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Drying kinetics and sorption isotherms of cornelian cherry fruits

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ABSTRACT

In this study, drying kinetics and sorption isotherms of cornelian cherry fruit are investigated under various drying air conditions. Experiments are conducted in a lab-scale convective drier under the following drying conditions: temperatures at 25, 30, 40, 50 and 60 °C; velocities at 0.3, 0.6 and 0.9 m/s; relative humidity values at 25%, 40%, 55% and 70%. Sorption isotherms of the dried cornelian cherry fruit are determined for different temperatures and water activity values at first. At a given water activity, the results show that the equilibrium moisture content decreases with increase in temperature. The experimental sorption curves are then described by the GAB, Oswin, Smith and Halsey models. A nonlinear regression analysis method was used to evaluate the constants of the sorption equations. The GAB model was found to be suitable for describing the sorption curves. Later, drying experiments are conducted for various values for drying air. The experimental moisture data were fitted to some models available in the literature, mainly the Henderson and Pabis model, the Lewis model and the two-term exponential model and, a good agreement was observed.

Keywords: Convective air drying; Cornelian cherry fruit; Drying kinetics; Sorption isotherm

1. Introduction

Cornelian cherry (Cornus mas L.) is one of the most important products in the Cornaceae commodity, growing in temperate zone on calcareous, well-drained forest soils. Cornelian cherry fruits are widely grown in Blacksea Region of Turkey. It is estimated that there are about 1 585000 cornelian cherry trees in Turkey, with a yield of approximately 14000 tons per year. The cornelian cherry fruits which have sour and sweat tasting juice, contain a high amount of vitamin C. Further, fruits are rich in sugar, organic acid and tannin [1,2].

Cornelian cherry fruits have very short shelf-life since they are highly perishable. Drying may be suggested as one of the preservation options to extend their shelf-life.

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Moisture sorption isotherms describe the relationship between the equilibrium moisture content and the water activity at constant temperature and pressures. For food materials these isotherms give information about the sorption mechanism and the interaction of food biopolymers with water [3]. The moisture sorption isotherms are extremely important in modelling the drying process, in design and optimization of drying equipment, in predicting shelf-life stability, in calculating moisture changes which may occur during storage and in selecting appropriate packaging material [4]. Yazdani et al. [4] determined the equilibrium moisture contents (EMC) of pistachio using the standard staticgravimetric method (COST 90) at 15, 25, 35 and 40 °C for pistachio powder, pistachio kernel and pistachio nut. Nogueira-Terrones et al. [5] evaluated the drying process of nejayote using a hot air cabinet dryer and analyzed the sorption isotherms of the product. Sorption isotherms were measured by the COST method.

Increasing the drying air temperature decreased the equilibrium moisture content and the total drying time. Trujillo et al. [6] studied sorption isotherm of lean beef using the COST 90 method at three different temperatures, i.e., 5, 15 and 20°C. Akanbi et al. [7] investigated vapor sorption isotherm of dehydrated tomato slices in the water activity (a_w) range of 0.08–0.85 at three temperature levels, i.e., 25, 30 and 40°C. Five sorption models were fitted with the adsorption data generated from the gravimetric method. GAB and Oswin models describe the adsorption characteristics of dehydrated tomato at 25°C better than other models with GAB model being the best applicable model. McLaughlin and Magee [8] determined sorption isotherms for potatoes at three different temperatures (30, 45 and 60°C), using a standard gravimetric method. The goodness of fit of four sorption models to experimental results was determined. Of the models tested the GAB, Oswin and Hasley models gave good fits while the BET model gave a poor fit. Park et al. [9] investigated the desorption isotherms of mint leaves at two temperatures (30 and 40°C). Experimental curves were fitted to sorpsion models. BET, GAB, Oswin and Peleg models could be used to describe the mint desorption isotherms.

Broad applications areas of drying and onging commercial interest on dried fruits have motivated a good deal of research interest on drying. Koyuncu et al. [1] investigated drying characteristics and energy requirement for drying of cornelian cherry fruits. Their results showed that drying air temperature significantly influenced the total drying time. Prakash et al. [10] experimentally studied the drying characteristics of carrots using a solar cabinet drier, fluidized bed drier and microwave oven drier. They determined that carrots dried by fluidized bed drying showed better color, rehydration properties, greater beta-carotene retention and better overall sensory acceptability than those dried by microwave oven and solar methods. Kiranoudis et al. [11] studied the influence of temperature on the drying kinetics with hot air drying of some fruits (namely, apple, pear, kiwi and banana) and determined the equilibrium moisture content of these fruits. Increasing the drying air temperature decreased the equilibrium moisture content and the total drying time. Kashaninejad and Tabil [12] determined the effects of drying air temperature on the drying kinetics of Purslane using an air recirculating dryer. As expected, drying time decreased with increasing drying temperature and drying rate increased with increasing drying temperature. Kaya et al. [13] determined the effects of drying air temperature, air flow rate and air relative humidity on the drying kinetics of quince, apple [14], pumpkin [15], carrot [16], kiwi [17] and Kaya and Aydın [18] cherry laurel fruit using a convective dryer. Increasing the temperature or velocity of the drying air decreased the total drying time, while decreasing the relative humidity decreased it.

