.46	1.309
b ₂ (for X ₂ -Slice thickness)	170.00	2.1585	-0.0028	-0.0015	-0.02700	-0.4995	-1.41	1.11	0.921
b ₃ (for X ₃ -Drying air velocity)	-28.00	-0.3119	0.6765	0.5600	0.00762	0.1358	-1.34	-1.09	-0.665
b ₄ (for X ₁ X ₂)	-32.0	-0.514	0.0005	-0.0002	0.00100	-0.0673	-0.16	0.65	1.90
b ₅ (for X ₁ X ₃)	14.0	0.293	0.0260	0.0597	-0.00075	-0.0178	4.22	0.73	3.25
b ₆ (for X ₂ X ₃)	10.0	0.298	-0.0060	-0.0063	-0.00600	-0.1327	-0.99	0.56	1.37
b ₇ (for X ₁ ²)	8.4	0.191	-0.0074	0.0058	-0.00423	0.0315	-5.79	-0.60	-1.08
b ₈ (for X ₂ ²)	70.4	1.760	-0.0069	-0.0232	0.00402	-0.0400	6.40	0.92	0.41
b ₉ (for X ₃ ²)	-55.6	-1.391	0.0100	0.0233	0.00977	0.2210	0.13	-2.10	-3.40
Lack of Fit	0.095	0.085	0	0	0.013	0.022	0.421	0.396	0.559
R ²	0.9886	0.9892	0.9928	0.9890	0.9772	0.9848	0.6977	0.4112	0.7497
Adj R ²	0.9740	0.9753	0.9835	0.9750	0.9479	0.9652	0.3091	0	0.4280

