Hindawi Publishing Corporation
Mathematical Problems in Engineering
Volume 2012, Article ID 386214, 18 pages
doi:10.1155/2012/386214

Research Article

Thin-Layer Drying Characteristics and Modeling of Chinese Jujubes

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Received 8 December 2011; Accepted 31 January 2012

Academic Editor: Zhijun Zhang

A mathematical modeling of thin-layer drying of jujubes in a convective dryer was established under controlled conditions of temperature and velocity. The drying process took place both in the accelerating rate and falling rate period. We observed that higher temperature reduced the drying time, indicating higher drying rates of jujubes. The experimental drying data of jujubes were used to fit ten different thin-layer models, then drying rate constants and coefficients of models tested were determined by nonlinear regression analysis using the Statistical Computer Program. As for all the drying models, the Weibull distribution model was superior and best predicted the experimental values. Therefore, this model can be used to facilitate dryer design and promote efficient dryer operation by simulation and optimization of the drying processes. The volumetric shrinkable coefficient of jujubes decreased as the drying air temperature increased.

1. Introduction

Jujube (*Zizyphus jujuba* Mill.) is a characterized Chinese fruit, whose cultivation area has reached more than 1.5 million hectares in China. Moreover, a lot of products are processed from jujubes, such as candied and drunk jujubes, and jujube tea, juice, and sugar. The vast majority of jujubes are dried and sold at home and abroad, except that a small proportion are reserved for fresh eating [1]. Jujubes play an important role in human nutrition as sources of sugar, vitamins, protein, and minerals [2]. For thousands of years, besides been used as food, jujube has been commonly used in traditional Chinese medicine. Jujubes tend to spoil because of their high moisture contents, which result in the production losses of 25–30% after harvest

[3]. Drying is one of the widely used methods for postharvest preservation of agricultural products. It is used to decrease considerable moisture content, reduce microbiological activity, and enable storability of the product under ambient temperatures [4, 5]. Dried food has longer shelf life in packages and lower transportation, handling, and storage costs [6].

Drying is a complicated process relating to simultaneous heat and mass transfer where water is transferred by diffusion from inside the food material to the air-food interface and from the interface to the air stream by convection [7, 8]. The amount of energy required to dry a product depends on many factors, such as initial moisture, desired final moisture, and drying air temperature and velocity [9]. Thin layer drying means to dry as one layer of sample particles or slices. Thin layer drying equations have been used for drying time prediction for generalization of drying curves [10]. Various mathematical models describing the drying characteristics of different fruits and vegetables have been proposed to optimize the drying process and design efficient dryers [11, 12]. There are many studies on the drying of fruits and vegetables, such as apricot [13], banana [14], carrot [15], fig [16], golden apples, grape [17], green pepper, stuffed pepper, green bean [18], litchi [19], mushroom, pistachio [20], onion [21], and pumpkin [22]. Several researchers have investigated the drying kinetics of various agricultural products in order to evaluate the Weibull distribution model for describing the thin-layer drying characteristics [23, 24]. In addition, some researchers proposed the drying properties and processing technologies of jujubes [25–28]. The Henderson and Pabis model (see Table 2) has been applied in the drying of jujubes [29]; however, although this model may describe the drying curve for the specific experiments conditions, it cannot give a clear and accurate view of the important processes during drying.

The objectives of this study are (1) to determine the effect of air temperature and air velocity on the drying of jujube and to obtain drying curves; (2) to establish a mathematical model for predicting the thin layer drying characteristics of convection drying of jujubes at different drying air temperature and velocity conditions.

2. Materials and Methods

2.1. Materials

Bioer jujube is one of the main Chinese jujubes varieties, which mainly grow in Shanxi and Xinjiang Province. Bioer jujubes used in the experiments were produced in Alar city, Xinjiang province and were chosen as drying materials in September, 2010. The appearances of jujubes were presented in Figure 1. The samples in the same species with full maturity and uniform size were stored in a refrigerator at 4°C before starting the experiments. The initial moisture content was about 70.12% wet basis (w.b.).

2.2. The Laboratory Dryer

The drying experiments were carried out by a laboratory dryer (BG-II) manufactured at College of Biological and Agricultural Engineering, Jilin University, Changchun city, Jilin province. A schematic view of the experimental arrangement was shown in Figure 2.

The overall dimensions of the dryer are $2.2 \times 0.6 \times 1.8\,\mathrm{m}$ and it mainly consisted of a fan, electrical heater, drying chamber, and temperature and humidity control unit. The favourable drying air velocity provided by the fan could be changed by the electrical motor without level. A 0–15 m/s range anemometer (LUTRON, AM-4201, Taiwan) measured the


(a) (b)

Figure 1: The appearances of jujubes: (a) fresh jujubes; (b) dry jujubes.

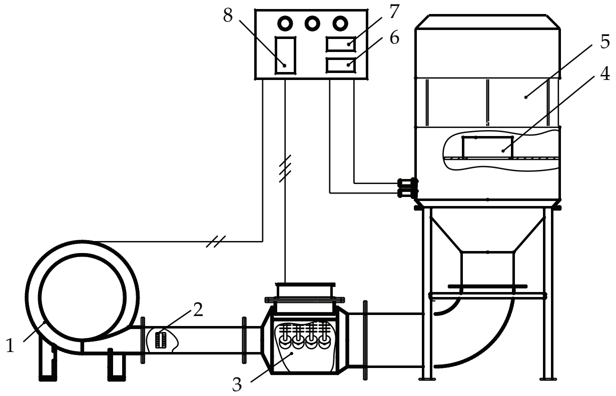


Figure 2: Schematic view of the experimental arrangements. 1: Fan; 2: Diffuser; 3: Heater; 4: Bucket; 5: Drying chamber; 6: Humidity control unit; 7: Temperature control unit; 8: Variator.

velocity of air passing through the system. The drying air temperature was automatically controlled by regulating the required voltage to the heaters inside the air channel. The heater consisted of four groups of resistance wires of 1,000 W, and each group could be used independently to control the temperature (30–110°C, dry bulb temperature) of air and in drying chamber. The dry bulb temperature inside the drying chamber was measured and controlled with an accuracy of ±0.1°C using a Pt 100, 1/10 DIN, thermometer inserted in the middle position of the inlet cross-section. Temperature-humidity sensor (GALLTEC, TFK80J, Germany) was used to measure the relative humidity with an accuracy of ±3%Rh. Resistance wires were on and off by the control unit based on temperature change to maintain adjusted temperature at the same level during the experiments. A digital electronic balance (OHAUS, CP3102, USA) in the measurement range of 0–3100 g and an accuracy of 0.01 g was used for the moisture loss of samples.

