A comprehensive analysis and comparison between vacuum and electric oven drying methods on Chinese saffron (*Crocus sativus* L.)

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Abstract The red stigmas of saffron are one of the most expensive spices in the world and serve as a traditional Chinese medicine. More saffron has been cultivated in China, and different drying technologies have been studied. However, a comprehensive and comparative analysis of different drying approaches has not been well studied. In this study, we compared electric oven and vacuum oven drying approaches on saffron. We found saffron was dried quicker under high vacuum drying mode with high temperature and the quicker drying rate provided, the more open microstructural interstices on the saffron surface. Both methods were best fit to Midilli and Kucuk model. Besides, the coloring, aroma and bitterness strength after drying showed the similar results. In sum, our data suggested the optimal drying temperature was 100 °C for 20 min for two evaluated methods, however considering

the machine cost, the electric oven drying would be the first choice.

Keywords Saffron · Thin layer drying · Kinetic model · Vacuum oven dry · Electric oven dry

Introduction

Saffron is derived from the stigma of *Crocus sativus* L. (Iridaceae family). It has a very high economic value which mainly used as spice, dye and food colorant (Ahrazem et al., 2015). Besides the usage as foods, saffron also shows the medical importance for human health (Christodoulou et al., 2015; Tuberoso et al., 2016), such as anti-myocardial ischemia (Chahine et al., 2016), anti-tumor (Bolhassani et al., 2014), anti-depression (Lopresti and Drummond, 2014), and preventing Alzheimer's disease (Akhondzadeh et al., 2010; Farokhnia et al., 2014). In China, saffron was initially introduced into the Shanghai's Chongming Island region in the 1980s. In 2013, the yield of Chinese saffron was about 1 ton, and 90% of them from Zhejiang Province (Tong et al., 2015).

Drying is the most common processes in food and traditional medicine industry for long-term storage, which achieves the purposes of reducing water activity, inhibiting microbial growth and reproduction (Erbay and Icier, 2010). As a valuable traditional herb in China, there is no standard procedure for drying processing saffron yet. The majority of saffron products were dried by water heating system by the operator's experience. Thus, this method is relatively less in control of the moisture content after drying. However, the saffron is highly susceptible to mildew once their moisture content exceeds the safety limit. Therefore, accurate quantitative description of saffron drying process

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with mathematical model and study of drying kinetics helps us accurately grasp the variation trends of moisture content in saffron. We believe our study has theoretical and application significances for setting drying time, adjustment of the drying process, improvement of efficiency, reduction of energy consumption and R&D of drying equipment.

The existing drying technologies for saffron include shade drying, sun drying (Raina et al., 1996), solar energy drying (Hamid Mortezaipoor et al., 2012), infrared drying (Torki-Harchegani et al., 2017), microwave drying (Maghsoodi et al., 2012), electric oven drying (Maghsoodi et al., 2012), freeze drying (Acar et al., 2011), hot air drying (Gregory et al., 2005), vacuum oven drying (Raina et al., 1996) and so on. The previous studies looked at the drying kinetics of freeze drying (Acar et al., 2015), infrared drying (Akhondi et al., 2011) and photovoltaic-thermal solar drying (Mortezaipoor et al., 2014). The mathematic model derived from kinetics research allows description of the drying process quantitatively and grasp of the moisture variation trends in the material over time. If saffron is dried for an excessively long time, the contents of picrocrocin and crocins in stigma will decrease, and the content of safranal, from thermal dehydration of picrocrocin, will also not increase as we expected (Carmona et al., 2005).

To find a fast and effective drying method of saffron through drying kinetic model under the premise of ensuring its quality, we dry saffron at different drying temperatures using the electric oven and vacuum oven to compare whether the vacuum influences the content of safranin saffron. Furthermore, we investigated the optimal mathematic model for thin layer drying process of saffron and calculate the effective diffusion coefficient and activation energy in the drying process. Also, the microstructure, relevant quality characteristics and secondary metabolite contents during the drying process of saffron were studied.

Materials and methods

Plant materials

Fresh saffron stigmas were collected on November 18, 2016, from local farmers in Zhejiang, China. The collected samples were kept in the icebox and processed immediately in the lab. The initial moisture content was 4.62 ± 0.06 kg water/kg dry matter (DM) determined according to the ISO 3632 method.

