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Drying kinetics and quality attributes of jujube (*Zizyphus jujuba* Miller) slices dried by hot-air and short- and medium-wave infrared radiation

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ABSTRACT

As representatives of the traditional and innovative drying method, hot-air (HA) and short- and medium-wave infrared radiation (SMIR) drying were chosen to conduct comparative study, respectively. In the present study, drying kinetics of jujube slices during HA and SMIR drying at 60, 70, 80 and 90 °C were investigated, quality attributes such as color, vitamin C (VC), total flavonoids content (TFC) and cyclic adenosine monophosphate (cAMP) content of dried jujube slices were evaluated. Both HA and SMIR drying process occurred mainly in the falling rate period. Drying time used in SMIR drying was 33~83% of that in HA drying. Logarithmic model and Two-term model were the best in describing the drying process in HA and SMIR drying, respectively. D_{eff} values of jujube slices were varied from 1.43×10^{-8} to 2.28×10^{-7} m^2/s. Values of D_{eff} in SMIR drying were two times higher than HA drying. Jujube slices dried by SMIR revealed better color, higher retentions of VC, TFC and cAMP content than HA drying. Compared with HA drying, SMIR drying showed shorter drying time, higher drying efficiency and better quality of products, indicating SMIR drying was a more promising drying method for jujube processing.

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1. Introduction

Chinese jujube (*Zizyphus jujuba* Mill.), belonging to the plant family Rhamnaceae, is indigenous in China and widely consumed in more than 30 countries around the world (Fang et al. 2011). Jujube fruits are rich in various nutrients such as polysaccharides, protein, fat, fiber, vitamin C (VC), cyclic adenosine monophosphate (cAMP), mineral substances of iron and potassium and phenolics (Chang, Hsu, & Chen, 2010; Gao et al., 2011). As a Chinese medicinal herb, jujube is used as analeptic, palliative and antibechic in China (Li, Fan, & Ding, 2007). Jujube is also famous for its various biological activities including antioxidant (Chang et al. 2010; Guil-Guerrero, Delgado, González, & Isasa, 2004; Li, Ding, & Ding, 2005; Wang et al., 2012; Zozio et al. 2014), liver protection (Guil-Guerrero et al. 2004; Wang et al. 2012), immune-enhancing (Zhang et al. 2013) and antitumor (Fatemeh, Mohsen, & Kazem, 2008). Unfortunately, fresh jujube fruits present rapid ripening after harvest and could not be stored for more than ten days under ambient conditions (Zozio et al. 2014). Hence, it is very important to explore jujube preservation methods for extending its shelf life.

Drying is one of the oldest and efficient preservation techniques in food industries. Microbial spoilage and deterioration reactions are greatly minimized after water removed (Xiao, Gao, Lin, & Yang, 2010). Hot-air (HA) drying is the most widely applied in food industry which is free from the climate influences and reducing the drying cycle (Fang, Wang, & Hu, 2009). However, many researchers paid more attention to innovative techniques such as short- and medium-wave infrared radiation drying (SMIR) which not only maintain product quality, but also increase the drying rate. The wavelength of SMIR is in the range of 1–4 μm which covers the maximum absorption wavelength of water molecule. As a consequence, high heating speed is one of the most obvious advantages of SMIR. Moreover, infrared drying could save up 50% energy compared to convective drying (Nowak & Lewicki, 2004). Although, infrared drying has been applied to the dehydration of fruits, vegetables, traditional Chinese medicines and grains (Hebbar, Vishwanathan, & Ramesh, 2004; Nowak & Lewicki, 2004; Shi et al., 2008; Toğrul, 2005, 2006; Vishwanathan, Giwari, & Hebbar, 2013), the study on SMIR drying of different materials was relatively less.

Drying kinetics is very valuable for process optimization and product quality improvement, and it is also useful for analysis of the mass and heat transfer process during drying (Wang, Fang, & Hu, 2009). In the previous study, studies on dried jujube products

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including the whole jujube and jujube powder had been done. Thin-layer mathematical modeling of HA drying, microwave drying, HA combined with microwave drying for the whole jujube had been investigated (Fang, Wang, Hu, 2009; Fang, Wang, Hu, Datta, et al., 2009; Fang et al., 2010, 2011; Wang et al., 2009); optimization of spray drying and SMIR drying of jujube powder had been done by our team before (Bi et al., 2014; Chen et al., 2014). Besides, physicochemical properties of dried jujube were investigated. Increased hot air drying temperature increases the retention of Vc and browning degree of jujube (*Zizyphus jujuba cv. Beijingbenzao*), while decreasing shrinkage and the density (Fang, Wang, Hu, et al., 2009). Du et al. (2013) had done comparative study of quality changes of explosion-puffed and sun-dried jujubes (*Ziziphus jujuba cv. Lizao*). Results showed explosion-puffed jujubes had the highest total gallic, p-hydroxybenzoic, vanillic, p-coumaric, ferulic acids, and rutin contents. Changes of sugars, organic acids, α-tocopherol, β-carotene, phenolic profiles and total phenolic content of *Zizyphus jujuba cv. Muzao* after four drying treatments (sun-, oven-, microwave- and freeze-drying) were investigated by Gao, Wu, Wang, Xu, and Du (2012). Freeze-dried jujubes showed higher β-carotene content, while, microwave-dried jujubes had higher contents of protocatechuic acid, catechin, and epicatechin. However, little information is available to compare the drying kinetics and product quality of jujube slices dried with HA and SMIR. In the present study, a systematic study of both HA and SMIR drying was used to estimate the drying efficacy on jujube slices, drying kinetics and quality attributes (color, VC, total flavonoids and cAMP) of jujube slices were evaluated.