The purpose of this study is focused on experimentally studying drying kinetics and sorption isotherms of cornelian cherry fruit at various drying air conditions.

2. Experimental study

2.1. Experimental setup and procedure

Experiments were conducted in a lab-scale convective air-dryer as shown in Fig. 1 which consists of a fan, a heater, an air conditioner, a humidifier, a fresh air damper, an air exit damper, a mixing damper, a dying tray, a loadcell, a data acquisition, and a desktop computer. It is equipped with controllers for controlling the temperature, airflow velocity and relative humidity. The rectangular-sectioned channel dimensions are 50 cm × 25 cm with 4000 cm length. In order to prevent the heat loss to the environment, the channels are well insulated. The mass flow rate of the drying air is regulated by a fan driven by a variable speed motor to obtain air velocities in the range from 0.3 to 0.9 m/s at the entrance of the channels. Drying basket with a holding area of 40 cm × 20 cm is included in the channels. Ripe fruits of cornelian cherry grown in Black Sea Region of Turkey were harvested manually and use for the investigation. The fruits with 16 mm long were cleaned from all dust, dirt, pieces of branches, leaves, etc. The test samples of the cornelian cherry fruits weighing about 500 g are placed in the drying basket. The initial moisture content of cornelian cherry is determined using the OHAUS MB45 moisture analyzer.

During the experiments, the sample weight was measured using load cells (model Lama, Esit, Turkey and accuracy 10000 ± 0.01g). The data collected were recorded at the intervals of 10 minutes for moisture using a data logger interfaced to a desktop computer. Furthermore, the air velocity in the drying channel was continuously monitored with anemometers (hot-wire and vine type) (model 4204AM) (hot-wire), 4202AM (vine), Lutron HT, Taiwan with an accuracy of 0.2–20.0 ± 0.05 m/s and model 407113 (vine), Extech Insturuments, USA with an accuracy of 0.0–30.0 ± 0.01 m/s, while the relative humidity in the test section was measured using a humidity/temperature meter (4204AM model, Lutron HT, Taiwan with an accuracy of 10–95 ± 1%).

2.2. Sorption isotherm

The sorption isotherm represents water activity of a product, suggesting the equilibrium relation between the water activity in the product and its moisture content. It is of particular importance in the design of a food dehydration process, especially in the determination of a drying end point which ensures economic viability and microbiological safety [8,19].