General materials

Electrothermal blast oven (BGZ-246, Boxun, Shanghai, China) and Vacuum drying oven (DZF-6020, Boxun,

Shanghai, China) was used. Saffron samples were weighed by an electronic balance (ME1002, Mettler Toledo, Greifensee, Switzerland). UV-Vis spectroscopy was recorded with a UV-Vis spectrophotometer (UV-1780, Shimadzu, Kyoto, Japan).

Electric oven drying

40 g of fresh saffron stigmas were weighed and laid in a thin layer (about 1 mm in thickness) in the sample tray. The average loading of the saffron sample in each tray was 60 g/m^2 . Previous studies (Tong et al., 2015; Torki-Harchegani et al., 2017) have shown that the best temperature to keep the active component is about 50–90 °C. So, we decided to use temperature from 40 to 100 °C. The oven drying experiments were carried out at different temperatures (40, 60, 80, 100 °C). When weighing, the trays were quickly removed from the drying chamber and weighed on an electronic balance next to the oven. The weighing was performed once every 5 min for the initial 30 min of drying process; once every 10 min for a period between 30 and 90 min; and once every 30 min after 90 min until the moisture content of saffron samples dropped to below the safe level of 0.1 kg water/kg DM (Torki-Harchegani et al., 2017).

Vacuum oven drying

The atmospheric pressure of the oven set to 10 kPa as a default setting. We also performed once every 5 min for the initial 30 min of drying process; once every 10 min for a period between 30 and 90 min; and once every 30 min after 90 min until the moisture content of saffron samples dropped to below the safe level of 0.1 kg water/kg DM (Torki-Harchegani et al., 2017).

Saffron extraction

10 mg of the saffron stigma power was dissolved in 40 ml of 50% ethanol and ultrasonic treatment for 20 min and the extract was filter with 0.22 μm filter (Xiaobin et al., 2018).

HPLC determination

Crocins (*trans*-crocins-4 and *trans*-crocins-3) and safranal contents were determined by HPLC (InfinityLab, Agilent Technologies, CA, USA). 10 μL of saffron extract was analyzed with Zorbax Eclipse Plus C18 column (Zorbax Eclipse Plus, Agilent, CA, USA) at 30 °C. The mobile phase consisted of purified water (MilliQ, Millipore, MA, USA) and methanol (67-56-1, Merck, NJ, USA), with the gradient of 20–100% during 0–60 min and the flow rate at 1.0 mL/min. DAD wavelength range was 200–600 nm.

The detection wavelength for *trans*-crocin-4 and *trans*-crocin-3 was 440 nm and 330 nm, respectively.

Determination of crocins contents: Calibration curves were plotted using the *trans*-crocin-4 (lot: 111588-201202, National institutes for food and drug control, Beijing, China) and *trans*-crocin-3 (lot: 111589-201304, National institutes for food and drug control, Beijing, China) standards. Equations were constructed with concentration X (mg/L) versus HPLC peak area Y at corresponding 440 nm. In the experiments, the safranal was quantified by plotting a calibration curve using the safranal standard (Sigma-Aldrich, Spain) (García-Rodríguez et al., 2017). The saffron extract was prepared based on Tong's method (Tong et al., 2015).

UV-Vis spectroscopy

The color values of saffron at different wavelengths were determined according to the ISO 3632 method. Different saffron samples filtered through a 0.45 μm ProMax-CA Syringe Filter (Dikma, Beijing, China) and placed in a quartz cell (1 cm $\times$ 1 cm $\times$ 4 cm) for absorbance measurement at 440 nm, 330 nm, and 254 nm. Absorbance values were measured in triplicates. The measured values were converted into $E_{1\text{cm}}^{1\%}$ values representing coloring strength, aroma strength, and bitterness strength according to the ISO 3632 standards.

Scanning electron microscope

The saffron samples dried at different temperatures were plated with a layer of gold coating on the surface, then observed and photographed on ZEISS EVO18 scanning electron microscope (Carl Zeiss NTS, Oberkochen, Germany) under electron accelerating voltage of 15 kV and the low vacuum pressure of 130 Pa.

