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DRYING CHARACTERISTICS AND QUALITY ANALYSIS OF HOT AIR-ASSISTED RADIO FREQUENCY AND HOT-AIR DRYING OF JUJUBE (*Zizyphus jujube* Miller cv. *Jinsixiaozao*)

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KEYWORDS

kinetic models, hot air-assisted radio frequency drying, drying rate, color, hot air drying.

ABSTRACT

Radio frequency (RF) drying is a rapid dehydration technique that reduces water activity and extends the shelf life of agricultural products. In this study, the drying characteristics of jujube during HARF and hot air (HA) were investigated, and quality analyses, such as color, vitamin C (VC) and total flavonoid content (TFC), of jujube were performed. The drying curves revealed that the drying time used to reduce the moisture content from 81.7 to 6.0% on a dry basis was 360 and 1320 min using HARF drying and hot air (HA) drying, respectively. The logarithmic model was the best to describe the HARF drying process with R^2, *RMSE* and *SSE* values of 0.998, 0.00508 and 0.000306, respectively. Quality analysis demonstrated significant differences in color, VC content and total flavonoid content between the HARF and HA treatments during the drying process and storage periods (P > 0.5), and the HARF-dried jujube product performed much better than that dried by HA. Compared with HA drying, HARF drying showed a shorter drying time, higher drying efficiency and better product quality, indicating that HARF drying was a more promising drying method for jujube with acceptable product quality.

INTRODUCTION

As a member of the *Rhamnaceae* family, Chinese jujube (*Zizyphus jujube* Mill.) is widely distributed in the subtropical and tropical regions of southern Asia, and China is the world's largest producer and exporter of jujubes (Song et al., 2020). Given its richness in various nutrients, such as sugars, polysaccharides, phenolics, proteins, organic acids, polyphenols and vitamin C (Wang et al., 2021), jujube is widely loved worldwide. As freshly harvested jujube has a high moisture content and high sugar content, it cannot be stored for more than ten days under ambient conditions (Song et al., 2020). Therefore, after harvesting, the moisture content (MC) of fresh jujube must be dried to 6.0% for long-term storage (Moradinezhad & Dorostkar, 2021). However, traditional drying methods, such as hot air (HA) drying, can easily cause deterioration of product quality. Therefore, it is necessary and important to explore new jujube preservation methods to extend its shelf life.

Drying is an old and efficient technique for agricultural product preservation. Drying reduces the water activity of agricultural products to the safety range, and lower water activity facilitates lower transport costs, easier processing, and better quality to reduce the possibility of deterioration during storage (Moradinezhad & Dorostkar, 2021). For the past few years, HA drying has been widely used for the drying of fruits and vegetables given the advantage of its high efficiency. However, hot air drying at high temperature frequently causes hardening of the skin material and quality loss (Wang et al., 2020). Compared with traditional hot air drying and infrared drying, microwave drying is a faster, more uniform and more efficient drying method. However, microwave drying without controlling the temperature produces uneven heating, possible textural damage and limited product penetration (Luo et al., 2017; Liu et al., 2020). Dielectric drying using radio frequency (RF) energy has been applied to improve the

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drying methods for preserving agricultural products. RF drying technology has some advantages over hot air drying and microwave drying, such as higher efficacy, better uniformity, greater penetration depth and more stable product temperature (Zhang et al., 2016; Zhou & Wang, 2018; Gong et al., 2020; Huang et al., 2016). However, limited information is available to compare the drying characteristics and quality of jujube dried with HARF and HA (Jahanbakhshi et al., 2020; Kaveh et al., 2020; Abbaspour-Gilandeh et al., 2019).

In the present study, a systematic study of both HA and HARF drying was applied to estimate the drying efficacy of jujube, and drying kinetics and quality analyses, such as color, vitamin C (VC) and total flavonoid content (TFC), of jujube were evaluated. The objective of this paper was (1) to determine a suitable electrode gap and hot air temperature for HARF drying protocols to achieve acceptable heating rates and uniformity in drying jujube, (2) to analyze the moisture content changes versus drying time between HARF drying and HA drying and to choose suitable drying kinetic models from 6 common drying kinetic models, and (3) to evaluate the effects of HARF drying on the quality and storage stability of jujube samples during accelerated shelf life tests.

MATERIAL AND METHODS

Materials and moisture measurement

Fresh jujube (Zizyphus jujube cv. *Jinsixiaozao*) samples used for drying experiments were obtained from farmland in Botou County, Hebei Province, China. After predrying and removing damaged samples, the jujube samples were selected based on their uniform size and then vacuum-packed into plastic bags stored in a refrigerator (BCD-210G/C, Haier Refrigeration Division, Xi'an, China) at 4±1 °C to prevent moisture loss until the drying experiment. Before each drying test, the jujubes sealed in the bags were equilibrated in an incubator (GSP-9080MBE, Shanghai Boxun Industry & Commerce Co., Ltd. Medical Equipment Factory, Shanghai, China) at 25±1 °C for at least 12 h. The whole jujube samples had an average initial MC of 1.38 g/g d.b., which was determined using the AOAC Official Method 925.40 (AOAC, 1995).

