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A novel dehydration technique for carrot slices implementing ultrasound and vacuum drying methods

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ABSTRACT

A novel drying technique using a combination of ultrasound and vacuum dehydration was developed to shorten the drying time and improve the quality of carrot slices. Carrot slices were dried with ultrasonic vacuum (USV) drying and vacuum drying at 65 °C and 75 °C. The drying rate was significantly influenced by the drying techniques and temperatures. Compared with vacuum drying, USV drying resulted in a 41–53% decrease in the drying time. The drying time for the USV and vacuum drying techniques at 75 °C was determined to be 140 and 340 min for carrot slices, respectively. The rehydration potential, nutritional value (retention of β-carotene and ascorbic acid), color, and textural properties of USV-dried carrot slices are predominately better compared to vacuum-dried carrot slices. Moreover, lower energy consumption was used in the USV technique. The drying data (time versus moisture ratio) were successfully fitted to Wang and Singh model.

1. Introduction

Carrots (*Daucus carota* L. subsp. *sativus*) are one of the most widely cultivated and consumed vegetables throughout the world [1–3]. In recent years, the consumption of carrot and its related products has increased steadily based on their higher concentration of carotene compared to other foods [1–3]. Carrots are a high-moisture food with moisture content of 90 g/100 g on a wet basis [2]. The dehydration of carrots seems to be a convenient alternative for long-term storage or usage. Dried carrots are used as an ingredient in various food products, such as soups, sauces, ready-meals as well as healthy snacks [4,5]. The high content of carotene is a unique property that makes dried carrot slices an excellent candidate for developing oil free, healthy snack foods. However, the nutritional value must be well preserved and a puffed texture should be generated in the drying process.

Dehydration, or drying, involves transient heat and mass transfer accompanied by physical, chemical, and phase change transformations. Unfortunately, these transformations may cause changes in the product's quality as well as the mechanisms of heat and mass transfer [6]. Presently, drying with hot air is the most widely used method. However, long drying times and overheating of surface during hot air drying consequently result in color darkening, loss of flavor, and decrease in rehydration ability [7]. Freeze drying produces a high quality product, but its application for vegetable drying is limited as it is an expensive process. Vacuum drying is another alternative method and is especially suitable for products that are prone to heat damage like fruits and vegetables. However, in vacuum processes that require heat, the transfer of heat energy to the workload becomes difficult since convection is ineffective at low pressure [7].

In recent years, attempts have been made to shorten the drying period and to improve the energy efficiency of the drying process and quality of the dried products [8]. It is possible to enhance the quality of the dried products by decreasing the drying temperature or shortening the drying time [8].

Ultrasonically assisted drying has been a topic of interest for many years. Ultrasound can be employed as a pre-treatment before drying to improve the drying kinetics and to reduce the energy costs involved in the unit operation [9,10]. On the other hand, many studies on the direct use of ultrasound during drying have been reported [10–13]. Applying ultrasound interrupts the continuity of the cytomembrane, and thus increases the mass transfer rate between the cell and its extracellular surroundings [10]. Ultrasound applied during dehydration process has proven to improve the quality of dried food due to its non-thermal character [10]. Moreover, the drying time can be reduced, and the process can be performed at lower temperature, which is notably significant for products containing thermolabile substances [11–13].

Although previous research suggests that ultrasound treatment can be used in many ways to accelerate drying processes, it is

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rarely connected with vacuum drying. Therefore, this work presents a new drying method by combining ultrasound and vacuum processes. In this method, the advantages (e.g., increase efficiency of heat energy transfer and accelerate dehydration) of both combined processes are used to shorten the drying period and improve the quality of dried food. The influences of drying technology on drying kinetics, dried material quality, and energy efficiency were investigated. To our knowledge, no studies have yet to be conducted on the combined use of ultrasound and vacuum to dry carrot slices or any other fruits and vegetables products.

2. Materials and methods

2.1. Materials

Carrots were purchased at a local market followed by a washing and then vertically sliced into disks before drying. The carrot samples were 2–3 cm in diameter and approximately 4 mm thick. β-Carotene and ascorbic acid standards were purchased from Sigma–Aldrich (St. Louis, USA). All other chemicals used in this work were purchased from commercial sources in China and were of analytical grade.