Kinetic modeling

In the drying experiments, relevant parameters were calculated as follows (Ertekin and Firat, 2017): dry basis moisture content (M_t) was calculated using Eq. (1):

$$M_t = \frac{W_t - G}{G} \quad (1)$$

where W_t was the mass (kg) of the material at time t ; G was the DM mass (kg) of the saffron sample. The DM mass was determined by heating in the 103 ± 2 °C oven at atmospheric pressure for 16 h.

Fitting of drying models

During the drying process, the moisture content of the material being dried at different times represented by the moisture ratio (MR). MR was defined as the ratio of free moisture content being removed at a certain time to the initial total free moisture content, which could be expressed by Eq. (2):

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (2)$$

where M_0 , M_t and M_e represented the initial dry basis moisture content (kg water/kg DM) of raw material; dry basis moisture content (kg water/kg DM) at time t ; and dry basis moisture content (kg water/kg DM) at the equilibrium drying state, respectively. In general, M_e value was minimal, so Eq. (2) could be simplified into Eq. (3) (Calín-Sánchez et al., 2014). Drying curve was plotted with the moisture ratio (MR) versus drying time (min).

$$MR = \frac{M_t}{M_0} \quad (3)$$

A Radj-Sq (R^2 adj) value was used as the primary factor of screening optimal drying model for the sample drying curves. Besides, the Chi square (χ^2) and root mean square error (RMSE) are also used to reflect the regression equation goodness of fit (Chayjan and Kaveh, 2014). These statistics were calculated according to Eqs. (4) and (5), respectively.

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{N - z} \quad (4)$$

$$RMSE = \left[\frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{N} \right]^{\frac{1}{2}} \quad (5)$$

where $MR_{exp,i}$ and $MR_{pre,i}$ represented the i th measured and predicted moisture ratios, respectively; N was the number of measurements; and z the number of parameters in the mathematical model equation.

Drying rate (DR) was the amount of moisture evaporated per unit time, and its formula was as follows:

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \quad (6)$$

where M_t , $M_{t+\Delta t}$ were the dry basis moisture contents (kg water/kg DM) of samples at times t , $t + \Delta t$; and Δt was the time interval (min). The drying behavior was determined based on the plot of drying rate versus drying time (min).

Calculation of drying kinetic parameters

The moisture transfer process of saffron was reflected by the effective moisture diffusion coefficient (D_{eff}). According to Fick's second diffusion law (Lopez et al., 2000), the

relationship between the D_{eff} and the moisture ratio MR was expressed as follows:

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{i=0}^{\infty} \frac{1}{(2i+1)^2} \exp \left[-\frac{(2i+1)^2 \pi^2}{4L^2} D_{eff} t \right] \quad (7)$$

where i was the number of expansion items $n = 1, 2, 3, \dots$; t was the drying time (s); D_{eff} was the effective moisture diffusion coefficient (m^2/s); and L the thickness of material (m). Under relatively long drying time, an i value of $i = 0$ could well meet the accuracy requirements, hence:

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

Logarithms of both sides of Eq. (8) were taken to obtain:

$$\ln MR = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{4L^2} \quad (9)$$

The influence of drying temperature on the D_{eff} could be expressed by Arrhenius formula as follows (Lopez et al., 2000):

$$D_{eff} = D_0 \exp \left(-\frac{E_a}{RT} \right) \quad (10)$$

where D_0 was the pre-exponential factor (m^2/s); E_a was the activation energy (kJ/mol) during drying process; R was the gas constant 8.314 kJ/(mol K); and T the absolute temperature (K). Logarithms of both sides of Eq. (10) were taken to obtain:

$$\ln D_{eff} = \ln D_0 - \frac{E_a}{RT} \quad (11)$$

Statistics analysis

ANOVA, Duncan's multiple-range test, and Spearman correlations were analyzed using SPSS 19.0 (SPSS Inc., USA). The p value less than 0.05 was considered as statistical significance.