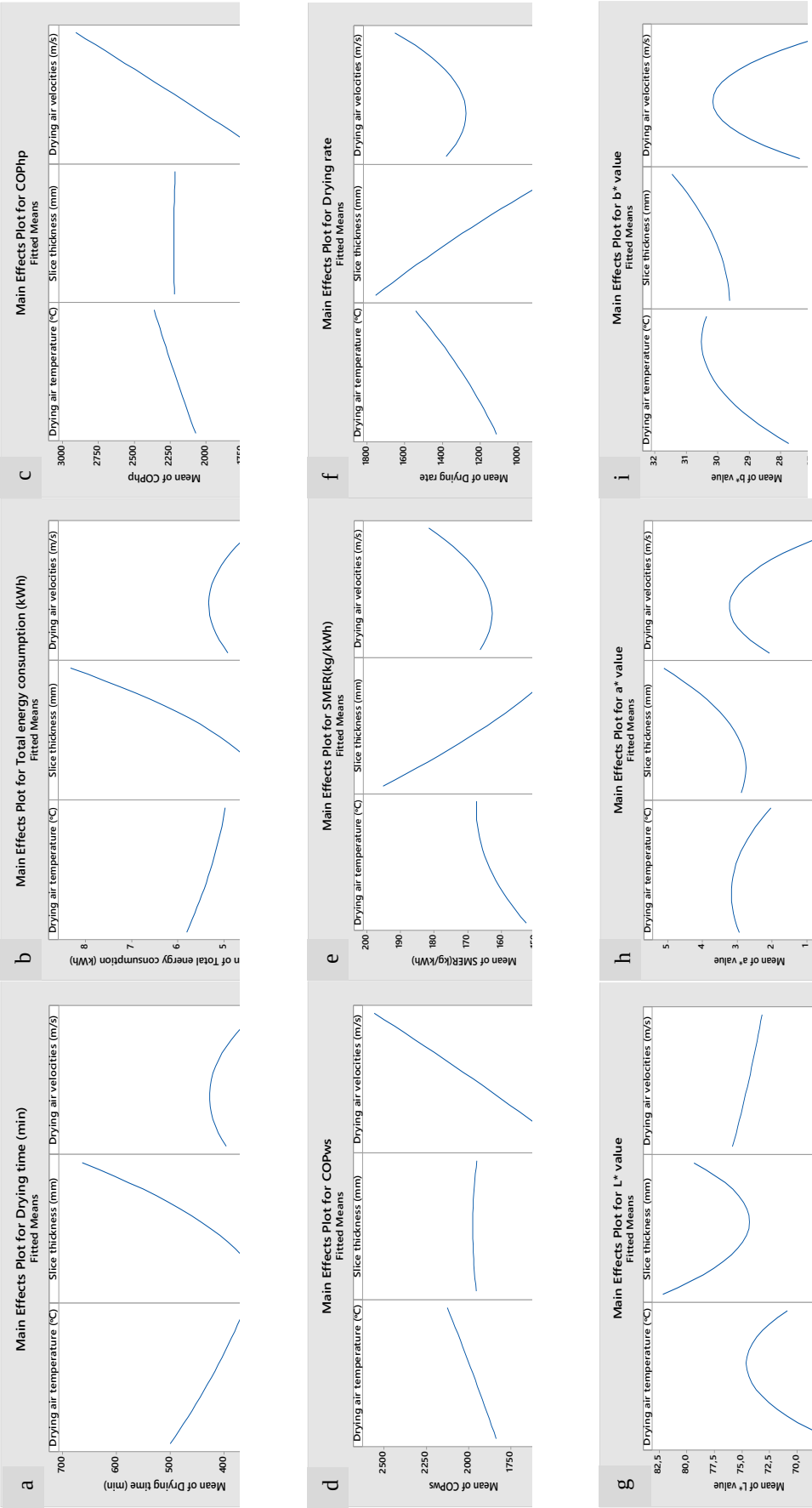


Figure 1. Response factorial plot showing the effects of drying air temperature, slice thickness and drying air velocities on the drying time, total energy consumption, COPhp, COPws, SMER, drying rate, L* value, a* value and b* value

drying air temperature (35 °C) had negative influence on *SMER* value. The effect of slice thickness (X_2) and drying air velocity (X_3) at center point of drying air temperature (40 °C) demonstrated that increase of slice thickness resulted in lower *SMER* value.

Drying rate

Drying rate (Y_6) changed between 0.718 and 2.295. The quadratic model for *SMER* can be expressed by the following Eq. (25):

$$Y_6 = 1.2948 + 0.2145X_1 - 0.4995X_2 + 0.1358X_3 + 0.0673X_1X_2 - 0.0178X_1X_3 - 0.1327X_2X_3 + 0.0315X_1^2 - 0.0400X_2^2 + 0.2210X_3^2 \quad (25)$$

According to Eq. 25, while drying air temperature and drying air velocity (X_1 and X_3) had positive correlation, linear and quadratic terms of slice thickness (X_2 and X_2^2) had negative correlation on drying rate. Quadratic term of drying air velocity (X_3^2) had highest positive effect on it ($p < 0.05$). Accordingly drying time, total energy consumption and *SMER* value, maximum drying rate was determined for in Run 11. However, minimum drying rate was found in Run 3. Factorial plots demonstrated that drying rate was reduced when both drying air temperature (X_1) decreased and slice thickness (X_2) increased (> 5 mm) (Fig. 1f). It can be observed that lower drying air velocity (X_3) (< 0.8 m/s) and lower drying air temperature (X_1) had negative influence on drying rate. The effect of slice thickness (X_2) and drying air velocity (X_3) at center point of drying air temperature (40 °C) indicated that decreased slice thickness (X_2) and increased drying air velocity (X_3) resulted in higher drying rate.

Colour values

L^* value

L^* value (Y_7) changed between 59.30 and 82.62. The quadratic model for L^* value can be expressed by the following Eq. (26):

$$Y_7 = 74.39 + 2.28X_1 - 1.41X_2 - 1.34X_3 - 0.16X_1X_2 + 4.22X_1X_3 - 0.99X_2X_3 - 5.79X_1^2 + 6.40X_2^2 + 0.13X_3^2 \quad (26)$$

While drying air temperature (X_1) had positive correlation, slice thickness and drying air velocity (X_2 and X_3) had negative correlation on L^* value. Moreover, L^* value was significantly negative influenced by the quadratic terms of drying air temperature (X_1^2). Quadratic term of slice thickness (X_2^2) had highest positive effect on it ($p < 0.05$). While maximum L^* value was determined for in Run 10, minimum L^* value was found in Run 7. Factorial plots showed that L^* value was reduced when minimum drying air temperature (X_1) applied and slice thickness (X_2) was between (6 – 8.5 mm). Especially 39 - 43 °C drying air temperatures caused the highest L^* value (Fig. 1g). It can be seen that low drying air velocity (X_3) (0.5 – 0.65 m/s) and lower drying air temperature (X_1) (37 - 41 °C) had highest positive influence on L^* value. The effect of slice thickness (X_2) and drying air velocity (X_3) at center point of drying air temperature (40 °C) was represented in Fig. 1g, demonstrated that 6.5 – 8 mm slice thickness and drying air velocity > 0.8 m/s resulted in lower L^* value. Moreover it can be seen from Table 3,

when the other two parameters were constant, reduction in slice thickness and increase in drying air temperature and drying air velocity caused higher L^* value. In general, non-enzymatic Maillard browning reactions and the decomposition of pigments are responsible for the advancement of discolouration in dried melon slices (Ibarz *et al.*, 1999).

