https://doi.org/10.17221/66/2024-CJFS

Kinetics and mathematical models of date paste dried using a convective infrared dryer

Mahmoud Younis[1,2]*, *Khaled Abdel Wahed Ahmed*[1,2], *Isam Ali Mohamed Ahmed*[3], *Hany Mohamed Yehia*[3,4], *Diaeldin Omer Abdelkarim*[1], *Ahmed Elfeky*[5]

[1]*Chair of Dates Industry and Technology, Department of Agricultural Engineering, College of Food and Agricultural Sciences, King Saud University, Riyadh, Saudi Arabia*
[2]*Agricultural Engineering Research Institute, Agricultural Research Center, Giza, Egypt*
[3]*Food Science and Nutrition Department, College of Food and Agricultural Sciences, King Saud University, Riyadh, Saudi Arabia*
[4]*Food Science and Nutrition Department, Faculty of Home Economics, Helwan University, Cairo, Egypt*
[5]*Department of Agricultural Engineering, College of Food and Agricultural Sciences, King Saud University, Riyadh, Saudi Arabia*
**Corresponding author: myounes@ksu.edu.sa*

Citation: Younis M., Ahmed K.A.W., Ahmed I.A.M., Yehia H.M., Abdelkarim D.O., Elfeky A. (2024): Kinetics and mathematical models of date paste dried using a convective infrared dryer. Czech J. Food Sci., 42: 465–475.

Abstract: Achieving the desired level of caramelisation in a date powder requires considerable effort. Consequently, an assessment was conducted on efficacy of thin-layer infrared dehydration for date paste. Various parameters were considered, including airflow velocities of 0.5, 1.0, and 1.5 $m\cdot s^{-1}$, radiation intensities of 0.076, 0.1528, and 0.228 $W\cdot cm^{-2}$, and date paste layer thicknesses of 3 mm and 5 mm. The study's findings indicated a positive correlation between drying rate and lowering airflow velocity and a negative correlation between drying time and decreasing airflow velocity, the thickness of date paste, and rising intensity of infrared. The effective moisture diffusivity (D_{eff}) was caculated by employing Fick's diffusion equation. For all situations under investigation, the mean values were within the range of 3.94×10^{-11} $m^2\cdot s^{-1}$ to 6.01×10^{-10} $m^2\cdot s^{-1}$. A relationship has been established between D_{eff} and moisture content. Seven distinct mathematical models were subjected to rigorous validation by applying non-linear regression analysis, aiming to accurately characterise the drying process of date paste. The modified two-term model provided the most accurate forecast of the drying process for date paste layers.

Keywords: drying rate; convection-infrared dryer; mathematical modeling; effective moisture diffusivity

The world food crisis requires many countries to focus on conserving and manufacturing locally available agricultural products and transforming them into consumer-friendly products to achieve food security. The date palms and their derivatives provide a significant economic asset for a substantial demographic engaged in the cultivation and trade of palm and date products, serving as a primary source of income.

Date palm is a produce that is extensively grown in more than thirty countries. An estimated 150 million trees are under cultivation, representing 5 000 distinct cultivars. According to El Bakouri et al. (2021), date fruits are produced on a global scale annually in excess eight million tons. Approximately 1 008 105 tons of dates from date palm are produced annually in the Kingdom of Saudi Arabia (KSA). these trees are planted on more than 156 023 ha, which equates to 24 378 594 trees in KSA. Dates have the highest fruit production in the KSA, accounting for approximately 55% of the entire domestic produce production. 400 distinct varieties of dates, en-

Supported by King Abdulazizi City for Science and Technology (KACST), Saudi Arabia, grant number 2-17-04-001-0015.

https://doi.org/10.17221/66/2024-CJFS

compassing sixty prevalent varieties, are produced by approximately 24 million palm trees (Nasser et al. 2016).

The production of secondary products that have added value, such as date powder, contingent upon the efficient utilisation of date fruit losses, particularly low-quality (second grade) dates like Sukkari, which are not preferred by consumers (Hobani et al. 2003). Sukari is a date variety that is particularly prevalent in the Qassim region. It is approximately 30 mm in length and is either yellow or red (Elsharawy et al. 2019). Food loss reduction is critical in solving the issue of hunger since it entails converting these losses into alternative goods with nutritional value for human consumption. Furthermore, this decline improves the economy by creating job possibilities and improving income levels. Moreover, it assumes a significant role in enhancing food security.

Dates are known to possess significant amounts of vitamin B and vitamin A. Additionally, they have a high sugar content, comprising up to 85% of their dry weight. Ghnimi et al. (2017) indicated that dates are among the most calorically dense fruits. Numerous enterprises have emerged in date cultivation, encompassing the production of date fruits, date paste, packaged fruits, date jam, date honey (dibbs), vinegar, and medical alcohol.

The present study focuses on producing date fruit powder as a potential alternative to cane sugar in various food methods, such as cookies (Alsenaien et al. 2015) and biscuits (Gamal et al. 2012). Nevertheless, drying a hygroscopic fruit with a sugar content over 65%, such as dates (Elleuch et al. 2008), poses a considerable challenge. Therefore, the objective was to address the difficulty of desiccating dates in a manner that would produce a powdered substance exhibiting a controlled degree of caramelisation.

Several methods for drying dates, in general, the literature has published a variety of drying methods, an example of sun drying (Seerangurayar et al. 2019), microwave dehydration (Benamara and Chekroune 2009), drying with heated air (Al-Awaadh et al. 2015), and freeze-drying (Seerangurayar et al. 2018). A vacuum drier was employed to convert date from different date varieties, characterised by varying levels of sugar content (Sahari et al. 2008), into a powdered form. In addition, previous research has explored the utilisation of foam-mat freeze drying (Seerangurayar et al. 2018) and drying with spray (Dev et al. 2018) techniques for producing date fruit powder. However, no prior investigations have specifically examined the application of infrared radiation for drying date paste. In addition, infrared heating provides various benefits over conventional drying procedures under identical settings.