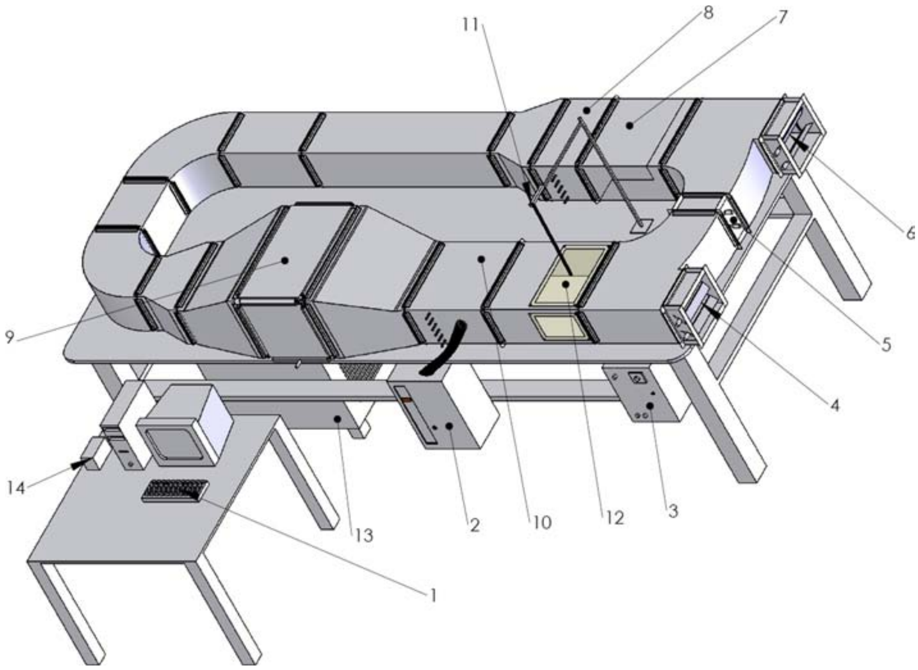

Fig. 1. The schematic of the experimental setup. 1-Computer, 2-Humidifier, 3-Control panel, 4-Air out damper, 5-Mixing damper, 6-Fresh air damper, 7-Fan, 8-Heater, 9-Condenser, 10-Heater, 11-Loadcell, 12-Test section, 13-Condenser unit (compressor, fan), 14-Data acquisition system.

The water activity of a food product can be defined as:

$$a_w = \frac{p_f}{p_0} = \frac{\phi_{eq}}{100} \tag{1}$$

where a_w is the water activity, p_f is the vapor pressure of the water in the product, p_0 is the vapor pressure of pure water and ϕ_{eq} is the equilibrium relative humidity of the salt solutions [8].

The sorption isotherms were determined gravimetrically by exposing the samples (about 4 g) to atmospheres of relative humidity controlled by different saturated salts according to the COST 90 method [20,21] at 25, 30, 40, 50 and 60 °C. Water activities of saturated salt solutions thus prepared were presented in the Table 1. Ten different saturated salt solutions, whose water activity a_w values varied between 0.105 and 0.97, are used (Table 1). Each solution is placed into separate glass jar, i.e. desiccators,

Table 1
Water activities of the saturated salt solutions used in the experimental study [21,27]

Salt solutions	T = 25 °C	a_w			
		T = 30 °C	T = 40 °C	T = 50 °C	T = 60 °C
LiCl	0.111	0.108	0.106	0.104	0.102
CH_3COOK	0.220	0.216	0.211	0.207	0.203
$MgCl_2$	0.330	0.323	0.317	0.311	0.304
K_2CO_3	0.420	0.412	0.403	0.395	0.387
$Mg(NO_3)_2 6H_2O$	0.570	0.569	0.557	0.546	0.536
$NaNO_2$	0.630	0.627	0.615	0.609	0.591
$SrCl_2$	0.700	0.692	0.672	0.666	0.646
NaCl	0.750	0.744	0.734	0.721	0.707
KCl	0.800	0.798	0.789	0.785	0.768
K_2SO_4	0.970	0.955	0.945	0.931	0.912

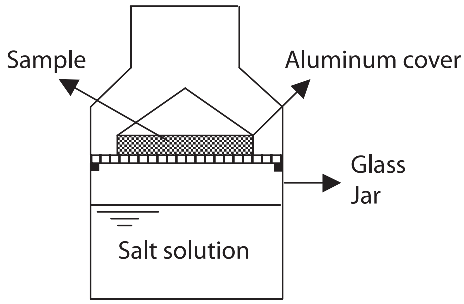

Fig. 2. The unit used to determine the sorption isotherm.

and the samples are placed as seen in Fig. 2. The glass jars which are tightly closed are then kept in an oven having a nearly isothermal condition at 25, 30, 40, 50 and 60 °C. The ten samples were weighed every two days. The dried samples equilibrate with the environment inside the jar until no discernible weight change is observed, when it is assumed that the equilibrium moisture is reached. It is observed from measurements using the CHYO-MP300 digital balance (with a measurement range of 0–300 g and an accuracy of ±0.001 g) that the equilibrium condition is usually reached in 30 days. Finally, in the equilibrium condition, the equilibrium moisture content of each sample was determined by moisture analyzer.

3. Results and discussion

Drying process started when outside air is brought to set conditions. The initial moisture content of cornelian cherry fruits was measured and found to be around 68.8% wb (2.21 dm). Experiments were conducted for the following ranges of the drying conditions: temperatures at 25, 30, 40, 50 and 60 °C; velocities at 0.3, 0.6 and 0.9 m/s; relative humidity values at 25%, 40%, 55% and 70%. Drying was continued until the equilibrium moisture content is reached. Experiments were repeated at least three times for any studying range in order to validate the results obtained.

