Comparative study on the effects and efficiencies of three sublimation drying methods for mushrooms

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Abstract: Freeze drying (FD) yields the best quality of dried mushrooms but needs long drying time and higher cost. Air drying (AD) gives relatively poor product quality. In order to achieve faster drying along with high product quality, microwave freeze drying (MFD) and atmospheric freeze drying (AFD) were developed to dry mushrooms. By comparison of three sublimation drying processes, it was concluded that FD could lead to the best product quality, but cost the highest energy consumption. AFD mushrooms had the worst quality and longest drying time, but the lowest energy consumption. Compared with FD and AFD, MFD could get relatively acceptable quality and drying efficiency. As a result, MFD can be used to replace traditional FD, and AFD also should be popularized because of its low energy consumption.

Keywords: mushroom, freeze drying, microwave freeze drying, atmospheric freeze drying

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1 Introduction

Mushrooms are popular and valuable foods, which are low in calories but higher in minerals, protein and fiber[1]. Their beneficial biochemical properties have also attracted much attention as functional health foods[2,3]. Mushroom annual production has increased to more than 25 million tons in China, which account for about 70 percent of the total yields of the world. The button mushroom (*Agaricus bisporus*) is the most widely cultivated and consumed mushroom throughout the world and it contributes about 40% of the total world production of mushroom[4]. The button mushrooms are extremely perishable and their shelf life is only about 24 h in ambient conditions. Various physiological and morphological changes occur after harvest, which make these mushrooms unacceptable for consumption[5]. Hence, they should be consumed or processed promptly after harvest and for this reason the mushrooms are traded mostly in dried form in the world market.

In China, the convective method is the most commonly used to dry mushrooms. Nevertheless, due to long drying time and high drying temperature at industrial scale, the problems of darkening in color, shrinkage, loss in flavor and decrease in rehydration ability easily occur. Freeze dried (FD) foods are characterized by high quality characteristics such as low bulk density, high porosity, superior taste and aroma retention including better rehydration properties, when compared to products processed by using alternative drying processes. However, it is well known that FD is an expensive process, and its application for mushroom drying is limited[6]. The desire to prevent significant quality loss

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and to achieve low energy consumption has resulted in increasing use of new methods for mushroom drying.

One way to reduce the costs of freeze drying is to avoid the need of a condenser for sublimated vapor, enhancing the contact between the heat and mass transfer phases, and operating the process at near-atmospheric pressures. It was found that the diffusion of water vapor from the drying boundary through the dried shell was facilitated primarily by the vapor pressure gradient, rather than by the absolute pressure in the system[7]. Hence, freeze drying is possible at atmospheric pressure if the partial pressure of water vapor in the drying medium is kept low enough to provide a mass transfer driving force for water vapor transfer from the frozen sample. This drying method can be called as atmospheric freeze drying (AFD). The use of heat-pump dryers (HPD) operating at atmospheric pressure and in freeze-drying mode can fulfill such requirements[8]. The main advantage of using AFD technology is the energy-saving potential[9].

Microwave drying is rapid, more uniform and energy efficient compared to conventional hot-air drying[10]. Used as the heat source of freeze drying, microwave can heat the material volumetrically[11] in a vacuum environment thus may greatly improve freeze drying rate, and this technique is called as microwave freeze drying (MFD). In recent years, MFD has been investigated as a potential method for obtaining high quality dried food products with low energy consumption[12-17].

Although both AFD and MFD have been investigated as the potential method to obtain high quality dried product for several years, there is no report about comprehensive comparison of three sublimation drying methods (FD, AFD and MFD). Especially for AFD and MFD, the effect of drying process on the quality of dried mushrooms is uncertain.

The objective of this paper was to examine effects of FD, MFD and AFD on the physical characteristics, microstructure and sensory evaluation of dried mushrooms.

2 Materials and methods

2.1 Materials

Fresh button mushrooms (*Agaricus bisporus*) were obtained from local market. Prior to dehydration, mushrooms were thoroughly washed to remove dirt and graded by size to avoid the variations in respect to exposed surface area. Then, surface water of the sample was removed by centrifugation. Slices of desired thickness were obtained by carefully cutting mushrooms vertically with a vegetable slicer and the slices from middle portions with characteristics mushroom shape were used for drying experiments without any pretreatment. They were immediately frozen at -25℃ for at least eight hours. The initial moisture content of the button mushrooms was 90% (wet basis).