As an end consequence, the current research was executed to assess the influence of various infrared (IR) radiation intensity, airflow velocity levels, and thickness of slices on the drying properties of date paste in a thin-layer setting. Furthermore, this objective of this study is to investigate the effective moisture diffusivity (D_{eff}) of date paste and evaluate the suitability of seven distinct models of drying in characterising and predicting the drying procedure of date paste.

MATERIAL AND METHODS

Sample preparation. The study utilised a cultivar of low-quality dates, namely Sukkari (Suk), classified as second-grade (*Phoenix dactylifera*). In June 2021, the date samples were acquired from the markets of Hail and Al-Qassim.

Production of date paste. The kernels were extracted after the dates were washed and superfluous water was wiped away. Freshly harvested dates have 20–23.5% w.b. (wet basis) moisture. A lab-scale mincer shredded date flesh (Al Halees Centre in Jeddah, KSA). The goal of mincing was to make a homogenous, smooth paste. The paste of date was shaped into two thicknesses (3 mm and 5 mm, accuracy ± 0.5 mm) while preserving a 20 mm width and 80 mm length (accuracy ± 2 mm). After freezing in hermetically sealed plastic containers, the paste samples were stored at room temperature for two hours before drying.

Experimental set-up and drying procedure. The drying procedure involved using an infrared (IR) dryer (Figure 1), which was made from a 1.5 mm galvanised metal sheet with a drying channel of 350 × 350 mm and 2 340 mm. The dryer was powered by electric heaters with a 0–3 kW range, and a 0.033 kW fan for airflow over the samples. A balance with the capacity range is 0–4 kg was included in the apparatus and 12 IR halogen lamps (0.5 kW) for emitting infrared radiation during drying. The samples of date paste were positioned on a tray in a chamber and exposed to infrared lamps. Radiation intensity was calibrated by employing a voltage regulator (0.076, 0.152, and 0.228 $W \cdot cm^{-2}$). The investigations were implemented at temperature of 40 °C for inlet air (Abe and Afzal 1997), and three airflow velocity of (0.5, 1.0, and 1.5 $m \cdot s^{-1}$). Mass monitoring was conducted on the samples until moisture content reached 2.2–2.5% on a wet basis, ensuring accurate measurements of radiation intensity.

Models for simulation of drying. The study aimed to identify the most suitable drying model for date paste, examining seven models to predict drying be-

https://doi.org/10.17221/66/2024-CJFS

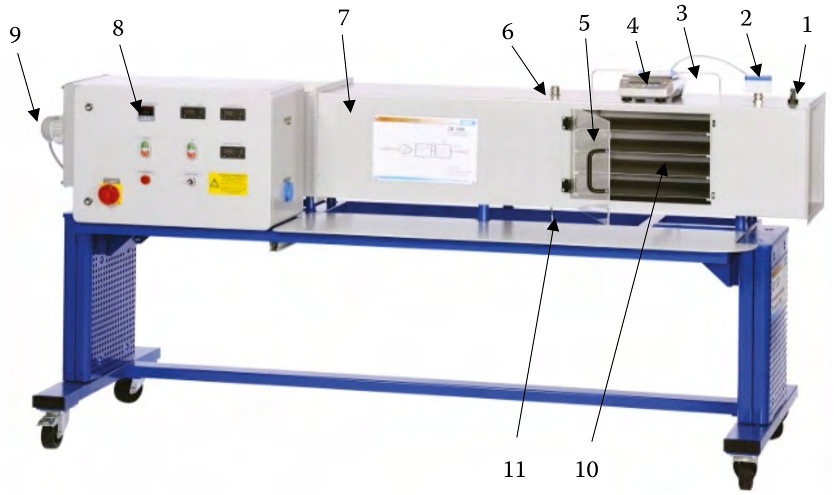

Figure 1. Diagram of the infrared drying system

1 – sensor of air velocity; 2 – measuring point for temperature and humidity; 3 – bracket for drying plates; 4 – digital balance; 5 – transparent door; 6 – measuring point with temperature and humidity sensor; 7 – drying channel; 8 – switch cabinet with digital displays; 9 – fan; 10 – drying plates; 11 – temperature sensor of the controller

haviour data (Table 1). The moisture ratio (*MR*) was used, which is commonly represented as:

$$MR = \frac{M_t - M_e}{M_0 - M_e}$$

where: M_t – moisture content at time t (g water per g dry matter); M_e – equilibrium moisture content (g water per g dry matter); M_0 – initial moisture content (g water per g dry matter).

Ertekin and Yaldiz (2001) suggest that the notation M_t/M_0 can be simplified due to the consistent changes in relative humidity in drying air. Additionally, this simplification is justified by the comparatively low value of M_e comparison to M_t and M_0 (Doymaz 2004). The regression analysis was conducted using a statistical process. The results were evaluated based on their goodness of fit using various statistical measures, including the sum of squared absolute error (SSE), root mean square error (RMSE), and coefficient of determination (R^2).

A good model is considered good when its R^2 is higher and its RMSE and SSE are lower. Formulas for moisture ratio prediction were developed through regression analysis. Various criteria were used to assess the adequacy of the models, which were computed using Equations 1–3:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{Exp} - MR_{Pre}\right)^2}{N}} \quad (1)$$

$$\text{SSE} = \frac{\left(MR_{Exp} - MR_{Pre}\right)^2}{N} \quad (2)$$

Table 1. The mathematical models employed to describe the dehydrating process of date paste

Model name	Equation	Reference
Approximation of diffusion	$MR = a \exp(-kt) + (1 - a) \exp(-kbt)$	Kassem 1998
Lewis	$MR = a \exp(-kt)$	Lewis 1921
Two-term	$MR = a \exp(-k_1 t) + b \exp(-k_2 t)$	Henderson 1974
Modified Page	$MR = a \exp[(-kt)^y]$	White et al. 1981
Wang and Singh	$MR = 1 + at + bt^2$	Wang and Singh 1978
Logarithmic	$MR = a \exp(-kt) + c$	Toğrul and Pehlivan 2002
Page	$MR = a \exp(-kt^y)$	Page 1949

MR – moisture ratio (dimensionless); a, b, c, y – empirical constants (drying model constants); k, k_1, k_2 – drying rate constants; t – drying time

https://doi.org/10.17221/66/2024-CJFS

$$R^2 = \frac{\sum_{i=1}^{N}\left(MR_{Exp} - MR_{Pre}\right)^2}{\sqrt{\left[\sum_{i=1}^{N}\left(MR_{Exp} - MR_{Pre}\right)^2\right] \times \left[\sum_{i=1}^{N}\left(MR_{Exp} - MR_{Pre}\right)^2\right]}} \quad (3)$$

where: RMSE – root mean square error; N – number of observations; MR_{Exp} – experimental moisture ratio (dimensionless); MR_{Pre} – predicted moisture ratio (dimensionless); SSE – sum of squared absolute error; R^2 – coefficient of determination.

