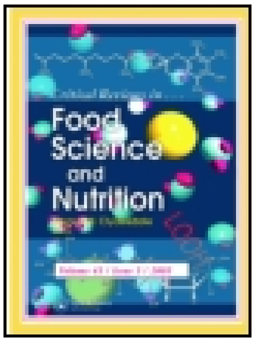

Critical Reviews in Food Science and Nutrition

ISSN: 1040-8398 (Print) 1549-7852 (Online) Journal homepage: http://www.tandfonline.com/loi/bfsn20

Recent developments in high efficient freeze-drying of fruits and vegetables assisted by microwave: A review

Kai Fan, Min Zhang & Arun S. Mujumdar

CRITICAL REVIEWS IN FOOD SCIENCE AND NUTRITION
https://doi.org/10.1080/10408398.2017.1420624

Recent developments in high efficient freeze-drying of fruits and vegetables assisted by microwave: A review

Kai Fan[a], Min Zhang[a,b], and Arun S. Mujumdar[c,d]

[a]State Key Laboratory of Food Science and Technology, Jiangnan University, Wuxi, Jiangsu, China; [b]Jiangsu Province Key Laboratory of Advanced Food Manufacturing Equipment and Technology, Jiangnan University, China; [c]Department of Bioresource Engineering, Macdonald Campus, McGill University, Ste. Anne de Bellevue, Quebec, H9 × 3V9, Canada; [d]Department of Chemical and Biochemical Engineering, Western University, London, Ontario, Canada

ABSTRACT
Microwave heating has been applied in the drying of high-value solids as it affords a number of advantages, including shorter drying time and better product quality. Freeze-drying at cryogenic temperature and extremely low pressure provides the advantage of high product quality, but at very high capital and operating costs due partly to very long drying time. Freeze-drying coupled with a microwave heat source speeds up the drying rate and yields good quality products provided the operating unit is designed and operated to achieve the potential for an absence of hot spot developments. This review is a survey of recent developments in the modeling and experimental results on microwave-assisted freeze-drying (MFD) over the past decade. Owing to the high costs involved, so far all applications are limited to small-scale operations for the drying of high-value foods such as fruits and vegetables. In order to promote industrial-scale applications for a broader range of products further research and development efforts are needed to offset the current limitations of the process. The needs and opportunities for future research and developments are outlined.

KEYWORDS
Microwave; Vacuum freeze-drying; Drying rate; Quality; Fruits and vegetables

Introduction

Vacuum freeze-drying (FD, also known as lyophilization) is a process of sublimation to achieve moisture removal, which can produce better quality of food products such as the fruit and vegetable compared to the other drying processes (Abbasi and Azari 2009; Argyropoulos et al. 2011; Pei et al. 2013; Huang and Zhang 2015; Monteiro et al. 2016). Freeze-dried food products have high porosity, low color, flavor, and nutrient degradations, and also good rehydration properties (Huang et al. 2011; Jiang et al. 2014a; Jiang et al. 2017). However, FD requires very long drying time and much energy consumption (Wang et al. 2012a; Mujumdar and Law, 2010; Fan et al. 2012; Jiang et al. 2015a; Valadez-Carmona et al. 2017). This is partly due to poor sublimation heat conductivity provided through a heated plate (Duan et al. 2007; Huang et al. 2009; Li et al. 2014). The costs of FD are more expensive than those of the other drying methods such as hot air drying (Jiang et al. 2014b; Ambros et al. 2016). Therefore, there is a need to search for a new technology to obtain good quality products at reduced cost.