2.2 Microwave freeze dryer

A microwave freeze dryer was developed by authors to perform MFD experiments[14]. An independent polypropylene drying cavity was set up in a rectangle resonant cavity, which could effectively avoid the corona discharge at the vacuum condition. The pressure of the drying cavity was operated at a range of 10 Pa to 30 kPa (absolute pressure). The power of microwave could be adjusted continually. The core temperature of materials was detected by the optic fiber sensor. The surface temperature of materials was detected by infrared thermometer. A schematic diagram of the dryer is presented in Figure 1. To avoid non-uniform distribution of the microwave field, three magnetrons were placed at different angles.

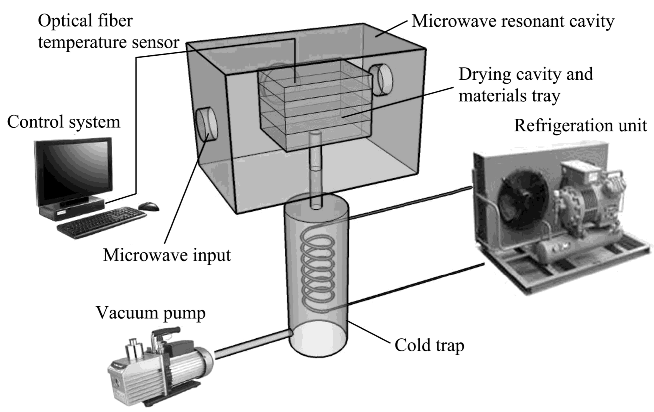


Figure 1 Schematic diagram of microwave freeze dryer

2.3 Atmospheric freeze dryer

The atmospheric freeze dryer was shown in Figure 2 and it had closed circuits for the drying air loop. To avoid heat losses all the necessary parts of the dryer were properly insulated. The cylindrical drying chamber is

0.4 m in diameter and 0.8 m in length. In the drying circuit the air was cooled in the evaporator and the condensed moisture was drained. Cold air was heated with both condenser and heating coils to secure inlet drying temperature from -10℃ to 40℃. The relative humidity (RH) of the inlet air was approximately 30% and the air velocity was about 1.5 m/s. The product slices were placed on perforated shelves in the drying chamber. Sensors placed at different points of the HPD allowed monitoring and continuous recording of the inlet-outlet conditions for each relevant component. All drying circuit is made of stainless steel for easy cleaning.

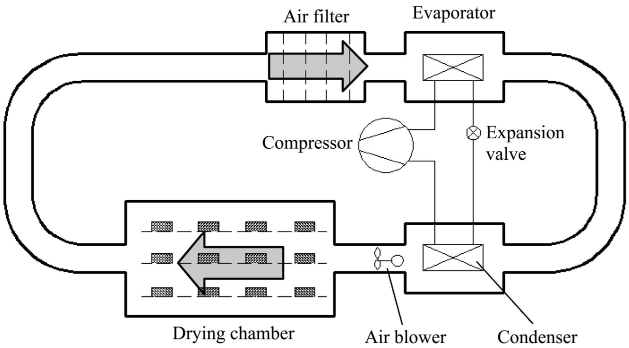


Figure 2 Schematic diagram of microwave freeze dryer

2.4 Drying experiments

The frozen mushroom slices were dried by different drying methods until the final moisture content was less than 7% (wet basis). These methods were described below.

1) The FD process

The frozen materials (500 g) were dried by a freeze dryer (LG-0.2, Shenyang Areo Space Xinyang Quick Freezing Equipment Manufacture Co. Ltd., China). Heating shelf temperature and cold trap was set at 60 ℃ and -40℃ respectively. The pressure of drying chamber was set at 50 Pa during drying process.

2) The MFD process

The frozen materials (500 g) were dried by the microwave freeze dryer. Microwave power and cold trap was set at 1 kW and -40℃, respectively. The pressure of drying chamber was set at 50 Pa during drying process.

3) The AFD process

The frozen materials (500 g) were dried by the atmospheric freeze dryer. Air temperature was set at -10℃ from 0 to 16 h, and 40℃ from 16 h to the end of the drying process respectively.

2.5 Analysis of samples

1) Moisture content

Moisture content was determined by the oven method[11]. At regular time intervals during the drying processes samples were taken out and dried in the oven for 7-8 h at 105℃ until constant weight. Weighing was performed on a digital balance, and then moisture content (wet basis) was calculated. The tests were performed in triplicates.