Effective moisture diffusivity (D_{eff}). Wang and Brennan (1992) found that the dehydration of food occurs during the falling rate period, and D_{eff} can be calculated by utilising (Crank 1979) method, as the following equation:

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

where: MR – moisture ratio (dimensionless); D_{eff} – effective moisture diffusivity ($m^2 \cdot s^{-1}$); t – drying time; L – thickness of the sample (slab) (mm).

The resulting equation was derived by implementing the natural logarithm to Equation 4 to obtain the following equation:

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

The estimation of Equation 5 is performed using arithmetic calculations, where

$$\left(\frac{D_{eff}\, t}{L^2}\right)$$

is substituted with F_0, which represents the Fourier number for diffusion.

$$\ln\left(MR\right) = \ln\left(\frac{8}{\pi^2}\right) - \left(\pi^2 F_0\right) \quad (6)$$

$$F_0 = -0.0212 - 0.0101424 \ln(MR) \quad (7)$$

The value of D_{eff} was derived from the subsequent equation:

$$D_{eff} = \frac{F_0 L^2}{t} \quad (8)$$

Statistical analysis. SPSS (version 26) was employed to conduct a unidirectional analysis of variance (ANOVA) for the analysis. Researchers implemented the Duncan Multiple Range Test to evaluate the means, with a significance level of $P < 0.05$. The varied constants in the evaluated models were determined using a non-linear regression procedure.

RESULTS AND DISCUSSION

Drying characteristics. Figure 2 depicts relationship between drying rate and the drying duration, as well as the variances in moisture ratio over-drying duration under different conditions. These conditions include varying of air velocity (0.5, 1.0, and 1.5 $m \cdot s^{-1}$), IR intensity (0.076, 0.152, and 0.228 $W \cdot cm^{-2}$), and thickness (3 mm and 5 mm) of date paste layers. The drying process begins quickly and gradually slows down throughout the subsequent phase. The entire phase is marked by a progressive decrease in the drying rate without any discernible period of consistent drying rate. The leading cause of this issue is the progressive reduction in moisture content of date samples through the drying experimental, which leads to not enough and irregular water supply. The primary physical mechanism that is accountable for the transport of water to the surface of date pastes after dehydrate is diffusion (Chen et al. 2019). Doymaz and Kocayigit (2012) and Ju et al. (2016) reported comparable findings in their investigation on sweet potatoes and yam, respectively. Based on the findings shown in Figure 2, it is clear that the moisture content of the date paste was greatly impacted by the radiation intensity, air velocity, and thickness, as anticipated. The drying time was depicted to decline from 245 min to 70 min and from 325 min to 110 min when the intensity of radiation increase from 0.076 $W \cdot cm^{-2}$ to 0.228 $W \cdot cm^{-2}$ while maintaining an airflow velocity of 0.5 $m \cdot s^{-1}$, as illustrated in Figure 3. The results of this study were obtained for samples with 3 mm and 5 mm of thicknesses, respectively. Furthermore, the drying time was declined from 670 min to 265 min and 1 600 min to 650 min when the velocity of air was risen to 1.5 $m \cdot s^{-1}$ for samples with 3 mm and 5 mm of thicknesses, respectively. The accelerated augmentation of the rate at which the drying process occurs, thereby diminishing the overall period