2. Material and methods

2.1. Materials and reagents

Fresh jujube (*Zizyphus jujuba* cv. *Zhanhuadongzao*) samples were harvested in October, 2013, from Shangdong Province, China. The average initial moisture content of jujube samples was 2.98 g/g expressed in dry basis (db), as measured by drying in the oven at 105 °C until the difference between two successive weighing was less than 2 mg (AOAC, 1984). Selected jujube samples were free from visible blemishes or damage. Jujube was stored at 4 °C in a refrigerator until used.

Methanol, monopotassium phosphate, sodium hydroxide, citric acid and oxalic acid were analytical grade, and purchased from Beijing Beihua Fine Chemicals Company (Beijing, China), 2, 6-Dichloroindophenol sodium salt hydrate (purity ≥ 95%) and cAMP (purity ≥ 99%) were obtained from Sigma–Aldrich Company (St. Louis, MO, USA). Rutin (purity ≥ 92%) was purchased from National Institutes for Food and Drug Control (Beijing, China).

2.2. Sample preparation

Fresh jujube was immersed in 20 g/L sodium hydroxide (NaOH) solution at 80 °C for 1 min to destroy the skin structure. Then, the jujube was taken out instantly and directly washed with running tap water to rinse out the NaOH from the jujube surface. After that, jujube was soaked in 5 g/L citric acid solution for 10 min for color protection. Finally, jujube was washed, pitted, sliced into eight parts, the thickness of each part was 6 mm.

2.3. Experimental procedure

Pre-weighed jujube slices (300 g) were dried in a HA drier (DHG-9240, Shanghai Bluepard Instruments Co., Ltd., Shanghai, China) and a laboratory-type SMIR dryer (Senttech Infrared Technology Co., Ltd., Jiangshu, China). The conditions of SMIR dry were air velocity of 2.11 m/s and infrared power of 1125 W. The size of sample tray in SMIR dryer was 31 × 37 cm, and the distance between the lights and the tray was 11 cm. The dryers were run for half an hour and 5 min prior to loading of samples to allow the heated air to stabilize at the desired temperatures (60, 70, 80 and 90 °C) both in hot-air and SMIR drying, respectively. The weight of jujube slices during drying experiment was measured by the digital top pan balance. The drying process would not stop until the equilibrium moisture content was achieved. Drying experiments were conducted in triplicate.

2.4. Theoretical considerations

2.4.1. Modeling of the thin-layer drying curves

Mathematical modeling of thin-layer drying is critical for investigation of drying characteristics and optimization of operating parameters in jujube drying process. Ten different commonly used moisture ratio equations given in Table 1 were taken into account for specifying the most adequate models in thin-layer drying of jujube. In these models, *MR* represents the dimensionless moisture ratio. The calculation of MR was according to the method of Xiao et al. (2010).

2.4.2. Correlation coefficients and error analyses

Nonlinear regression was used to obtain each constant of the selected mathematical models. The fitting of a model to experimental data was evaluated with the adjusted coefficient of determination (*Adj.* R^2), the reduced chi-square (χ^2) and the root mean square error (*RMSE*). The highest value of *Adj.* R^2, the lowest values of χ^2 and *RMSE* (close to zero) were chosen for goodness of fit (Wang et al., 2007).

2.4.3. Effective moisture diffusivity

The falling rate period can be described by using Fick's diffusion equation for the drying characteristics of biological products (Wang et al. 2007). The effective moisture diffusivity (D_{eff}) of jujube slices could be calculated by equation (7) proposed by Crank (1975) based on the assumptions that mass transfer is by diffusion only, diffusion coefficient is constant and no shrinkage (Sharma, Verma, & Pathare, 2005).

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff} t}{4L^2}\right) \quad (1)$$

where D_{eff} is the effective moisture diffusivity (m^2/s), L is the thickness of jujube slices (m), t is the time (s).

Equation (1) could be rewritten as:

$$D_{eff} = L^2 \times (-0.101 \ln MR - 0.0213)\big/t \quad (2)$$

2.5. Physicochemical properties of the jujube slices

2.5.1. Color

Color of fresh and dried jujube slices was measured in terms of the CIE L^*, a^*, b^* values using a colorimeter (D-25L, Hunterlab, USA). Prior to determination, the colorimeter was calibrated with a standard white ceramic plate. L^* value represents the degree of lightness to darkness, a^* value indicates the degree of redness (+) to greenness (−), and b^* value is the degree of yellowness (+) to blueness (−) (Duangmal, Saicheua, & Sueeprasan, 2008). The total color difference (△E) was determined by these parameters using the following formula:

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