a^* value

a^* value (Y_8) changed between -2.95 and 6.73. However Oliveira *et al.* (2020) reported a^* value as between -0.74 and 3.22 in melon snack enriched in calcium. The quadratic model for a^* value can be expressed by the following Eq. (27):

$$Y_8 = 3.08 - 0.46X_1 + 1.11X_2 - 1.09X_3 + 0.65X_1X_2 + 0.73X_1X_3 + 0.56X_2X_3 - 0.60X_1^2 + 0.92X_2^2 - 2.10X_3^2 \quad (27)$$

From the Eq. (27), it can be observed that both of the terms X_1 and X_3 (drying air temperature and drying air velocity) had negative impact, while X_2 had positive effect on a^* value. Moreover, a^* value was significantly negative influenced by the quadratic terms of drying air temperature (X_1^2 and X_3^2). Quadratic term of slice thickness (X_2^2) had positive effect on it ($p < 0.05$). When the highest a^* value was found at Run 16, the lowest a^* value was found at Run 7. From the Fig. 1h the influence of slice thickness and drying air temperature on a^* value demonstrated that when 38 - 43 °C drying air temperature and the highest slice thickness (9 mm) applied, a^* value was the highest. Minimum a^* value was obtained when 43 - 45 °C drying air temperature applied to melon slices having thickness below 7 mm. It can be also observed that 0.6 - 0.7 m/s drying air velocity and drying air temperature below 40 °C caused highest a^* value. The effect of slice thickness (X_2) and drying air velocity (X_3) at center point of drying air temperature (40 °C) showed that 0.9 – 1 m/s drying air velocity and slice thickness lower than 7 mm resulted in lower a^* value. The increase of a^* value in dried melon slices might be due to the Maillard reaction and degradation of pigments such as carotenoids (Özkan Karabacak *et al.*, 2020).

b^* value

b^* value (Y_9) changed between 18.51 and 33.20. The quadratic model for b^* value can be expressed by the following Eq. (28):

$$Y_9 = 30.13 + 1.309X_1 + 0.921X_2 - 0.665X_3 + 1.90X_1X_2 + 3.25X_1X_3 + 1.37X_2X_3 - 1.08X_1^2 + 0.41X_2^2 - 3.40X_3^2 \quad (28)$$

According to Eq. (28), while linear terms of drying air temperature and slice thickness (X_1 and X_2) had positive correlation, drying air velocity (X_3) had negative correlation on b^* value. Moreover, b^* value was significantly positive influenced by the quadratic terms of (X_2^2). Quadratic terms of drying air temperature and drying air velocity (X_1^2 and X_3^2) had negative effect on it ($p < 0.05$). Maximum b^* value was determined for in Run 4. Similar to L^* value and a^* value, minimum b^* value was also found in Run 7. Factorial plots depicted that b^* value was minimum when drying air temperature was 35 °C and

Table 5. Criteria for optimization for process conditions

Response	goal	lower	upper	experi- mental condition	pre- dicted condi- tion
Drying time (min)	Min		792.00	205.00	216.58
Total energy consumption (kWh)	Min		9.26	3.93	2.94
COP_{hp}	Max	1.43		2.88	3.08
COP_{ws}	Max	1.36		2.65	2.75
$SMER$ (kg/kWh)	Max	0.13		0.21	0.22
Drying rate	Max	0.72		2.37	2.53
L^* value	Max	59.30		81.67	82.53
a^* value	Min		6.73	-1.35	-1.83
b^* value	Max	18.51		26.33	25.82

Composite desirability = 0.9125

slice thickness was between 6.5 - 9 mm. Besides that, when drying air temperature was between 43 – 45 °C and slice thickness was below 6 mm, b^* value also reduced (Fig. 1i). It can be observed that drying air velocity between 0.65 - 0.95 m/s and drying air temperature higher than 39 °C resulted in higher b^* value. The effect of slice thickness and drying air velocity at center point of drying air temperature (40 °C) was represented in Figure 1i, demonstrated that slice thickness between 8.5 – 9 mm and drying air velocity 0.65 – 0.85 m/s resulted in higher b^* value. Oliveira *et al.* (2020) determined that all dried melon samples showed higher b^* values (17.40 - 26.47) than fresh melon. Similarly, the b^* values found in our research were obtained in a range of 18.51 - 33.20.