3.1. Sorption isotherms

Initially, the sorption isotherm representing the variation of the moisture content with the water activity, a_w, is plotted in Fig. 3. It is seen that equilibrium moisture contents increases with decreasing temperature. Similar characteristics were reported by McLaughlin and Magee [8], Palipane and Driscoll [22], Litchfield and Okos [23] and Timoumi and Zagrouba [24]. This trend may be explained by considering excitation states of molecules. At increased temperatures molecules are in an increased

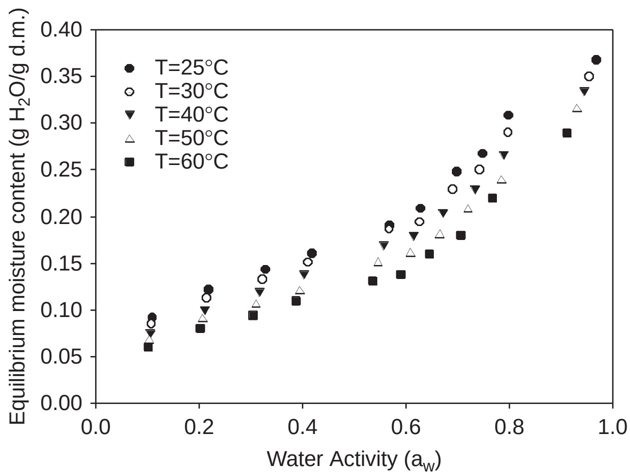

Fig. 3. Sorption isotherms of cornelian cherry fruits at 25, 30, 40, 50 and 60 °C.

state of excitation, thus increasing their distance apart and decreasing the attractive forces between them. This leads to a decrease in the degree of water sorption at a given relative humidity with increasing temperature. It is also shown that equilibrium moisture content increases with increasing water activity at constant temperature. These changes in equilibrium moisture content are due to an inability of the foodstuff to maintain vapor pressure at unity with decreasing moisture content. As moisture content decreases, moisture in the food tends to show a lower vapor pressure, acting as if in solution, changing with atmospheric humidity [8,25].

For this work, we used three two-parameter and one three parameter models for fitting the experimental data to moisture sorption isotherms for cornelian cherry fruits. These equations are shown in Table 2. The model parameters were determined by applying the nonlinear regression method to obtain data as detailed in Table 3. The mean standard error of estimation SEE and regression coefficient R^2 are also given in Table 3. As shown, for all the cases studied, the GAB model has shown a better fit to the experimental data as compared to the other models considered as shown Fig. 4. It should be noted from the Table 3 that monolayer moisture content values (X_m), which were the measure of sorption possibility of the material obtained by the GAB model, approximately decreased with increasing temperature. Similar results were reported by Akanbi et al. [7] and Quirijns et al. [26].

3.2. Drying kinetics

The variations of the moisture content with drying time for varying values of the drying conditions in terms of temperature, velocity and relative humidity of the drying air were determined. Fig. 5a shows

Table 2
Different models for determination sorption isotherms

Reference	Model
Oswin [28]	$M_e = c_1\left(\dfrac{a_w}{1-a_w}\right)^{c_2}$
Smith [29]	$M_e = c_1 - c_2\ln(1-a_w)$
Halsey [30]	$M_e = \left(-\dfrac{c_1}{\ln(a_w)}\right)^{1/c_2}$
GAB [31]	$\dfrac{M_e}{M_m} = \dfrac{c_1 c_2 a_w}{(1-c_2 a_w)(1-c_2 a_w + c_1 c_2 a_w)}$

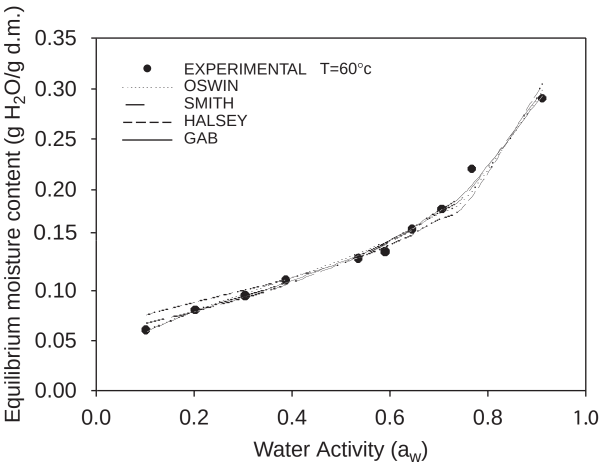

Fig. 4. Experimental and predicted sorption isotherms of cornelian cherry at 60 °C.

effect of air velocity on the time-dependent moisture content variation at ϕ = 25% and T = 25 °C. An increase in the velocity of the drying air results in decreasing drying times as a result of increasing convective heat and mass transfer coefficients between the drying air and the fruit. As seen from the figure, increasing the value for U from 0.3 m/s to 0.9 m/s decreased the total drying time from about 110 h to about 98 h (a decrease of 10.9%).

