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Pulsed vacuum drying enhances drying kinetics and quality of lemon slices

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ABSTRACT

The effect of drying temperature (60, 65, 70, and 75 °C) on drying characteristics, shrinkage, rehydration kinetics, microstructure and color profiles of lemon slices were investigated using a far-infrared radiation heating assisted pulsed vacuum dryer. Results showed that the drying time of lemon slices was reduced from 10.5 to 5.5 h when the drying temperature was increased from 60 to 75 °C. Weibull model could precisely describe the drying of samples under different drying temperatures ($R^2 > 0.99$). Moisture effective diffusivity (D_{eff}), which was determined by taking shrinkage effect into consideration, varied with moisture content. At the initial drying stages, the volume shrinkage of samples followed a linear relationship with decreasing moisture content as the volume shrinkage is approximately equal to the volume of evaporated water. Microstructure observation illustrated that the “skeleton” was fixed when moisture content decreased to approximate 60% w.b. Page model could well model the rehydration kinetics ($R^2 > 0.98$). In terms of color evaluation, temperature of 75 °C significantly caused color deterioration and it recorded the highest color change (ΔE) of 14.23, Browning Index (BI) of 27.14 and lowest Hue Angle (H^0) of 79.46. The findings indicate that FIR-pulsed vacuum drying is a promising alternative method for lemon slices as it can enhance drying process as well as preserve the quality attributes of lemon slices.

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1. Introduction

Lemon (*Citrus limon* (L.) Burm. f), is a popular fruits with attractive color, aroma and rich in nutrients such as ascorbic acid, citric acid, flavonoids and minerals etc (González-Molina et al., 2009; Lorente et al., 2014). Drying is one of the most frequently used methods for lemon preservation as a reduced moisture content can hinder growth and reproduction of microorganisms, and minimize many moisture-mediated deteriorative reactions (Xiao et al., 2012). The quality attributes of products in terms of color, rehydration capacity and appearance are affected by pretreatment, drying technology as well processing conditions employed (Deng et al., 2017).

Open sun-drying is still practised for lemon dehydration in almost all lemon-growing countries, especially for small scale production, which results in yellowish-brown, nonuniform shrinkage and contamination of products which are undesirable (Sadeghi et al., 2013). In addition, the open sun-drying method has several disadvantages, such as long drying time, rotting or rewetting caused by poor weather, dust and insects pollution (Xiao et al., 2015). Hot-air drying method is widely applied in industrialized production of agricultural materials due to the simple equipment, diversified form of energy utilization, mass production etc. (Chen et al., 2005; Sadeghi et al., 2013). However, hot-air drying can cause some undesirable quality changes in products including browning, oxidation, and case hardening as well as degradation of

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nutrition and flavour's due to prolonged exposure to high air temperature or long processing time which leads to product degradation. Therefore, in order to improve drying process to minimize color and nutrients loss, the traditional open sun-drying and hot air drying methods may be replaced by a more efficient and advanced drying technologies.

In fact, many investigations have been carried out to explore alternative drying technologies, kinetic modelling and quality attributes during lemon slices drying. The closed-type dryer associated with a photovoltaic system, microwave, combined microwave-convective and air-ventilated oven dryer have been employed in lemon drying (Chen et al., 2005; Sadeghi et al., 2013; Torki-Harchegani et al., 2016; Torki-Harchegani et al., 2015). These technologies can shorten drying time and improve quality of lemon slices compared with the traditional open sun drying method. However, how to protect the product's color is still a challenge as browning reactions often occur during drying process due to oxygen. The Dincer and Dost model could well predict mass transfer for all treatments of lemon slices during convective, microwave and combined microwave-convective drying (Sadeghi et al., 2013), while the Midilli and Kucuk model fitted the experimental data well during air-ventilated (Torki-Harchegani et al., 2016). As the main by-product, drying of lemon peel is crucial for its functional component content and sensory quality. There are many researches focused on the pretreatment methods to enhance the drying rate and the quality of dehydrated lemon peel, such as ultrasound (García-Pérez et al., 2009; Garcia-Perez et al., 2007). However, thus far hot air drying is still the main drying method employed in the lemon processing industry in producing dehydrated lemon peel.

Pulsed vacuum drying (PVD) is a novel drying technology developed in recent years, which uses successive change of vacuum pressure in the drying chamber to enhance moisture transfer during drying process (Xie et al., 2017a). During PVD processing, the pulsed vacuum environment creates an oxygen deficient environment, which can reduce adverse biochemical reactions, such as oxidation deterioration, browning reactions and thereby improve the quality attributes of dried products (Bai, 2014; Xie et al., 2017a). Additionally, pressure pulsation results in a tunneling effect to enlarge and interconnect the micropores in the products (Moreno et al., 2016) and periodic pressure change can generate porous and fissured structures in the peel, that enhances the mass transfer through them (Mounir et al., 2014). With so many advantages, PVD has been employed in the drying of wolfberry (Xie et al., 2017a), rhizoma dioscoreae (Xie et al., 2017b) and seedless grape (Bai, 2014).

