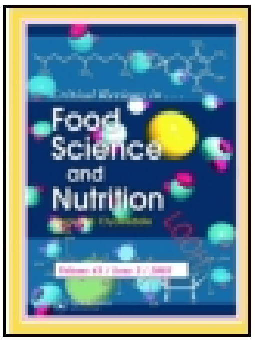

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REVIEW

High efficient freeze-drying technology in food industry

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ABSTRACT
Freeze-drying technology is an interdisciplinary and complex technology, combined with freezing and vacuum drying, It has become an important technology for heat-sensitive drugs and food preservation. Freeze-dried foods are classified into meat, vegetables, fruits, fungus, and micro-powders, etc. In this paper, the definition, principle, steps, advantages and disadvantages of freeze-drying are summarized, and the research progress of freeze-drying in food industry in recent years is reviewed, including the technological parameters and influencing factors.

KEYWORDS
Freeze-dying; technology; food; influence factors

Introduction

Freeze-drying technology is a efficient dehydration method which was firstly used in food industry in western European countries and then diffused across United States, England, France and Japan etc. It is the most important drying technique in food industry and has led to the rapid development in 21st centry (G 2015; Han-Shan et al. 2008). Freeze-drying technology has been widely used in food used in field operations such as aerospace, navigation, military, mountaineering and exploration.

In this technique, water in food is frozen at low temperatures and then sublimated directly from a solid to a gas in a vacuum (Tse-Chao Hua and Zhang 2010).

In food industry, freeze-drying has significant advantages over other dehydration methods: (1) It preserve the original color, fragrance, flavor, color and taste and appearance of original fresh food, to the greatest extent and protect the composition and avoid the loss of nutritional ingredient, especially suitable for heat-sensitive products (Berk 2013; Cheng-Hai et al. 2008). (2) the freeze-dried food can be easily reconstituted with quick rehydration speed (Anonymous 2015; Cheng-Hai et al. 2008). (3) The freeze-dried food keep the moisture content at a low leve, and it is an ideal food for meals, tourism, gathering and entertainment (Anonymous 2015; Cheng-Hai et al. 2008). However, there are also some disadvantages in freeze-drying, such as time-consuming and costly. Freeze drying is a very complex heat and mass transfer process, and its effects on the quality of freeze-dried food should be investigated (Tse-Chao Hua and Zhang 2010).

Because dehydration is more thorough, Freeze-dried products can be stored and transported at room temperature for a long time after packaging. There is no surface hardening problem and the interior is porous and spongy, so it has excellent rehydration. Compared with other drying methods, the shrinkage rate of the products is much lower than that of fresh materials. The drying process of materials is completed at very low temperatures. It fully preserves the nutrients and active substances in raw materials, and maintains the natural color and smell.

Some applications and examples of freeze-drying in food industry are illustrated in Figure 1.

The principle of freeze-drying technology

The principle of freeze-drying is based on the three-state change of water (Han-Shan et al. 2008). According to the thermodynamic phase equilibrium theory, the triple point temperature of water is 0.0098 °C and the pressure is 4.579 mmHg. In the phase transition process of water, when the pressure is below the triple point at which solid, liquid, and vapor coexist in thermodynamic equilibrium, solid ice can sublimate directly to gaseous water vapor without being converted to liquid water (Guo-Yan et al. 2010; Zhang 2005a). The change relationship can be expressed by the phase diagram in Figure 2.

Freeze-drying process can be analyzed using freeze-drying curves (Figure 3):

Pretreatment

For food ingredients, some physical and chemical pretreatments must be performed prior to freeze drying, including classification, washing, slicing, blanching and concentration etc. The steps may vary depending on food type.

Quick freezing

Prior to sublimation drying, the pretreated food raw materials are rapidly frozen from free water into a solid state. It can reduce the heat denaturation and prevent frothing during vacuum drying (Zhang 2005a).

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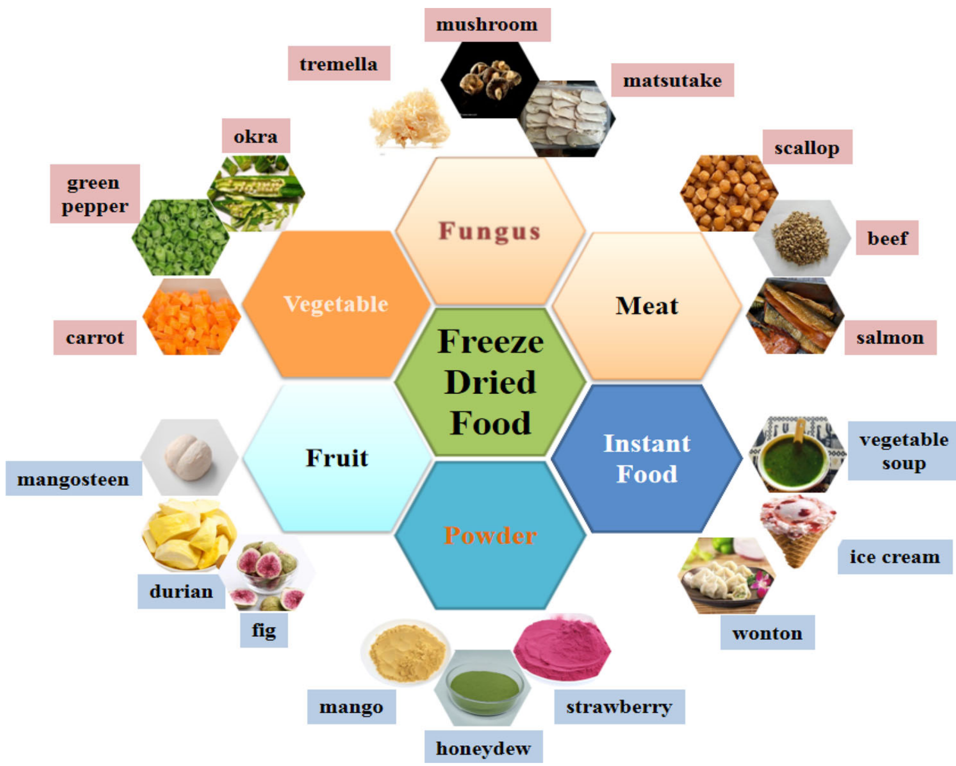

Figure 1. Applications and examples of freeze-drying in food industry.

Sublimation drying

When the frozen product is heated, the ice crystals sublimate to vapor and escape, dehydrating and drying the product, removing 90～95% of the water. During the drying process, the product temperature should be kept below eutectic or vitrification temperature in order to maintain its structure.

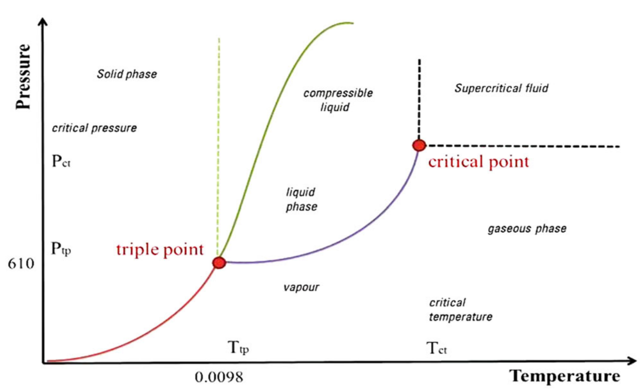

Figure 2. Three-phase diagram of water.

Desorption drying

After sublimation drying, there is still residual moisture adsorbed on the surface of the apparently dry structure, it should be removed by desorption at higher temperature. The desorption temperature should not be too high to cause denaturation of food. The remaining moisture is about 0.5～3%

Insulation

After desorption drying, the products should be sealed and packed in vacuum or inert gas to keep the moisture content of the product even, so as to reduce oxidation denaturation. Freeze-dried products are generally stored at room temperature, while some special freeze-dried products need to be stored at −4 °C∼ −20 °C (Tse-Chao Hua and Zhang 2010).

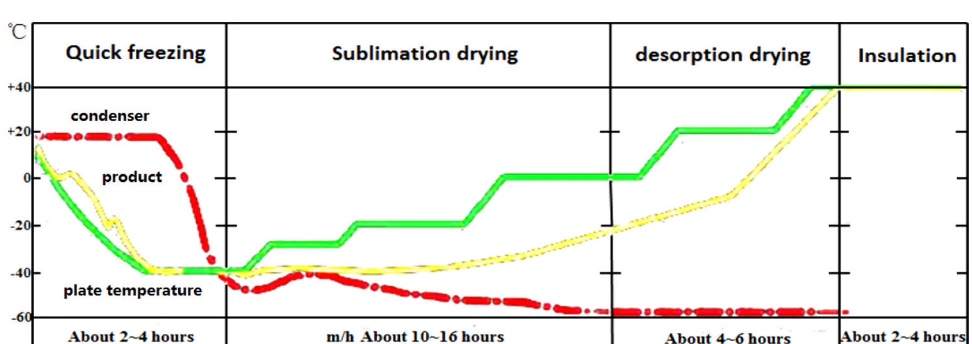

Figure 3. Freeze-drying curves.

Influence factors of freeze-drying technology

During the freeze-drying process, factors such as pretreatment, loading capacity, freezing, vacuum degree and heating temperature will affect the appearance, nutrition composition, moisture content and other qualities of the product.