Hot-air assisted RF heating system

Air-assisted radio frequency drying of jujube was performed in the combined RF and hot-air heating system, which is illustrated in Fig. 1. A more detailed description of the RF heating system was reported previously (Liu et al., 2019). The system mainly consist of a 6 kW, 27.12 MHz free-running oscillator type pilot-scale RF system (GJX-6B-27II-JY, Huashijiyuan High Frequency Equipment Co., Ltd., Shijiazhuang, Hebei province, China), a fiber optical sensor (HA-FTS-PJBOA-0300, Herch Opto Electronic Technology Co., Ltd., Xi'an, Shaanxi province, China) and a hot air heating system of a 6.0 kW electrical strip heater and a fan. Hot air was blow into the RF cavity through the inlet holes in the bottom plate. To improve the heating uniformity and drying efficiency of jujube samples, forced hot air at a velocity of 1.5 m/s was added to the RF cavity. The electrode gap could be varied between 40 and 300 mm by moving the top electrode plate (500 mm × 700 mm) to adjust the RF energy for specific applications.

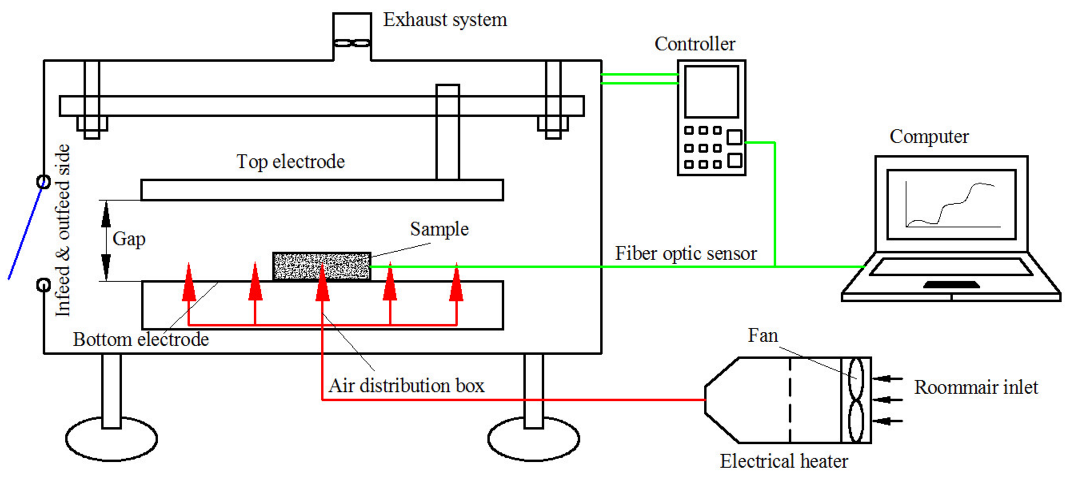

FIGURE 1. Diagram of the RF/hot air drying system.

The jujube samples were dehydrated under stationary conditions in a plastic container (28.0 L×20.0 W×9.0 H cubic meter) made of Teflon with perforated side and bottom walls. As illustrated in Fig. 2, to ensure repeatability of the experimental results and limit the influence of the nonuniform electromagnetic fields on the sample drying, the plastic container was fixed on the bottom plate during all the experiments.

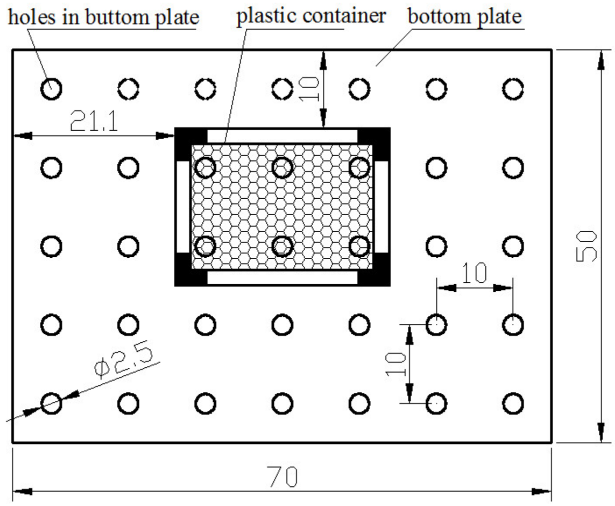

FIGURE 2. Hot air inlet distribution on the bottom electrode and the location of the sample container (in centimeters).