2.2. Physicochemical properties of carrot samples

Dry matter content of sliced carrot was determined by a modified procedure of AOAC (1995) [14]. Carrots samples were dried at 105 °C in a drying oven until constant weight was reached. The total carbohydrate content in the carrot samples was quantified by the phenol–sulfuric acid colorimetric method using glucose as the standard [15]. Protein content of the samples was determined by the Kjeldahl method (AOAC 1995), and the factor 6.25 was used for calculation [14]. Fat content of samples was determined by the Soxhlet method and was extracted from the dried material with hexane by the Soxhlet extraction system (BSXT-02, Shanghai Bilon Instrument Co., Ltd., China). After evaporation of hexane by a rotary evaporator, the extracted fat was weighed and was divided by initial weight of the carrot sample to determine the total fat content. Ash content of the carrot was determined by incinerating it at 600 °C for 5 h in a muffle oven (ZDGW3-4-1400, Shenzhen, China).

2.3. Drying of carrot slices with USV and vacuum drying techniques

The USV technique is composed of an ultrasound water bath (40 kHz, 200 W; Type: NP-B-400-15; volume: 10 L; Newpower Co. Ltd., Kunshan, China) equipped with a digital timer, a temperature controller, and a vacuum pump as shown in Fig. 1. In this technique, 500 g samples of carrot slices were put into a conical flask, which was connected to a vacuum pump (Fig. 1). Then, vacuum treated sample was sonicated using an ultrasonic bath. Ultrasonic mode is 10 s on and 5 s off. The bath temperature was maintained within ±1 °C. The weight of the carrot slices dried with the two different techniques at various temperatures was measured every 20 min. Vacuum drying of carrot slices was carried out in vacuum drying apparatus (DZG-6021, Shanghai Senxin Instrument Co., Ltd., China). In both methods used, the vacuum degree was maintained between 0.02 and 0.03 MPa. In this study, 65 °C and 75 °C were chosen as drying temperatures because these two temperatures are often used in traditional hot-air drying.

2.4. Mathematical modeling of drying kinetics

In hot-air drying, moisture level of the final product is about 12–13%. So this moisture level was considered as the final dehydration in our research. Carrot slices were dried with USV drying and vacuum drying at 65 °C and 75 °C until about 12% moisture content (dry base) was obtained. The moisture ratio (MR) in the sample is calculated using Eq. (1):

$$\mathrm{MR} = (w - w_e)/(w_0 - w_e) \quad (1)$$

where w is the moisture content at any time; w_e is the equilibrium moisture content; and w_0 is the initial moisture content of the carrot samples. In the present study, this equation was simplified to MR = w/w_0 considering that w_e is negligible compared to w or w_0 [16].

The effective moisture diffusivity (D_{eff}) was calculated according to Eq. (2) for carrot samples [17].

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

where D_{eff} is the effective moisture diffusivity (m^2/s); and L is the half thickness of carrot slice.

Moreover, in the present study, the obtained drying data (time versus MR) were also modeled by 10 different empirical models and equations of them are presented in Table 1 [18,19].

2.5. Quality evaluation

2.5.1. Color analysis

The color of the samples was measured using a Spectrophotometer (PC-1, Shanghai Jia Bao Testing instrument Co., Ltd.) and reported using the Hunter Lab color scale. The scale pronounces L is the lightness, a is the red/green coordinate, and b is the yel-

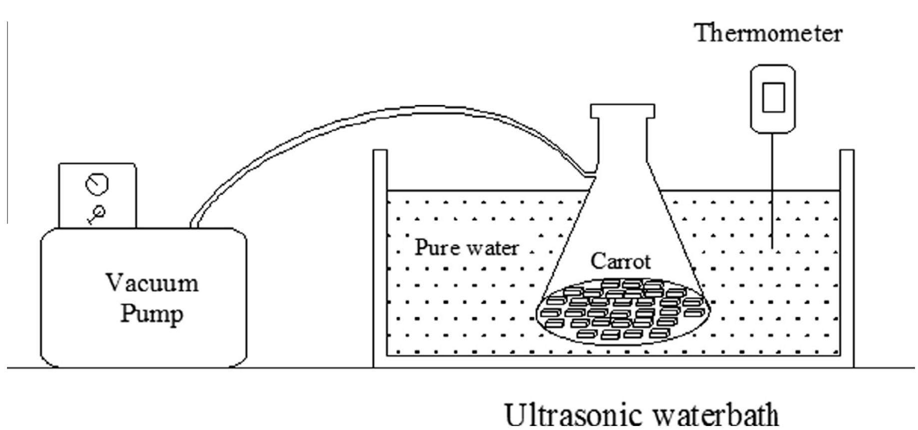

Fig. 1. A schematic view of the novel drying technique composed of ultrasound and vacuum systems.