Microwave is an electromagnetic wave with a frequency of 300 MHz-300 GHz (Onwude et al. 2016). A microwave oven or apparatus heats food products without supplemental thermal gradients at 915 and 2,450 MHz, of which 2450M is widely applied (Wray and Ramaswamy 2015a). Microwave ovens have been successfully used as heat source in the food industry, because microwaves penetrate directly into the products, causing rapid internal heating through dipole rotation and ionic conductance in the matrix materials (Jiang et al. 2010a; Jiang et al. 2011; Jiang et al. 2013; Bórquez et al. 2014). The microwave field as a heat source is used in FD that can improve the drying efficiency with little energy requirement (Valadez-Carmona et al. 2017; Zhang et al. 2007; Duan et al. 2010a; Duan et al. 2012; Motavali et al. 2013; Zielinska et al. 2015). Freeze-drying coupled with microwave heating is called microwave-assisted freeze-drying (MFD). However, there are still some problems in the application of MFD technology, thus the research and application is still at the experimental stage and it is difficult to be applied at industrial scale (Cui et al. 2008; Duan et al. 2015). The problems of MFD technology mainly have non-uniform temperature distribution (Duan et al. 2008a; Vadivambal and Jayas 2008; Cao et al. 2016; Li et al. 2011; Wang et al. 2013a), corona or plasma discharge (Duan et al. 2010a; Duan et al. 2012; Wang et al. 2012b), impedance matching and efficiency of the applicators (Wang et al. 2012c; Zhang et al. 2015; Zhang et al. 2017). Some researchers have given some solutions to solve these problems for MFD technology. Lombrana et al. (2001) presented that the microwave power and the chamber pressure were regulated to avoid overheating and corona discharge. Duan et al. (2010a) designed an effective multimode microwave resonant cavity to make the electric field distribution uniform. Duan et al. (2012) presented that the critical microwave power and pressure are

CONTACT Min Zhang min@jiangnan.edu.cn State Key Laboratory of Food Science and Technology, Jiangnan University, Wuxi, Jiangsu, China

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/bfsn.

related for corona discharge during MFD. In recent years, the studies of MFD for fruits and vegetables in comparison to the traditional FD have been summarized in Table 1. MFD provided a similar good product quality compared to FD process at reduced cost.

In order to promote industrial applications, future research and development for MFD technology is needed because of smaller footprint, higher energy efficiency and better quality compared to conventional freeze-drying with long vacuum vessels and huge product loads. The increasing demand of high quality product for consumer in the fast dehydrated form has increased in the 21st century. The application of MFD in industrial drying systems is of growing interest due to the high energy efficiency and achievement potential. The MFD technology has been increasingly studied in the following years. Some papers have reviewed on the application of microwave in freeze-drying (Duan et al. 2010; Zhang et al. 2010). For example, Duan et al. (2010) showed principles, limitations and advantages of microwave-assisted freeze-drying, heat and mass transfer models, applications (vegetable drying, beef and royal jelly drying, seafood drying). They also discussed dielectric properties and gave suggestions for future research dealing with equipment, temperature monitoring, simulation of microwave electric field distribution, studies on dielectric properties. However, they had a certain limited coverage of MFD technology. Much progress has been made to study and solve the drawbacks of microwave-assisted freeze-drying in past several years. Therefore, the aims of this paper were to present an overview of the recent developments in MFD of fruits and vegetables and prospects further research and possible industrial applications.

Principles of MFD

Basic principles of MFD

MFD is a conventional freeze dryer with allowing microwave to be applied in the drying chamber. The whole drying process is carried out under vacuum condition by sublimation. The quality of microwave-assisted freeze-dried products is similar to conventional freeze-dried products (Jiang et al. 2010a). The basic principles of MFD are not different from conventional FD. In MFD systems, the matrix materials are dried layer by layer starting from the outside compared with traditional FD. The microwave system produces heat in the product volumetrically, causing sublimation throughout the complete product (Zhang et al. 2006; Duan et al. 2010b). The microwave energy is directly absorbed by the water molecules of products in the microwave-assisted freeze-drying process. When the microwave penetration depth is significant and energy can be transferred, the dielectric loss of water is neglected. Therefore, drying time of MFD is shorter than conventional FD (Duan

Table 1. Selected recent studies on some main results of vegetables and fruits dried by microwave freeze drying.