Determination of electrode gap and hot air temperature

Different electrode gaps of the RF system result in different corresponding electric currents (I, A) and output powers (P, kW). The general relationship between the RF output power and electric current was $P = 2.217I - 0.838$ ($R^2 = 0.998$), which was derived experimentally with 500 g of pure water load based on the method of Zhou et al. (2018).

To determine the appropriate electrode gap, plastic containers filled with and without jujube samples of 2.0 kg were placed on the bottom electrode. Without hot-air heating, the RF system was turned on, and the electric current was recorded when the electrode gap increased from 9.0 to 21.0 cm with a distance interval of 1.0 cm. Each test was repeated thrice. Based on the measured current, three electrode gaps (19.0, 20.0, 21.0 cm) were selected for further drying tests.

To determine an effective RF drying protocol for high efficiency and ensuring product quality, three hot air temperatures at 40, 50, and 60 °C were chosen for hot-air assistant RF drying tests under the previously selected electrode gap. As shown in Fig. 3, the sample temperature at seven positions of the container was measured using seven fiber optical sensors (HA-FTS-PJBOA-0300, Herch Opto Electronic Technology Co., Ltd., Xi'an, China). The sensors were inserted into jujube through predrilled holes. Temperatures were acquired every 10 s and recorded every 5 min over 120 min. The average and standard deviation values for the temperature of jujube samples over the six locations were calculated to determine a suitable electrode gap and hot air temperature that might obtain the minimum sample temperature for further RF drying tests.

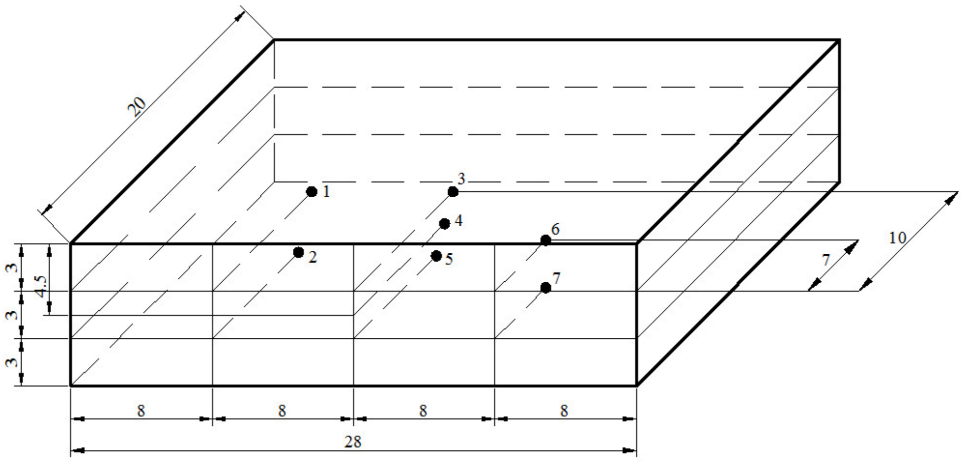

FIGURE 3. Plastic container with six fiber-optic locations for sample temperature measurement (in cm).

Hot-air assistant RF drying test

Based on the experimental results above, an optimal electrode gap (20.0 cm) and hot air temperature (50 °C) were selected. The plastic container loaded with jujube samples was placed on the bottom electrode plate for drying tests. The container was removed from the RF system every 30 min during the whole drying process until the MC of the sample decreased to approximately 6.0% d.b. The weight and surface temperature of jujube samples were measured and recorded within 30 s. The sample weight in the container was measured by an electronic balance (UTP313, Hochoice Scientific Instrument, Co. Ltd. Shanghai, China) with a sensitivity of 0.01 g. The surface temperature of samples in the containers was measured and recorded by an infrared camera (TESTO 875-2i, Testo International Trade Co., Ltd., Germany) with an accuracy ± 2 °C. For each thermal image, approximately 40000 fixed individual surface temperature data points were recorded and used for statistical analysis. After the measurement, the samples in the container were placed back into the RF system for further drying under the same conditions. The tests were conducted in triplicate.

TABLE 1. Jujube temperatures during hot air-assisted RF heating as influenced by the electrode gaps and air temperatures.

NO.	Electrode gap (cm)	Air temperature (°C)	Average heating rate for the first 60 min (°C/min)	Sample temperature during RF heating between 60 and 120 min (°C, average±SD)
1	19	40	0.78	72.69±2.15
2	19	50	0.92	81.29±2.52
3	19	60	1.06	90.65±2.96
4	20	40	0.48	55.01±1.36
5	20	50	0.56	60.99±1.66
6	20	60	0.70	70.09±1.73
7	21	40	0.37	49.30±1.18
8	21	50	0.53	59.84±1.74
9	21	60	0.65	66.67±1.73

Hot air drying test

Compared with hot-air assistant RF drying, the highest temperature at 80 °C in the drying test was selected to study hot-air only drying. The test and measurement processes were the same as those described in Section 2.4. The jujube surface temperature and weight in the container were obtained every 60 min. The hot-air drying tests also continued until the MC of the sample decreased to approximately 6.0% d.b. The tests were repeated thrice.