As well documented in the existing literature, drying air temperature has a profound effect on drying. At higher temperature, due to the quick removal of moisture, the drying time was found to decrease. For U = 0.3 m/s and the ϕ = 25%, increasing the temperature T from 25 °C to 60 °C decreased the total drying time about 50.9% (Fig. 5b).

Despite its considerable effect on the drying process, the effect of the relative humidity ϕ has been disregarded in many studies in the existing literature. In this study, a special attention was paid on this effect by designing an experimental set-up conditioning the air as explained above. At T = 25 °C and U = 0.3 m/s, decreasing the relative humidity ϕ from 70% to 25% decreased the total drying time about 40.2% (Fig. 5c). Due to the increasing mass transfer, decreas-

Table 3
Estimated parameters of different models for the sorption isotherms of cherry fruits at different temperature

Model	Constants	25 °C	30 °C	40 °C	50 °C	60 °C
Oswin	c_1	0.1869	0.1751	0.1613	0.1438	0.1298
	c_2	0.2183	0.2503	0.2776	0.3164	0.3546
	SEE	0.0061	0.0058	0.0055	0.0050	0.0042
	R^2	0.9457	0.9668	0.9789	0.9903	0.9923
Smith	c_1	0.1204	0.1035	0.0881	0.0701	0.0566
	c_2	0.0829	0.0911	0.0948	0.0979	0.0997
	SEE	0.0059	0.0057	0.0054	0.0050	0.0043
	R^2	0.9339	0.9597	0.9748	0.9903	0.9938
Halsey	c_1	0.0008	0.0017	0.0025	0.0040	0.0060
	c_2	4.0111	3.4150	3.0405	2.6263	2.3009
	SEE	0.0057	0.0055	0.0052	0.0048	0.0042
	R^2	0.9128	0.9398	0.9563	0.9754	0.9834
GAB	Mm	0.1397	0.1271	0.1144	0.0951	0.0819
	c_1	16.1196	17.1479	16.6801	19.8730	22.2704
	c_2	0.6620	0.6864	0.7127	0.7603	0.7958
	SEE	0.0067	0.0061	0.0056	0.0050	0.0043
	R^2	0.9903	0.9935	0.9960	0.9977	0.9959