Pretreatment

Lihui Zhang et al. compared three pretreatment methods of strawberry slices with ultra-high pressure treatment (UHP), ultrasonic treatment (US) and UHP + US combined treatment (UHP + US) (Figure 4). The drying rates for pretreatment samples were significantly higher than those of control samples. Compared with UHP and US pretreatment, the total phenol content and total flavonoid content of UHP + US pretreatment samples were higher ($P < 0.05$), the energy consumption was reduced, and the qualities such as color and antioxidant activity were significantly improved (Zhang et al. 2020) (Figure 5).

Loading capacity

The heat and mass transfer of freeze-drying is from the outer surface of food to the inner part. The more and thicker the raw materials are, the slower the drying rate and the longer the drying time will be. Therefore, the smaller the loading amount and thickness, the lower the energy consumption per unit time will be, and the shorter the drying time will be (Fang and Zheng 2006). Rui Wang et al. investigated the effects of different material loads (150, 300, 450, and 600 g) on the drying characteristics and sensory quality of instant vegetable soup. The results show that the smaller the loading, the shorter the drying time and the higher the product quality. The sensory quality of the product with more than 300 g loading is better, and the best loading quantity is 450 g (Wang et al. 2009). In addition, product thickness also plays an important role in freeze-drying process. Volkan Kırmacı et al. demonstrated a linear relationship between freeze-drying time and product thickness and the time required for a 7 mm strawberry samples exceeding 5 mm samples.

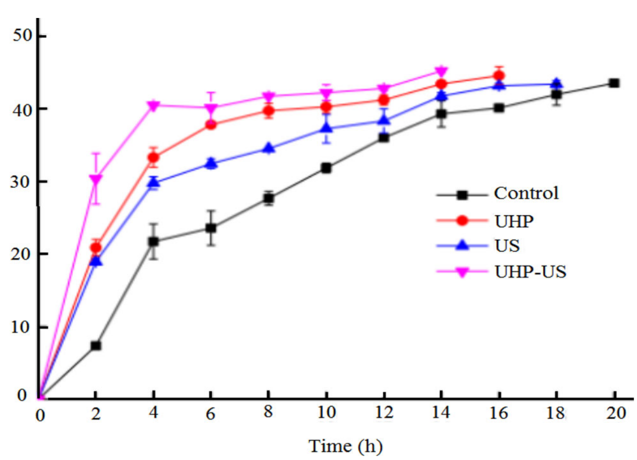

Figure 4. Drying rates of different pretreatment methods for strawberry slices.

Freezing

Freezing can be divided into rapid freezing and slow freezing. Rapid freezing can form well-distributed ice crystals, maintain the internal structure of the material rehydrate well, but sublimate slowly. Large ice crystals and cracks will be formed in slow freezing, which is conducive to heat and mass transfer and drying rate, but will destroy cell membranes and cause poor rehydration rate (Fang and Zheng 2006; Xiao-Hong 2004).

Jian Peng et al frozen carrot slices at different temperatures (−18 °C, −40 °C, −80 °C, and −196 °C) and found that with the decrease of freezing temperature, the cooling rate increased and freezing time decreased. After freezing, the hardness and brittleness of the sample decreased and the brittleness increased, and the color of the sample at −40 °C was closest to that of the fresh sample (Figure 6) (Peng et al. 2018).

ESNA T. et al. discussed the effect of pre-freezing speed and temperature on broccoli products. In order to obtain a higher survival rate, better physical properties and solubility, and promote sublimation in the drying process, the freezing rate of broccoli was determined to be 0.1–1.5 °C/min, and the freezing temperature was −30 °C to −35 °C (Yuhuan et al. 2008).

Vacuum degree

Low vacuum is beneficial to promote the heating plate to provide heat, but too low vacuum will increase the drying time and limit the moisture transfer rate, too high vacuum

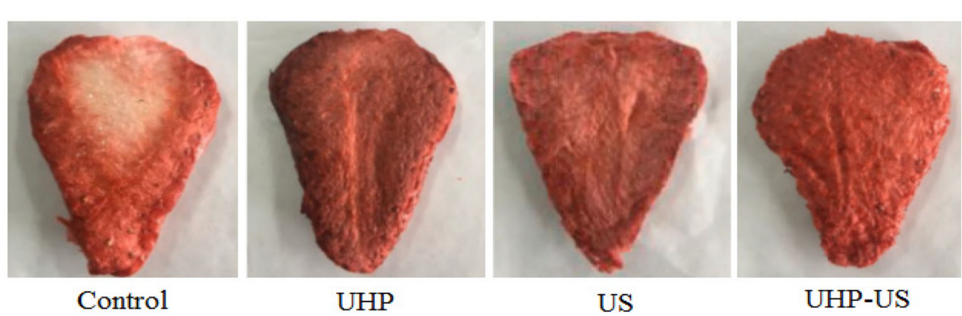

Figure 5. Appearances of freeze-dried strawberry chips with different pretreatment methods.

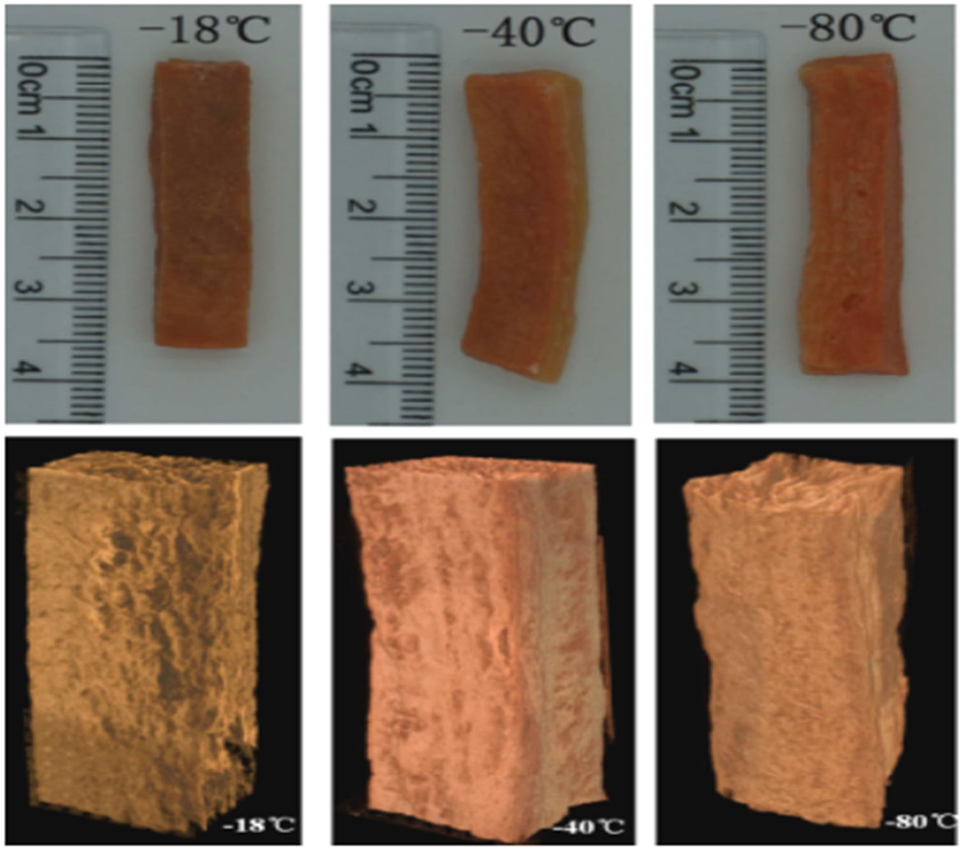

Figure 6. Frozen carrot slices at different temperatures.

degree will lead to the material foam or collapse, and the proportion of rehydration will be reduced.

Ayon Tarafdar et al. studied vitamin C content in mushrooms with different vacuum degrees of 0.04 mbar, 0.07 mbar and 0.1 mbar using response surface method. At 0.04mbar, it was found that the degree of structural collapse was higher, the drying time was prolonged at 0.07mbar, vitamin C was gradually oxidized, and vitamin C content was the lowest at 0.1 mbar (Ayon et al. 2017).

Heating temperature

In the freeze-drying process, the temperature of heating should be controlled to ensure the dissolution of ice crystals, and the drying part should not be overheated and denatured. Increasing the heating temperature of will speed up drying, but overheating will cause denaturation of the material.

Dariusz dziki et al. studied the temperature of the heating plate in the freeze-drying process of kale. The temperature of the heating plate was 20 °C, 40 °C and 60 °C, respectively. The results show that the drying time decreased with the increase of temperature. Drying time at 60 °C was only 1/2 of that at 20 °C (Lundell 2013).

Different heating temperatures have different effects on the appearance of the lyophilized product. Stanisław Rudy et al. analyzed the difference of L-ascorbic acid content, the phenolics content, the antioxidant activity, and color at various heating plate temperatures of 30, 50 and 70 °C in cranberry. The results showed that the freeze-drying time at 70 °C was about 40% shorter than that at 30 °C, while the content of L-ascorbic acid and the total phenolics decreased with the increase of temperature. The results showed that the brightness and reddency of the freeze-dried samples increased and the antioxidant activity decreased with the increase of drying temperature.

Ayon TARAFDAR et al. also found that increasing the heating temperature could shorten the drying time and reduce the content of ascorbic acid, but had no significant effect on the content of mushroom protein (Ayon et al. 2017).