2.3. Drying Procedures

Drying experiments were carried out at different drying temperatures of 45, 55, and 65°C and different velocities of 0.5, 1.0, and 2.0 m/s. The drying air temperature was automatically controlled at ±1°C by regulating an electrical heating device and the air velocity was measured by an anemometer at precision of 0.1%.

Table 1: Uncertainties of the parameters during drying of jujubes.

Parameter	Unit	Comment
Fan inlet temperature	°C	±0.5
Heater outlet temperature	°C	±0.5
Drying chamber inlet temperature	°C	±0.3
Drying chamber outlet temperature	°C	±0.3
Ambient air temperature	°C	±0.3
Inlet of fan with dry and wet thermometers	°C	±0.5
Mass loss values	min	±0.1
Temperature values	min	±0.1
Uncertainty in the mass loss measurement	g	±0.5
Uncertainty in the air velocity measurement	m/s	±0.14
Uncertainty of the measurement of relative humidity of air	RH	±0.1
Uncertainty in the measurement of moisture quantity	g	±0.001
Uncertainty in reading values of table (ρ, cp.)	%	±0.1-0.2

The dryer took some time to reach the desired value after starting up. Approximately 200 g of samples were put into a stainless-steel mesh bucket of 200 mm diameter, and then they were put into the dryer after weighting. In all the experiments, samples were kept the same thickness and tiled into the layers. The weighing interval of the drying samples was 1 h during the drying process. Since the weighing process only took a few seconds, no considerable disturbances were imposed. According to the standards set by General Administration of Quality Supervision, Inspection and Quarantine (AQSIQ) [30], the drying process was continued until the moisture content of the samples reached below 25% (w.b.). After the drying experiments, the samples were put into an electric constant temperature blower oven, maintaining at 105 ± 2°C until their weight remained unchanged. This weight was used to calculate the moisture content of the samples.

2.4. Experimental Uncertainly

Errors and uncertainties in experiments can arise from instrument selection, condition, calibration, environment, observation, reading, and test planning [31]. In the drying experiments of jujubes, the temperatures, velocity of drying air, and weight losses were measured with appropriate instruments. During the measurements of the parameters, the uncertainties occurred were presented in Table 1.

2.5. Theoretical Considerations and Mathematical Formulation

Moisture contents of jujubes during thin layer drying experiments were expressed in dimensionless form as moisture ratios MR with the following equation [32, 33]:

$$\mathrm{MR} = \frac{(M - M_e)}{(M_0 - M_e)}, \tag{2.1}$$

Table 2: Mathematical models applied to the moisture ratio values.

Eq. no.	Model name	Model equation	References
(2.1)	Lewis	$\mathrm{MR} = \exp(-kt)$	[47]
(2.2)	Page	$\mathrm{MR} = \exp(-kt^n)$	[48]
(2.3)	Modified Page	$\mathrm{MR} = \alpha \exp[-(kt^n)]$	[49]
(2.4)	Overhults	$\mathrm{MR} = \exp[-(kt)^n]$	[50]
(2.5)	Henderson and Pabis	$\mathrm{MR} = \alpha \exp(-kt)$	[51]
(3.1)	Logarithmic	$\mathrm{MR} = \alpha \exp(-kt) + c$	[39]
(3.2)	Two term exponential	$\mathrm{MR} = \alpha \exp(-kt) + b \exp(-k_1 t)$	[52]
(3.3)	Wang and Singh	$\mathrm{MR} = 1 + \alpha t + bt^2$	[49]
(3.4)	Thompson	$t = \alpha \ln(\mathrm{MR}) + b \ln(\mathrm{MR})^2$	[53]
(3.5)	Weibull distribution	$\mathrm{MR} = \alpha - b \exp[-(kt^n)]$	[54]

M is the mean jujubes moisture content, M_0 is the initial value, and M_e is the equilibrium moisture content. The drying rates of jujubes were calculated by using (2.2) [34, 35]

$$\text{Drying rate} = \frac{M_{t+\Delta t} - M_t}{\Delta t}. \tag{2.2}$$

M_t and $M_{t+\Delta t}$ are the moisture content at t and moisture content at $t + \Delta t$ (kg water/kg dry matter), respectively, t is the drying time (h).

Convection drying of fruits occurs in the falling rate drying period, thus the well-known semiempirical and empirical models could be applied to the drying data. To select a suitable model for describing the drying process of jujubes, drying curves were fitted with 10 thin-layer drying moisture ratio models (Table 2). During the analysis of mathematical drying models, it was assumed that materials contained the same initial moisture content; there was no heat loss with insulation of dryer walls; material internal temperature gradient, drying air humidity, and heat transfer between materials and volume contraction rate during drying were negligible.