Drying kinetics models

To describe the drying characteristics of jujube under HARF mathematically, experimental data were applied to various mathematical models developed for thin-layer drying models. Six common thin-layer kinetic models are listed in Table 2.

TABLE 2. Selected thin-layer drying mathematical models.

No.	Models	Equations	Reference
1	Wang and Singh	$MR=1+bt+at^2$	(Ahmet & Derya BO 2020)
2	Newton	$MR=\exp(-kt)$	(White et al., 1981)
3	Page	$MR=\exp(-kt^n)$	(Chkir et al., 2015)
4	Henderson and Pabis	$MR=a\exp(-kt)$	(Khodifad & Kumar, 2020)
5	Logarithmic	$MR=a\exp(-kt)+b$	(O'callaghan et al., 1971)
6	Midilli	$MR=a\exp(-kt^n)+bt$	(Moradi et al., 2019)

In these models, MR represents the instantaneous moisture ratio, t is the drying time, and a, b, k, and n are the undetermined coefficients in the model. The moisture ratio (MR) and drying rate (DR) of jujubes during the drying experiments were calculated using the following equations:

$$MR=\frac{M_t-M_e}{M_0-M_e} \quad (1)$$

$$DR=\frac{M_{t+\Delta t}-M_t}{\Delta t} \quad (2)$$

Where:

M_t - moisture content at any time of drying (%);

M_0 - initial moisture content (%);

M_e - equilibrium moisture content (%);

t - the drying time (min),

$M_{t+\Delta t}$ - moisture content at time $t+\Delta t$ (%).

Nonlinear regression analysis was performed using the statistical software SPSS version 15.0 (SPSS Inc., Chicago, IL, USA). To model the drying kinetics, the goodness of fit between the predicted and experimental data was evaluated based on statistical analyses, including the coefficient of determination (R^2, [eq. (3)], root mean square error (RMSE, [eq. (4)] and chi-square (χ^2, [eq. (5)]. The model was considered best when R^2 was at a maximum value and *RMSE* and χ^2 were at a minimum value.

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{\mathrm{pre},i}\right)^2}{\sum_{i=1}^{N}\left(\overline{MR_{\exp,i}} - MR_{\mathrm{pre},i}\right)^2} \quad (3)$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{\mathrm{pre},i}\right)^2}{N}} \quad (4)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{\mathrm{pre},i}\right)^2}{N - z} \quad (5)$$

Where:

$MR_{exp,i}$ - the *i*th experimental *MR* (%);

$MR_{pre,i}$ - the *i*th predicted *MR* (%);

MR_{exp} - the average experimental *MR* (%);

N - the number of observations,

z - the number of constants in the model.

Quality evaluation and storage test

Quality attributes, including color, VC content and TFC, were selected as major quality parameters and analyzed during drying experiments and after accelerated storage tests. For the drying process tests, the quality evaluation was conducted at 0, 180, and 360 min and 0, 180, 360, 840 and 1320 min during HARF drying and HA only drying, respectively. For storage tests, HARF and HA-only dried jujube (500 g) were packed in bags individually and stored in an incubator set to 35±0.5 °C with relative humidity (RH) set at 30% for 20 days to simulate commercial storage at 4 °C for 2 years. The jujube samples were removed every 10 days for quality tests. Triplicate experiments were conducted.

The color analysis was performed in a determination system of the CIE consisting of L*, a*, b* values measured using a colorimeter (D25L, Hunterlab, USA). Before the measurement, the colorimeter was calibrated, and the color balance was adjusted with a standard white ceramic plate (Duangmal et al., 2008). The total color difference was calculated using the following formula:

$$\Delta E = \sqrt{\left(L - L^*\right)^2 + \left(a - a^*\right)^2 + \left(b - b^*\right)^2}$$

Where:

ΔE - the total color difference;

*L**, *a** and *b** - the values of fresh jujube sample,

L, a and *b* - the values of dried jujube sample.

The 2,6-dichloroindophenol titrimetric method was applied to measure the VC content value of the jujube sample (AOAC, 1995). VC content was expressed as milligrams of vitamin C in every 100-g sample jujube powder.

An ultraviolet spectrophotometer detector (T6 UVeVis spectrophotometer, Beijing Purkinje General Instrument Co., Ltd., China) was used to determine the TFC of the jujube sample at a wavelength of 510 nm with rutin as the reference standard. The detailed measurement procedures and calculation of TFC have been previously reported (Anand et al., 2018). TFC results are expressed as milligrams of rutin equivalents per 100 g sample. Experiments were performed in triplicate.