B. Optimization of levels of independent variables

In order to optimize the levels of the independent variables for drying melon slices having high quality, the responses were assigned equal importance on the basis of their effects on the quality of final product. The used criteria, actual and predicted responses were given in Table 5. The optimal condition for all responses with composite desirability of 0.9125 was: 45 °C (X_1), 1 m/s (X_3) and 5.04 mm (X_2).

C. Effective moisture diffusivity (D_{eff})

Effective moisture diffusivity (D_{eff}) values obtained for each runs were presented in Table 3. D_{eff} values of melon slices were in the range of 7.075E-10 - 1.843E-07 m²s⁻¹. These values were stated in the common range (10⁻¹¹- 10⁻⁶ (m²s⁻¹)) determined for the dehydration of food products (Surendhar *et al.*, 2019). Increasing drying air temperature, drying air velocity and slice thickness (X_1 , X_2 and X_3) led to an increment on D_{eff} of the melon slices. Higher drying temperatures and velocities lead to higher heating energy and thus water molecules with increased activity cause high moisture diffusion (Akoy, 2014; Phahom *et al.*, 2021). The effect of slice thickness

(X_2) on D_{eff} was more important than the other parameters. Because slice thickness (L) is directly related with D_{eff} (Eq. 18). If a melon slice is thin, diffusion occurs in one direction from internal part of the slice through its external surface, while side diffusion is negligible. On the other hand, considering a thick melon slice, diffusion may also take place from side surfaces which enhance the removal rate of water from a slice. In addition, surface hardening effect occurs faster at thinner melon slices which will hinder the diffusion of moisture in thin melon slices, resulting lower effective moisture diffusivity in thinner melon slices (Chin *et al.*, 2015). In accordance with our results, Xia *et al.* (2014) found that D_{eff} of Hami-melon slices varied from 10.65×10⁻¹⁰ to 33.76×10⁻¹⁰ m²/s and from 8.06×10⁻¹⁰ to 39.97×10⁻¹⁰ m²/s with increasing drying temperature (from 50 °C to 80 °C) and sample thickness (from 3 mm to 11 mm), respectively. Our results are also consistent with this existing in the literature for dried melon (*Cucumis melo*) slices obtained by air drying varied from 1.21×10⁻⁸ m²/s to 4.18×10⁻⁸ m²/s for slice thickness of 4 mm, and from 1.69×10⁻⁸ to 8.54×10⁻⁸ m²/s for slice thickness of 6 mm (Azadbakht *et al.*, 2012).

D. Thin layer drying models

Drying behavior of melon slices with optimal conditions (45 °C drying air temperature, 1 m/s drying air velocity and 5.04 mm slice thickness) acquired with Box-Behnken design, was evaluated with seven different thin layer drying models. The statistical parameters based on R², RMSE and χ^2 values ranged from 0.8804 to 0.9940, 0.001459 to 0.0024127 and 0.000136 to 0.037927, respectively. The most proper model to represent the drying characteristics of melon slices were chosen Wang & Singh model. This result was coherent with previous study reported that Wang & Singh model for mint leaves was accepted as the most suitable theoretical model (Kavak Akpinar, 2010). Regarding the studies based on melon, Azadbakht *et al.* (2012) found Midilli model as the most appropriate one and da Cunha *et al.* (2020) reported that the best fit was obtained by using the Logarithmic and Wang & Singh models for ethanol pre-treated melon samples while The Two Terms exponential gave good statistical values for the dried melons without the pre-treatment during convective drying.

IV. CONCLUSIONS

In this study, the optimization process was obtained by using RSM for having high quality drying melon slices with closed loop HPD system. An optimum drying temperature of 45 °C, air velocity of 1 m/s and slice thickness of 5.04 mm were recommended with following predicted responses close to experimental values: drying time 216.58 min, total energy consumption 2.94 kWh, COP_{HP} 3.08, COP_{WS} 2.75, $SMER$ 0.22 kg/kWh, drying rate 2.53, L^* value 82.53, a^* value -1.83 and b^* value 25.82. The most suitable model to represent the drying behavior of optimum melon slices was chosen as Wang & Sing. Effective moisture diffusivities (D_{eff}) of the melon slices

were ranging from $7.075\text{E-}10$ - $1.843\text{E-}07$ m^2s^{-1} and increasing drying air temperature, drying air velocity and slice thickness led to an increment of D_{eff} . By the optimization of drying parameters of melon slices novel healthy snacks were provided with minimum energy consumption and maximum moisture diffusivity and attractive colour properties.