Shrinkage, color and rehydration capacity are frequently used to evaluate the quality of dried products. During drying volume of sample decreases and due to moisture loss, surface area also simultaneously shrink, which significantly influence the drying process and the products quality attributes such as rehydration capability and texture (Koua et al., 2017; Ramallo and Mascheroni, 2012). Therefore, the relationship between shrinkage and moisture changes deserves more attention. Color is one of the most important quality attributes as the first quality judgment made by a consumer is by the products color and it influences consumer's food choices, perceptions, and purchase behaviour (Nourian et al., 2003). Color is also an indicator of thermal processing severity and it can be used to predict the corresponding quality deterioration caused by heat exposure (Pathare et al., 2013). Dried lemon slices are usually consumed as lemon tea, which is prepared or produced via a rehydration process. It is a complex process composed of two simultaneous processes: the absorption of water by dried product and the diffusion of soluble (Cunningham et al., 2008). Rehydration capability is one the important quality attributes for dried products as it could indicated the physico-chemical changes such as cellular structure and water holding capacity (Zielinska and Markowski, 2016). Rapid and complete rehydration is a desired property of dried products. However, to the best of our knowledge, no reports have been found detailing the effect of pulsed vacuum drying on drying kinetics, shrinkage, color and rehydration capacity of lemon slice.

Therefore, the objectives of this study are: 1) to explore the pulsed vacuum drying characteristics of lemon slices under different drying temperature via drying curves, further, study the Weibull and first-order model, and determine moisture effective diffusivity, 2) to analyze the shrinkage ratio versus moisture content during pulsed vacuum drying processing, as well as the microstructure observation, 3) to measure the rehydration kinetics and establish the mathematical model of shrinkage using Page model, 4) to evaluate the product color attributes in terms of a^*, b^*, L^*, total color difference (ΔE), browning index (BI) and hue angle (H^0).

2. Materials and methods

2.1. Materials

The fresh ripened lemons (*Citrus limon* (L.) Burm. f, Sichuan Anyue variety) were purchased from Qinghe vegetable market, Beijing. All samples were stored in a refrigerator at 4 °C and 90% relative humidity prior to experiments. To ensure uniformity of the physical characteristics of samples, lemons with the same size (average diameter, length and weight were 63 ± 3 mm, 86 ± 3 mm, and 145.8 ± 3.8 g, respectively) were selected. The initial moisture content (85.29 ± 1.61%, w.b.) of samples were determined by vacuum drying at 70 °C for 24 h.

2.2. Pulsed vacuum dryer

Pulsed vacuum dryer installed in the College of Engineering of China Agricultural University, Beijing, China was used in the present study. A schematic diagram of the pulsed vacuum drying equipment is shown in Fig. 1. The PVD equipment mainly consists of heating, cooling, control and vacuum systems, which have been described in detail by Xie et al. (2017a). A vacuum pump (2BV4-2060, Bo-Tong, Shanghai, China) is used to regulate the pressure within the drying chamber. The pressure is measured with CYYB-110 Pressure Transmitter (Shi Da Chuang Ye, Beijing, China) in drying chamber. The thermocouple signals are collected by SHT75 sensors (Sensirion, Shenzhen, China). A Proportional-Integral-Derivative (PID) controller (Omron, model E5CN, Tokyo, Japan) with accuracy of ±0.1 °C is used to control the temperature of water tank and pressure in the drying chamber. An electromagnetic valve isolates the pressure chamber from the ambient air and adjusts the air flow rate from the ambient back into the chamber. Both pressure and thermocouple signals are shown in real time in the touch screen (Weinview, Shenzhen, China). The minimum pressure level that the system can produce is 8.0 kPa (0.08 bar) and the time taken for the system to reach this minimum pressure from atmospheric pressure is approximately 40 s.

The drying chamber pressure change kinetics during PVD is shown in Fig. 2. During drying, air is expelled from the drying chamber to a pre-set vacuum state and maintained for a predetermined time. This step is followed by a pressure recovery step where it is held for specified duration. This procedure varies according to the properties of the treated products and the operating conditions (e.g., drying temperature, vacuum amplitude, intermittent time). P_A and P_V indicate the highest and lowest pressure in drying chamber. The t_{AP} and t_{VP} are the duration at the highest and the lowest pressure, respectively. The t_s and t_d are the time required

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