Results and discussion

Drying curves and drying rate of saffron using electric or vacuum oven drying

To find fast and effective drying approaches for saffron, we compared electric and vacuum oven technology. Different temperatures and drying time were investigated, and the results showed that moisture ratios of saffron sample decreased with increasing drying time at different

temperatures for both methods [Fig. 1(A), (C)]. With drying temperature from 40 to 100 °C, the time required for electric oven drying to reach safe moisture content were from 150 to 20 min [Fig. 1(A)], while vacuum oven drying was slightly faster [Fig. 1(C)]. The dry rate was calculated in each condition. We observed that the spacing between maximum drying rates at different temperatures showed a gradual upward trend with the rise of temperature, suggesting that the influence of temperature on drying rate was more evident at a higher temperature [Fig. 1(B), (D)]. Also, no constant-rate drying period was observed in both methods suggesting that the drying of saffron samples occurred mainly during the falling-rate drying period [Fig. 1(B), (D)].

Our results indicated that vacuum oven drying had a significant influence on the drying rate of saffron. Comparison between Fig. 1(A), (C) showed that at the same temperature, vacuum oven drying required shorter time than electric oven drying about 5–30 min. The main reason was because the vacuum environment allowed rapid evaporation of moisture on the saffron stigma surfaces in a short time. After the evaporation of surface moisture, the internal moisture diffused to the surface at an accelerated speed (Mongpraneet et al., 2002). It also can be reflected by the drying rate showing that the vacuum drying was quicker than the non-vacuum drying, especially in the early stage [Fig. 1(B), (D)]. Our data indicated that vacuum oven drying method promoted material moisture evaporation to accelerate the drying, consistent with one previous study (Orikasa et al., 2014).

Mathematical modeling of drying curves

We next investigated which models can fit to our current drying data. The 11 drying models established by previous studies as summarized in Table S1. According to the value of R^2 , χ^2 and RMSE given in Table 1, and we found that the Midilli and Kucuk model, Page model and Two-term model fit for electric oven drying with R^2 adj value is greater than 0.995 in all temperatures we tested. Among them, Midilli and Kucuk model was best fit for the model with the largest R^2 adj and the smallest χ^2 and RMSE. We also found in vacuum oven drying experiment, Midilli and Kucuk model yielded the largest R^2 adj the smallest χ^2 and RMSE. Therefore, Midilli and Kucuk model had the best fitting effect for both approaches. The constant's value of this model was given in Table S2. To verify the Midilli and Kucuk model, the actual experimental MR and predicted MR were plotted in Fig. S1. The results showed that all the data points were distributed around a 45-degree straight line suggesting that Midilli and Kucuk model applied to the saffron drying experiment, which could accurately predict the MR values under different drying times.

Fig. 1 Variations on drying curves using electric oven drying method (A) and vacuum oven drying method (C). And drying rate curves for electric oven and vacuum oven drying method are shown in (B) and

(D), respectively for saffron during drying at various temperatures and drying methods as indicated. The error bars indicate the standard deviations of the three replicates

Comparison of effective moisture diffusivity (D_{eff}) and activation energy (E_a) between electric and vacuum oven drying

In general, the drying method will affect the technique of moisture movement toward evaporation for the drying process and moisture movement depends on the effective moisture diffusivity (D_{eff}) and activation energy (E_a). We first tested whether our drying process is fit to Fick's second law. Figure S2 illustrated the linear relationship between the $\ln MR$ and the drying time at the different

temperature level. Therefore, D_{eff} can be calculated from the slopes of straight lines according to Eq. (9). Our results showed that the D_{eff} for vacuum drying fell in the range of $2.202E-10$ – $1.761E-09$ m^2/s , while $1.736E-10$ – $1.379E-09$ m^2/s for electric oven drying (Table 2). Clearly, vacuum drying increase D_{eff} by 12.97–27.67% at the same drying temperature. Most likely, the vacuum drying can accelerate the moisture–heat exchange between the material and the dry environment, therefore increasing the moisture potential and temperature differences of material and promoting the moisture transfer