Characterization of freeze-dried product

Once the food has been freeze-dried, it is important to characterize and evaluate its quality. The characterization methods can be used to optimize process conditions and the optimal formulation (Morais et al. 2016; Yali and Dongguang 2018).

Appearance

The color and shape of the freeze-dried products were observed and compared with fresh food. Color is measured by a colorimeter. The main indicators include three color values: **L*** (degree of light and darkness, 0 is black, 100 is white), **a*** (degree of red and green, positive value is red, negative value is green) and **b*** (degree of yellow and blue, a

Table 1. Color values of fresh and dried pineapple slices by different drying methods.

	Color parameters					
Drying method	L^*	a^*	b^*	C	α^o	ΔE
Fresh	69.28 ± 0.45	0.48 ± 0.03	41.86 ± 0.27	41.86 ± 0.27	89.38 ± 0.04	–
Convective drying						
60 °C	68.17 ± 0.49	4.98 ± 0.31	49.56 ± 0.18	49.81 ± 0.17	84.31 ± 0.36	9.09 ± 0.17
70 °C	67.80 ± 0.79	8.16 ± 0.10	48.38 ± 1.74	49.06 ± 1.72	80.46 ± 0.34	10.38 ± 1.13
80 °C	48.70 ± 2.75	13.69 ± 0.58	39.77 ± 2.20	42.06 ± 2.27	71.03 ± 0.30	25.16 ± 2.20
90 °C	40.08 ± 1.29	15.49 ± 0.69	30.34 ± 1.24	34.06 ± 1.42	62.99 ± 0.14	35.30 ± 1.18
Microwave drying						
120W	65.37 ± 1.50	8.63 ± 0.35	35.62 ± 1.56	36.65 ± 1.53	76.40 ± 0.73	11.35 ± 0.95
350W	54.63 ± 1.47	11.20 ± 0.58	30.90 ± 1.15	32.88 ± 0.99	70.09 ± 1.41	21.65 ± 0.97
Freeze drying	74.53 ± 0.60	0.23 ± 0.07	42.95 ± 0.29	42.95 ± 0.29	89.73 ± 0.10	4.83 ± 0.63

Table 2. Color parameters of mushroom slices dried by three different methods.

Drying process	L^*	a^*	b^*	c^*	h	ΔE^*
Convective air drying	80.35 ± 2.91^a	-1.66 ± 0.86^a	31.11 ± 7.1^a	31.71 ± 7.1^a	93.13 ± 1.69^a	24.26 ± 6.91^a
Combined air and microwave-vacuum drying	77.74 ± 4.81^a	-2.88 ± 0.80^b	21.90 ± 2.85^b	22.10 ± 2.18^b	97.64 ± 2.38^b	17.05 ± 4.67^b
Freeze drying	92.56 ± 0.82^b	-1.58 ± 0.27^a	8.64 ± 0.76^c	8.79 ± 0.75^c	100.42 ± 1.88^c	6.75 ± 1.59^c

Mean ± standard deviation with same letters in the same column is not significantly different for Tukey's test, $P < 0.05$.

positive value is yellow, a negative value is blue). Based on the three measured data values, the total color difference with the fresh sample can be calculated by $\Delta E = \sqrt{(\mathbf{L}^* - \mathbf{L}_0^*)^2 + (\mathbf{a}^* - \mathbf{a}_0^*)^2 + (\mathbf{b}^* - \mathbf{b}_0^*)^2}$, where $\mathbf{L}_0^*$, $\mathbf{a}_0^*$ and $\mathbf{b}_0^*$ are the $\mathbf{L}^*$, $\mathbf{a}^*$ and $\mathbf{b}^*$ of the standards. This property is mainly applied to vegetables and fruits.

Nazmi Izli et al. dehydrated and dried pineapple by convection drying, microwave drying, freeze drying and other methods. The results showed that $\mathbf{a}^*$ treated by freeze-drying was similar to that of fresh samples, and $\mathbf{a}^*$ of the other drying methods were much larger than those of the fresh samples (Table 1) (Izli, Izli, and Taskin 2018).

The decrease of $\mathbf{L}^*$ or increase of $\mathbf{b}^*$ are both indicators of the color degradation of lentinus edodes. Dimitrios argyropoulos et al. compared the effects of convection hot air drying combined with microwave vacuum drying and freeze drying on the quality of mushrooms. The results showed that the $\mathbf{L}^*$ of convective hot-air drying and hot air combined with the microwave vacuum drying was lower than that of freeze drying. It is speculated that the high temperature of the drying process causes enzymatic browning and non-enzymatic browning. The $\mathbf{b}^*$ of freeze drying is lower than that of the other two drying methods, the total color difference is the smallest, only 1/4 of convective air drying, and 1/3 of combined air and microwave-vacuum drying (Table 2) (Argyropoulos, Heindl, and Müller 2011).

Moisture content

Methods used to measure residual moisture in the freeze-dried final products include conventional drying loss, Karl Fischer, gas chromatography, thermogravimetry (TG) and thermogravimetry/mass spectrometry (TG/MS) (Ostermann-Porcel et al. 2017). Humidity measurement is generally conducted in a 105 °C oven for 2–3 h, and weighed regularly to constant weight.; or use the Karl Fischer method to determine the moisture content of lyophilized products (Zhang et al. 2020).

Rehydration

Rehydration refers to the ability of a dry product to regain its original freshness after water absorption. The higher the the degree of rehydration, the better the quality of dry product. Studies by E. Lopez Quiroga et al. showed that the effects of rehydration media at different temperatures on the rehydration rate of lyophilized tomatoes were different. The higher the temperature of rehydration media, the higher the rehydration rate and the higher the final moisture content (52% at 50 °C, only 37% at 20 °C). The rehydration rate of freeze-dried tomatoes was 4 times higher than that of hot air drying and 6 times higher than that of infrared (IR) dring (Lopez-Quiroga et al. 2019). Qingqing Xu et al. found that rehydration was faster in the initial stage, and the rehydration ratio almost did not increase after 20 minutes, which was the same as the moisture content curve. At this time, the rehydration ratio of vacuum freeze-dried blueberries was as high as 2.15 g/g, while that of hot-air-dried blueberries was only 1.21 g/g (Qing-Qing et al. 2014).

Antioxidant activity

Certain substances in food have antioxidant properties that prevent food from browning. There are two main methods for the determination of antioxidant activity. (1) DPPH (1,1-diphenyl-2-picrylhydroxyl) assay. DPPH appears purple at 520 nm wavelength. When DPPH is injected into a hydrogen donor, a stable nonradical form of DPPH is generated, and the purple turns pale yellow.

Hacer et al. tested hawthorn prepared by freeze drying, oven drying and microwave drying by DPPH method. The DPPH of freeze-dried samples was 32.77 mmol TE kg^{-1} DW, and it was considered that this drying method was the best drying method to preserve the antioxidant components in the dried products (Hacer et al. 2018). DPPH method was used to determine the content of antioxidants in eggplants. According to the experimental results, it is speculated that phenolic content is positively correlated with antioxidant capacity, because phenol is an effective hydrogen donor (Mbondo et al. 2018).

Total phenolic content

The classical method for the determination of total phenol content is the specific reaction with Folin-Ciocalteu reagent, and the reaction product is most absorbed at a specific wavelength. Małgorzata Materska found higher levels of phenolic resin in peel ratio extracted from placenta by Ethanolic. In the freeze-dried chili, the porosity increased and the phenol content also increased (Materska and Magorzata 2014). Amin et al. found that phenol were heat-sensitive. In order to prevent the loss of phenols, freeze drying was needed at low temperature (Amin, Norazaidah, and Hainida 2006). The total phenol content of freeze-dried product is twice that of hot-air drying (Orak et al. 2012).

Scanning electron microscopy (SEM)

SEM is an important technology to observe the surface morphology of materials under freeze-dried conditions, which provides information about the internal structure of materials (Morais et al. 2016). Qun Yu et al. conducted SEM on fresh and dried asparagus (Figure 7). The average diameter of asparagus after freeze-drying was smaller than that of fresh asparagus, but much larger than that after vacuum drying, far infrared drying and hot air drying. The freeze-dried asparagus remained intact in pore size, vacuum bundle, and epithelial cells, and no fractures were observed (Qun et al. 2019). SEM of freeze-dried strawberries with different pretreatment methods showed that different forms of water migration may lead to cell rupture and porous structure differences (Figure 8) (Zhang, L et al. 2020). UHP pressure had certain damage to cell wall and cell membrane, while US caused cell expansion and contraction due to the presence of ultrasound, thus forming cell microchannel.

Application of freeze-drying technology in food industry

Vegetables

Vegetables are rich in vitamins and minerals, which can improve the body's immunity and prevent the occurrence of diseases. It is an indispensable substance in people's daily diet. Freeze drying can effectively retain the nutrients of vegetables. The following are examples of the application.

Asparagus

Asparagus has a good health care function, which can effectively control the abnormal growth of cancer cells, improve the metabolism of human body, and play a certain role in prevention and treatment of hypertension, heart disease, edema, nephritis, etc (Wu 1996). However, the quality of green asparagus deteriorates rapidly after harvest and is perishable.