Statistical analysis

Mean values and standard deviations (SD) were calculated from the data in triplicate for the control and various HARF and HA-only drying treatments using SPSS version 16.0 (SPSS Inc., Chicago, IL, USA). Statistically significant differences ($p<0.05$) among various drying treatments were determined by analysis of variance (ANOVA) and Duncan's test using SAS 9.0 (SAS Institute Inc., USA).

RESULTS AND DISCUSSION

The electric current under different gaps

Figure 4 demonstrates the relationship between the electric current and electrode gap for the RF system with and without jujube samples. Without jujube samples, the electric current fluctuated in a narrow range of approximately 0.43 A as the electrode gap increased. With the samples, the electric current was reduced rapidly as the electrode gap increased from 9.0 cm to 18.0 cm but remained almost constant at approximately 0.45 A as the electrode gap increased continuously from 19.0 cm to 21.0 cm. Similar trends were also observed by Zhou et al. (2018) and Zhang et al. (2016). On the basis of these results, subsequent experiments were performed with three electrode gaps (19.0, 20.0 and 21.0 cm) to obtain a suitable heating rate and acceptable product quality.

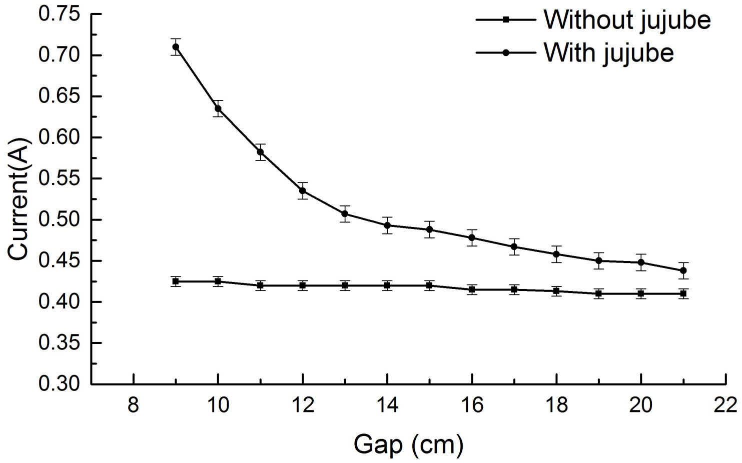

FIGURE 4. Electric current of the RF system as a function of electrode gap.

Selection of electrode gaps and hot air temperature for HARF drying

Fig. 5 shows the temperature change of jujubes versus time with three electrode gaps (19.0, 20.0 and 21.0 cm) when assisted by hot air (40, 50 and 60 °C) heating. During the first 60 min of heating, the average temperature rapidly increased with increasing heating time. For a given electrode gap, as the hot air temperature increased, the heating rate and the maximum temperature tended to increase. Since the absorbed RF power was balanced by the latent heat of water evaporation after heating for 60 min, the sample temperature was maintained at a fairly constant value. Finally, the sample temperature began to decline slowly because the RF power absorbed by the jujubes decreased with the reduced MC.

Similar trends were also observed by Zhang et al. (2016), who used HAEF drying for in-shell walnuts and macadamia nuts (Zhang et al., 2016; Zhou et al., 2018; Gong et al., 2020). To obtain the required drying rate and avoid jujube quality degradation, a process that combined an electrode gap of 20.0 cm with hot air at 50 °C was selected for further drying tests.