The regression analysis was performed with the STATISTICA computer program developed by Statistical Package for Social Science (SPSS) 18. The coefficient of determination R^2 was one of the primary criteria when selecting the best equation to account for variation in the drying curves of dried samples [36–38]. In addition, the goodness of fit was determined by various statistical parameters such as reduced chi-square, χ^2 mean bias error and root mean square error (RMSE). For a qualified fit, R^2 should be high while χ^2 and RMSE are low [39, 40]. These statistical values are calculated as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} \left(\mathrm{MR}_{i,\mathrm{pre}} - \mathrm{MR}_{i,\mathrm{exp}}\right)^2}{\sum_{i=1}^{n} \left(\mathrm{MR}_{i,\mathrm{exp}} - \mathrm{MR}_{i,\mathrm{pre}_{\mathrm{mean}}}\right)^2}, \tag{2.3}$$

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(\mathrm{MR}_{\mathrm{exp},i} - \mathrm{MR}_{\mathrm{pre},i}\right)^2}{N - z}, \tag{2.4}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} \left(\mathrm{MR}_{i,\mathrm{pre}} - \mathrm{MR}_{i,\mathrm{exp}}\right)^2}{N}}. \tag{2.5}$$

$\mathrm{MR}_{\mathrm{exp},t}$ is the ith experimental moisture ratio, $\mathrm{MR}_{\mathrm{pre},i}$ is the ith predicted moisture ratio, N is the number of observations, and z is the number of constants in the drying model.

3. Results and Discussion

3.1. Drying Characteristics of Jujubes

The changes in moisture ratios with time for different drying air temperatures are shown in Figure 3. The final moisture content of samples dried under different conditions ranged from 28% to 25% (w.b.). The drying rate is higher for higher air temperature. As a result, the time taken to reach the final moisture content is less, as shown in Figure 3. Therefore, the drying air temperature has an important effect on the drying of jujubes. The changes of the moisture ratios at different air velocities (0.5, 1.0 and 2.0 m/s) under each air temperature (45, 55, and 65°C) were shown in Figure 4. The data revealed that the drying air velocities had little effect on the drying process. Similar results have been reported for plum [41], rosehip [42].

3.2. Drying Rate of Jujubes

The changes in the drying rates with moisture content for different drying air temperatures and velocities are shown in Figures 5 and 6. It is apparent that the drying process involved two periods, accelerating period and falling period, without a constant-rate drying period. At the beginning of the drying process, the drying rate increases rapidly with decreasing moisture content and reaches the maximum. Then drying rate decreases continuously with decreasing moisture content, and the drying operations are seen to occur in the falling rate period. It was also noted the predominant direct effect of air temperature on the drying rate, as clearly shown in the figures for all temperatures. Due to the fact that the relative humidity of the drying air at a higher temperature was less compared to that at a lower temperature, the difference in the partial vapor pressure between the radishes and their surroundings was greater for the higher temperature drying environment [43]. The data revealed that the drying air velocities had little effect on the drying rate. These results are in agreement with the previous works [31, 44].

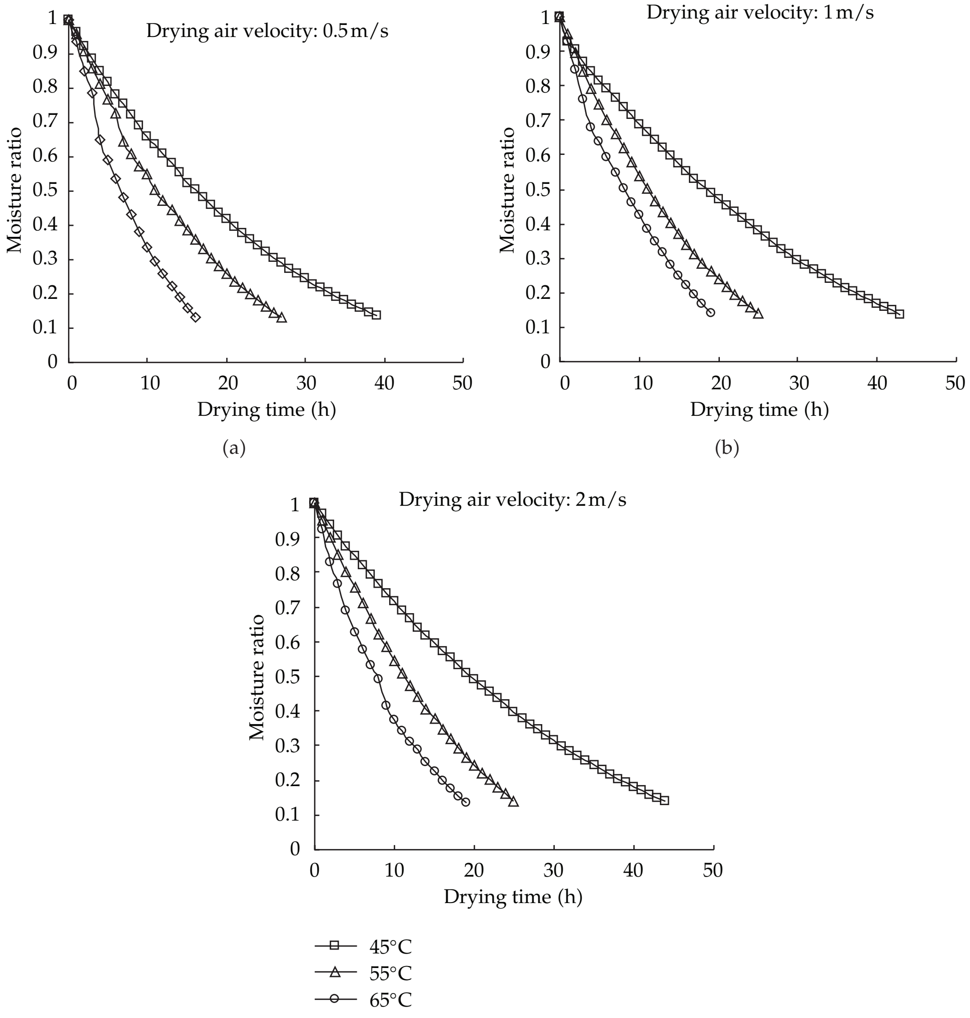
3.3. Mathematical Modelling of Thin-Layer Drying