Table 1 Statistical results obtained from the mathematical models

Model	40 °C				60 °C				80 °C				100 °C			
	R ²	Adj	χ^2	RMSE	R ²	Adj	χ^2	RMSE	R ²	Adj	χ^2	RMSE	R ²	Adj	χ^2	RMSE
<i>Electric oven drying temperature</i>																
Lewis	0.99446		0.000593	0.023523	0.99110		0.001040	0.030578	0.99753		0.000299	0.016163	0.99921		0.000133	0.010298
Page	0.99528		0.000506	0.020116	0.99948		0.000061	0.006516	0.99972		0.000034	0.004593	0.99986		0.000023	0.003044
Weibull	0.99545		0.000487	0.020543	0.99955		0.000053	0.006517	0.99977		0.000028	0.004593	0.99387		0.000846	0.026038
Aghbashlo et al.	0.99424		0.000616	0.023108	0.99780		0.000257	0.014353	0.99956		0.000053	0.006321	0.99988		0.000020	0.003448
Henderson and Pabis	0.99516		0.000518	0.020494	0.99240		0.000887	0.026646	0.99747		0.000306	0.015166	0.99895		0.000175	0.010249
Logarithmic	0.99533		0.000500	0.019983	0.99468		0.000622	0.020857	0.99843		0.000191	0.010927	0.99940		0.000100	0.006329
Midilli et al.	0.99743		0.000275	0.014189	0.99949		0.000060	0.005997	0.99965		0.000042	0.004589	0.99974		0.000043	0.002941
Two term	0.99510		0.000524	0.019613	0.99955		0.000053	0.005634	0.99621		0.000460	0.015166	0.99975		0.000042	0.002912
Verma et al.	0.99616		0.000411	0.018129	0.99468		0.000621	0.020857	0.99890		0.000134	0.009143	0.99841		0.000265	0.010298
Wang and Singh	0.93800		0.006630	0.075829	0.99273		0.000848	0.026058	0.98161		0.002230	0.040911	0.95000		0.008350	0.070767
Parabolic	0.95322		0.005010	0.063288	0.99228		0.000901	0.025120	0.98328		0.002030	0.035602	0.93337		0.011120	0.066708
<i>Vacuum oven drying temperature</i>																
Lewis	0.99621		0.000391	0.019068	0.99661		0.000386	0.018529	0.99904		0.000118	0.010068	0.99834		0.000346	0.016125
Page	0.99603		0.000410	0.017948	0.99929		0.000081	0.007351	0.99978		0.000027	0.003939	0.99933		0.000138	0.005883
Weibull	0.99605		0.000408	0.018708	0.99938		0.000070	0.007394	0.99617		0.000496	0.019300	0.99873		0.000160	0.010313
Aghbashlo et al.	0.99604		0.000409	0.018727	0.99841		0.000181	0.011879	0.99963		0.000046	0.005756	0.91710		0.017240	0.065651
Henderson and Pabis	0.99636		0.000376	0.017948	0.99689		0.000354	0.016600	0.99893		0.000132	0.009726	0.99751		0.000518	0.015927
Logarithmic	0.99734		0.000275	0.014687	0.99724		0.000314	0.014453	0.99911		0.000110	0.007922	0.99764		0.000491	0.011077
Midilli et al.	0.99794		0.000213	0.012335	0.99935		0.000074	0.006397	0.99984		0.000019	0.002883	0.99941		0.000074	0.006103
Two term	0.99708		0.000301	0.014663	0.99565		0.000496	0.016610	0.99984		0.000019	0.002889	0.99904		0.000121	0.006342
Verma et al.	0.99552		0.000462	0.019068	0.99738		0.000298	0.014103	0.99988		0.000015	0.002889	0.99501		0.001040	0.016330
Wang and Singh	0.91509		0.008770	0.086685	0.98451		0.001760	0.037044	0.95767		0.005240	0.061167	0.99947		0.000111	0.007456
Parabolic	0.93971		0.006230	0.069939	0.98527		0.001680	0.033433	0.95890		0.005090	0.053918	0.95637		0.009070	0.067361

Table 2 Drying kinetic parameters for saffron

Drying temperature	D_{eff}	R^2	E_a	R^2
<i>Electric oven drying</i>				
40 °C	1.736E-10	0.9680	32.36	0.9836
60 °C	4.634E-10	0.9928		
80 °C	7.092E-10	0.9924		
100 °C	1.379E-09	0.9961		
<i>Vacuum oven drying</i>				
40 °C	2.202E-10	0.9851	32.64	0.9918
60 °C	5.235E-10	0.9970		
80 °C	8.504E-10	0.9956		
100 °C	1.761E-09	0.9932		

through the material. This also explained why the vacuum drying was less time-consuming compared to electric oven drying.