2) Rehydration ratio (*RR*)

The dried samples were soaked in 25℃ distilled water for 10 min, and then put on the filter paper of a Büchner funnel, which was held on a suction flask evacuated for 30 s to remove free water on the surface. The sample weighing was performed in triplicate. The rehydration ratio (*RR*) was estimated as $RR=W_d/W_r$, where W_d and W_r were the weights (g) of samples before and after rehydration, respectively. These tests were performed in triplicates.

3) Bulk density

Spiked millet substitution method was used to detect the volume of dried samples. The granularity of spiked millet is between 0.9-1.1 mm[18]. The experiment was replicated three times. The bulk density ρ of the dried material is defined as:

$$\rho=m/V \quad (1)$$

Where, m is the mass of dried slices, kg; V is total volume of dried slices, m^3.

4) Texture analysis

A TA-XT2i Texture Analyzer (Stable Micro Systems Ltd., Vienna Court, Surrey, UK) was used to measure the hardness and crispness. The cylinder penetrometer probe (5 mm in diameter) was passed through the sample with the test parameters set as: 2 mm/s of pre-speed and post-speed, 2 mm/s of test speed and 20 g trigger. In the penetration test, hardness is the maximum force required to break the sample, and crispness denotes if the sample fractures in an abrupt manner after applying a relatively small force (the first peak force) on the sample. Eight samples were used in each treatment.

5) Shrinkage ratio (*SR*)

Ten pieces of samples undergoing different treatments were used to determine the degree of shrinkage in terms of the volume change ratio. The degree of shrinkage was calculated using the volume of the sample at the end of drying process along with its initial volume as shown in following equation:

$$SR=V/V_0 \quad (2)$$

Where, V is the volume of mushroom after drying, m^3; V_0 is the volume of mushroom before drying, m^3. The sample volume (V) was determined by n-heptane displacement. The weight of the sample displaced in n-heptane was measured using a digital balance. The average values of ten samples were then reported.

6) Determination of ascorbic acid

Ascorbic acid content was determined using the standard 2,6-dichloro-indophenol titration method[19]. Data were calculated on dry basis and expressed as micrograms per 100 g solids, and the total vitamin C (Vc) retention at the end of drying was calculated. The analyses were carried out in triplicates.

7) Color evaluation

The appearance of samples was assessed by a color-difference meter technique. Color measurement numerically defines any color in terms of Hunter parameters L, a, and b (L=0 is black and L=100 is white). The button mushrooms will brown during drying process, so the color of dried mushrooms was described by the extent of browning. Browning was determined by changes in reflectance L-values. The color of dried samples was measured using a spectrocolorimeter (Model WSC-S, Shanghai Shenguang Instrument and Meter Co., Ltd., Shanghai, China), and each treatment was determined in triplicates.

8) Microstructure analysis

A small specimen (ca. 5 mm×5 mm×3 mm) was cut from the dried sample and placed in a fixative containing 3% glutaraldehyde overnight at 4℃. The specimens were then rinsed in a phosphate buffer, post-fixed in 1% osmium tetroxide in phosphate buffer and dehydrated in a serial ethanol solution containing 30%, 50%, 70%, 90% and 100% ethanol for 15 min in each solution. After critical point drying, the dehydrated samples were sputtered immediately (CPD-030, BAL-TEC Company). Finally, the specimen fragments were mounted on aluminum stubs, coated with gold and photographed using a scanning electron microscope (SEM) (Quanta-200, FEI, Eindhoven, The Netherlands) using an accelerating voltage of 5 kV.

9) Energy consumption

The total energy consumption during drying process was measured by an ammeter (Le Qing Electrical Energy Instrument Ltd., Shanghai, China), and the energy consumption required to remove 1 kg of water was calculated.

2.6 Statistical analysis

Analysis of variance (ANOVA) and the test of mean comparison according to Tukey's honest significant difference (HSD) were conducted at the level of significance of 0.05. The statistical software of SPSS System (version 10.0) for Windows was used for the analysis.