The mathematical drying models were based on the experimental moisture contents and dry weights. Then continuous data were obtained at different drying air temperatures and velocities and they were converted into moisture ratios and fitted over drying time. According to the statistical results of the determination coefficient R^2, chi-square (χ^2), and RMSE, ten thin-layer drying models were compared and shown in Table 3. The data showed that the highest coefficient (R^2), and the lowest chi-square (χ^2) and RMSE were obtained with the Weibull distribution model. Consequently, it could be concluded that the Weibull distribution model could sufficiently define the thin layer drying of jujubes. The model could be expressed in the following equation:

$$\mathrm{MR} = a - b\exp[-(kt^{n})]. \tag{3.1}$$

Table 3: Statistical results of 10 models at different drying conditions.

Model	Drying air velocity (m/s)	Drying air temperature (°C) 45 R^2	45 χ^2	45 RMSE	55 R^2	55 χ^2	55 RMSE	65 R^2	65 χ^2	65 RMSE
Lewis	0.5	0.999383	0.000036	0.005982	0.996556	0.000207	0.014172	0.995002	0.000303	0.016965
	1.0	0.996838	0.000192	0.013757	0.995763	0.000253	0.015644	0.982534	0.000854	0.028524
	2.0	0.993384	0.000431	0.020594	0.995183	0.000294	0.016885	0.999249	0.000042	0.006356
Page	0.5	0.999835	0.000010	0.003099	0.999336	0.000041	0.006223	0.998104	0.000121	0.010450
	1.0	0.997864	0.000132	0.011306	0.999782	0.000013	0.003547	0.992789	0.000371	0.018327
	2.0	0.998801	0.000079	0.008765	0.999893	0.000007	0.002516	0.999265	0.000043	0.006291
Modified Page	0.5	0.999835	0.000010	0.003091	0.999433	0.000036	0.005751	0.998495	0.000102	0.009311
	1.0	0.999847	0.000010	0.003024	0.999929	0.000005	0.002025	0.996819	0.000173	0.012172
	2.0	0.999355	0.000044	0.006429	0.999934	0.000004	0.001983	0.999305	0.000043	0.006116
Overhults	0.5	0.999835	0.000010	0.003099	0.999336	0.000041	0.006223	0.998104	0.000121	0.010450
	1.0	0.997864	0.000132	0.011306	0.999782	0.000013	0.003547	0.992789	0.000371	0.018327
	2.0	0.998801	0.000079	0.008756	0.999893	0.000007	0.002516	0.999265	0.000043	0.006291
Henderson and Pabis	0.5	0.999689	0.000019	0.004249	0.999068	0.000058	0.007371	0.998404	0.000102	0.009588
	1.0	0.996848	0.000195	0.013735	0.998067	0.000119	0.010567	0.986812	0.000679	0.024785
	2.0	0.995737	0.000283	0.016531	0.998223	0.000112	0.010256	0.999250	0.000044	0.006355
Logarithmic	0.5	0.999739	0.000016	0.003892	0.999441	0.000036	0.005707	0.998589	0.000096	0.009015
	1.0	0.999721	0.000018	0.004083	0.999823	0.000011	0.003196	0.993283	0.000365	0.017688
	2.0	0.999929	0.000005	0.002137	0.999703	0.000019	0.004193	0.999301	0.000043	0.006134
Two-term exponential	0.5	0.999689	0.000020	0.004249	0.999068	0.000062	0.007371	0.998404	0.000115	0.009588
	1.0	0.996848	0.000202	0.013735	0.998067	0.000128	0.010567	0.997733	0.000130	0.010276
	2.0	0.995737	0.000293	0.016531	0.998223	0.000120	0.101256	0.999304	0.000045	0.006122
Wang and Singh	0.5	0.998691	0.000079	0.008711	0.998516	0.000092	0.009304	0.996917	0.000197	0.013324
	1.0	0.995748	0.000263	0.015952	0.999753	0.000263	0.003775	0.970316	0.001528	0.037185
	2.0	0.998902	0.000073	0.008388	0.999889	0.000007	0.002565	0.995006	0.000030	0.016395
Thompson	0.5	0.999326	0.157846	0.389583	0.999528	0.045533	0.026818	0.998947	0.038918	0.187152
	1.0	0.999568	0.138582	0.366112	0.999774	0.019316	0.134424	0.994631	0.217603	0.443711
	2.0	0.999771	0.071202	0.262351	0.999367	0.057569	0.232317	0.999557	0.025016	0.151707
Weibull distribution	0.5	0.999926	0.000005	0.002076	0.999454	0.000032	0.005643	0.998643	0.000098	0.008839
	1.0	0.999939	0.000004	0.001916	0.999960	0.000003	0.001523	0.997498	0.000144	0.010796
	2.0	0.999943	0.000004	0.001911	0.999935	0.000004	0.001962	0.999306	0.000044	0.006113



(a) (b)