Mingkong Wang et al. systematically studied the pre-freezing process and drying process of vacuum freeze-drying of green asparagus. The pre-freezing temperature (−20 °C) and pre-freezing time (4 h) were determined by two-factor comparison test and L_9 (3^4) orthogonal test (Li et al. 2016). Qun Yu et al. compared the effects of freeze-drying, far-infrared drying, vacuum drying and hot air drying on the structural characteristics, bioactive substances and anti-tyrosinase activity of asparagus. The results showed that freeze-drying was the best method and the contents of chlorophyll and total saponins were kept at a high level. The inhibition rate of asparagus to tyrosinase activity was higher after freeze-drying (Qun et al. 2019).

Daylily

The nutrients of daylily flowers is rich (Deng 2003; Fu 2006). It contains protein, vitamins, inorganic salts and a variety of essential amino acids, with high edible value and medicinal value (Guo 2013; Hong et al. 2003). In order to improve the drying quality of daylily and optimize the vacuum freeze-drying process, Guoning Xu et al. determined the optimal vacuum freeze-drying process of daylily by taking reducing sugar content, vitamin C content and rehydration rate as evaluation indexes (Guo-Ning et al. 2013). Wei Liu studied the effects of vacuum freeze-drying, sun drying and hot air drying on the quality of daylily. The flow injection mass spectrometry fingerprint (FIMS) analysis showed that freeze drying was the most effective method for nutrient drying (Liu et al. 2017). The research by Tai et al. demonstrated that freeze-drying prevented the degradation of carotenoids better than hot air drying, but there was little change in each carotenoid (TaiChen 2000).

Tomato

Ching Hui Chang et al. studied the antioxidative effect of freeze-drying on tomato, and the results showed that free-drying could increase the content of total flavonoids, total phenols and lycopene in tomatoes. Freeze-dried tomato extract could be further used as a food additive in other food fields (Chang et al. 2006). Lopez-Quiroga et al. studied the effect of temperature on tomato rehydration kinetics, and the results showed with the increase of temperature, the rehydration capacity and equilibrium water content of tomatoes increased, and the rehydration capacity reached 58% at 50 °C (Lopez-Quiroga et al. 2019). Sylvie sé Rino et al. found that freeze-dried tomato powder was less sensitivity to oxidation and temperature. After 3.5 months of storage, the content of vitamin C was relatively stable (Serino 2019).

Okra

The storage period of the okra fruit is extremely short at normal temperature. Zhang et al. found that freeze-dried okra had good appearance, high color retention, low polysaccharide loss rate, and low antioxidant loss rate (Zhang 2019). Dong et al. determined the freezing time of various okra tissues, and studied the sublimation drying temperature (Xiu-Li et al. 2016). Ning Jiang et al. evaluated the antioxidant property, sensory quality and energy consumption of

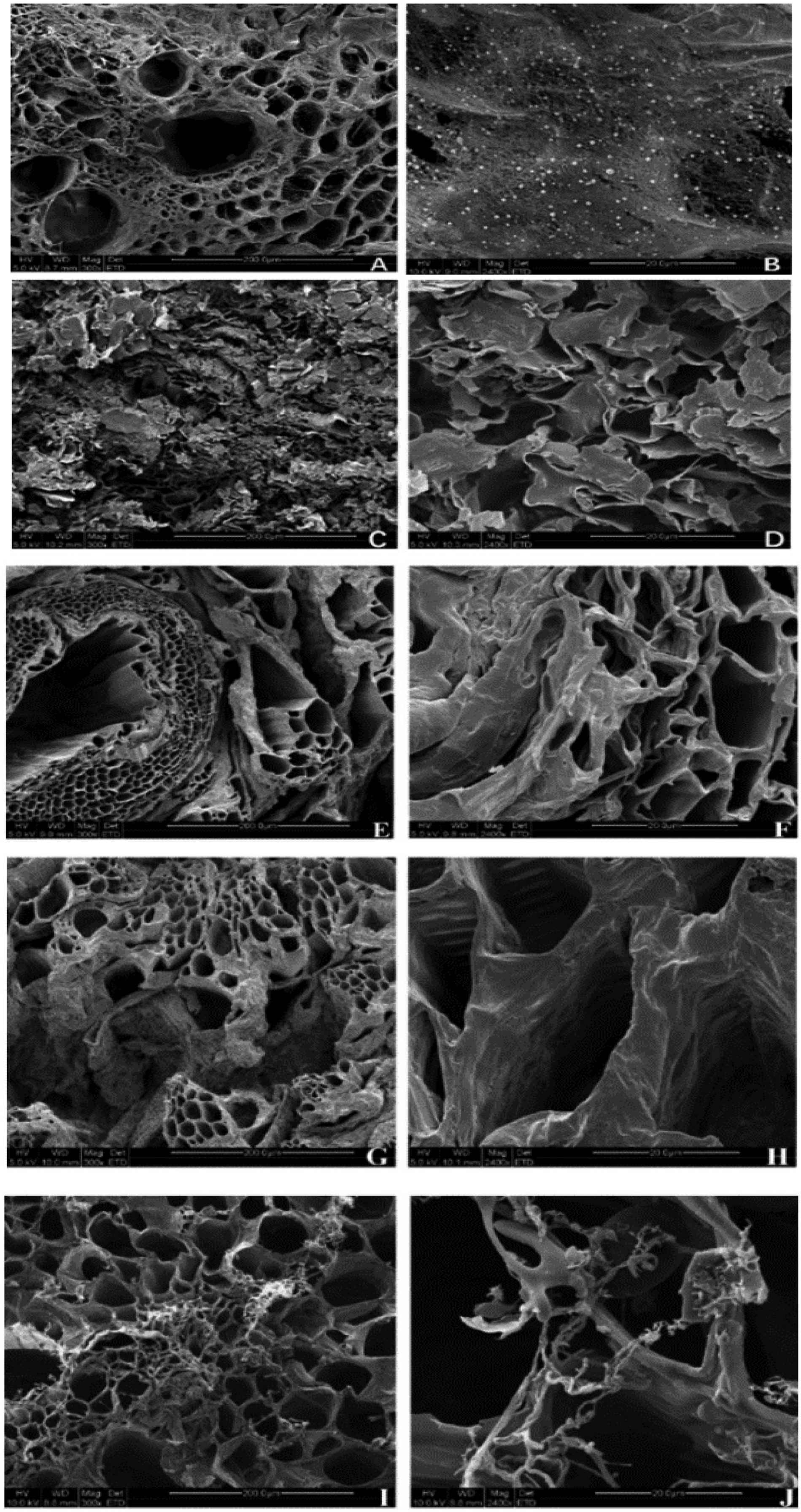

Figure 7. SEMs of asparagus stems after different drying methods.(A:fresh, 300×;B: fresh, 2400×; C: VD, 300×; D:VD, 2400×; E: FIRD, 300×; F: FIRD, 2400×; G: HAD, 300×; H: HAD, 2400×; I: FD, 300×; J: FD, 2400×).

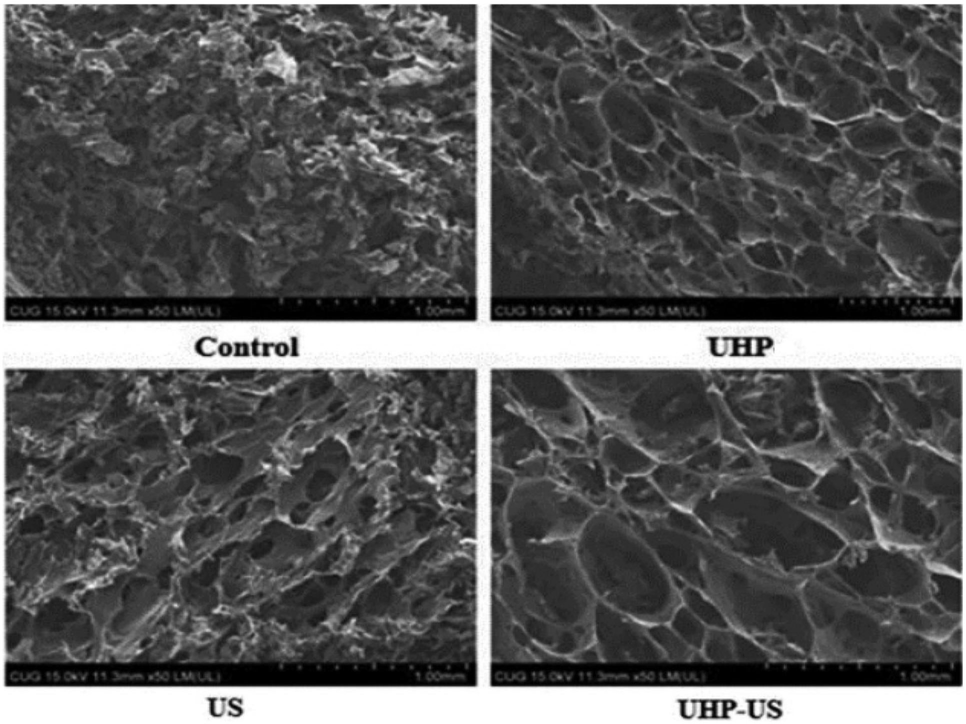

Figure 8. SEMs of vacuum-freeze dried strawberry chips with different pretreatment methods.(UHP: Ultra-high pressure; US: Ultrasound; UHP-US: Ultra-high pressure in combination with Ultrasound).