Materials	Operating conditions	Main results	References
Apple	Microwave power: 1.5, 2.5, 3 W/g; Vacuum pressure: 60 Pa; Cold trap temperature: -40°C	MFD greatly reduce the drying time and can provide high product quality.	(Duan et al. 2012)
Button mushroom	Microwave power: 1, 1.2 kW; Vacuum pressure: 50, 500 Pa; Cold trap temperature: -40°C	MFD can lead to similar product quality compared with FD, color deterioration of MFD mushroom is higher than FD ones.	(Duan et al. 2016b)
Banana	Microwave power: 1.5, 1.7, 2.0, 2.2W/g; Vacuum pressure: 100 Pa; Cold trap temperature: -40°C	The drying time was shortened with increase of both microwave power and degree of maturity of the banana. MFD can obtain better product quality	(Jiang et al. 2010b)
	Microwave power: 2 W/g; Vacuum pressure: 100 Pa; Cold trap temperature: -40°C	Results for MFD and FD samples are similar, major changes found in the primary drying stage in starch content, reducing sugar content, structure and color, major change in expansion ratio occurs in the secondary drying stage.	(Jiang et al. 2010a)
	Microwave power: 2 W/g; Vacuum pressure: 120 Pa; Cold trap temperature: -35°C	Compared with FD, MFD can accelerate drying rate. Temperature distribution is uniform during sublimation stage, but not at start of the desorption stage. The major dissimilarity between the FD and MFD samples observed in their pore size and distribution.	(Jiang et al. 2012)
	Microwave power: 1, 1.5, 2 W/g; Vacuum pressure: 100 Pa; Cold trap temperature: -40°C	Method that increases the heating power in secondary drying stage of MFD can potentially reduce the energy consumption without sacrificing color of dried product.	(Jiang et al. 2013)
Cabbage	Microwave power: 600, 700, 800, 900 W; Vacuum pressure: 50, 100, 150 Pa Cold trap temperature: -40°C	MFD greatly reduces the drying time compared with FD and has a notable sterilization effect.	(Duan et al. 2007)
Carrot	Microwave power: 2 W/g; Vacuum pressure: 100 Pa; Cold trap temperature: -40 °C	Rehydration ratio of MFD carrot pieces was almost the same as that of freeze-dried products, the higher retention of carotene and vitamin C observed in MFD	(Yan et al. 2010)
Instant vegetable soup	Microwave power: 1, 1.5, 2 W/g; Vacuum pressure: 100 Pa; Cold trap temperature: -40°C	Microwave power significantly influenced total drying time and sensory quality of product.	(Wang et al. 2009)
Potato	Microwave power: 1.6 W/g; Vacuum pressure: 100 Pa; Cold trap temperature: -40°C	Total drying time for MFD process reduced by about 37% in comparison with FD. MFD yielded product similar in quality to that obtained in vacuum freeze drying with conductive heating.	(Wang et al. 2010c)
Re-structured mixed potato with apple	Microwave power: 1.6 W/g; Vacuum pressure: 100 Pa; Cold trap temperature: -40°C	Drying time for MFD was lower than that for FD and improved quality of dried products.	(Huang et al. 2011)
Stem lettuce	Microwave power: 1 kW; Vacuum pressure: 80 Pa; Cold trap temperature: -45°C	MFD duration of microwave blanched samples reduced by 30% compared to boiling water blanching. Microwave blanched product quality equal to FD.	(Wang et al. 2012d)

et al. 2012). The drying cost using microwave-assisted freeze-drying can be reduced by the experiments and numerical predictions (Wu et al. 2004; Duan et al. 2010b).