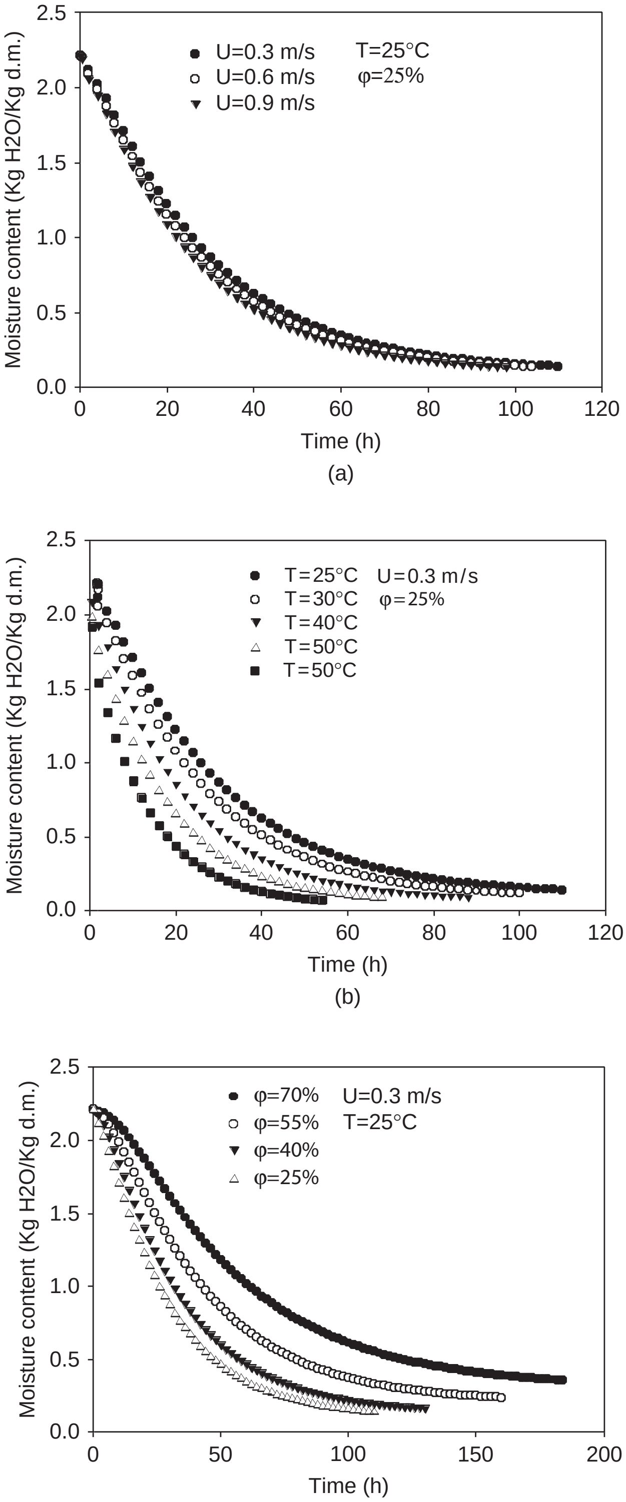

Fig. 5. (a) The variation of the moisture content with t for various U values at T = 25 °C and ϕ = 25% (a), the variation of the moisture content with t for various T values at U = 0.3 m/s and ϕ = 25% (c), the variation of the moisture content with t for various ϕ values at U = 0.3 m/s and T = 25 °C.

ing the value for ϕ decreased the total drying time. In fact, decreasing the value for ϕ increased the difference between the concentrations of water in the drying air and the product [13,14,17].

The time-dependent drying rate, DR, of the cornelian cherry fruit during drying process can be determined using the following equation:

$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t} \tag{1}$$

which is graphically shown in Fig. 6 with varying velocity, temperature and relative humidity of the drying air, respectively. Due to the moisture diffusion process, the drying rate decreases with time and becomes time-dependent. The cornelian cherry fruit tested did not exhibit a constant rate period of drying (Fig. 6). This clearly shows that the resistance to the moisture diffusion within the material was negligible small. If there was a considerable resistance, one would end up with reasonably long constant-rate period. Apparently, here in this case, the entire drying process occurred in the falling rate period, during which internal molecular diffusion is the predominant mechanism of mass transfer. From Fig. 6a, it can be seen that for higher air velocity drying rate is also higher. For the effect of the temperature of the drying fluid, similar behaviors were obtained (Fig. 6b). For higher values of the moisture content, increase in drying temperature resulted in higher drying rate. This can be explained by an increasing temperature difference between the drying air and the product and in follows water migration. Fig. 6c shows the influence of relative humidity on the drying rate. As expected decreasing the relative humidity intensifies drying rate. As seen from Fig. 6, temperature and relative humidity of the drying air have higher influence on the drying rate of cornelian cherry fruit than the velocity of the drying air [13,14,17].

Thin-layer drying models presented in Table 4 were used to describe the drying behavior of the cornelian cherry fruit. The results of the statistical computations carried out to evaluate three drying models when applied to the experiment are presented in Table 5. The values of R^2, is also included in Table 5. In all cases, the values of R^2 for the models were greater than an acceptable threshold of 0.90, giving a credit to the validity of the models used. As shown, for all the cases studied, the two-term exponential and the Henderson and Pabis models have shown a better fit to the experimental drying data as compared to the other models considered as shown Fig. 7.