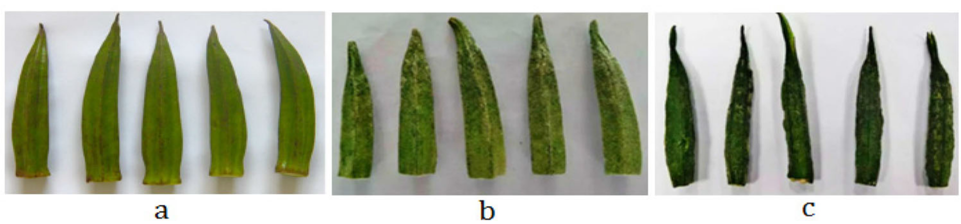

Figure 9. Color and state of Okra. (a: fresh samples; b: FD samples; c: FD-MVD samples).

okra by freeze-drying and microwave vacuum drying. The levels of quercetin 3-O-diglucoside and quercetin 3-O-(malonyl) glucose in fresh okra were 346.3 and 253.4 μg/g respectively, and the levels of Quercetin 3-O-diglucoside and quercetin 3-O-(malonyl) glucose in freeze-dried samples were 325.1 and 247.78 μg/g, respectively. Freeze-dried products had higher oxidation resistance, and better color (Figure 9) (Jiang et al. 2017).

Broccoli

Yuhuan Liu et al. discussed the technological parameters and characteristics of the vacuum freeze-drying process of broccoli, in order to provide reference for the industrial freeze-drying of broccoli (Liu 2008). It was found that the vitrification transformation and solid melting temperature of broccoli decreased with the decrease of solid content, and the freezing point decreased with the increase of solid content (Suresh et al. 2017). Andrea Mahn et al. found that freeze-dried broccoli can maintain higher polyphenol content, semse-cysteine content and radiation resistance compared with fresh vegetables (Mahn et al. 2012).

Carrot

Carrot contains a variety of vitamins and minerals, which can reduce the incidence of cancer. Cui et al. investigated the carrot cakes with a diameter of about 40 mm and a thickness of 8 mm, frozen at −25 °C for 20 min, hot plate temperature at 30 °C, vacuum at 0.2 KPa for 26 h, until the water content was about 7%. The results showed that the total loss rate of freeze-dried carotene was 4.6%, and its characteristic color was maintained (Cui et al. 2008). Research by Gomathi Rajkumar et al. has shown that freeze-drying preserves the aroma, color and appearance of carrots. Despite the high cost of the freeze-drying process, it is considered the best way to obtain high-quality carrot products (Rajkumar et al. 2017).

Pepper

Park et al. studied the effects of pretreatment conditions and freeze-drying temperature on the kinetics and physicochemical properties of pepper. By establishing a drying curve, the highest quality of dry products could be obtained (the highest level of phenolics content, antiradical activity and L-ascorbic acid) when the temperature of heating was 40 °C, and the addition of citric acid could improve the reddishyellow degree of drying products (Andrzej et al. 2018). Birina Luz Caballero Gutiérrez et al. studied the thermodynamic adsorption of pepper by freeze-drying at 15, 25 and 35 °C by gravimetric method. The Gibbs energy indicated that the differential entropy (ΔS) was small at 15 °C, making the adsorption process thermodynamically favorable at low temperatures (Gutiérrez, Velásquez, and Ciro-Velásquez 2018). Małgorzata et al. extracted phenolic substances from freeze-dried pepper and fresh pepper. The results showed that the extraction rate of phenolic increased with the increase of tissue porosity (Materska and Magorzata 2014).

Coriander

Coriander is rich in carotene, iron, protein, vitamins and various trace elements (Anonymous 2006). Coriander has a short storage time of 1–2 days at room temperature, and wilt, yellow or rot at 3–4 days at low temperature, which greatly affects its nutrition. Studies had shown that freeze drying could effectively preserve the aroma of coriander after rehydration, which provided value for the preservation, further processing and development of coriander (Lu and Yan 2006). In order to solve the problem of color, fragrance and taste during the drying of coriander, Zhang et al. carried out freeze-drying experiment on fresh coriander and got a better technology (Zhang Z 2005b).

Beetroot slices

Mahal Gobara et al. sun-dried, hot-dried and freeze-dried fresh beetroot slices. and the chemical composition, nitrate and betaine of fresh and dry sections were determined. The results showed that the chemical composition and mineral content in the freeze-dried part were higher than that in the traditional thermally dried part, and the activity of bioactive compounds and antioxidants was also higher than that in the fresh part, without significant influence on the color characteristics. This showed that freeze-drying is a good way to keep the nutrition and color of slices (Hamid and Nour 2018). Francisca Vallespir et al. also found that the freeze-dried beetroot samples had shorter drying time, higher total phenol content and high antioxidant activity (Vallespir, Carcel, and Marra 2018).

Eggplant

Naomi N. Mbondo et al. investigated the effects of four drying methods on total phenolics, carotene, antioxidant capacity and lycopene in African eggplant. Compared with sun drying, vacuum drying and oven drying, freeze-drying had the highest retention rate of total phenols (95.05%), possibly due to the mild freeze-drying process, which largely avoided enzyme, bacterial and chemical changes (Mbondo et al. 2018).

Shepherd's purse

Yanjun Xue compared the effect of freeze-drying, hot air drying, vacuum drying and microwave drying and found that the color change of shepherd's purse after freeze-drying was significantly reduced, the rehydration was good, and the content of chlorophyll and vitamin C was high (Xue 2014). Zhang et al. used the above four drying technologies to treat shepherd's purse, and analyzed the influence of its aroma components by GC-MS. The results showed that freeze-drying could significantly reduce the color change of products, the rehydration time was short, the rehydration rate was high, the retention rate of chlorophyll and vitamin C was high, and the unique aroma composition of shepherd's purse was successfully preserved (Li et al. 2016).

Others

Massimiliano Renna et al. treated sea fennel by microwave drying, air drying, freeze drying and microwave-assisted air drying, and analyzed its surface color, coloring intensity and sensory evaluation. The freeze-drying process retains more surface color parameters than other drying processes, providing the best color intensity for the product (Renna et al. 2017).

Simona Mattioli also found that freeze drying process could better preserve the estrogen, phytosterol and total tocopherol in plants. Due to the low temperature, freeze-drying minimized the chemical changes of the product, preserved the antioxidant and improved the utilization of phytosterol better (Mattioli et al. 2019).

Fruits

Fruits are rich in vitamins and amino acids, but the storage time of fresh fruits is short and inconvenient to carry. The researchers studied the effect of freeze-drying on fruit quality.

Strawberry

Strawberry is rich in dietary fiber, vitamin A and carotene, which can promote digestion and alleviate night blindness, but it is easy to corrode and soften (Cao et al. 2012). After ultra-high pressure and ultrasonic treatment, the redness and anti-oxidation substances of dried products increased, and the combination of the two reduced the energy consumption and drying time (Zhang et al. 2020). The energy consumption of freeze-drying strawberries after osmotic treatment was only 25% of that of freeze-drying (Prosapio, Norton, and De Marco 2017). Compared with the hot air drying (AD), freeze-drying had no browning reaction, and the color parameters of dried strawberry were higher, which could better protect the red surface and yellow inner surface of strawberries. Ascorbic acid (AA) degrades at a lower rate than AD because AA is a heat-resistant vitamin. Freeze-drying prevents long-term exposure of AA – rich foods to high temperatures (Orak et al. 2012).

Raspberry

Raspberry is rich in flavonoids, vitamins and anthocyanins, which has anti-tumor, anti-inflammatory and antibacterial effects and are easily absorbed by the body. Zhao et al.

discussed and compared the effects of drying time, vacuum degree of drying chamber and temperature of heating on the quality of freeze-dried raspberries, and determined the optimal process parameters. Under this experimental condition, the products with good color, fragrance and taste could be obtained (Shan 2013). Different pretreatment methods have different effects on freeze-dried products. Paula Sette pretreated the raspberry with sugar, added citric acid to obtain different pH gradients, and then lyophilized them. The sugar content of pretreated raspberries was significantly higher than that of unpretreated raspberries (Sette et al. 2017). Microwave combined with freeze drying can reduce energy consumption. M. Ozceli et al. treated the raspberry with microwave freeze-drying method. Compared with FD, there was no significant difference in nutrient composition, taste and product quality, but drying time was shortened by nearly 70%, and the energy consumption was reduced (Ozcelik et al. 2019).

Blueberry

Blueberry is rich in anthocyanins, which can protect eyesight, fight against cancer and enhance the body's immunity. They also play a certain role in preventing brain nerve aging. Alejandro Reyes et al. Freeze-dried Blueberry at $-48\,^{\circ}C$ and 60 Pa. They found that freeze-dried blueberries significantly reduced ascorbic acid levels and showed no significant reduction in antioxidant activity compared to fresh blueberries (Reyes et al. 2011). The freezing rate had effect on the appearance and aroma of the blueberry. The slower the freezing speed is, the darker the color, the smaller the volume of the freeze-dried product is, and the higher the volatility of the aromatic components are (Thi et al. 2017). Compared with hot air drying, freeze-drying had obvious advantages in maintaining rehydration, sensory quality and active ingredients of blueberries (Qing-Qing et al. 2014).