Heat and mass transfer models of MFD

Some researchers have simulated the heat and mass transfer in microwave-assisted freeze-drying process, which is helpful to predict the drying process and optimize the drying parameters. A mathematical model for microwave-assisted freeze-drying is presented in Fig. 1. Some assumptions for this model were taken into consideration: ice front retreats uniformly during sublimation and diffusion of water vapors, and uniform distribution of microwave field in the materials. This model has been commonly used to simulate the microwave-assisted freeze-drying process according to some report (Wang and Shi 1998; Wang and Chen 2003; Wang and Chen 2005a; Wang and Chen 2007; Duan et al. 2016a). For example, Tao et al. (2005) provided a numerical simulation of conjugate heat and mass transfer process of MFD within a cylindrical porous media with cylindrical dielectric cores. They found that an increase in loss factor of cylindrical dielectric core can shorten the drying time. Similarly, as reported by Wang and Chen (2005b), they developed a heat and mass transfer model of dielectric material assisted MFD of skim milk with hygroscopic effect. They found that the dielectric material (silicon carbide) was used in the microwave-assisted freeze-drying process resulting in the drying time to reduce by 33.1%. Nastaj et al. (2008) presented that one-dimensional two-region model of MFD process for random solids takes into account unknown a priori sublimation temperature and mass concentration of water vapor at moving ice front. Results showed that there was a relationship between temperature dependency of material loss factors and electric field strength during drying process. This mathematical model can used to predict the drying kinetics for the random solids. The same results were reported by Nastaj and Witkiewicz (2009) and Witkiewicz and Nastaj (2010). Therefore, the dielectric property of materials studies is important for optimizing and controlling MFD process.

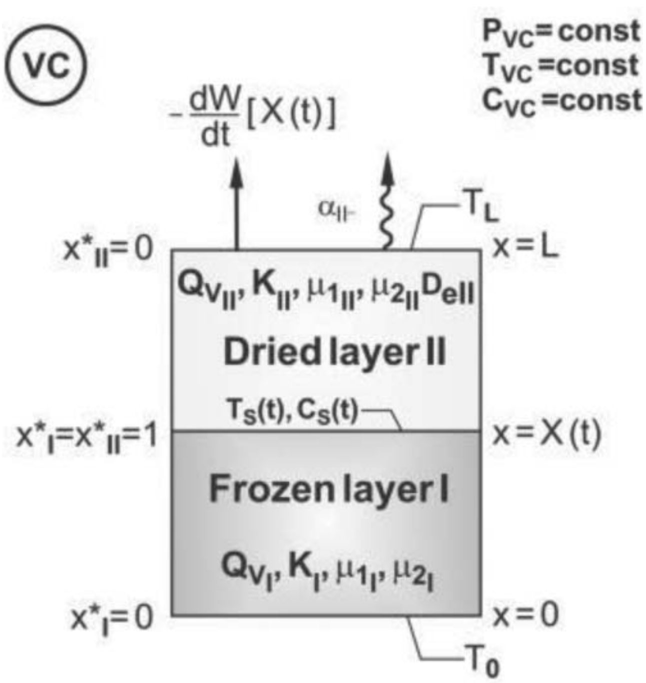

Figure 1. One-dimensional physical model of the primary microwave freeze-drying (Nastaj and Witkiewicz, 2010).

Microwave freeze dryer

Many studies showed that the application of microwave heating in the freeze-drying greatly accelerated the drying process. For this reason, the microwave-assisted freeze-drying method is useful especially for temperature-sensitive materials such as fruits and vegetables. Recently, some researchers have developed some microwave-assisted freeze drying apparatus for the use in food processing.