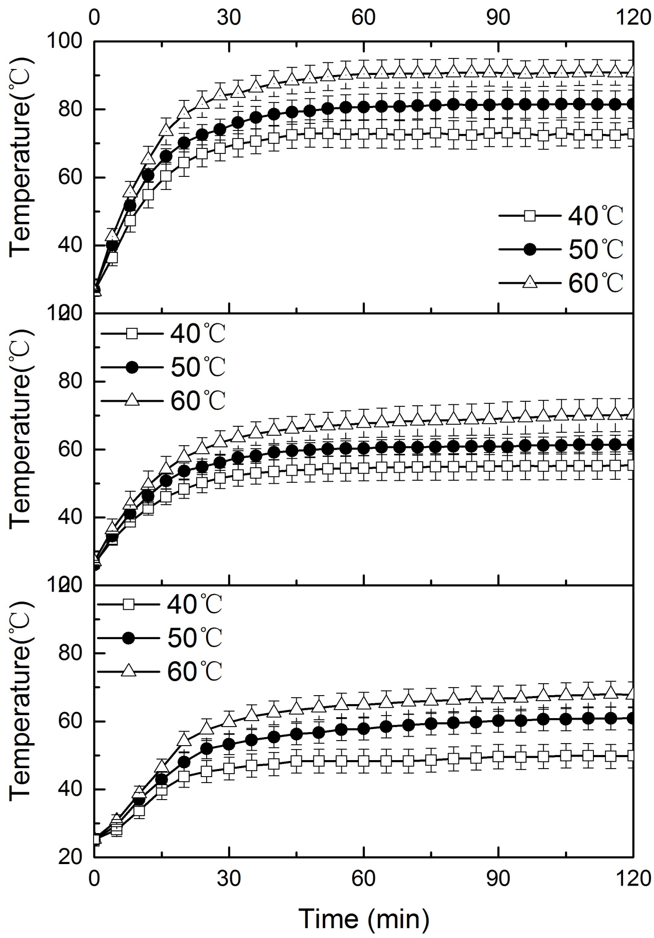

FIGURE 5. Average and standard deviation values of jujube temperatures over sis locations with 19.0 cm (a), 20.0 cm (b), and 21.0 cm (c) when subjected to hot air (40, 50 and 60 °C)-assisted RF drying.

Drying curves

The change in the MC versus drying time for jujube in HARF drying is shown in Fig. 6. During the first 120 min of HARF drying, the MC decreased dramatically, and the drying rate reached the maximum level. The drying rate gradually decreased when the drying time increased from 150 min to 360 min. After HARF drying for 360 min, the target MC of jujubes reached 6.0% (d. b.).

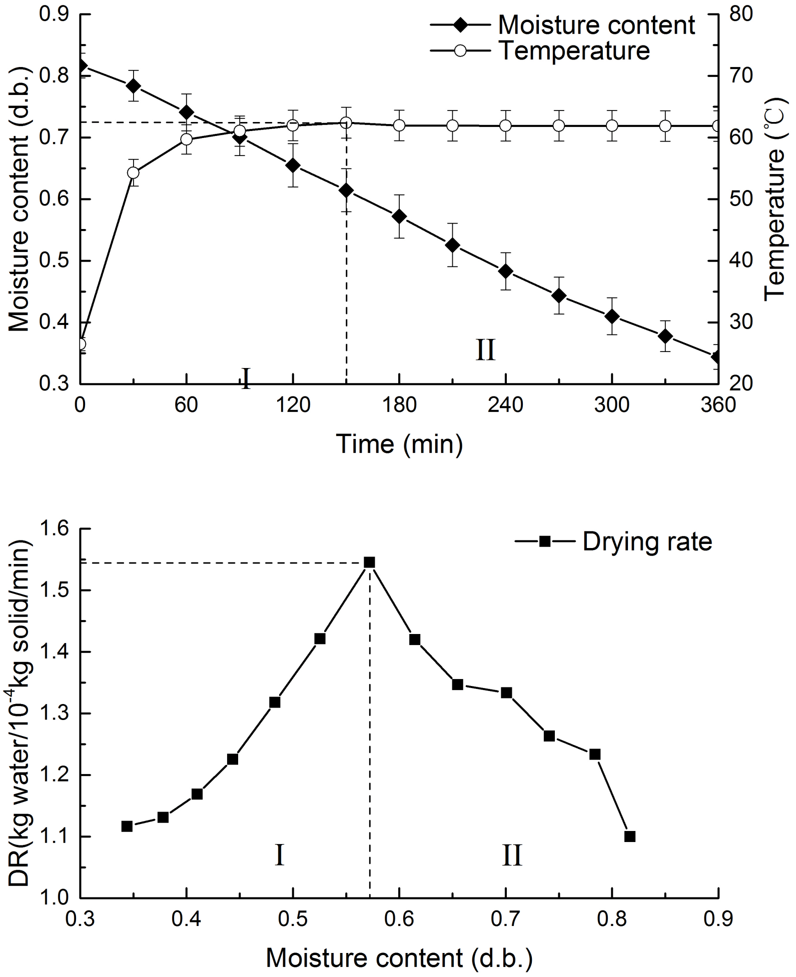

FIGURE 6. Drying curves (a) with average sample surface temperatures and drying rate (b) when subjected to hot air (50 °C)-assisted radio frequency drying with an electrode gap of 20.0 cm.

Figure 7 presents typical drying curves when using hot air at 80 °C. The drying rate was much lower than that in HARF drying, resulting in the need for a longer drying time (1320 min) to reach the target MC of 6.0% d.b. for jujube. The gradual growth of the sample surface temperature, which was always below the hot air set point (80 °C) is notable. The drying curves exhibited a typical profile for traditional HA drying (Fig. 5A) and were similar to those observed in industrial convection drying of jujube. The HARF drying rate (Fig. 6b) was faster than that of HA drying alone (Fig. 7b). Given that a positive temperature gradient remained due to RF heating, the vapor pressure gradient from the sample center to the surface enhanced the drying process.