Apple

Ilija Djekica et al. cut apples into different shapes and sizes, and found that for apples of the same size, the smaller the sample, the shorter the drying time, while the rectangular sample had the shortest drying time (Defraeye 2017). Maria Esperanza Dalmau et al. found that after freeze-drying, the microstructure and initial composition of apple changed, and freeze-drying reduced the total polyphenol content and antioxidant activity (Dalmau et al. 2017). The results of vacuum dipping and adding blueberry juice showed that the content of anthocyanin in freeze-dried apples was higher (Castagnini et al. 2015). When frozen in liquid nitrogen, the degradation rate of quercetin derivatives was lower, the overall color change of apple slices was lower, the porosity was significantly higher, and the shrinkage rate was the lowest (Schulze, Hubbermann, and Schwarz 2014).

Banana

Bananas are rich in many nutrients but have a short shelf life. On the basis of dehydrating and preserving nutrients, banana can prolong its storage time.Jasim Ahmed et al. found that freeze-dried products had a larger resistant starch and a smaller diameter than hot-air drying (Ahmed, Thomas, and Khashawi 2020). Bananas have slightly different textures in different freeze-drying cycles. Through different freeze-drying cycles, it was found that the samples with longer cycle time were more likely to have influence on the tissue structure than the samples with shorter cycle time. In order to obtain the best quality of bananas, the drying cycle should be shortened and the cost reduced (Roa Andino et al. 2019).

Mango

Mango is an important tropical and subtropical fruit with rich flavor, unique flavor and rich nutrition. Dalbir Singh Sog et al. dehydrated mango using hot air, freeze-drying, infrared and vacuum drying methods. The results showed that the total content of phenols, ascorbic acid and carotenoid in the freezing-dried samples was 1725.2 GAE/100g dB, 225.38 mg/100g and 5.17 mg/100g (Sogi, Siddiq, and Dolan 2015). Compared with other drying methods, freeze-drying could reduce the loss of phenolic content and ascorbic acid. Natalia A. Salazar et al. studied the rehydration ability, total color difference and polyphenol content of mango slices during freeze drying. The research highlights that choosing the appropriate operating conditions for freeze-drying mango slices can significantly reduce the total processing time (30%), thereby reducing the energy cost and environmental impact (Salazar, Alvarez, and Orrego 2018).

Mulberry

At present, traditional processing methods such as sun drying and hot air drying are generally used for mulberry drying products, but the sun exposure would lead to the loss of fruit nutrients, and the sanitary conditions are difficult to control (Zhang and Huang 2011).

Li et al. studied the vacuum freeze-drying technology of mulberry and obtained the best processing technology and parameters for mulberry (Jiao et al. 2015). Chen et al. studied the effects of different drying methods on the physicochemical properties, nutrient content and antioxidant capacity of black mulberry. The results showed that the water content of mulberry fruit was kept at a low level and the rehydration was the best. The sensory quality and color of dried mulberry fruit were good, and the content of vitamin C, total phenol and anthocyanin in mulberry fruit was higher. The appearance is intact, but the brittleness is low (Chen et al. 2017). The comprehensive evaluation results are shown in Figure 10.

Powder

Fruit powder

Blueberry powder. Sandi darniadi et al. carried out freeze-drying on blueberries and the results showed that freeze-drying was a feasible method to produce blueberry juice powder, which made the freeze-drying product have higher

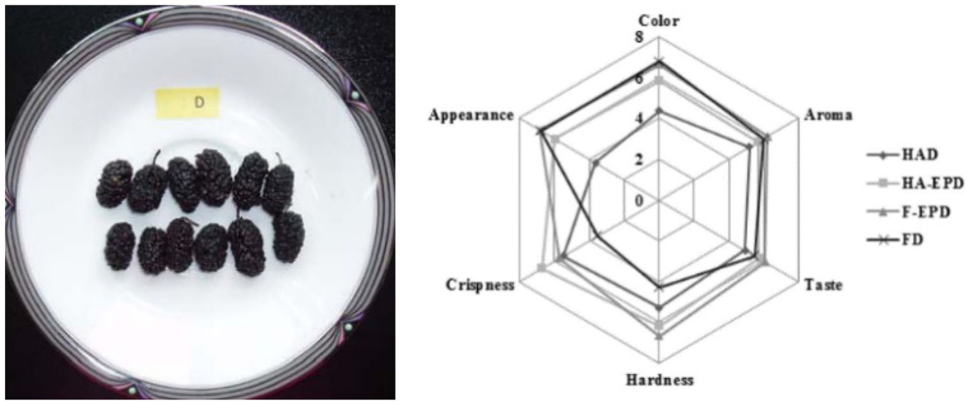

Figure 10. Freeze-drying diagram of mulberry.

content than the original juice of spray drying (Darniadi, Peter, and Murray 2018).

Guava powder. Mudita Verma et al. used different drying methods to dehydrate guava. The results showed that the bulk density of freeze-dried powder was lower than thatof tunnel drying powder, and the content of ascorbic acid and phenolic substances was higher than that of vacuum-drying (Verma et al. 2013). After freeze-drying, the fruit has low moisture content, small grain size and good dispersibility, which preserves the original color, flavor and quality of guava (Zhou and Zhou Lili et al. 2019).

grapefruit powder. C Agudelo et al. cut the grapefruit into 0.5 cm thick, ffroze grapefruit at −45 °C for 48 h, and froze grapefruit at −59 °C for 24 h with 0.021 Pa. The results showed that freeze-dried products have high content of vitamin C and total carotenoids. In addition, healthier compounds were retained and less by-products were avoided (C. et al. 2017).

Plum powders. Anna Michalska et al. dried whole plums by freeze-drying them. It was found that the high porosity of plum powder may be related to the high water absorption rate of the special structure of plum powder, while the higher drying temperature may make the product denser and harder (Michalska et al. 2016).

Walnut jujube compound powder. The walnut jujube slurry was pre-frozen at −40 °C for 12 h, and freeze-dried at −60 °C, 10 Pa for 48 h. The results showed that freeze-dried powder collection rate of freeze-drying was significantly higher than that of spray drying (Lu-Ying et al. 2019).

Vegetable powder

Pumpkin powder. Pumpkin contains a lot of flavonoids, amino acids, vitamins and carbohydrates (Ping 1998). Pumpkin is processed into powder for easy storage and use.

Emine Aydin et al. freeze-dried the pumpkin at −65 °C to −60 °C, under pressure of 130 ~ 135 Pa for 72 hours, sliced and screened pumpkin powder. The freeze-dried pumpkin powder was dark orange and had better functional characteristics: high water holding capacity (92 ml 100 g^{-1}), better oil binding capacity (314 ml 100 g^{-1}) and synergistic emulsification with BSA (Emine 2015).

Yam powder. Li et al. studied the effects of different drying methods on the physical and chemical properties, functional properties, gelatinization properties, thermal properties, rheological properties and microstructure of yam. The results showed that the average particle size of freeze-dried powder was $195 \pm 42\ \mu m$. FD sample had the highest water binding capacity, the highest protein content, the highest starch content, and the lowest solubility (Li et al. 2019). Compared with the blanching and sun-dried flow, the freeze-dried yam starch showed a smooth surface (Figure 11). Compared with solar drying, the freeze-dried yam starch had a higher whiteness, a higher Δ h gel value, and the highest solubility (Suriya et al. 2016).

Others. Hua yang et al. studied the main components and quality changes of Broccoli pollens before and after vacuum freeze-drying. The study found that vacuum freeze-drying can better retain protein, vitamin C and chlorophyll, and the resulting product had good rehydration ratio and dispersibility (Suriya et al. 2016).

Junxiang Zhu et al. pulped and freeze-dried tomatoes to extract lycopene from freeze-dried tomato powder. The extraction rate of ultrasonic assisted extraction was 6.04%, higher than that of traditional solvent extraction, and the extraction time was reduced by 92.47% (Zhu, Hao, and Shaolan 2013).

Coffee powder

Most of the coffee currently in circulation is fried and ground. Yasuyuki Sagara et al. studied the effect of freeze-drying conditions on aroma retention. During the drying process, the surface temperature of sample was 25, 45, 60 and 80 °C, respectively. With the increase of drying temperature, the variation trend and degree of different aroma were also different (Sagara et al. 2005). Different temperatures could be set according to the coffee aroma to meet the needs.

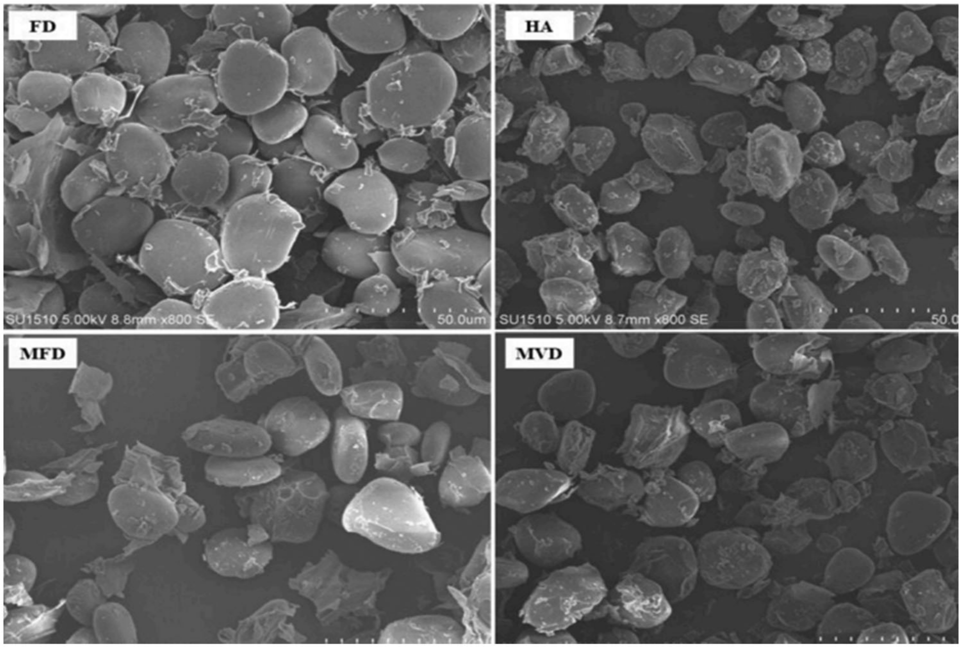

Figure 11. SEM of dried yam powder by different methods(800×).