REFERENCES

- Abano, E.E., Ma, H. and Qu, W. (2011) Influence of air temperature on the drying kinetics and quality of tomato slices. *J Food Process Technol.* **2**, 2–9.
- Akoy, E.O.M. (2014) Experimental characterization and modelling of thin-layer drying of mango slices. *Int. Food Res. J.* **21**, 1911–1917.
- Aktaş, M., Taşeri, L., Şevik, S., Gülcü, M. and Uysal, G. (2019) Heat pump drying of grape pomace : Performance and product quality analysis. *Drying Technol.* **37**, 1766–1779.
- Azadbakht, M., Darvishi, H., Rezaeiasl, A. and Asghari, A. (2012) Thin layer drying characteristics and modeling of melon slices (*Cucumis melo*). *J. Agric. Technol.* **8**, 1867–1880.
- Azuara, E., Flores, E. and Beristain, C.I. (2009) Water diffusion and concentration profiles during osmodehydration and storage of apple tissue. *Food Bioproc Tech.* **2**, 361–367.
- Bennett, L.E., Jegasothy, H., Konczak, I., Frank, D., Sudharmarajan, S. and Clingeffer, P.R. (2011) Total polyphenolics and anti-oxidant properties of selected dried fruits and relationships to drying conditions. *J. Funct. Foods.* **3**, 115–124.
- Chapchaimoh, K., Poomsa-ad, N., Wiset, L. and Morris, J. (2016) Thermal characteristics of heat pump dryer for ginger drying. *Appl. Therm. Eng.* **95**, 491–498.
- Chin, S.K., Siew, E.S. and Soon, W.L. (2015) Drying characteristics and quality evaluation of kiwi slices under hot air natural convective drying method. *Int. Food Res. J.* **22**, 2188–2195.
- Coskun, S., Doymaz, İ., Tunçkal, C. and Erdoğan, S. (2017) Investigation of drying kinetics of tomato slices dried by using a closed loop heat pump dryer. *Heat Mass Transf.* **53**, 1863–1871.
- da Cunha, R.M.C., Brandao, S.C.R., de Medeiros, R.A.B., da Silva Junior, E.V., da Silva, J.H.F. and Azoubel, P.M. (2020) Effect of ethanol pretreatment on melon convective drying. *Food Chem.* **333**, 127502.
- Dias da Silva, G., Meireles, Z., Barros, P., Augusto, R., Medeiros, B. De, Brian, C., Carvalho, O. De, Clyde, S. and Brand, R. (2016) Pretreatments for melon drying implementing ultrasound and vacuum. *LWT - Food Sci. Technol.* **74**, 114–119.
- Gamlı, Ö.F., Süfer, Ö. and Eker, T. (2018) Dehydration Kinetics and Infusion Attributes of Microwave Dried Olive Leaves. *Turk. J. Agric. - Food Sci Technol.* **6**, 963–970.
- Ibarz, A., Pagan, J. and Garza, S. (1999) Kinetic models for colour changes in pear puree during heating at relatively high temperatures. *J Food Eng.* **39**, 415–422.
- Jeyaprakash, S., Frank, D.C. and Driscoll, R.H. (2016) Influence of heat pump drying on tomato flavor. *Drying Technol.* **34**, 1709–1718.
- Jia, X., Jolly, P. and Clements, S. (1990) Heat pump assisted continuous drying part 2: Simulation results. *Int. J. Energy Res.* **14**, 771–782.
- Kavak Akpınar, E. (2010) Drying of mint leaves in a solar dryer and under open sun : Modelling , performance analyses. *Energy Convers. Manage.* **51**, 2407–2418.
- Kırbaş, İ., Doğuş, A., Şirin, C. and Usta, H. (2019) Modeling and developing a smart interface for various drying methods of pomelo fruit (*Citrus maxima*) peel using machine learning approaches. *Comput. Electron. Agric.* **165**, 104928.
- Koşan, M., Demirtaş, M., Aktaş, M. and Dişli, E. (2020) Performance analyses of sustainable PV / T assisted heat pump drying system. *Sol Energy.* **199**, 657–672.
- Kuan, M., Shakir, Y., Mohanraj, M., Belyayev, Y., Jayaraj, S. and Kaltayev, A. (2019) Numerical simulation of a heat pump assisted solar dryer for continental climates. *Renew. Energy.* **143**, 214–225.
- Ndukwu M.C. (2009) Effect of Drying Temperature and Drying Air Velocity on the Drying Rate and Drying Constant of Cocoa Bean. *Int. J. Agric. Eng.* **1091**, 1–7.
- Oliveira, M.H.S.B.O., Filho, A.J.M.F., Junior, E.V.S., Silva, E.S., Paim, A.P.S., Honorato, F.A. and Azoubel, P.M. (2020) Impregnation and drying to develop a melon snack enriched in calcium. *J Food Sci. Technol.* **58**, 672–679.
- Özkan Karabacak, A., Acoğlu, B., Yolci Ömeroğlu, P. and Çopur, Ö.U. (2020) Microwave pre-treatment for vacuum drying of orange slices: Drying characteristics, rehydration capacity and quality properties. *J Food Process Eng.* **43**, e13511.
- Perera, C.O. and Rahman, M.S. (1997) Heat pump dehumidifier drying of food. *Trends Food Sci. Technol.* **8**, 75–79.
- Petkova, Z. and Antova, G. (2015) Proximate composition of seeds and seed oils from melon (*Cucumis melo* L .) cultivated in Bulgaria. *Cogent Food Agric.* **1**, 1018779.
- Phahom, T., Juntharat, N., Premstutrat, P., Paosunthia, Y. and Roudaut, G. (2021) Evaluation of desorption isotherms, drying characteristics and rehydration properties of crab stick by-product. *Heat Mass Transf.* **57**, 1039–1052.
- Prasertsan, S. (2010) Heat pump drying of agricultural materials. *Drying Technol.* **16**, 235–250.
- Sadin, R., Chagini, G.R. and Sadin, H. (2014) The effect of temperature and slice thickness on drying kinetics tomato in the infrared dryer. *Heat Mass Transf.* **50**, 501–507.