3 Results and discussion

3.1 Effects of drying methods on drying rates of mushrooms

As shown in Figure 3, the drying rate of AFD was the slowest, and followed by FD. MFD could lead to the most rapid drying rate. Drying curves shown in Figure 3 indicated the drying time for the AFD and FD process was 24 h and 15 h, respectively while the drying time of MFD was 8 h. It suggests that microwave application can strengthen heat and mass transfer, resulting in increase of the drying rate, as expected. This phenomenon agrees with many reports about microwave drying methods[4,6]. The drying curve of AFD showed an evident two-stage tendency because the air temperature applied two levels (-10℃ and 40℃). The most important method of AFD is convective drying at temperatures below the freezing point of the product. Nevertheless, lower air temperature reduces the ability to remove moisture. As a result, generally a step-up temperature program is performed in AFD process in order to improve drying rate. Compared to FD, the temperature is higher. What is more, a food product undergoing AFD has a freezing point depression due to reduction in solvent fraction while increasing the solute concentration[20]. As a result, ice thawing is easier to take place in AFD than in traditional FD. Therefore, low air temperature should be applied when the moisture content of the samples is high. In order to reduce the drying time, air temperature can be increased after most water is removed.

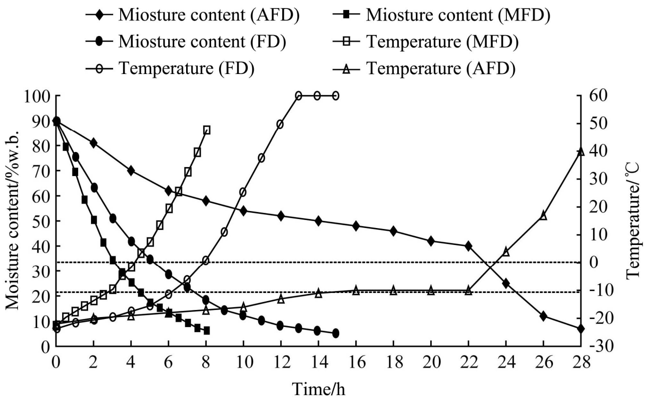


Figure 3 The profiles of product temperature and moisture content during different drying processes

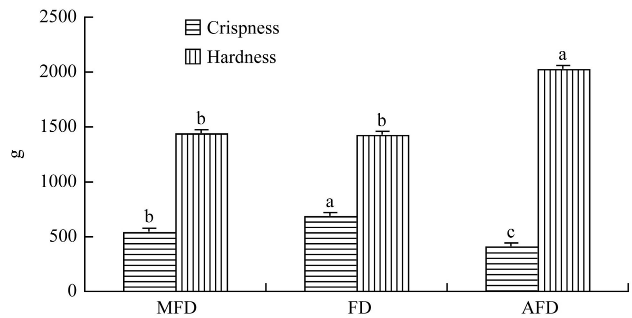
3.2 Effects of different drying methods on product quality and energy consumption of drying

Table 1 shows the result of rehydration ratio, *L*-value, shrinkage ratio, bulk density and Vc preservation rate of the products dried by the three different drying methods. It can be seen that the AFD products have lower *L*-value than that of MFD and FD products, which means AFD leads to more browning. The possible reason is that AFD is carried out at atmospheric condition resulting in some oxidation reaction. Besides, it can be seen that the bulk density of AFD samples is the biggest, followed by that of FD and MFD products, respectively. Microwave application leads to reduced shrinkage and thus provides a more porous structure in vacuum environment[21]. This can be used to explain that the bulk density of MFD products was lower than that of FD products. The bulk density of AFD products is higher than MFD and FD samples because AFD also leads to a more significant shrinkage than that of FD and MFD (Table 1). On the other hand, the Vitamin C content of AFD products was higher than that of FD samples. The possible reason is that most of AFD process undergoes low temperature resulting in preventing Vitamin C from degradation as it is a heat sensitive component. From Table 1, it also can be found that the rehydration ratio of AFD samples is the lowest, and FD can lead to the highest rehydration capability. It is well known that the more water is removed by sublimation, the better form and structure can be retained during drying[22]. Therefore, it is likely that AFD treatment leads to more water thawing, which removed by evaporation rather than sublimation, resulting in the porous structure destroyed.