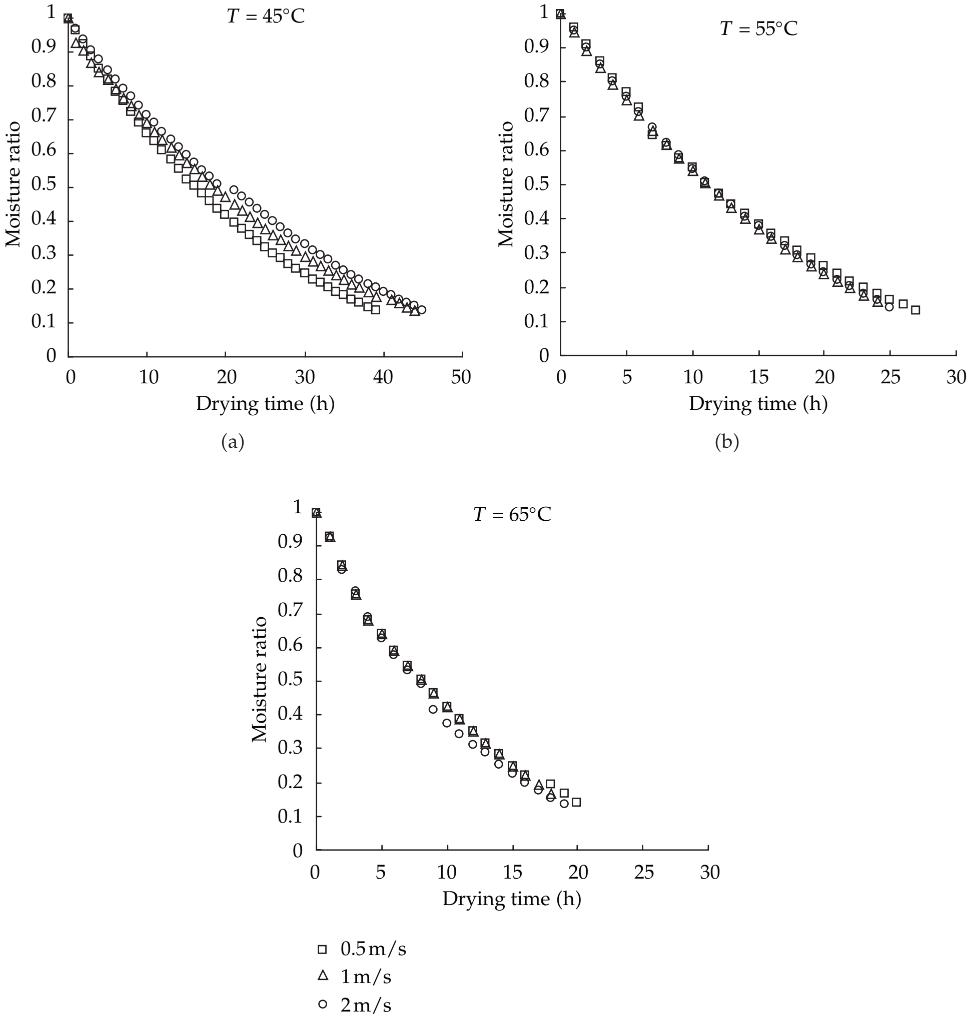
(c)

Figure 3: The experimental moisture ratios at different drying temperatures under each air velocity.

MR is the moisture ratio; k is drying rate constant (h^{-1}); t is time (h); a, n and b is experimental constants. R^2, changed between 0.997498 and 0.999960; χ^2, 0.000003–0.000144; RMSE, 0.001523–0.010796.

The Weibull distribution model was analyzed according to the different drying air temperatures and velocity conditions. The individual constants were obtained (Table 4). Furthermore, the multiple regression analysis was adopted to determine the relationship between drying air temperature, velocity, and the drying constants a, k, n, b based on the drying experiment data. All possible combinations of different drying variables were tested and included in the regression analysis [45]. The drying constants and coefficients of the model were as follows:

$$a = -0.408876 + 0.004101 \cdot T - 0.021508 \cdot v, \tag{3.2}$$



(a)

(b)

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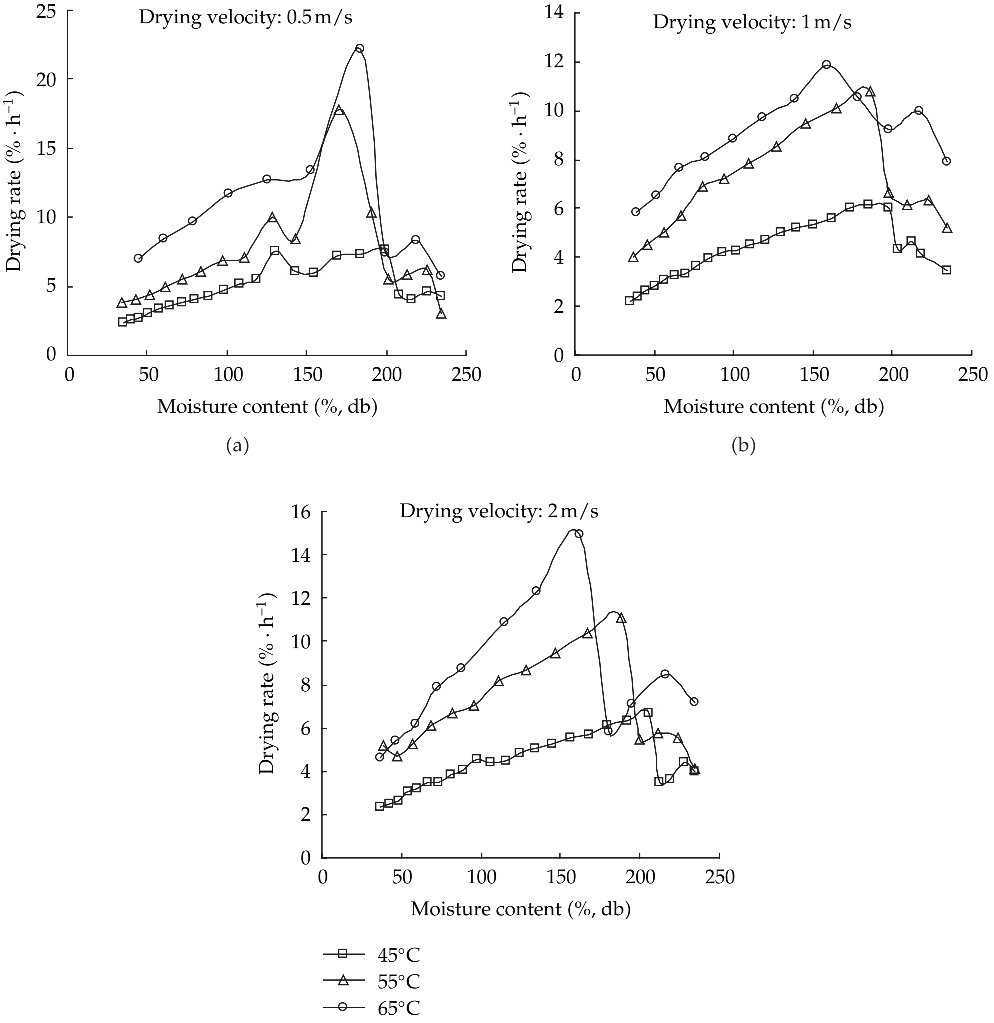
Figure 4: The experimental moisture ratios at different air velocities under each drying temperature.