https://doi.org/10.17221/66/2024-CJFS

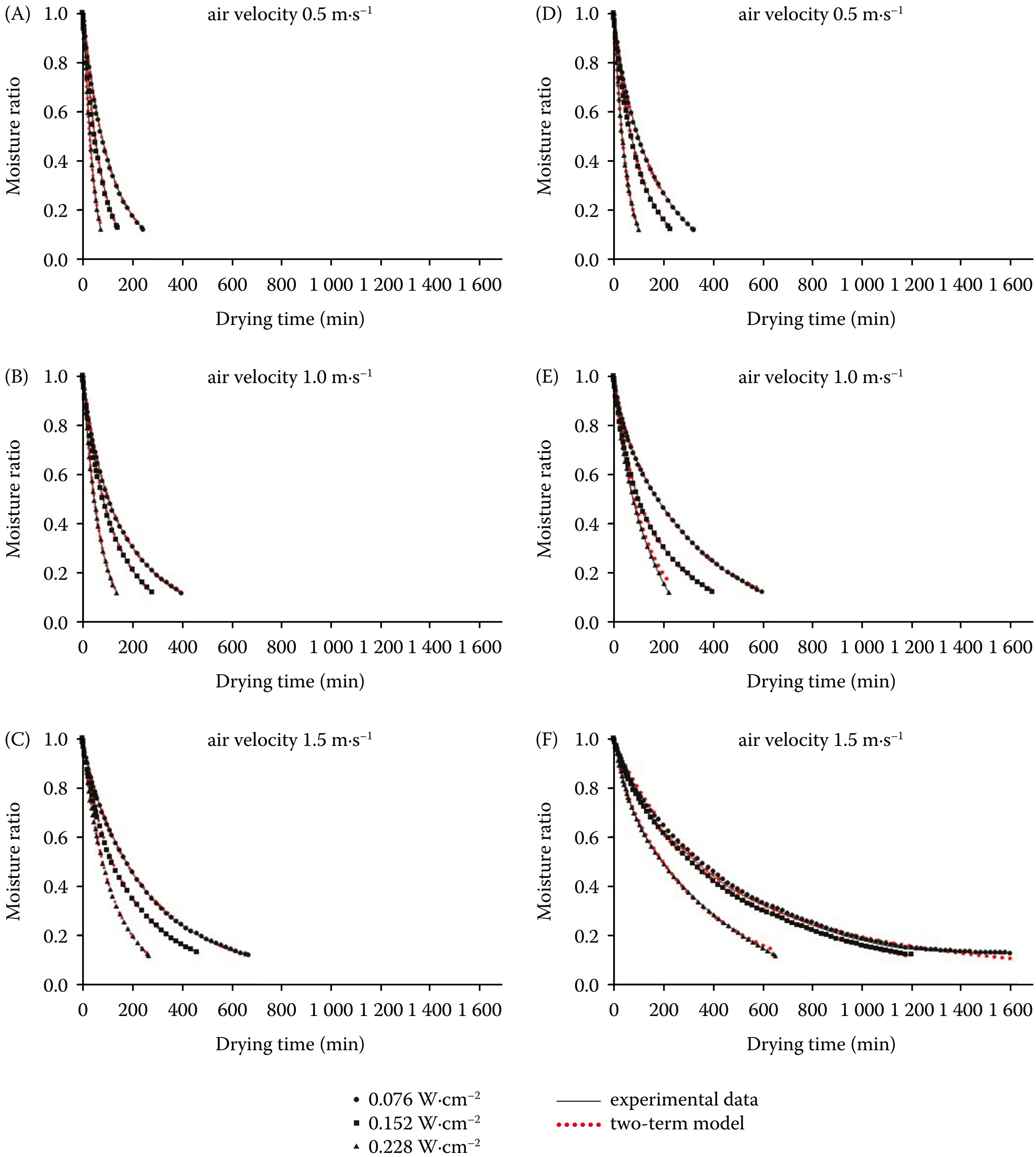

Figure 2. The predicted and experimented moisture ratios by the model that fits the best with drying time at varying air velocity and radiation intensity for (A–C) 3 mm and (D–F) 5 mm thickness

of drying and achieving the desired temperature within layers of date paste, can be ascribed to the infiltration of infrared radiation into the outermost layer, resulting in supplementary heat generation (Jeevarathinam et al. 2021). Doymaz (2012) has demonstrated a relationship between a reduction in thickness and an augmentation in drying rate for root and tuber crops.

Drying curves modeling. Seven distinct models of drying have been employed to characterise drying curves. Table 2 presents the model equations, RMSE, SSE, and R^2, for the models utilised to characterise the time-varying fluctuations of the moisture ratio. The seven models had high values of R^2, ranging from 0.8911 to 1.0000. According to the obtained results,