Witkiewicz and Nastaj (2010) developed experimental equipment for microwave-assisted freeze-drying, as shown in Fig. 2. This equipment consists of microwave circuit, the vacuum system, the refrigeration system, the temperature and weight measurement devices and the data acquisition system. The microwave applicator (2450 MHz) placed in the vacuum chamber is a section of rectangular brazen waveguide 50 × 100 × 200 mm (rectangular resonant cavity). The main advantage of this equipment can allow to measure temperature and weight loss of material in the drying process. The material temperature was measured by using a fluoroptic thermometer FOT Lab Kit (Luxtron Co., USA). The weight loss of material was measured by using electronic balance. A cylindrical Teflon container was filled with coolant circulating inside the vacuum chamber to keep temperature at about -25°C. The process pressure was maintained at 100 Pa by a vacuum pump. This equipment has been used by Witkiewicz and Nastaj (2010) for investigation of granular materials and foodstuffs in MFD process. Results showed that the measurements of temperature dependency of material loss factors and a variety of electric field strengths can improve the mathematical model and well understand the drying

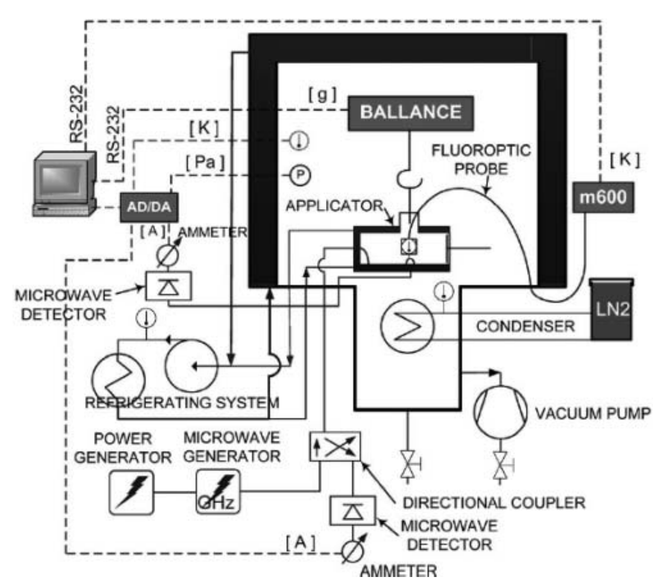

Figure 2. Schematic diagram of microwave freeze-drying equipment (Witkiewicz and Nastaj, 2010).

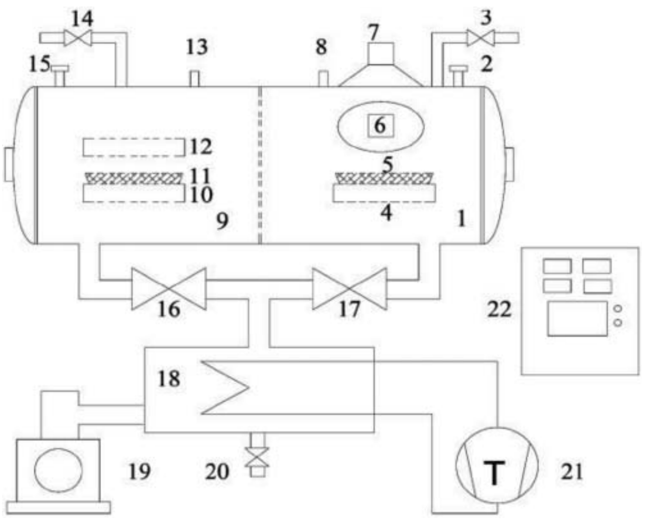

Figure 3. Schematic diagram of a typical microwave freeze dryer (Jiang et al., 2010b). 1. Microwave freeze drying chamber; 2. Optical fiber temperature sensor; 3. Vacuum breakage valve, for MFD; 4. Sample supporting plate; 5. MFD sample; 6, 7. Microwave source; 8. Pressure sensor, for MFD chamber; 9. Freeze drying chamber; 10, 12. Heating plate; 11. FD sample; 13. Pressure sensor, for FD chamber; 14. Vacuum breakage valve, for FD; 15. Temperature sensor; 16. FD vacuum valve; 17. MFD vacuum valve; 18. Cold trap; 19. Vacuum pump; 20. Draining valve; 21. Refrigeration compressor; 22. Control system.

kinetics during the drying process. Therefore, Changes in the dielectric properties of materials can enhance MFD process.