We next calculated the E_a value according to the Arrhenius formula (Fig. S3), and the E_a values for the electric and vacuum oven drying processes are 32.36 kJ/mol and 32.64 kJ/mol, respectively (Table 2). This value fell under the E_a values range 12.7–110 kJ/mol of general vegetables and fruits during drying process (Zogzas et al., 1996) and also very consistent with the previous study showing that the activation energy 27.86 kJ/mol of infrared thin layer dried saffron (Torki-Harchegani et al., 2017). Of note, the E_a values from these two methods were very close and this explained that the drying activation energy was an essential property of the material, which was associated with the variety, composition, shape, and texture of the material, while independent of external conditions such as drying methods as well as drying parameters.

Fig. 2 SEM photographs of saffron under different drying conditions. (A) Naturally air-dried; (B) electric oven drying temperatures at 40 °C; (C) electric oven drying temperatures at 100 °C, (D) vacuum oven drying temperatures at 100 °C

Fig. 3 ISO 3632 quality standards of saffron at various temperatures and drying method. **(A)** Coloring strength, **(B)** aroma strength, **(C)** bitterness strength. Different lowercase letters above the bars indicate significant differences based on a Duncan test at a level of significance of $p < 0.05$. The error bars indicate the standard deviations of the three replicates

Microstructures of saffron changes under different drying condition

To investigate the changes in the product quality, especially the changes in texture drying process between different methods at different temperature level, the sample was analyzed by using scanning electron microscopy (SEM). The microstructures of saffron under different drying conditions are shown in Fig. 2. After electric oven drying at different temperatures, saffron formed varying degrees of cell interstices [Fig. 2(B), (C)]. We found at higher drying temperatures, the compactness between epidermal cells decreased, and the orientation of

protrusions became irregular as compared to naturally air-dried Saffron control [Fig. 2(A)]. This might be attributed to the slow moisture transfer inside naturally air-dried saffron, and an insignificant change in the surface microstructure due to moisture loss shrinkage. At lower electric oven drying temperatures, the moisture transfer decelerated, and some loose, porous structures were formed on the micro-surface of saffron. When the drying temperature was high, the moisture transfer rate inside the material and the moisture diffusion rate to the drying medium were both high. Massive stress was produced in the microstructure of material due to decreased moisture, and the degree of porous structure on the dry surface was intensified. This was consistent with the Carmona's observations on the high-temperature drying of saffron, which influenced the surface porosity of saffron samples (Carmona et al., 2005).

It is believed that changes in the material microstructure directly reflected the length of drying time. Naturally air-dried saffron had a compact microstructure, low surface dehydration rate and extended drying time. Irregular interstices structure was formed on the surface of electric oven dried saffron, which facilitated faster moisture transfer, and shortened the drying time. As shown in Fig. 2(D), the microstructure of 100 °C vacuum dried saffron had markedly elongated protrusions. Vacuum posed a certain degree of damage to the surface structure of saffron, which might be associated with moisture transfer during the drying process. The boiling point of water was directly proportional to the ambient pressure. Under vacuum conditions, the boiling point of water decreased. When the drying temperature reached or approached the boiling temperature, the moisture in the material boiled to the maximum evaporation state, which damaged the histological structure of the material.

Quality characteristics of saffron using ISO 3632 standards

We further investigate the quality of our dry saffron according to ISO 3632 quality standards which mainly including coloring strength, aroma strength, and bitterness strength. The results indicated that the coloring strength was significantly higher at high drying temperatures (80–100 °C) than the lower ones (40–60 °C) in both drying methods which consistent with Carmona's finding that high-temperature short-term drying yielded higher coloring strength than the low-temperature long-term drying (Carmona et al., 2005) [Fig. 3(A)]. We found that aroma strength increased with rising drying temperature. This was because aroma compounds were primarily safranal, which was produced by thermal dehydration of picrocrocin or 4-Hydroxy-2,6,6-trimethyl-1-cyclohexene-1-

Table 3 Quantitation of crocins and safranal in saffron samples submitted to different drying processes