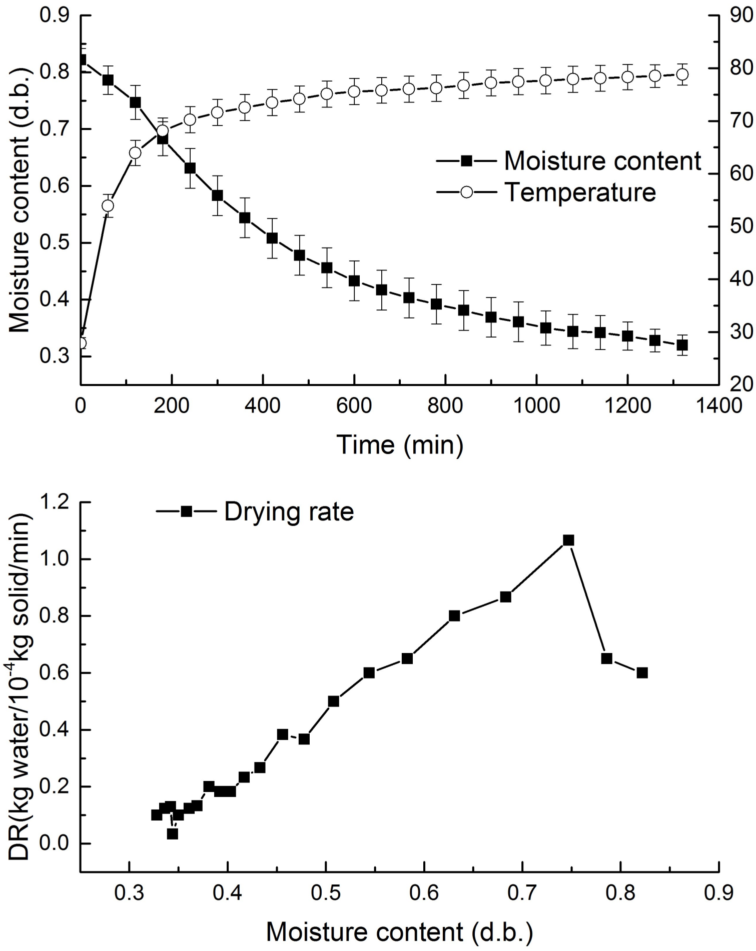

FIGURE 7. Drying process (a) and drying rate (b) when subjected to hot air drying at a temperature of 80 °C.

The HARF drying process could be divided into two stages (Fig. 7): stage I (from 0 to 150 min) was an acceleration drying stage when the jujube temperature gradually reached the maximum value; stage II (from 150 to 360 min) was a deceleration drying stage when the jujube temperatures were maintained stably. At stage I, as the drying process began, the evaporation remains low, the energy gained from the HARF system was greater than that lost for moisture vaporization, and the jujube sample temperatures increased from an initial value (25 °C) to a maximum value (62.5 °C). However, with increasing sample temperature and evaporation rate, the heating rate decreased gradually. During stage I, RF heating contributed the greatest energy due to the high loss factor of the high moisture jujube sample. In stage II, heat loss from water evaporation was balanced with RF input energy; thus, the jujube sample temperature remained almost stable. In addition, as the drying time increased, the drying rate was gradually reduced due to the continuous moisture loss in the jujube samples. A similar trend was found in HARF drying of in-shell walnuts and in-shell almonds (Zhou et al., 2018; Gong et al., 2020).

Drying kinetics of HARF-dried jujube

The moisture content data obtained during the HARF drying process were fitted to the six models listed in Table 3. The drying model coefficients and the comparison criteria were calculated to evaluate goodness of fit (R^2, SSE and *RMSE*) in HARF drying. The best model was the logarithmic model with R^2, *RMSE* and *SSE* values of 0.998, 0.00508, and 0.000306, respectively. The model with the worst fit was that of the Page model with an R^2 of 0.927. Thus, the logarithmic model is listed below to best describe the drying kinetics of jujube under HARF heating:

$$MR = 2.74\exp\left(-0.000545t\right) - 1.914$$

TABLE 3. Kinetic models for hot air-assisted RF drying of jujube.

Model	R^2	*RMSE*	*SSE*	*k*	*n*	*a*	*b*	*c*
Newton	0.981	0.0964	0.0626	0.00317				
Page	0.927	0.0560	0.0407	0.0158	0.702			
Modified Page	0.981	0.0694	0.0262	2.070	0.00152			
Henderson and Pabis	0.991	0.0147	0.00281	0.00234		0.847		
Logarithmic	0.998	0.00508	0.000336	0.000545		2.740		-1.914
Wang and Singh	0.949	0.0674	0.0589			-0.00334	4.497	

Quality analysis of jujubes during drying and storage

Table 4 shows the quality evaluations of the jujube sample during the drying process by the HARF and HA-only drying methods. As shown in Table 4, with increasing drying time, drying caused an increase in $\triangle E$ for both drying methods in comparison with the fresh jujube sample. A significant difference (P<0.5) was observed for the whole drying process for HARF and HA drying. Generally, a lower $\triangle E$ value was favorable. The $\triangle E$ value in HA drying was greater than that in HARF drying for the final jujube samples.

