Original scientific paper

THIN LAYER DRYING OF ZUCCHINI IN SOLAR DRYER LOCATED IN OSMANIYE REGION

Kamil Neyfel ÇERÇİ, Özge SÜFER, Mustafa SÖYLER, Ertaç HÜRDOĞAN, Coşkun ÖZALP

Abstract: In this study, the dehydration behavior of zucchini using solar assisted drying system was examined according to 22 thin layer drying models available in literature. The correlation coefficient (R^2), chi-square (χ^2) and root mean square error (RMSE) values were calculated to check the suitability of models by non-linear regression analysis. It was found that Cubic and Modified Midilli-1 models were the most suitable equations and their R^2 values were calculated as 0.99963. χ^2 and RMSE values of related mathematical expressions were 1.89343×10^{-5}, 1.91692×10^{-5} and 0.01685×10^{-3}, 0.01721×10^{-3} respectively. In addition, heat transfer, mass transfer and diffusion coefficients, which were important parameters in design of drying systems were also determined as 5.18124 W/m²°C, 1.57129×10^{-7} m/s and 2.335718×10^{-9} m²/s respectively.

Keywords: diffusion coefficient; heat and mass transfer coefficient; mathematical modeling

1 INTRODUCTION

Drying basically starts with the solution of coupling forces between water and material which will be dried. There is a specific energy requirement and this must be given to material continuously as heating for the evaporation of moisture to the surface and pores of the layer. In this sense, the drying process is the heat and mass transfer processes that take place at the same time [1,2]. If product is not dried up sufficiently, it affects the quality of the food negatively due to changes in chemical, biochemical and physical characteristics [3,4].

In this context, scientists have been working on mathematical models and computer simulations to design and develop dryers for efficient dehydration. In order to accurately describe the drying kinetics of food products, mathematical modeling is one of the most appropriate approaches. Factors affecting heat and mass transfer between food product and drying air, deviations in case of equilibrium between product and dry air, the change of physical properties of product, water vapor and air by changing humidity and temperature are considered by using these models [5-10].

In the literature, there are many studies about the determination of heat and mass transfer, mathematical modeling, computer simulations in order to design and develop drying systems for different types of fruit and vegetables [11-16]. Midilli and Kucuk [17] carried out drying experiments for nuts under natural and forced convection in solar assisted drying. The scientists found that the logarithmic model could be the most appropriate model to define thin layer forced solar drying. However, they saw that the two-term model was more appropriate in natural solar drying. Younis et al. [18] carried out experiments for the drying of garlic slices; infrared drying was applied at different air velocities and radiation intensities onto materials. The results indicated that decreasing air velocity and rising radiation intensity caused an increase in drying rate and a decrease in drying time. Bozkır [19] developed a mathematical model in thin film formation of washed apricots. The experiments carried out at different temperatures and velocities. Data from experiments was analyzed by Page's drying equations.

In this work, air solar collector assisted drying system was used for modelling zucchini drying. The zucchini contains mineral elements such as potassium, phosphorus, calcium, magnesium, sodium, iron. There is a great difference in nutritional values between consuming the same amount of fresh zucchini and dried zucchini, but when the benefits are compared, the dried zucchini is almost as useful as the fresh zucchini. Dried zucchini can be used for ready-made sacks, bulgur, rice mixtures, bird and pet food. [20]. To investigate the availability of models, correlation coefficient (R^2), root mean square error (RMSE) and chi-square (χ^2) values were calculated. In addition, convective mass and heat transfer coefficients were calculated for contributing to the literature in drying design.

Table 1 The devices used for measurements and their specifications

Device	Measurement parameters	Accuracy
Testo 435 air speed probe	Air velocity	0.1 m/s
Ledmer digital temperature measurement probe	Temperatures	0.1 °C
Dikomsan Model electronic balance	Product weight	0.1 gr
Testo 435 humidity measuring probe	Relative humidity	2-3 %
Eko model MS-410 type pyranometer	Radiation	-
Laboratory type oven (JSR, 400, England)	Initial and final moisture contents of samples	-

2 EXPERIMENTAL STUDY

Schematic illustration and the image of the solar assisted drying system are shown in Fig. 1. The ambient air enters the solar collector (state 1) and leaves the collector (state 2) hotter. Then, hot air is passed to the drying cabinet for drying the products. The drying chamber was designed specifically to distribute hot air uniformly. Finally, the air exits the cabinet with more moisture than when entered the cabinet. More

detailed information about the system is given in reference [21].