Drying method	Drying temperature (°C)	<i>Trans</i> -crocins-4	<i>Trans</i> -crocins-3	<i>Trans</i> -crocins-4 + <i>trans</i> -crocins-3	Safranal
Electric oven drying	40	11.45 ± 0.38 ^c	7.34 ± 0.32 ^a	18.79 ± 0.29 ^c	N/A ^b
	60	10.50 ± 0.66 ^c	7.46 ± 0.16 ^a	17.96 ± 0.59 ^c	N/A ^b
	80	13.00 ± 0.76 ^b	7.47 ± 0.31 ^a	20.47 ± 0.45 ^b	0.27 ± 0.083 ^a
	100	14.58 ± 0.64 ^a	7.45 ± 0.26 ^a	22.03 ± 0.53 ^a	0.20 ± 0.092 ^a
Vacuum oven drying	40	11.62 ± 0.60 ^c	6.49 ± 0.34 ^a	18.11 ± 0.32 ^c	N/A ^c
	60	12.42 ± 0.42 ^c	5.89 ± 0.87 ^a	18.31 ± 0.49 ^c	N/A ^c
	80	13.73 ± 0.50 ^b	6.62 ± 0.27 ^a	20.35 ± 0.76 ^b	0.23 ± 0.081 ^b
	100	15.40 ± 0.32 ^a	7.03 ± 0.65 ^a	22.43 ± 0.93 ^a	0.43 ± 0.092 ^a

Different lowercase letters indicate significant differences based on a Duncan test at a level of significance of $p < 0.05$

carboxaldehyde (HTCC) (Kanakakis et al., 2004). Interestingly, we found that vacuum drying yielded slightly increased aroma strength compared to the electric oven drying, especially at lower drying temperatures [Fig. 3(B); Table 3]. Hossain et al. (2010) also found that vacuum drying preserved better antioxidant activity compared to freeze-drying due to more aromatic constituents with antioxidant capacity under vacuum drying for labiate herbs. However, the latest reports suggested that 330 nM was not obviously correlated with the content of aromatic constituent safranal (García-Rodríguez et al., 2017); and more accurate analytical technique was needed. The bitterness strength was followed the same trend as coloring strength [Fig. 3(C)]. According to our data analysis, vacuum drying environment might be conducive to the increased quantity of aromatic constituents.

Influences of drying conditions on chemical constituents of saffron

As the significant biological active constituents of saffron, the quantity of *trans*-crocins-4 and *trans*-crocins-3 was also one of the crucial indicators for quality evaluation of saffron. We found that the quantity of *trans*-crocins-4 from electric oven drying and vacuum drying was positively correlated with the temperature but not for *trans*-crocins-3. The sum of *trans*-crocins-4 and *trans*-crocins-3 is very similar in both drying methods (Table 3). Consistent with our results, Maghsoodi et al. (2012) study demonstrated that drying temperature at 90 °C for 47 min yielded the highest crocins content, which increased by 45% compared to drying at 60 °C for 95 min (Maghsoodi et al., 2012). Gregory et al. (2005) also found that drying of saffron at higher temperatures (80–90 °C) for 20 min followed by drying at a lower temperature (43 °C) till drying off resulted in an 18% difference in crocins quantity compared to the low-temperature drying (Gregory et al., 2005).

In this study, we also determined the quantity of safranal by HPLC. The expression of safranal can be detected when the temperature was higher than 80 °C. The safranal contents in the vacuum-dried saffron were in the range of 0.23–0.43%, which presented an increasing trend with rising temperature. In contrast, the safranal content in the electric oven-dried saffron was 0.27% at 80 °C but dropped to 0.20% at 100 °C. The data suggested that high temperature was required for safranal production during the saffron drying process, yet temperature had no definite relation with the yield of safranal. However, this theory remains controversial in the field. Some studies believed that the drying dehydration temperature was responsible for the production of safranal from picrocrocins (Himeno and Sano, 1987). However, other studies reported that the increase of drying temperature and the decrease of picrocrocins quantity could not lead to the production of safranal (Carmona et al., 2005; Tong et al., 2015).

In sum, considering the farmer production mode of Chinese saffron and costs of drying equipment, the most appropriate method of drying saffron is thin layer drying in the electric oven at 100 °C for 20 min. The expression for drying curve is $MR = 1.00003 \exp(-0.28551t^{0.8727}) - 0.00014$, by which the moisture ratio of saffron at a 100 °C drying temperature can be estimated, to better control the drying time and ensure the quality of saffron.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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