$$b = -1.371752 + 0.003420 \cdot T - 0.021282 \cdot v, \tag{3.3}$$

$$k = -0.084196 + 0.002463 \cdot T - 0.001119 \cdot v, \tag{3.4}$$

$$n = 1.036553 + 0.000147 \cdot T - 0.008976 \cdot v. \tag{3.5}$$

These expressions could be used to accurately predict the moisture ratio at any time during a drying process. The consistency of the Weibull distribution model and relationships between the coefficients and drying variables were shown in Table 5. As shown, R^2 changed between



(a) (b)

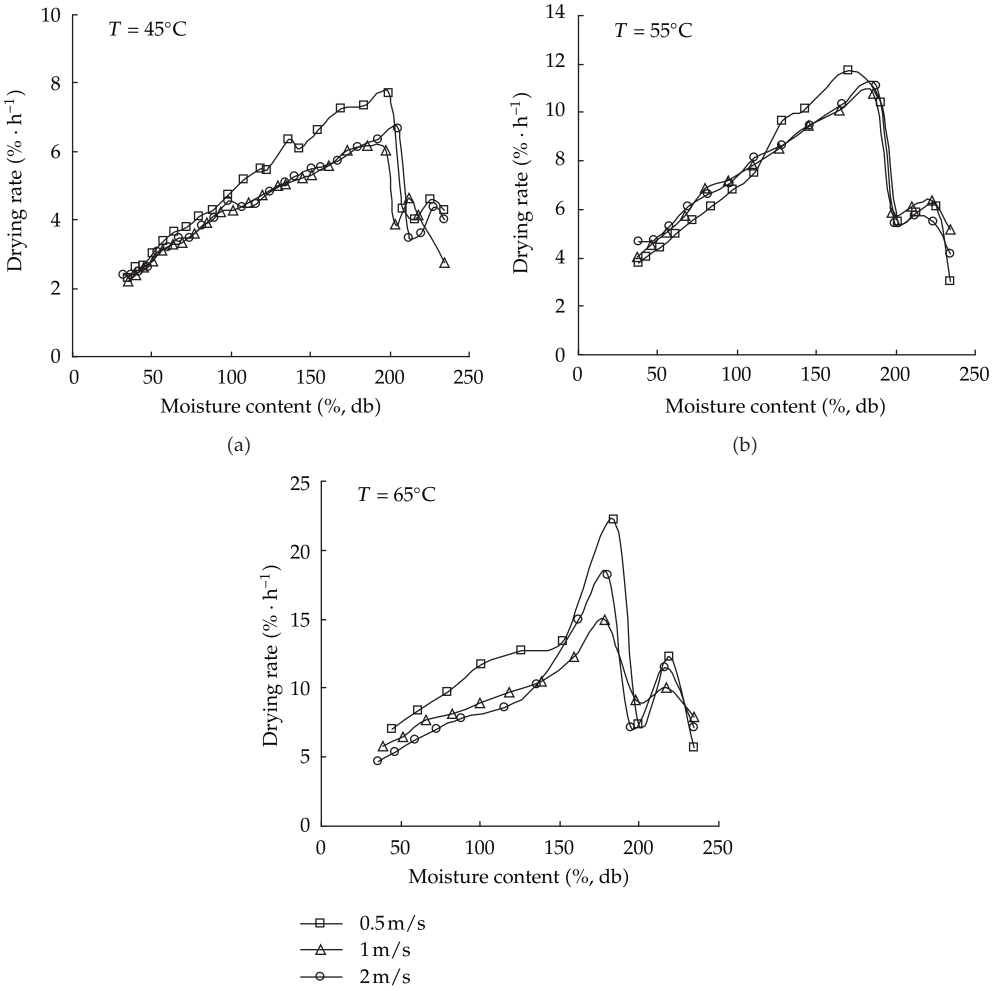
(c)

Figure 5: The experimental drying rate at different drying temperatures under each air velocity.

0.993345 and 0.999878, χ^2 was between 0.000008 and 0.000133, and RMSE was between 0.002704 and 0.018925.

In Figure 7, we compared the experimental and predicted moisture ratio at different air temperatures (45, 55 and 65°C) under each velocity (0.5, 1.0 and 2.0 m/s). It could be concluded that the established model was in good agreement with the experimental results at all drying conditions. In this picture figure, a higher drying air temperature produced a higher drying rate and the moisture ratio decreased faster.

To verify the established mathematical drying model, the experimental and predicted values of the moisture ratio at some particular drying conditions were compared. These values were located near a straight line of 45°, as shown in Figure 8, indicating that the drying data were well fitted with the model. Thus, the drying model could be used to well describe the thin-layer drying characteristics of jujubes.



(a)

(b)

(c)

Figure 6: The experimental drying rate at different air velocities under each drying temperature.