Zucchini samples were procured from Erzin region, Hatay/ Turkey. They were cut into average 47 mm of diameter

and 5 mm thickness and lined up on the tray.

Tab. 1 shows the devices used for measurements and their specifications.
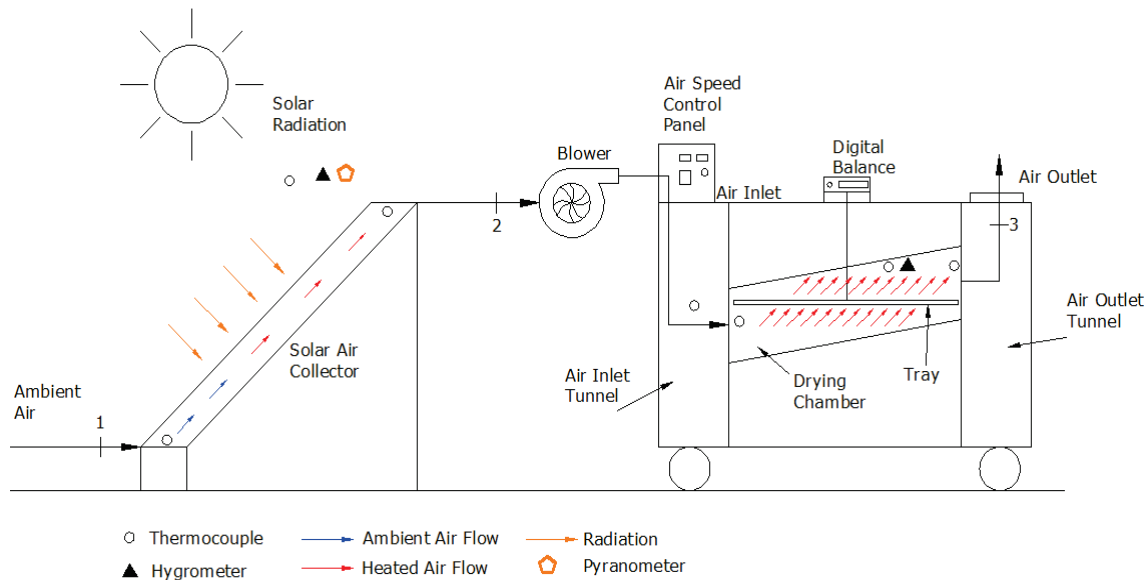

Figure 1 Schematic illustration (a) and the image (b) of the solar-assisted drying system

2.1 Computation Procedure

The data obtained from the drying process were fitted to 22 thin layer models given in Tab. 2. k, k_0, k_1 and n denote drying constants and a, b, c, d are statistical parameters.

MR is moisture ratio and it was calculated by using Eq. (1).

$$MR = \frac{M - M_e}{M_0 - M_e} \tag{1}$$

In the related equation, M is the amount of moisture at

any time, M_e is the amount of moisture in equilibrium, and M_0 is initial moisture content. To simplify MR, it can be expressed by M/M_0, because of M_e is lower than M and M_0 values [42, 43].

Regression analysis was done by using Origin pro program 2016 (Origin Lab, USA).

Correlation coefficients (R^2) were taken as the basic criteria to select the best equation that describes the drying curves of the products [44].

The most suitable model was determined using root mean square error ($RMSE$) and chi-square (χ^2) values after R^2 and calculated as:

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

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(MR_{exp,i} - MR_{pre,i} \right)^2}{N - z} \qquad (3)$$

$MR_{exp,i}$ is an MR value in i, $MR_{pre,i}$ value is an estimated MR value. N is experiments number, z is constant number. The $MR_{exp,i}$ is an MR value in i, $MR_{pre,i}$ value is an estimated MR value. N is experiments number, z is constant number.