Table 1 Effects of different drying methods on the dried product quality

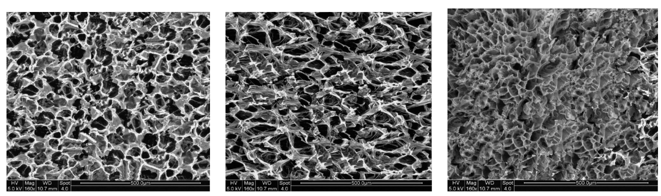
Drying	*L*-value	Bulk density /g·cm^{-3}	RR	SR	Vc preservation rate/%
MDF	60.28±2.42b	0.20±0.02c	4.66±0.24b	0.68±0.24a	72.42±2.21c
AFD	42.46±2.38c	0.38±0.02a	3.42±0.28c	0.51±0.28b	84.64±3.18a
FD	62.26±2.22a	0.22±0.01b	5.38±0.42a	0.69±0.22a	80.68±2.46b

Texture is considered one of the most important criteria concerning consumer acceptance of dehydrated foods. What is more, it also can reflect the quality of drying products. For example, higher hardness and lower crispness generally imply more shrinkage and deformation[18]. Figure 4 gives results of texture tests. The hardness of AFD samples was the highest, and its crispness was the lowest. The possible reason is that AFD leads to a higher shrinkage, which agrees with the result of shrinkage test mentioned above. Moreover, from the SEM pictures (Figure 5), it can be observed that FD and MFD result in a more clearly porous structure, which explains low hardness of FD and MFD products. Thus, it can be concluded that shrinkage and porous structure are dominant effects on the texture of dried products.



Note: Different letters a, b indicate a significant difference (p<0.05).

Figure 4 Effects of different drying methods on the texture of dried products

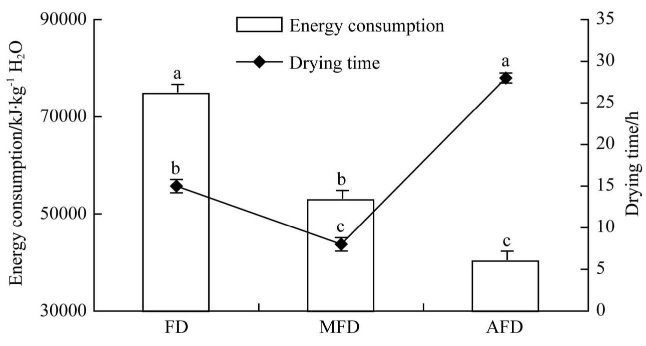


a. MFD b. FD c. AFD

Figure 5 Effects of different drying methods on the microstructure of dried products

From discussion above, it can be concluded that AFD leads to stronger browning reaction, shrinkage, bulk density and less rehydration capability compared with FD and MFD treatments. The only advantage of AFD product is its higher Vc preservation rate. According to some reports[22], the co-melting temperature of vegetables is about -10℃. From Figure 3, it can be observed that about 55% of total water was removed below -10℃ during the MFD process, and about 60% of the total water was removed below -10℃ during the FD process. While, only less than 50% of water was removed below -10℃ during the AFD process, which implies that more than 50% of water was removed by evaporation rather than by sublimation during the AFD process, resulting in more deterioration of color and structure. This is an obvious disadvantage of AFD, which needs to be resolved in the future.

As is shown in Figure 6, even though processing time is longer with AFD than FD and MFD, AFD has the lowest energy consumption. This is because AFD is carried out at atmospheric condition and the vacuum pump and cold trap is cancelled. What is more, heat pump can make full use of latent and sensible heat from moisture air. Compared to FD, MFD can also cost lower energy consumption. Its lower energy consumption is attributed to the reduction in drying time and the decline in working time of the vacuum system and the refrigeration system.



Note: a, b Different letters indicate a significant difference (p<0.05).

Figure 6 Effects of different drying methods on the texture of products

4 Conclusions

Different sublimation drying methods such as FD, MFD and AFD had different effects on the quality and total drying time of the dehydrated mushrooms. FD, MFD and AFD may lead to different temperature profiles, which leads to different quantities of sublimated water. By comparison of dying curves, about 55% of total water was sublimated during the MFD process, and about 60% of the total water was sublimated during the FD process. However, less than 50% of water was sublimated during the AFD process, which implied that the AFD process could lead to more ice thawing resulting in greater deterioration of color and structure. Mushrooms by AFD had the worst quality and longest drying time, but cost the lowest energy consumption. Compared with FD and AFD, MFD could get relatively better quality and drying efficiency. As a result, MFD can be used to replace traditional FD, and AFD also should be popularized because of its low energy consumption.

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