3.4. Volume Shrinkage

Jujubes have a porous structure. There are volume shrinkage and deformation during drying process. If ignoring the thermal expansion of materials, the volume shrinkage coefficient equation is expressed as [46]

$$\beta_V = \frac{dV/V}{dM}, \tag{3.6}$$

where V is the volume of jujubes and M is the wet-based average moisture content. Assuming that β_V is constant during the drying process, the above equation can be transformed as follow:

$$V = V_0 e^{-\beta_V (M_0 - M)}. \tag{3.7}$$

Table 4: Statistical results of Weibull distribution model and its constants and coefficients at different drying conditions.

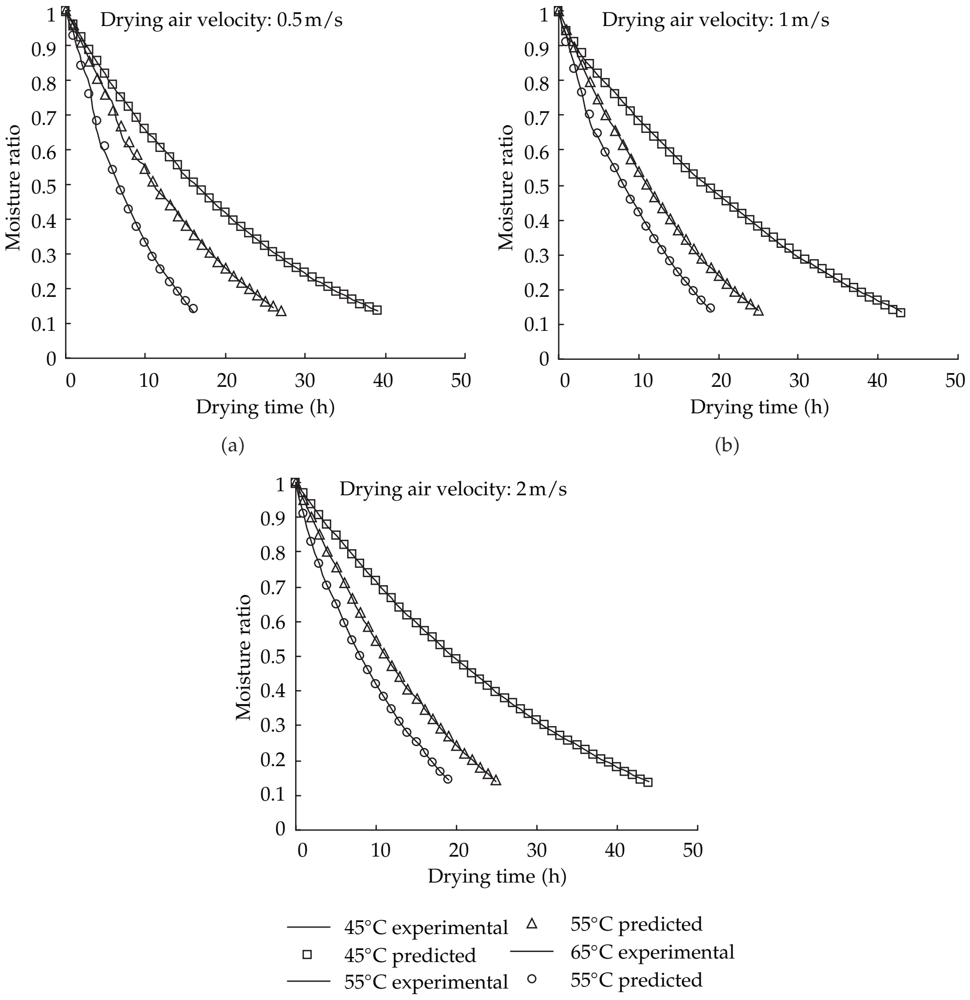
Drying air temperature (°C)	Drying air velocity (m/s)	A	k	n	b	R^2	χ^2	RMSE
$\mathrm{MR} = a - b \exp\left[-(kt^n)\right]$								
45	0.5	−0.134726	0.032960	1.029610	−1.132454	0.999926	0.000005	0.002076
	1.0	−0.434287	0.027195	0.935657	−1.415498	0.999939	0.000004	0.001916
	2.0	−0.281029	0.024410	1.011860	−1.279307	0.999943	0.000004	0.001911
55	0.5	−0.077911	0.045093	1.087933	−1.083897	0.999454	0.000032	0.005643
	1.0	−0.197083	0.043597	1.047830	−1.195635	0.999960	0.000003	0.001523
	2.0	−0.189766	0.041694	1.063013	−1.190183	0.999935	0.000004	0.001962
65	0.5	−0.051858	0.080259	1.103842	−1.060497	0.998643	0.000098	0.008839
	1.0	−0.451906	0.071394	0.859843	−1.460438	0.997498	0.000144	0.010796
	2.0	−0.078706	0.081792	1.013627	−1.079853	0.999306	0.000044	0.006113

Table 5: Influences of drying air temperatures and velocities on Weibull distribution model coefficients.

Drying air temperature (°C)	Drying air velocity (m/s)	R^2	χ^2	RMSE
$\mathrm{MR} = (-0.408876 + 0.004101 \cdot T - 0.021508 \cdot v) - (-1.371752 + 0.003420 \cdot T - 0.021282 \cdot v) \cdot \exp\{-[(-0.084196 + 0.002463 \cdot T - 0.001119 \cdot v) \cdot t^{(1.036553 + 0.000147 \cdot T - 0.008976 \cdot v)}]\}$				
45	0.5	0.998378	0.000098	0.009698
	1.0	0.999878	0.000008	0.002704
	2.0	0.999001	0.000066	0.007970
55	0.5	0.999369	0.000039	0.006064
	1.0	0.999855	0.000009	0.002891
	2.0	0.999737	0.000017	0.003949
65	0.5	0.998525	0.000094	0.009217
	1.0	0.997425	0.000133	0.010952
	2.0	0.993345	0.000389	0.018925

The coefficients of volume shrinkage at different drying air temperatures are shown in Figure 9. We can see from the figure that the coefficients, which rang from 0.011 to 0.020, decline with the increase of air temperature under same air velocity, due to the larger changes of moisture content at higher temperature. The coefficients, measured by least-square method, are shown in Table 6.