Egg powder

Fresh eggs deteriorate and damage over time, making them unsuitable for long-distance transportation. At present, there are two main processing methods for egg powder: hot air spray drying and freeze drying (Yu-Xia et al. 2006).

Zhao and others freeze-dried the whole egg, the egg powder is porous and the pore diameter of the part in contact with the tray is large (Yu-Xia et al. 2006). Qing Shen et al. found that the moisture content, water activity, solubility and foaming property of freeze-dried whole egg powder were 3.05%, 0.299%, 93.32% and 62.6%, respectively (Shen et al. 2015).

Duck eggs mainly contain calcium, iron, phosphorus and other nutrients, which can clear the lungs. Zhou Bing et al. combined microwave drying with freeze drying, and the results showed that microwave drying could significantly shorten the drying time, and its powder had better color, lower apparent density, lower foaming stability and higher emulsification index (Bing et al. 2014).

Others

Tofu is an ingredient in the production of gluten-free flour. Maria V. Ostermann-Porcel et al. studied drying products by microwave drying, rotary drying and freeze drying. They found that lyophilized bean dreg had strong water absorption capacity and the highest whiteness index (WI) (Ostermann-Porcel et al. 2017).

Renata Vardanega et al. studied the effects of spray drying and freeze drying on the chemical and nutritional quality, morphology and redispersion of Brazilian ginseng root powder. The results showed that the wettability of lyophilized particles was low, and lyophilized particles had no effect on the content of functional compounds in BGR powder (Renata et al. 2019).

Meat

Fish

There are many kinds of fish, most of which are delicious and nutritious.They are a major source of some minerals and vitamins and are low in fat.

Li Fengli found that the color, shape, aroma, taste and digestibility of the freeze-dried fish were basically unchanged, and the rehydration performance was also good. The appearance, consistency and smell of the freeze-dried fish are similar to those of cooked frozen fish (Fengli 2010). Yanyan Zhang found that the content of organochlorine pesticides in the muscle tissue of freeze-dried fish was significantly reduced (Zhang et al. 2014). Elavarasan et al. freeze-dried fish slices and dried them in oven, and the results showed that the total color difference of freeze-dried fish slices was very small (Elavarasan et al. 2016).

Scallop

There are more than 400 scallops, fresh and nutritious, and most of them are farmed. Li Shuhong et al. studied the effects of different drying methods on the physical and chemical properties of scallops, and the results showed that the content of essential amino acids and flavor amino acids in scallops was the highest after freeze-drying. Li et al. (2011), etc. Xiaoqiang et al. obtained the sublimation drying time under primary and secondary influencing factors under experimental conditions. Through quadratic orthogonal regression analysis, they found that the heating temperature significantly affected the vacuum freeze-drying process, as well as the quadratic function of the sublimation drying time and material thickness, drying chamber pressure and heating temperature changes (Min and Xiaoqiang 2007). Li Min et al. optimized the process parameters by studying scallop quality, freeze-drying time and energy consumption.

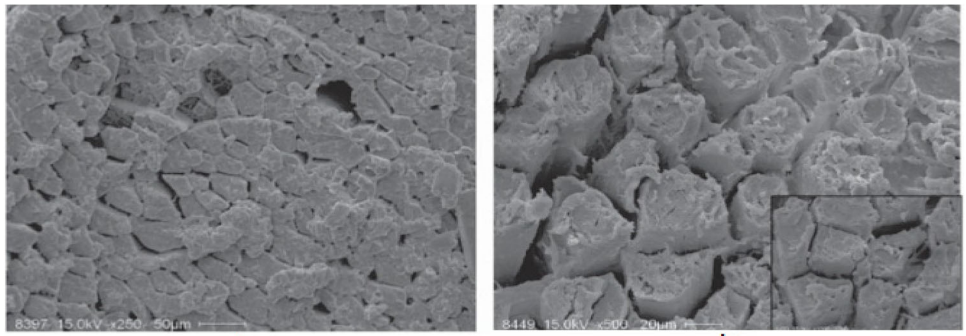

Figure 12. SEM of Semitendinosus freeze-dried beef samples. (a:250×; b: 500×).

Compared with conventional freeze-drying, the rehydration rate of scallop reached 83.7% (12.20% higher than conventional freeze-drying), energy consumption was reduced by 2.17%, and drying time was shortened by 20% (Li et al. 2012).

Beef

Beef contains a lot of amino acids and proteins. Messina et al. studied the performance of bovine muscle under freeze-drying conditions and evaluated its physical and chemical indexes. They found that samples maintained good integrity and different thickness had a significant impact on energy consumption (Figure 12) (Messina et al. 2015). Luo Ruiming et al. analyzed dry cut beef with a thickness of 6,8,12, and 15 mm, and the results showed that when the slice thickness was 6 mm, the energy consumption was the lowest and the productivity was the highest (Luo et al. 2009).

Others

Yan Ma et al. determined the optimum technological parameters of freeze-dried ham through orthogonal test and range analysis: the drying temperature was 45 °C, the desorption drying time was 3 h, and the material thickness was 1 mm. Inner meat desorption drying temperature was 45 °C, desorption drying time was 4 h, and material thickness was 3 mm (Ma et al. 2018).

The nutritional value of silkworm chrysalis is very rich. It contains 18 amino acids the body needs for growth and is as nutritious as eggs and milk. However, due to the high cost of storage in cold storage and the easy flatness of the process, it is difficult to maintain shape. Lu Chunxia et al. analyzed the freeze-drying quality of silkworm chrysalis. The results show that the freeze-drying technology not only helps to maintain the original color, aroma, taste, shape and nutrients of silkworm cocoons, but also provides a good way for the processing of leisure food of silkworm cocoons and helps to reduce the storage cost (Lu 2018).

Freeze-drying techniques can also be applied to cooked foods, such as steamed pork.Xu Jing studied the effects of material thickness, vacuum degree in sublimation stage, pressure and heating temperature in drying stage on materials through orthogonal experiments.The process parameters were determined according to the appearance, smell and taste of the freeze-dried materials after rehydration. The process parameters were −40 °C, 12–18 h, the cold trap temperature was −45 °C, the drying time was 5–6 h, and the heating temperature did not exceed 40 °C (Jing 2009).

Fungus

Fungus food is an indispensable part of People's Daily life, including mushrooms, tremella, matsutake and other fungus food, with rich varieties and short growth cycle. It has the function of anti-tumor, anti-aging and improving human immunity.

Mushrooms

Fresh mushrooms have a shelf life of about three days. Exposed to the air for a long time, mushrooms will consume their own nutrients, easily lose water, and even become woody, reducing their merchandability (Wen et al. 2014). Therefore, after harvest, shiitake mushrooms are often processed into dried products through drying technology for easy storage and the formation of its unique flavor.

The effects of freeze-drying and microwave vacuum drying on volatile components of Lentinus edodes were compared. Studies have found that lyophilization can preserve esters, alcohols and alkanes in mushrooms and protect heat-sensitive substances (Pei et al. 2016). Xiao Yang et al. dehydrated mushrooms by hot air drying and freeze drying. The water content of the freeze-dried sample was 3.57%, and the pH value was similar to that of tricholoma fresh (Yang et al. 2019). Dimitrios Argyropoulos et al studied the effects of convection hot air drying, freeze drying and microwave vacuum drying on the quality of color and structure of mushrooms. The results showed that the freeze-dried mushrooms were of better color, soft texture, lowest apparent density and the strongest rehydration ability, but produced a brittle sponge structure (Figure 13) (Argyropoulos, Heindl, and Müller 2011).

Tremella. Fresh tremella is rich in nutrition and high in water content, which is not easy to store and keep fresh. The drying technology of Tremella experienced a long development process (Ping 2013; Zhen et al. 2013). Tremella is freeze-dried with Muncie sunshine, which basically keeps the state of fresh tremella.The color is good, but the

Figure 13. Slices of fresh shiitake mushrooms(a) and freeze-dried shiitake mushrooms(b).

structure is loose, fragile and white. The appearance was well preserved and the rehydration rate was significantly higher than that of other groups. Different drying methods have different physical parameters, such as shrinkage, rehydration rate, color, and protein. Li Yahuan et al. used methods of hot air drying, vacuum drying and freeze drying to detect tremella. In a comprehensive analysis, the texture quality and nutrient composition of freeze-dried tremella are the best (Huan et al. 2016).