Jiang et al. (2010b) developed a laboratory scale microwave-assisted freeze-drying equipment (YT2S-01, Nanjing Yatai Microwave Power Technology Research Institute, China), as shown in Fig. 3. The FD and MFD tests can be done in this equipment. The FD test was carried out by the electrically shelf heating. The MFD test was carried out by microwave field heating at 2450 MHz. The pressure was maintained at 100 Pa by a vacuum pump during drying process. The temperature of the cold trap (-40 to -45 °C) is enough to condense water vapor. Three magnetrons were placed at the angle between two magnetrons of 60° to avoid non-uniform distribution of the microwave field. The range of microwave power can be regulated from 0 to 2000 W. This equipment automatically controlled the material temperature by automatically regulated magnetrons. The material temperature was measured by an optical fiber probe. This equipment has been used in the drying of different products. For example, MFD process of sea cucumber shortened the drying time by about 50% and reduced energy consumption by about 32% in comparison to the conventional FD process (Duan et al. 2010a). MFD process of banana chips shortened the drying time by 40% and reduced energy consumption by 35.7% in comparison to the conventional FD process (Jiang et al. 2013). MFD of banana cubes shortened drying time by 50% compared to the FD process (Jiang et al. 2014b). Therefore, MFD is a promising method in an increase of the drying rate.

Wang et al. (2012b) developed a newly laboratory scale pulse-spouted microwave-assisted freeze-drying (PSMFD) apparatus at Jiangnan University, as shown Fig. 4. The apparatus can be used for FD, MFD, and PSMFD tests. During PSMFD test, the pressure range inside the drying chamber is held at 80±5 Pa to 1.2 kPa by a vacuum pump. The pressure fluctuation is typically 800 Pa for spouting. The dried samples were spouted in the time interval of 10 min and held for 2 s. Nitrogen gas temperature and velocity in PSMFD were set at 25±1 °C and 3.5 m/s. The temperature of the cold trap is -40 to -45 °C. Four microwave generators (2450 MHz) were used in the drying and the power output range of each magnetron is 0.1–0.6 kW. The bottom in drying chamber was blocked with a silicon rubber stopper together with the gas distributor and the fiber optic temperature probe in order to monitor temperature of the dried sample. The main advantage of this equipment can solve the drying non-uniformity of MFD process by using pneumatic pulse agitation. This equipment has been applied in the drying of different products. For example, PSMFD of stem lettuce slices shortened the total drying time by more than 20% compared to MFD (Wang et al. 2012b). Fresh duck egg white powder produced by PSMFD shortened the drying time by 50% compared