- Surendhar, A., Sivasubramanian, V., Vidhyeswari, D. and Deepanraj, B. (2019) Energy and exergy analysis, drying kinetics, modeling and quality parameters of microwave-dried turmeric slices. *J. Therm. Anal. Calorim.* **136**, 185–197.
- Süfer, Ö., and Palazoğlu, T.K. (2019) A study on hot-air drying of pomegranate: Kinetics of dehydration, rehydration and effects on bioactive compounds. *J. Therm. Anal. Calorim.* **137**, 1981–1990.
- Tüfekçi, S. and Özkal, S. G. (2017) Enhancement of drying and rehydration characteristics of okra by ultrasound pre-treatment application. *Heat Mass Transf.* **53**, 2279–2286.
- Tunçkal, C. and Doymaz, I. (2020) Performance analysis and mathematical modelling of banana slices in a heat pump drying system. *Renew. Energy.* **150**, 918–923.
- Wang, Y., Li, M. and Qiu, Y. (2019) Performance analysis of a secondary heat recovery solar-assisted heat pump drying system for mango. *Energy Explor. Exploit.* **37**, 1377–1387.
- Welti-Chanes, J., Vélez-Ruiz, J.F. and Barbosa-Cánovas, G.V. (2002) *Transport phenomena in food processing*. (1st ed.). English. CRC.
- Xia, Z., Hongwei, X., Lihong, W., Qian, Z., Junwen, B., Long, X., Haoyu, J. and Zhenjiang, G. (2014) Shortening drying time of Hami-melon slice using infrared radiation combined with air impingement drying. *Trans. Chin. Soc. Agric. Eng.* **30**, 262-269.
- Yuan, Y., Lin, W., Mao, X., Li, W., Yang, L., Wei, J. and Xiao, B. (2019) Performance analysis of heat pump dryer with unit-room in cold climate regions. *Energies.* **12**, 3125
- Zanoni, B., Peri, C., Nani, R. and Lavelli, V. (1999) Oxidative heat damage of tomato halves as affected by drying. *Food Res. Int.* **31**, 395-401.

Received: August 17, 2021

Sent to Subject Editor: September 16, 2021

Accepted: November 9, 2021

Recommended by Subject Editor Laura Briand