Tricholoma matsutake. Fresh matsutake cannot be stored, and is easy to go bad and rot. Vacuum freeze-drying technology can make the best use of matsutake nutrition. Yang Changping et al. processed matsutake by freeze-drying method, analyzed its dynamic changes, and determined the structure and nutritional indexes of lyophilized matsutake. It has been found that freeze-drying has little effect on total phenol, protein and aliphatic nutrients of matsutake, and has good rehydration performance, which can effectively inhibit Maillard reaction, maximize the yellow degree of matsutake, and reduce the red degree (Lili et al. 2019). Compared with the traditional dried matsutake, the content of protein, vitamin, sugar and other substances of freeze-dried matsutake was higher than that of the traditional dried matsutake, with short rehydration time and high water absorption, which proved the superiority of the freeze-dried matsutake processing technology (Zhenqiong and Xinzhi 2000).

Instant food

Instant rice

Vasiliki P. Oikonomopoulou et al. studied the effects of different processing conditions on the structure and properties of freeze-dried rice, such as bulk density, porosity and true density. The results showed that the freeze-drying conditions and boiling time had significant effects on the bulk density and porosity of dry rice. In the freeze-drying process, with the decrease of the pressure of the box, the density of the pile decreases and the porosity increases. In addition, rice cooked for 4 minutes has the lowest porosity and the highest bulk density, while rice cooked for 24 minutes has the highest porosity and the lowest bulk density (Oikonomopoulou, Krokida, and Karathanos 2011). Wang Changgang et al. found that the addition of compound additives can improve the gelatinization degree of convenient rice products and inhibit regeneration. In addition, it can also improve the sensory score of rice after rehydration and improve the quality of freeze-dried rice (Chang-Gang et al. 2015). Pu Biao et al. freeze-dried 22 kinds of rice and studied their appearance, taste and properties (crude protein, crude fat and amylose). The results showed that rice varieties with low chalky content, high gel consistency and low protein and amylose content should be selected as the freeze-dried raw materials, so that the freeze-dried rice has excellent quality, good taste and high quality (Biao 2007).

Instant soup

Taking traditional Chinese egg soup as the research object, Zhang Zhaomin et al. processed a convenient ready-to-eat egg soup with good rehydration properties through raw material selection, seasoning, freeze-drying and other technological operations (Zhao-Min, Jing-Rong, and Mei-Hong 2013). Wang Rui et al. studied the dehydration of instant vegetable soup by combining microwave vacuum drying with freeze drying. The results show that the drying time increases with the increase of material thickness and load. If high microwave power is used, product quality will be affected. Based on the research, appropriate process parameters were finally determined to ensure a high quality product in a short period of time (Wang et al. 2009). Zhang Min et al. studied microwave freeze-dried instant vegetable soup with NaCl content of 3.2-5.3 g/100 g water, sucrose content of 2 ~ 6.8 g/100 g water, and sodium glutamate content of less than 4.5 g/100 g water. The drying time is short and the product quality is high. The study found that the proportion of food ingredients would affect the microwave freeze-drying speed of vegetable soup and shorten the drying time (Wang, Zhang, and Mujumdar 2010).

Aviation food

Elena Venir et al. froze about 10 mm thick yogurt on a tray and dried it at 20 Pa, with a sublimation temperature of

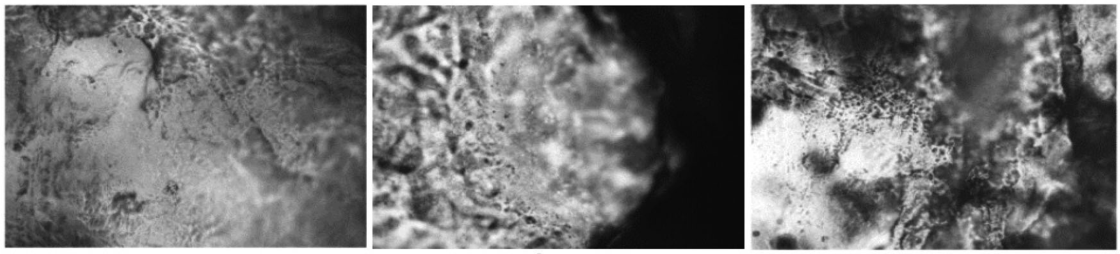

Figure 14. Microstructure of rice with different drying methods(a:Hot air drying; b:Vacuum drying; c: Freeze-drying).

−34 °C. The addition of sucrose increased the initial melting point and vitrification temperature of yogurt, thus improving the freeze-drying and storage suitability of yogurt (Venir et al. 2007). Jae Nam Park et al. prepared free-dried rice by placing 15 ± 0.5 g of cooked rice in petri dishes, freezing it at −70 °C for 5 h, and then drying it to 9.0 ± 1.0%. The results showed that freeze-dried rice had higher rehydration and porous structure (Park et al. 2009). According to the special requirements of astronaut food, Suyun Li studied drying of yuxiang pork by freeze-drying. The optimum freeze-drying process was determined by orthogonal test as follows: thickness of 5 mm, sublimation drying vacuum of 140 Pa, drying vacuum of 30 Pa and heating plate temperature of 20 °C (Li 2005).

Freeze-dried porridge

Through the comparison of hot air drying, vacuum drying and freeze-drying technology, Li Xinjian et al. found that the freeze-dried glutinous rice porridge had higher dehydration rate and rehydration rate, which could better maintain the original form of food. As can be seen from Figure 14, the internal structure of vacuum freeze-dried glutinous rice is relatively loose and the macropore structure is more obvious (Xinjian et al. 2019).

Others

Jing Fang et al. studied the effects of pre-freezing rate, vacuum degree of drying chamber, temperature of heating and loading amount on the drying time and rehydration ratio of wonton, and determined the best process parameters: pre-freezing rate was 2 °C/min, vacuum degree of drying chamber was 53.3pa, temperature of heating plate was 50 °C, loading amount was 4.2 kg/m^2 (Fang and Zheng 2006). The dry sweet corn was prepared by freeze-drying method. The preparation parameters were as follows: plate thickness of 3.5 cm, 60 Pa; drying temperature was initially set at 100 °C, maintained for 5 h, and then heating at 90 °C- 80 °C- 70 °C- 55 °C. When the temperature of the material center was maintained above 50 °C for 3 h, the freeze-dried product has the best taste, color and appearance (C. Y, Liang, and Liu 2012). Sameer Ahmad et al. used three drying methods to dry kelp batter: sun-drying, oven-drying and freeze-drying. Finally, the freeze-dried sera had the highest water absorption, lowest oil absorption and highest carbohydrate content (Ahmad, Nema, and Bashir 2018).

Combination application of different freeze-drying methods

Although freeze-drying has been widely used in the food industry, it consumes more energy, which increases the cost of the product. Therefore, it is very important to develop new methods of freeze-drying technology while reducing energy consumption and production costs. In recent years, the combination of freeze-drying and other drying methods are effective ways to reduce the cost of freeze-dried food, such as, ultrasonic combined freeze-drying technology, microwave freeze-drying technology, etc.

Microwave assisted freeze-drying（MD-FD）

Microwave drying has the advantages of short drying time and good product quality. MD-FD can accelerate drying, produce high-quality products, reduce the loss of antioxidant components, improve tissue quality, and reduce energy consumption.

Ning Jiang et al. found that MD-FD freeze-dried products had higher sensory quality, medium hardness and brittleness, higher retention of antioxidant components, and smaller color difference, and a 25% and 28% reduction in total drying time and energy consumption compared to freeze-drying methods (Jiang et al. 2017).

The drying rate of MD-FD of Chinese cabbage was twice that of freeze-drying. MD-FD has more influence on drying rate than constant- speed drying. The drying rate of MD-FD increases with the decrease of material thickness and cavity pressure. In addition, MD-FD has a significant bactericidal effect on food materials due to the combination of thermal and biological effects (Duan, Zhang, & Mujumdar, 2007).

Far-infrared radiation assisted freeze-drying (FIR-FD)

Far-infrared heating technology has the advantages of fast heating speed, low production cost and high heating efficiency. In the second drying stage of freeze drying, far infrared radiation heating technology can significantly shorten the drying time and improve product quality. found that the heating time of FIR -FD heater was 25% shorter than that of freeze-dried samples under the condition of 32 °C∼37 °C, and the product quality had no significant influence on the temperature of FIR-FD heater (Lin et al. 2007).

Foam-mat freeze-drying (FM-FD)

Before freeze-drying, the addition of foaming agent to the liquid sample can change the liquid sample into foam and increase the total surface area of drying, thus accelerating the drying speed. At the same time, the drying temperature of this method is lower than the traditional drying temperature, which can prevent the volatilization or denaturation of heat-sensitive substances, thus maintaining the flavor or color of food (Muthukumaran, Ratti, and Raghavan 2008). Sandi Darniadi et al. prepared blueberry powder by FM-FD and spray drying (SD) method, and the results showed the yield of FM-FD (> 72%) was higher than SD(62%), and the moisture content was 26～40%, slightly higher than SD (Darniadi, Peter, and Murray 2018).

Conclusion

As a new method of dehydrating, freeze-drying technology has great application value in food industry. Freeze-drying process is affected by many factors, including different pre-treatment, heating temperature, loading capacity, freezing temperature and rate, and vacuum degree, etc. Different operating conditions influenced the appearance, water content, antioxidant ingredients, rehydration and total phenol content of the product. The selection of various characterization methods and the best parameters are needed.

Disclosure statement

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