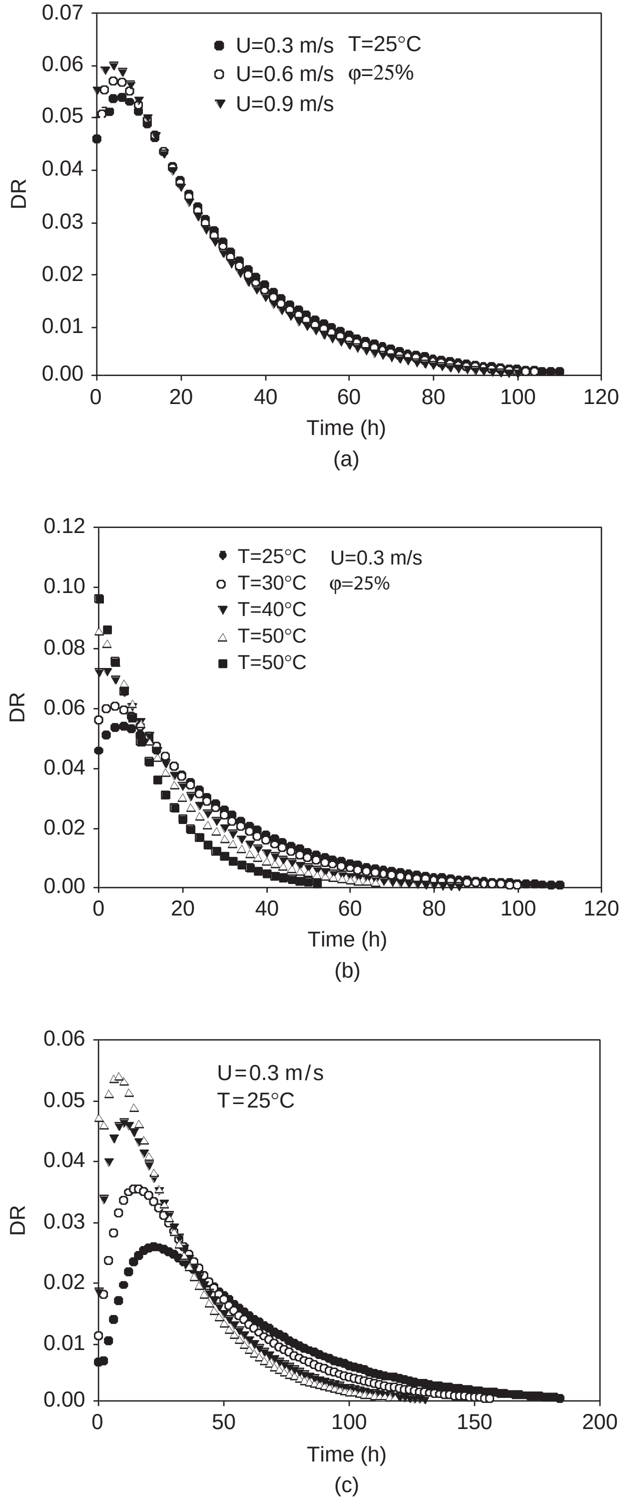

Fig. 6. The influence of U on the variation of the drying rate with t at T = 25 °C and ϕ = 25% (b), the influence of T on the variation of the drying rate with t at U=0.3 m/s and ϕ = 25% (c), the influence of ϕ on the variation of the drying rate with t at U = 0.3 m/s and T = 25 °C.

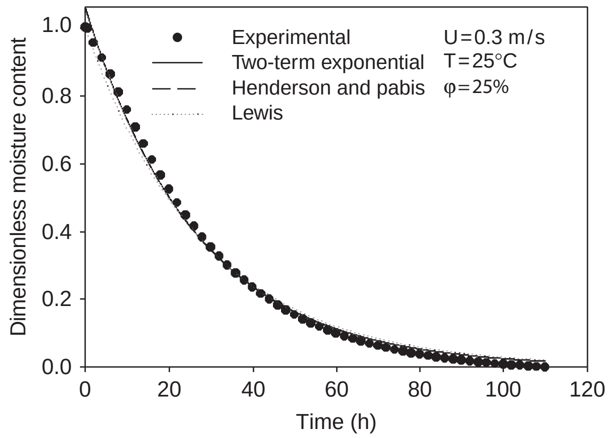

Fig. 7. Experimental and predicted moisture ratios.

Table 4
Thin-layer drying models

Model name	Equation	Reference
Lewis	MR = exp(−kt)	Mujumdar [32]
Henderson and Pabis	MR = a exp(−kt)	Henderson and Pabis [33]
Two term exponential	MR = a exp(−$k_0 t$) +b exp(−$k_1 t$)	Henderson [34]

MR, moisture ratio; a, b drying coefficient specific to each model; k, k_0 and k_1, drying constants; t, drying time.

4. Conclusions

The following conclusions can be summarized from the study:

1. The sorption isotherm of cornelian cherry fruit was determined for five various temperatures. It is concluded that the equilibrium moisture content decreases with increasing temperature while it increases with increasing water activity.
2. The experimental data were fitted to four sorption isotherm models. GAB model describe the desorption isotherms of the cherry fruit better than other models.
3. The effects of the drying conditions on the total drying time were studied. Increasing the temperature or the air velocity decreases the total drying time, while decreasing the relative humidity decreases it. Increasing U from 0.3 m/s to 0.9 m/s has lead to a decrease of 10.9% in the total drying time. An increase in T from 25 °C to 60 °C decreased the total drying time 50.9%. A decrease in ϕ from 70% to 25% decreased the total drying time 40.2%.