https://doi.org/10.17221/66/2024-CJFS

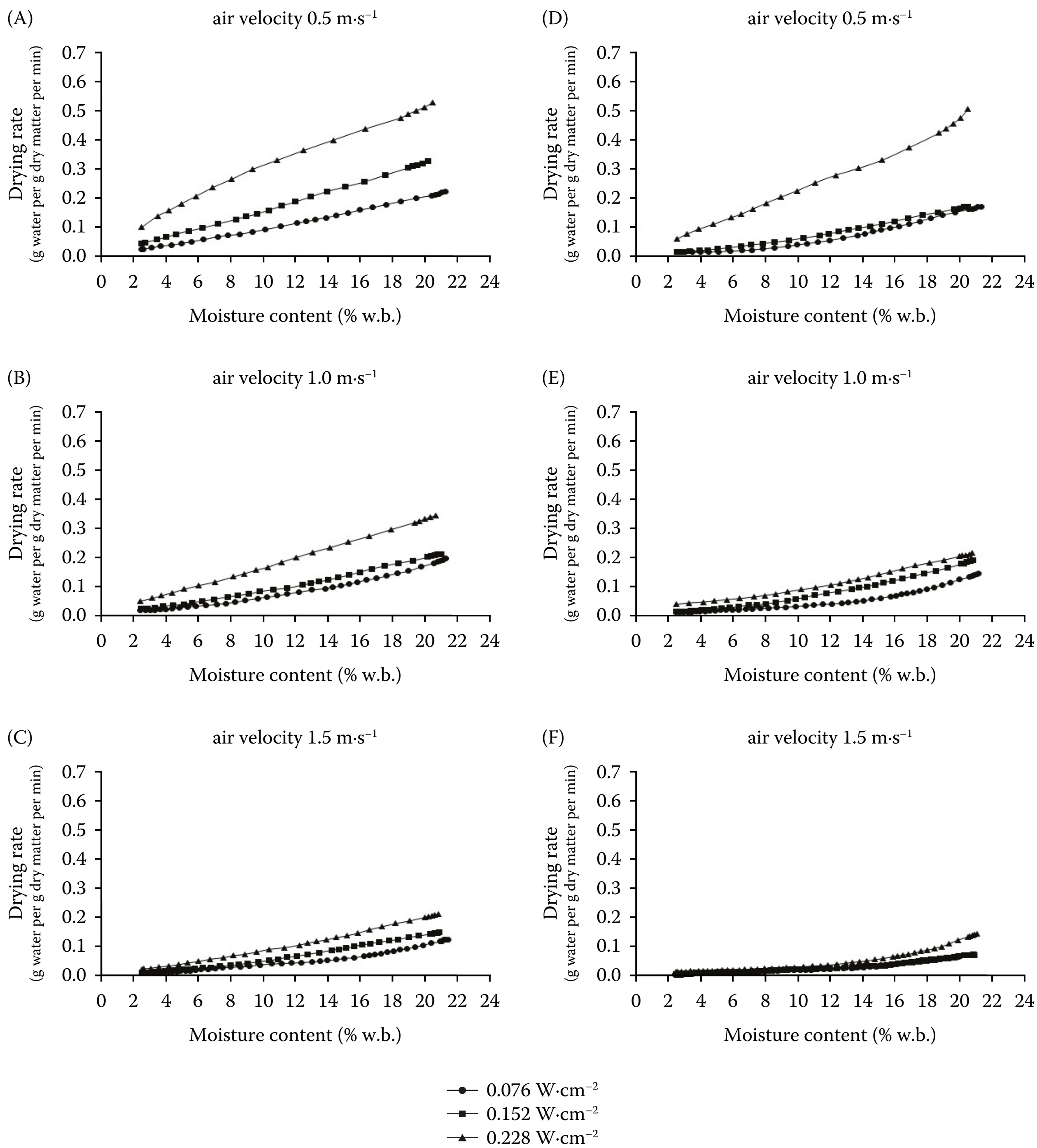

Figure 3. The influence of moisture content on the date paste drying rate under varying velocity of air and radiation intensity conditions for (A–C) 3 mm and (D–F) 5 mm thickness

w.b. – wet basis

it can be concluded that all of the examined models could effectively represent the behaviour of drying of date paste using the infrared method. However, the two-term model (Henderson 1974) exhibited the greatest average R^2 value (0.9998), the lowest SSE value (0.00097), and the lowest RMSE value (0.00276). Therefore, this model performs better than the other examined models in precisely representing the thin-layer drying traits of the date paste layer for the investigated conditions. The variables related to the optimal model (two-term) for characterising the drying curves of thin-layer date paste are displayed in Table 3.

https://doi.org/10.17221/66/2024-CJFS

Table 2. Statistical variables were acquired utilising various thin-layer drying equations

Assessment criteria	Thickness of layers (mm)	Airflow (m·s^{-1})	IR radiation intensity (W·cm^{-2})	Model name						
				approximation of diffusion	Lewis	logarithmic	modified Page	Page	two-term	Wang and Singh
RMSE	3	0.5	0.076	0.00083	0.01055	0.00216	0.01074	0.00446	0.00082	0.99130
			0.152	0.00302	0.00363	0.00343	0.00371	0.01346	0.00230	0.99540
			0.228	0.02198	0.02207	0.02248	0.02280	0.01346	0.00130	0.99930
		1.0	0.076	0.03117	0.03031	0.01074	0.03074	0.00535	0.00108	0.97590
			0.152	0.00076	0.01724	0.00317	0.01753	0.00663	0.00077	0.98720
			0.228	0.00139	0.00242	0.00181	0.00247	0.10940	0.00143	0.99590
		1.5	0.076	0.00310	0.02864	0.00959	0.02893	0.02918	0.00412	0.97990
			0.152	0.00142	0.03387	0.01179	0.03430	0.00852	0.00130	0.97350
			0.228	0.00062	0.01374	0.00531	0.01397	0.00213	0.00062	0.98960
	5	0.5	0.076	0.00258	0.01834	0.00980	0.01862	0.00430	0.00261	0.98580
			0.152	0.00095	0.00992	0.00273	0.01010	0.00261	0.00093	0.99260
			0.228	0.00148	0.00343	0.00157	0.00352	0.00243	0.00143	0.99600
		1.0	0.076	0.00320	0.03332	0.01743	0.03369	0.00839	0.00323	0.97360
			0.152	0.00140	0.03498	0.01249	0.03547	0.00764	0.00141	0.97110
			0.228	0.00649	0.00937	0.00811	0.00955	0.00727	0.00660	0.99250
		1.5	0.076	0.01129	0.03758	0.01056	0.03778	0.01053	0.00979	0.97300
			0.152	0.00387	0.03252	0.01309	0.03273	0.00447	0.00381	0.97660
			0.228	0.00628	0.03789	0.02090	0.03828	0.01137	0.00622	0.96780
SSE	3	0.5	0.076	0.00002	0.00323	0.00013	0.00323	0.00054	0.00002	0.02730
			0.152	0.00019	0.00030	0.00024	0.00030	0.00272	0.00011	0.01987
			0.228	0.00676	0.00780	0.00657	0.00780	0.00272	0.00277	0.00800
		1.0	0.076	0.03303	0.03308	0.00392	0.03308	0.00100	0.00004	0.04531
			0.152	0.00002	0.00892	0.00029	0.00892	0.00123	0.00002	0.03259
			0.228	0.00004	0.00013	0.00007	0.00013	0.20330	0.00004	0.01876
		1.5	0.076	0.00047	0.04102	0.00442	0.04102	0.04088	0.00080	0.04312
			0.152	0.00008	0.04589	0.00529	0.04589	0.00283	0.00006	0.04823
			0.228	0.00001	0.00566	0.00079	0.00566	0.00013	0.00001	0.02975
	5	0.5	0.076	0.00021	0.01110	0.00298	0.01110	0.00059	0.00021	0.03470
			0.152	0.00002	0.00275	0.00019	0.00275	0.00018	0.00002	0.02512
			0.228	0.00004	0.00022	0.00004	0.00022	0.00011	0.00004	0.01870
		1.0	0.076	0.00045	0.05108	0.01336	0.05108	0.00316	0.00045	0.04713
			0.152	0.00007	0.04405	0.00530	0.04405	0.00204	0.00007	0.04927
			0.228	0.00105	0.00237	0.00164	0.00237	0.00137	0.00104	0.02405
		1.5	0.076	0.01199	0.13560	0.01049	0.13560	0.01053	0.00891	0.04902
			0.152	0.00111	0.08036	0.01268	0.08036	0.00291	0.00106	0.04547
			0.228	0.00182	0.07035	0.02052	0.07035	0.00621	0.00182	0.05166
R^2	3	0.5	0.076	1.0000	0.9987	0.9999	0.9987	0.9998	1.0000	0.9916
			0.152	0.9999	0.9998	0.9999	0.9998	0.9981	0.9999	0.9956
			0.228	0.9952	0.9945	0.9954	0.9945	0.9981	0.9997	0.9993