For both drying methods, the VC content decreased with increasing drying time. Compared with the fresh samples, 52.8% of the VC content remained after the HARF drying treatment. Of note, the HA drying product lacked VC content. A significant difference (P<0.5) was observed for the VC content during the whole drying process for the HARF and HA drying methods.

In the HARF and HA drying processes, TFC increased with increasing drying time. A significant difference (P<0.5) for the TFC throughout the drying process for HARF and HA drying. The TFC value in HARF drying was higher than that in HA drying for the final jujube product.

Table 5 shows the quality characteristics of jujube samples during storage after HARF and HA drying treatments. During the whole accelerated shelf life storage test, the $\triangle E$ value of HARF-dried jujubes was significantly lower than that of HA-dried jujubes (P<0.5), and the VC content and TFC content of HARF-treated samples were greater than those of HA-only dried jujubes. No significant difference (P<0.5) in the $\triangle E$ value was noted throughout the whole accelerated shelf life storage time for either the HARF or HA drying treatment. The HA-only dried jujube samples lacked VC content. The VC and TFC contents of jujube samples dried by the HARF method showed a downward trend. Significant differences (P<0.5) in the VC and TFC contents were noted between the HARF and HA dried samples throughout the whole accelerated shelf life storage time.

TABLE 4. Quality properties (mean ± SD) of jujube as influenced by drying time when subjected to hot air (HA) and hot air assisted RF (HARF) drying.

Drying time (min)	Color ($\triangle E$)		Vitamin C (mg/100 g)		TFC (g/100 g)	
	HARF	HA	HARF	HA	HARF	HA
0	-	-	564.82±25.58aA	564.82±25.58aA	10.44±1.24cA	10.44±1.24aA
180	16.25±0.98bB	20.45±1.25dA	354.75±20.67bA	278.54±17.67bB	14.56±1.98bA	12.26±1.57bB
360	24.34±1.52aB	27.56±1.67cA	298.45±17.67cA	154.26±13.78cB	20.07±2.12aA	14.23±1.68cB
840	-	30.25±1.85b	-	89.56±10.84d		16.54±1.74d
1320	-	35.01±2.24a	-	-		17.54±1.97e

Mean values are not significantly different (P>0.5) for the same lowercase letters within a column among the drying times and for the same capital letters within a row among the heating treatments.

TABLE 5. Storage quality characteristics (mean ± SD) of jujube after hot air (HA) and hot air assisted RF (HARF) drying.

Storge time(d)	Color ($\triangle E$)		Vitamin C (mg/100 g)		TFC (g/100 g)	
	HARF	HA	HARF	HA	HARF	HA
0	24.34±1.52aB	35.01±2.24aA	298.45±17.67a	-	20.07±2.12aA	17.54±1.97aB
10	25.56±1.87aB	34.51±2.54aA	186.78±12.68b	-	15.54±1.61bA	12.68±1.08bB
20	25.45±2.36aB	35.47±2.68aA	91.56±8.57c	-	10.35±1.18cA	8.68±0.76cB

Mean values are not significantly different (P>0.5) for the same lowercase letters within a column among the drying times and for the same capital letters within a row among the heating treatments.

CONCLUSIONS

Drying characteristics and quality analysis of jujube in HA and HARF drying were investigated. When hot air (50 °C) was applied, an electrode of 20 cm was demonstrated to be suitable for jujube drying based on the desirable hearting rate and acceptable product quality and stable sample temperatures. This study found that HARF treatments could significantly reduce the drying process of jujube compared to HA-only drying. The drying curves revealed that the drying time used to reduce the moisture content from 81.7 to 6.0% on a dry basis was 360 and 1320 min using HARF and HA drying, respectively. Mathematical modeling results showed that the logarithmic model was the best to describe the HARF drying process of jujube. Quality analysis demonstrated a significant difference in color, VC content and total flavonoid content between the HARF and HA treatments during the drying process and storage periods (P > 0.5), and the HARF-dried jujube product performed much better than that dried by HA. Compared with HA drying, HARF drying exhibited a shorter drying time, increased drying efficiency and better product quality, indicating that HARF drying was a more promising drying method for jujube with acceptable product quality. More broadly, further research is also necessary to determine the optimization of RF treatment protocols using computer simulation to improve the drying efficiency and scale-up for industrial application.

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