Table 5
Prediction of the model coefficients

Drying air parameter	Two-term exponential U, m/s				R^2	Henderson and Pabis U, m/s				R^2	Lewis U, m/s				R^2
	Parameter	0.3	0.6	0.9		Parameter	0.3	0.6	0.9		Parameter	0.3	0.6	0.9	
T = 25°C	a	0.5479	0.5391	0.5305	0.9975	a	1.0572	1.0465	1.0362	0.9975	k	0.0354	0.0381	0.0410	0.9961
φ = 25%	k_0	0.0373	0.0398	0.0424		k	0.0373	0.0398	0.0424						
	b	0.5093	0.5074	0.5056											
	k_1	0.0373	0.0398	0.0424											
T = 30°C	a	0.5281	0.5202	0.5138	0.9980	a	1.0330	1.0233	1.0155	0.9980	k	0.0409	0.0432	0.0450	0.9977
φ = 25%	k_0	0.0422	0.0442	0.0457		k	0.0422	0.0442	0.0457						
	b	0.5049	0.5030	0.5017											
	k_1	0.0422	0.0442	0.0457											
T = 40°C	a	0.4911	0.4799	0.4701	0.9987	a	0.9886	0.9756	0.9644	0.9987	k	0.0521	0.0562	0.0597	0.9973
φ = 25%	k_0	0.0515	0.0548	0.0576		k	0.0515	0.0548	0.0576						
	b	0.4975	0.4957	0.4943											
	k_1	0.0515	0.0548	0.0576											
T = 50°C	a	0.4493	0.4348	0.4253	0.9992	a	0.9424	0.9302	0.9257	0.9951	k	0.0689	0.0747	0.0799	0.9868
φ = 25%	k_0	0.0649	0.0693	0.0732		k	0.0649	0.0693	0.0732						
	b	0.4930	0.4954	0.5004											
	k_1	0.0649	0.0693	0.0732											
T = 60°C	a	0.4173	0.4056	0.3930	0.9992	a	0.9060	0.8963	0.8861	0.9863	k	0.0975	0.1040	0.1131	0.9693
φ = 25%	k_0	0.0876	0.0921	0.0987		k	0.0876	0.0921	0.0987						
	b	0.4887	0.4907	0.4931											
	k_1	0.0876	0.0921	0.0987											
T = 25°C	a	0.5803	0.5720	0.5636	0.9959	a	1.0947	1.0844	1.0742	0.9959	k	0.0296	0.0316	0.0336	0.9912
φ = 40%	k_0	0.0322	0.0341	0.0360		k	0.0322	0.0341	0.0360						
	b	0.5143	0.5125	0.5106											
	k_1	0.0322	0.0341	0.0360											
T = 25°C	a	0.5967	0.5871	0.5792	0.9944	a	1.1145	1.1026	1.0927	0.9944	k	0.0230	0.0254	0.0273	0.9873
φ = 55%	k_0	0.0255	0.0278	0.0297		k	0.0255	0.0278	0.0297						
	b	0.5178	0.5155	0.5136											
	k_1	0.0255	0.0278	0.0297											
T = 25°C	a	0.6175	0.6124	0.6069	0.9895	a	1.1417	1.1350	1.1281	0.9895	k	0.0175	0.0188	0.0201	0.9755
φ = 70%	k_0	0.0198	0.0211	0.0225		k	0.0198	0.0211	0.0225						
	b	0.5242	0.5227	0.5212											
	k_1	0.0198	0.0211	0.0225											

4. The two-term exponential and Henderson and Pabis models provided the best simulation of the drying curves of cornelian cherry fruits.

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Symbols

a_w	—	water activity
a	—	drying coefficient
b	—	drying coefficient
c_1	—	constant
c_2	—	constant
DR	—	drying rate, (kg H_2O)/ (kg d.m. h)
e.r.h	—	equilibrium relative humidity (%)
k	—	drying constants, 1/s
k_0	—	drying constants, 1/s
k_1	—	drying constants, 1/s
M	—	moisture content at t, (kg H_2O/ kg d.m.)
M_e	—	equilibrium moisture content, (kg H_2O/ kg d.m.)
M_m	—	monomolecular moisture content
M_n	—	initial moisture content, (kg H_2O/kg d.m.)
MR	—	moisture ratio, $\left(\mathrm{MR}=\dfrac{M_t-M_e}{M_0-M_e}\right)$
R^2	—	coefficient of determination
SEE	—	standard error of estimation
T	—	temperature, °C
t	—	time, h
U	—	velocity, m/s
ϕ	—	relative humidity

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