https://doi.org/10.17221/66/2024-CJFS

Table 2. To be continued

Assessment criteria	Thickness of layers (mm)	Airflow (m·s^{-1})	IR radiation intensity (W·cm^{-2})	Model name: approximation of diffusion	Lewis	logarithmic	modified Page	Page	two-term	Wang and Singh
R^2	3	1.0	0.076	0.9892	0.9892	0.9987	0.9892	0.9997	1.0000	0.9766
			0.152	1.0000	0.9964	0.9999	0.9964	0.9995	1.0000	0.9876
			0.228	1.0000	0.9999	1.0000	0.9999	0.8911	1.0000	0.9960
		1.5	0.076	0.9999	0.9911	0.9990	0.9911	0.9912	0.9998	0.9803
			0.152	1.0000	0.9869	0.9985	0.9869	0.9992	1.0000	0.9742
			0.228	1.0000	0.9978	0.9997	0.9978	0.9999	1.0000	0.9900
	5	0.5	0.076	0.9999	0.9960	0.9989	0.9960	0.9998	0.9999	0.9862
			0.152	1.0000	0.9988	0.9999	0.9988	0.9999	1.0000	0.9928
			0.228	1.0000	0.9999	1.0000	0.9999	0.9999	1.0000	0.9962
		1.0	0.076	0.9999	0.9868	0.9966	0.9868	0.9992	0.9999	0.9742
			0.152	1.0000	0.9854	0.9982	0.9854	0.9993	1.0000	0.9719
			0.228	0.9995	0.9989	0.9992	0.9989	0.9993	0.9995	0.9928
		1.5	0.076	0.9986	0.9841	0.9988	0.9841	0.9988	0.9990	0.9733
			0.152	0.9998	0.9880	0.9981	0.9880	0.9997	0.9998	0.9769
			0.228	0.9996	0.9827	0.9950	0.9827	0.9985	0.9996	0.9685

RMSE – root mean square error; SSE – sum of squared absolute error; R^2 – coefficient of determination; IR – infrared

Table 3. The statistical results of two-term model equation [$MR = a \exp(-k_1 t) + b \exp(-k_2 t)$] and its constants and coefficients for various dehydration methods

Coefficients	Air velocity (m·s^{-1}) 0.5			1.0			1.5		
	radiation intensity (W·cm^{-2})								
	0.076	0.152	0.228	0.076	0.152	0.228	0.076	0.152	0.228
Thickness 3 mm									
k_1	0.00829	0.01513	0.02693	0.01922	0.02616	0.01550	0.01261	0.01541	0.02704
k_2	0.02917	0.01506	0.02597	0.00459	0.00697	0.09630	0.00293	0.00364	0.00751
a	0.89860	−0.43290	2.58000	0.25630	0.15980	0.99010	0.21000	0.31120	0.12810
b	0.10200	1.43200	−1.56100	0.74150	0.84050	0.00940	0.78410	0.69050	0.87160
R^2	1.00000	0.99990	0.99970	1.00000	1.00000	1.00000	0.99980	1.00000	1.00000
SSE	0.00002	0.00011	0.00277	0.00004	0.00002	0.00004	0.00080	0.00006	0.00001
RMSE	0.00082	0.00230	0.00130	0.00108	0.00077	0.00143	0.00412	0.00130	0.00062
Thickness 5 mm									
k_1	0.03891	0.01835	0.03619	0.03313	0.01932	0.09352	0.00304	0.00165	0.03081
k_2	0.00617	0.00804	0.02134	0.00321	0.00436	0.00876	0.00080	0.01014	0.00284
a	0.09180	0.24590	−0.00760	0.12480	0.29430	0.02860	0.61250	0.81400	0.13750
b	0.90830	0.75340	1.00200	0.87630	0.70520	0.97350	0.36780	0.18320	0.86290
R^2	0.99990	1.00000	1.00000	0.99990	1.00000	0.99950	0.99900	0.99980	0.99960
SSE	0.00021	0.00002	0.00004	0.00045	0.00007	0.00104	0.00891	0.00106	0.00182
RMSE	0.00261	0.00093	0.00143	0.00323	0.00141	0.00660	0.00979	0.00381	0.00622

MR – moisture ratio (dimensionless); a, b – empirical constants (drying model constants); k_1, k_2 – drying rate constants; t – drying time; R^2 – coefficient of determination; SSE – sum of squared absolute error; RMSE – root mean square error

https://doi.org/10.17221/66/2024-CJFS

Effective moisture diffusivity (D_{eff}). The moisture diffusivity is contingent upon the system and context and is impacted by the moisture content. The (D_{eff}) of a food material refers to its inherent ability to move moisture, encompassing several mechanisms such as molecule diffusion, vapor diffusion, hydrodynamic movement liquid diffusion, and other means (Sharma et al. 2005).

Data in Figure 4 indicates that the plots have exhibited a modest departure from linearity for all investigated drying settings. The observed discrepancy can be attributed to several factors, such reflects the unequal starting moisture content distribution, product shrinkage, variations in moisture diffusivity as a function of moisture content, and fluctuations in product