Table 2 Different thin layer drying models available in literature

Model Name	Equation	Reference
Lewis	$MR = exp(-kt)$	[22]
Page	$MR = \exp(-kt^n)$	[23]
Modified Page	$MR = \exp(-kt)^n$	[24]
Henderson & Pabis	$MR = a \exp(-kt)$	[25]
Logarithmic	$MR = a \exp(-kt) + c$	[26]
Two-term	$MR = a \exp(-k_0 t) + b \exp(-k_1 t)$	[27]
Wang and Singh	$MR = 1 + at + bt^2$	[28]
Weibull	$MR = \exp(-(\frac{t}{b})^a)$	[29]
Midilli et al.	$MR = a \exp(-kt^n) + bt$	[30]
Parabolic	$MR = a + bt + ct^2$	[30]
Cubic	$MR = a + bt + ct^2 + dt^3$	[31]
Sigmoid	$MR = a + \frac{b}{1 + e^{k(t-c)}}$	[32]
Thompson	$t = a \ln(MR) + b [\ln(MR)^2]$	[33]
Vega-Lemus	$MR = (a + bt)^2$	[34]
Rational	$MR = \frac{a + bt}{1 + ct + dt^2}$	[35]
Vega Galvez-1	$MR = n + k\sqrt{t}$	[36]
Vega Galvez-2	$MR = \exp(n + kt)$	[36]
Hii et al.	$MR = a \exp(-k_0 t^n) + b \exp(-k_1 t^n)$	[37]
Mod. Midilli-1	$MR = \exp(-kt^n) + bt$	[38]
Mod. Midilli-2	$MR = \exp(-kt) + bt$	[39]
Sripinyowanich & Noomhorn	$MR = \exp(-kt^n) + bt + c$	[40]
Noomhorn & Verma	$MR = a \exp(-k_0 t) + b \exp(-k_1 t) + c$	[41]

The effective moisture diffusivity was computed with respect to Fick's second law. Some assumptions can be made within the framework of this law:
a. The humidity distribution is uniform in the cylindrical geometry of the product.
b. Mass transfer is symmetric according to the center of zucchini slice.
c. The surface resistances in mass transfer can be ignored.
d. The diffusion coefficient is assumed to be constant.

The correlation between MR and diffusion coefficient were indicated by Eq. (4):

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

D_{eff} is the diffusion coefficient (m²/s), r is the radius of the samples (m), t is time (s) [45].

Activation energy of zucchini samples was specified using Arrhenius type equations [14]:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT} \right) \qquad (5)$$

E_a is activation energy (kJ/mol), R is universal gas constant (8.3143 J/mol K), T is ambient temperature (K), and D_0 is predominant exponential factor (m²/s). The activation energy is formed of the slope of the linearized line of Eq. (5).

Besides, the convective mass transfer coefficient (α, m/s) was obtained by Eq. (6) [46]:

$$\alpha = -\frac{V}{A_t} \ln(MR) \qquad (6)$$

where, V is volume of product (m³), A_t is product area (m²).

The convective heat transfer coefficient (h_c, W/m²°C) was calculated for forced convection by Eq. (7) [47].

$$h_c = \frac{Nu K_v}{x} \quad \text{or} \quad h_c = \frac{K_v}{x} C (Re\, Pr)^n \qquad (7)$$

where, Nu is Nusselt Number, K_v is thermal conductivity (W/m,°C), Re is Reynolds Number, Pr is Prandtl Number, C and n are constants for calculating heat transfer coefficient value.

The rate of required heat to evaporate moisture ($\dot{Q}_e$) was computed by Eq. (8) [48].

$$\dot{Q}_e = 0.016 h_c [P(T_c) - \gamma P(T_e)] \qquad (8)$$

where, T_c is product temperature and T_e is exit air temperature.

The moisture evaporated was calculated by Eq. (9). Here, Eq. (8) was divided with latent heat of vaporization (λ), and multiplied with the area of tray (A_t) and time interval (t).

$$\dot{m}_{ev} = \frac{\dot{Q}_e}{\lambda} A_t t \qquad (9)$$

where, $Z = 0.016 \frac{K_v}{x\lambda} [P(T_c) - \gamma P(T_e)] A_t t$

$$\frac{\dot{m}_{ev}}{z} = C (Re\, Pr)^n \qquad (10)$$

The logarithms of both sides of Eq. (10) are taken,

$$\ln\left[\frac{\dot{m}_{ev}}{z} \right] = \ln C + n \ln(Re\, Pr) \qquad (11)$$

Eq. (11) similar to an equation of straight line,
$$Y = b_1 X + b_0$$

where, $Y = \ln\left[\dfrac{\dot{m}_{ev}}{z}\right]$, $b_1 = n$, $X = \ln(Re\,Pr)$, $b_0 = \ln C$

C and n values were determined using linear regression analysis with the obtained experimental data of exit air relative humidity, the product and exit air temperatures and moisture evaporated at the specific time intervals.