Figure 10 shows that the volume changes with time at different drying air temperatures. The figure shows that the changing trend is basically identical with the change of moisture content. It means that with the increase of air temperature, the material shrinkage becomes more and more obvious during the drying process. Thus, when we choose air temperature, not only the drying rate but also the morphology and quality of the products should be taken into consideration.



(a)

(b)

(c)

Figure 7: The experimental and predicted moisture ratios at different temperatures under each air velocity.

Table 6: Values of volumetric shrinkable coefficient obtained from different temperatures.

Drying air temperature (°C)	β_v	R^2
45	0.020	0.995
55	0.014	0.992
65	0.011	0.993

4. Conclusions

Thin-layer drying of jujubes were investigated in this study. Ten models selected from the literatures were referred to illustrate the characteristics of the drying process and establish mathematical drying models of jujubes. Drying process for jujubes involved two periods, accelerating rate and falling rate period, no constant-rate period of drying was observed.

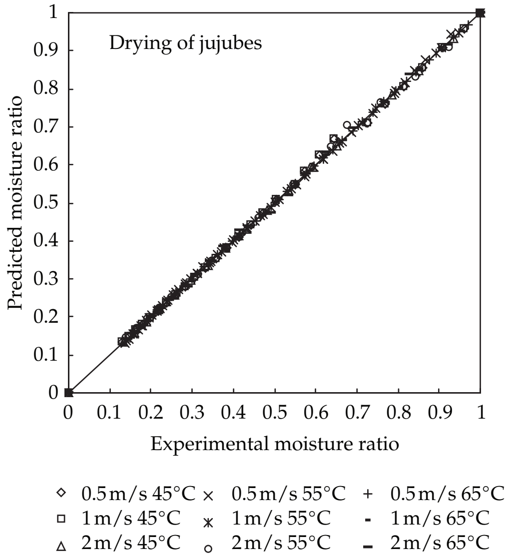


Figure 8: A comparison of experimental and predicted values by the Weibull distribution model at different drying conditions.

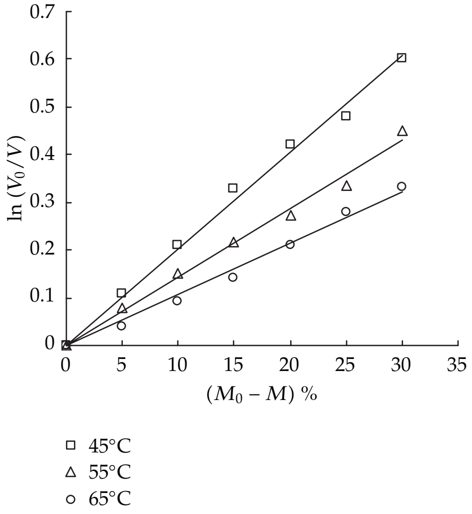


Figure 9: Coefficients of volume shrinkage at different temperature.

After comparing the calculated R^2, χ^2, and RMSE in each model, Weibull distribution model showed the best agreement with the experimental data. Furthermore, the effects of the drying air temperatures and velocities on the drying constants and coefficients of the Weibull distribution model were closely examined. We found that this model could be used to predict the moisture ratios of the jujubes during a drying process at any time, particularly at drying temperatures of 45–65°C and velocities of 0.5–2.0 m/s. Moreover, our results showed that the drying air temperature had a bigger effect on drying rate than the velocity. The

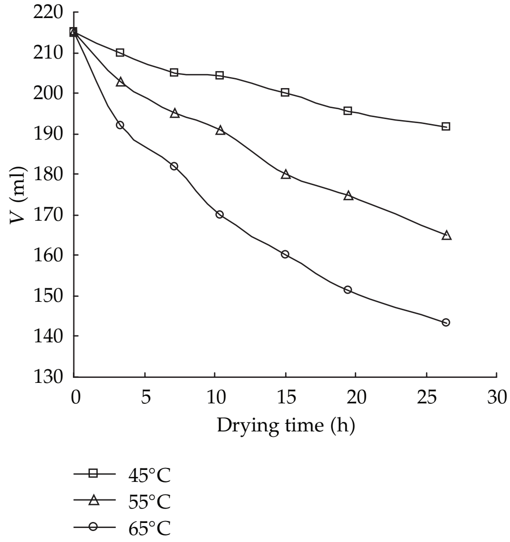


Figure 10: Volume changes with time at different temperatures.

volumetric shrinkable coefficient of jujubes was found to be in the range of 0.011–0.020 at drying temperatures of 45–65°C.

Nomenclature

α, b, c, g, p, n: Drying coefficients
k, k_1: Drying constants
M: Moisture content at any time, kg water/kg dry matter
M_e: Equilibrium moisture content, kg water/kg dry matter
M_0: Initial moisture content, kg water/kg dry matter
M_t: Moisture content at t, kg water/kg dry matter
$M_{t+\triangle t}$: Moisture content at $t+\triangle t$, kg water/kg dry matter
MR: Dimensionless moisture ratio
$\mathrm{MR}_{\mathrm{exp}}$: Experimental dimensionless moisture ratio
$\mathrm{MR}_{\mathrm{pre}}$: Predicted dimensionless moisture ratio
N: Number of observations
χ^2: Chi-square
R^2: Coefficient of determination
RMSE: Root mean square error
z: Number of drying constants
t: Drying time, h
T: Temperature, °C
v: Velocity, m/s
V: Volume, mL
V_0: Initial volume, mL
β_v: Volumetric shrinkable coefficient.

Acknowledgment

This work is supported by National Natural Science Foundation of China (no. 10964009).

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