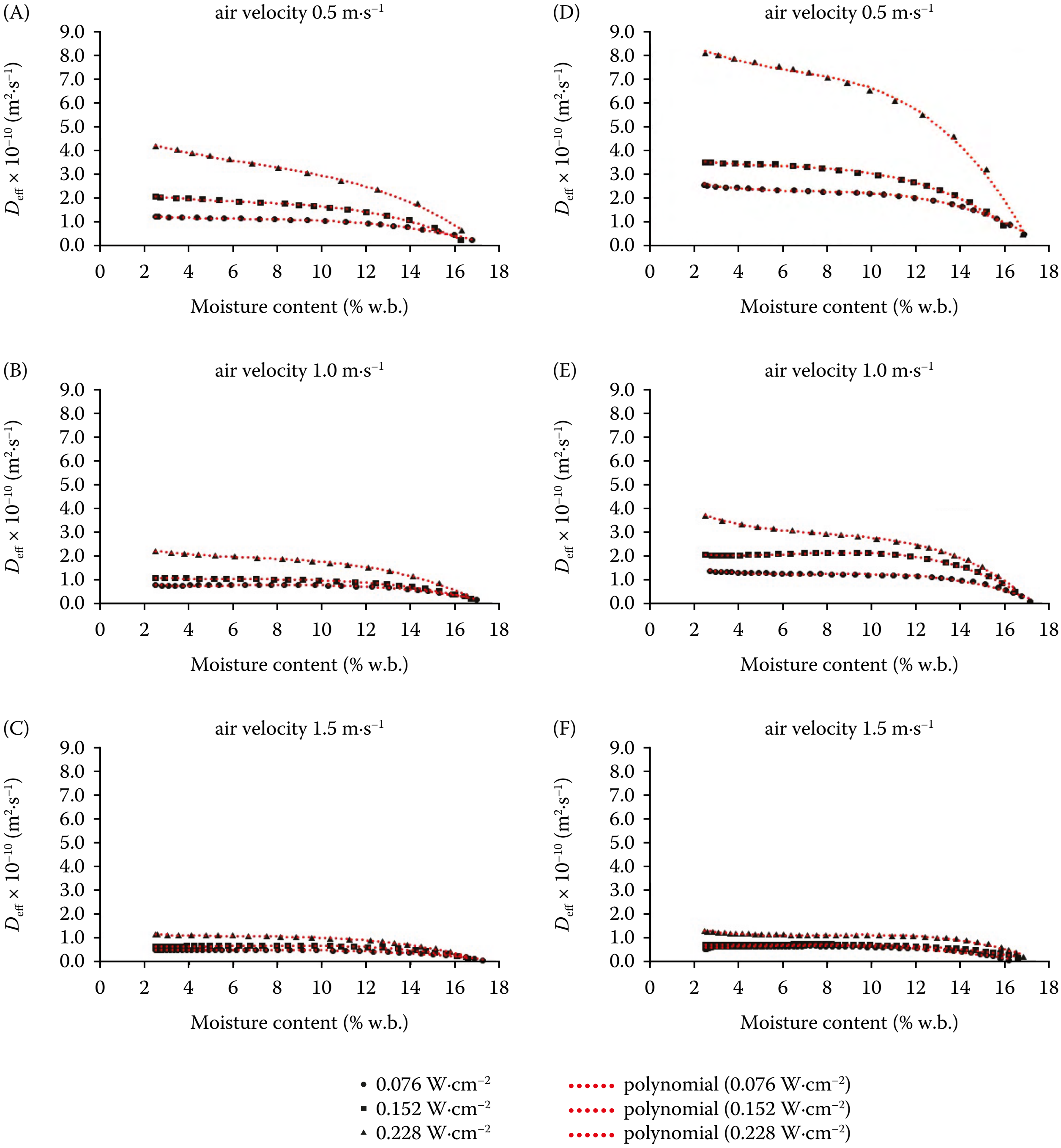

Figure 4. The impact of temperature and air velocity on the effective diffusivity of date paste at varying thickness levels: (A–C) 3 mm and (D–F) 5 mm

w.b. – wet basis; D_{eff} – effective moisture diffusivity

https://doi.org/10.17221/66/2024-CJFS

temperature throught the dehydration process (Adu and Otten 1996). In general, an increase in the date paste thickness (3–5 mm), a decrease in air velocity (1.5–0.5 m·s^{-1}), and an increase in radiation intensity (0.076–228 W·m^{-2}) resulted in a commensurate increase in D_{eff}. The D_{eff} varied from 3.94 × 10^{-11} m·s^{-1} to 6.01 × 10^{-10} m^2·s^{-1}, with the lowest and greatest values observed, respectively. According to Sharifian et al. (2023), the increased rate of water molecule evaporation in date paste this may be the result of the heightened intensity of infrared radiation, which facilitates the diffusion of water within the samples of date paste. Moreover, the fluctuations in D_{eff} values can be ascribed to a multitude of factors, including the utilisation of different drying methods, variations in the types of cultivars employed, discrepancies in cellular composition, discrepancies in the drying equipment utilised, disparities in the employed drying technique, different in the samples' sizes and shapes, and differences in the initial and final moisture content (Miraei et al. 2018).

CONCLUSION

The effect of numerous dehydrating variables were examined in this study, including radiation intensities (0.076, 0.152, and 228 W·cm^{-2}), layer thickness (3 mm and 5 mm), and airflow velocities (0.5, 1, and 1.5 m·s^{-1}), on the combined convection-IR drying of date paste in thin layers. The study's findings revealed a rise in drying rate, a reduction in drying time as IR intensity increased, and a drop in airflow velocity and date paste layer thickness. The performance of date paste drying may be effectively described, and the variations in date paste's moisture content layers can be accurately predicted using the two-term model. The D_{eff} positively correlated with air temperature, air velocity, and thickness, resulting in a range of values spanning from 3.94 × 10^{-11} m^2·s^{-1} to 6.01 × 10^{-10} m^2·s^{-1}.

Acknowledgement. The authors would like to thank King Abdulazizi City for Science and Technology (KACST) for financially supporting this research through project number 2-17-04-001-0015.

REFERENCES

Abe T., Afzal T.M. (1997): Thin-layer infrared radiation drying of rough rice. Journal of Agricultural Engineering Research, 67: 289–297.

Al-Awaadh A.M., Hassan B.H., Ahmed K.M.A. (2015): Hot air drying characteristics of sukkari date (*Phoenix dactylifera* L.) and effects of drying condition on fruit color and texture. International Journal of Food Engineering, 11: 421–434.

Alsenaien W.A., Alamer R.A., Tang Z.X., Albahrani S.A., Al-Ghannam M.A., Aleid S.M. (2015): Substitution of sugar with dates powder and dates syrup in cookies making. Advance Journal of Food Science and Technology, 8: 8–13.

Benamara S., Chekroune M. (2009): Colour change during hot air and microwave complementary dehydration of naturally dried date (*Phoenix dactylifera* L.) fruits. World Journal of Dairy and Food Sciences, 4: 8–13.