The different physical properties of humid air, such as density (ρ_v), thermal conductivity (K_v), specific heat (C_v) and viscosity (μ_v), were calculated by using T_i, which is taken as an average of product temperature (T_c) and exit air temperature (T_e) for calculating Reynolds number (Re) and Prandtl number (Pr) [49].

$$\rho_v = \frac{353.44}{(T_i + 273.15)} \quad (12)$$

$$K_v = 0.0244 + 0.6773 \times 10^{-4} T_i \quad (13)$$

$$C_v = 999.2 + 0.1434 T_i + 1.101 \times 10^{-4} T_i^2 - 6.7581 \times 10^{-8} T_i^3 \quad (14)$$

$$\mu_v = 1.718 \times 10^{-5} + 4.620 \times 10^{-8} T_i \quad (15)$$

$$P(T) = \exp\left[25.317 - \frac{5144}{T_i + 273.15}\right] \quad (16)$$

3 RESULTS AND DISCUSSION

In the study, the drying behaviors of the zucchini samples were investigated by using experimental data collected from the solar energy-assisted dryer.

The highest correlation coefficient (R^2) values were found as 0.99963 for Spirinyowanich and Noomhorn, Cubic, Rational, Modified Midilli-1 and Midilli models. The best results of χ^2 values were seen in Cubic and Modified Midilli-1 models because of the lowest levels. The values obtained from indicated models were 1.89343×10^{-5} and 1.91692×10^{-5}, respectively. In addition, RMSE values for Cubic and Modified Midilli-1 models were calculated as 0.01685×10^{-3} and 0.01721×10^{-3} respectively. The values of Spirinyowanich and Noomhorn, Cubic, Rational, Modified Midilli-1 and Midilli models were shown in Table 3 since they have the best correlation coefficient values (R^2).

The variation of the convective mass transfer coefficient (m/s) and lnMR values with time were shown in Fig. 2 and 3 respectively.

According to Fig. 2, the convective mass transfer coefficient values varied between 8.65264×10^{-8} and 1.97664×10^{-7} m/s. The average convective mass transfer coefficient was calculated as 1.57129×10^{-7} m/s. The average diffusion coefficient of zucchini samples was obtained as 2.33572×10^{-9} m^2/s. It is seen that the diffusion coefficient

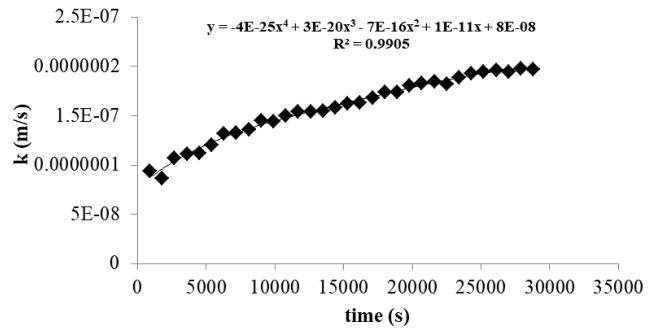values calculated in this study are in accordance with the literature [50, 51, 52, 53].

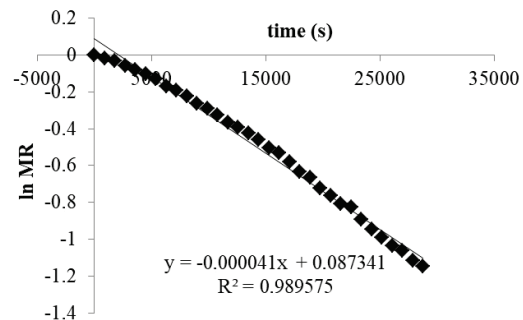**Figure 2** Variation of mass transfer coefficient with drying time

Figure 3 ln MR with drying time

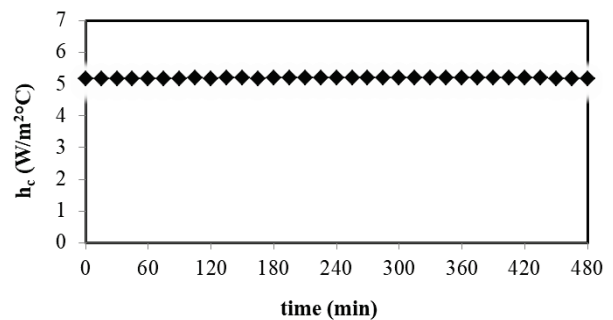The variations in convective heat transfer coefficient with time are presented in Fig. 4.

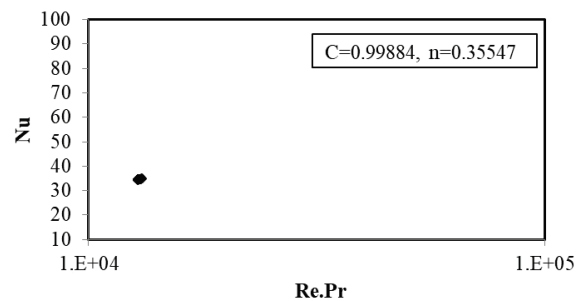**Figure 4** Variation of heat transfer coefficient with drying time

Figure 5 The relation between Nu-Re·Pr for zucchini samples drying at forced convection

The convective heat transfer coefficient values varied between 5.16841-5.18672 W/m^2°C during drying process. The variation remained almost constant during drying. The air

velocity, which is an important parameter in forced convection is kept constant during the experiment. Akpinar [50, 54], evaluated convective heat transfer coefficient values for different food products for forced convection in literature. The convective heat transfer coefficient values varied at between 0.644 and 10.94 W/m^2°C. It was seen that these values are in accordance with the literature [50, 54].

The relation between Nusselt and Reynolds-Prandtl numbers were given in the following graph (Fig. 5).

It could be seen from the figure that the heat transfer carried out under the laminar regime because of $Re \cdot Pr \leq 10^5$ [55]. The Nusselt number values of the zucchini samples were found between 34.29895-34.76936. Also, C and n constants were found 0.99884 and 0.35547 respectively. Similar results were found by Jain and Tiwari [56]. They indicated laminar regime on drying of peas in greenhouse dryer for forced convection.

Table 3 The statistical parameters of Spirinyowanich and Noomhorn, Cubic, Rational, Modified Midilli-1 and Midilli models

Model name	R^2	χ^2	SSE	RMSE	k	n	a	b	c	d
Midilli et al.	0.99963	0.00193×10^{-2}	0.00056	0.01698×10^{-3}	0.00038	1.29122	0.99809	-	-	-
Mod. Midilli-1	0.99963	0.00189×10^{-2}	0.00057	0.01721×10^{-3}	0.00041	1.27906	-	−0.00005	-	-
Spirinyowanich & Noomhorn	0.99963	0.00193×10^{-2}	0.00056	0.01698×10^{-3}	0.00038	1.29093	-	−0.00004	−0.00192	-
Cubic	0.99963	0.00191×10^{-2}	0.00056	0.01685×10^{-3}	-	-	1.00634	−0.00137	0.00001×10^{-1}	0
Rational	0.99963	0.00196×10^{-2}	0.00057	0.01729×10^{-3}	-	-	1.00347	−0.00081	0.00042	0

4 CONCLUSIONS

In this work, air solar collector assisted drying system was used to investigate the availability of the models for zucchini drying. The correlation coefficient (R^2), root mean square error (RMSE) and chi-square (χ^2) were calculated. It was seen that the highest values for the correlation coefficient were found as 0.99963 in Spirinyowanich and Noomhorn, Cubic, Rational, Modified midilli-1 and Midilli models. Besides, the lowest values of the chi-square were obtained in Cubic and Modifid Midilli-1 models. Also, RMSE values of those models were computed as 0.01685×10^{-3} and 0.01721×10^{-3} respectively. Finally, the convective mass and heat transfer coefficients and diffusion coefficient, which are important parameters in determining the drying performance, have been calculated. The average convective mass transfer coefficient and diffusion coefficient were calculated as 1.57129×10^{-7} m/s and 2.33572×10^{-9} m^2/s respectively. The average convective heat transfer coefficient for forced convection was calculated as 5.18124 W/m^2°C. Also, C and n values, which are used for calculating convective heat transfer coefficient, were found as 0.99884 and 0.35547 respectively.

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Authors' contacts:

Kamil Neyfel ÇERÇİ, Res. Assist.
Mustafa SÖYLER, Res. Assist.
Ertaç HÜRDOĞAN, Assoc. Prof. Dr., Corresponding author
Coşkun ÖZALP, Assoc. Prof. Dr.
Department of Energy Systems Engineering,
Osmaniye Korkut Ata University,
Osmaniye, 151-742, Turkey,
+90 328 8251818-3503/+90 328 825 00 97,
ehurdogan@osmaniye.edu.tr

Özge SUFER, Res. Assist.
Department of Food Engineering,
Osmaniye Korkut Ata University,
Osmaniye, 151-742, Turkey,