Chen Q., Song H., Bi J., Chen R., Liu X., Wu X., Hou H. (2019): Multi-objective optimization and quality evaluation of short- and medium-wave infrared radiation dried carrot slices. International Journal of Food Engineering, 15: 20180234.

Crank J. (1979): The Mathematics of Diffusion. 2nd Ed. Oxford, Oxford University Press: 414.

Dev S.R.S., Annamalai M., Orsat V., Raghavan V.G.S., Ngadi M. (2018): Nanostructural characterization and sorption isotherm analysis of spray-dried date powder. Drying Technology, 36: 1531–1541.

Doymaz İ. (2004): Convective air drying characteristics of thin layer carrots. Journal of Food Engineering, 61: 359–364.

Doymaz İ. (2012): Infrared drying of sweet potato (*Ipomoea batatas* L.) slices. Journal of Food Science & Technology, 49: 760–766.

Doymaz İ., Kocayigit F. (2012): Effect of pre-treatments on drying, rehydration, and color characteristics of red pepper ('Charliston' variety). Food Science and Biotechnology, 21: 1013–1022.

El Bakouri Z., Meziani R., Mazri M.A., Chitt M.A., Bouamri R., Jaiti F. (2021): Estimation of the production cost of date fruits of cultivar Majhoul (*Phoenix dactylifera* L.) and evaluation of the Moroccan competitiveness towards the major exporting regions in the world. Agricultural Science, 12: 1342–1351.

Elleuch M., Besbes S., Roiseux O., Blecker C., Deroanne C., Drira N., Attia H. (2008): Date flesh: Chemical composition and characteristics of the dietary fibre. Food Chemistry, 111: 676–682.

Elsharawy N. T., Mashael A. L., Alayafi A. (2019): Different types of dates in Saudi Arabia and its most fungal spoilage and its most preservation methods. International Journal of Recent Scientific Research, 10: 35787–35799.

Ertekin O., Yaldiz C. (2001): Thin layer solar drying of some different vegetables. Drying Technology, 19: 583–596.

Ghnimi S., Umer S., Karim A., Kamal-Eldin A. (2017): Date fruit (*Phoenix dactylifera* L.): An underutilized food seeking industrial valorization. Nutrition and Food Science Journal, 6: 1–10.

Henderson S.M. (1974): Progress in developing the thin layer drying equation. Transactions of the American Society of Agricultural Engineers, 17: 1167–1168.

https://doi.org/10.17221/66/2024-CJFS

Hobani A.I., Thottam A.M., Ahmed K.A.M. (2003): Development of a neural network classifier for date fruit varieties using some physical attributes. King Saud University, Research Centers, 126: 5–18.

Jeevarathinam G., Pandiselvam R., Pandiarajan T., Preetha P., Balakrishnan M., Thirupathi V., Kothakota A. (2021): Infrared assisted hot air dryer for turmeric slices: Effect on drying rate and quality parameters. LWT – Food Science and Technology, 144: 111258.

Ju H.-Y., El-Mashad H.M., Fang X.-M., Pan Z., Xiao H.-W., Liu Y.-H., Gao Z.-J. (2016): Drying characteristics and modeling of yam slices under different relative humidity conditions. Drying Technology, 34: 296–306.

Kassem A.S. (1998): Comparative studies on thin layer drying models for wheat. In: Proceedings of the 13th International Congress on Agricultural Engineering, 6: 2–6.

Lewis W.K. (1921): The rate of drying of solid materials. Journal of Industrial and Engineering Chemistry, 13: 427–432.

Miraei A.S.-H., Sturm B., Nasirahmadi A. (2018): Effects of hot-air and hybrid hot air-microwave drying on drying kinetics and textural quality of nectarine slices. Heat and Mass Transfer, 54: 915–927.

Nasser R.A., Salem M.Z.M., Hiziroglu S., Al-Mefarrej H.A., Mohareb A.S., Alam M., Aref I.M. (2016): Chemical analysis of different parts of date palm (*Phoenix dactylifera* L.) using ultimate, proximate and thermo-gravimetric techniques for energy production. Energies, 9: 374.

Page G.E. (1949): Factors influencing the maximum rates of air drying shelled corn in thin layers. [MSc. Thesis.] Purdue, Purdue University, Department of Mechanical Engineering.

Sahari M.A., Esfahani Z.H., Samadlui H.-R. (2008): Optimization of vacuum drying characteristics of date powder. Drying Technology, 26: 793–797.

Seerangurayar T., Manickavasagan A., Al-Ismaili A.M., Al-Mulla Y.A. (2018): Effect of carrier agents on physicochemical properties of foam-mat freeze-dried date powder. Drying Technology, 36: 1292–1303.

Seerangurayar T., Al-Ismaili A.M., Jeewantha L.H.J., Al-Habsi N.A. (2019): Effect of solar drying methods on color kinetics and texture of dates. Food and Bioproducts Processing, 116: 227–239.

Sharifian F., Gharkhloo Z.R., Yamchi A.A., Kaveh M. (2023): Infrared and hot drying of saffron petal (*Crocus sativus* L.): Effect on drying, energy, color, and rehydration. Journal of Food Process Engineering, 46: e14342.

Sharma G.P., Verma R.C., Pathare P. (2005): Mathematical modeling of infrared radiation thin layer drying of onion slices. Journal of Food Engineering, 71: 282–286.

Toğrul İ.T., Pehlivan D. (2002): Mathematical modelling of solar drying of apricots in thin layers. Journal of Food Engineering, 55: 209–216.

Wang N., Brennan J.G. (1992): Effect of water binding on the drying behavior of potato. Drying, 92: 1350–1359.

Wang C.Y., Singh R.P. (1978): Use of variable equilibrium moisture content in modeling rice drying. Transactions of the American Society of Agricultural Engineers, 11: 668–672.

White M.G., Ross I.J., Poneleit C.G. (1981): Fully-exposed drying of popcorn. Transactions of the ASAE, 24: 466–468.

Received: April 5, 2024
Accepted: November 25, 2024
Published online: December 11, 2024