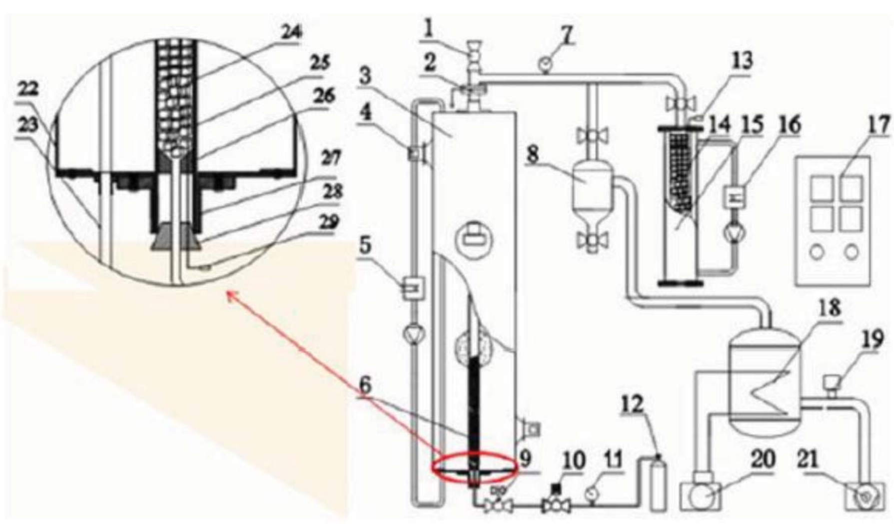

Figure 4. Schematic diagram of freeze-drying system for PSMFD, MFD, and FD (Wang et al., 2012b). 1. Feeding ball valve; 2. Plate valve with 3-mm diameter hole; 3, 22. Microwave heating cavity; 4. Magnetron; 5, 16. Circulating water unit; 6. Drying chamber for MFD and PSMFD; 7, 11. Pressure gauge; 8. Solid-gas separator; 9. Gas flow electromagnetic valve; 10. Gas flow adjustable valve; 12. Nitrogen gas source; 13, 29. Fiber optic temperature sensor; 14, 24. Sample; 15. Drying chamber with a jacket for FD; 17. Control panel; 18. Vapor condenser; 19. Vacuum pressure transducer; 20. Refrigerator unit; 21. Vacuum pump unit; 23. Water load pipe; 25. Teflon tube; 26. Gas distributer; 27. Fixed unit for drying chamber holder; 28. Silicon rubber stopper.

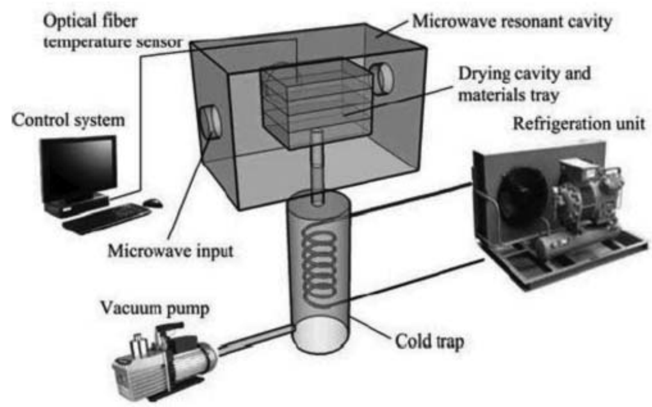

Figure 5. Schematic diagram of the microwave freeze dryer (Duan et al., 2015).

to the conventional FD (Wang et al. 2013b). PSMFD of banana cubes carried out at the microwave power of 1 W/g took 1 h longer than that at 2 and 3 W/g (Jiang et al. 2015b). Therefore, PSMFD can improve the drying uniformity to reduce the drying time.

Ren et al. (2015) designed a new microwave-assisted freeze dryer, as shown in Fig. 5. This equipment is fitted with a separate polypropylene drying cavity to avoid corona discharge in the rectangle resonant cavity. The equipment were placed three magnetrons (2450 MHz) at different angles in order to avoid non-uniform distribution of the microwave field. The pressure range was 10 Pa to 30 kPa (absolute pressure) in the drying cavity. The microwave power can be regulated continually. The material core temperature was measured by an optical fiber sensor. This equipment has been used in the drying of vegetables. For example, the step-down microwave loading scheme based on the glass transition temperature can significantly improve the product quality and does not increase the drying time in the MFD of mushroom (Ren et al. 2015). The MFD of button mushrooms took place non-enzymatic browning and enzymatic browning, but enzymatic browning significantly affected the drying process and a low microwave power can avoid browning behavior (Duan et al. 2016a). Therefore, MFD technology is greatly potential in food processing.

Discharge studies in MFD process

MFD application was limited due to the corona or plasma discharge problems (Duan et al. 2015). Discharge is a relatively complicated process. It is essential to study the phenomena of discharge so as to promote the improvement of MFD apparatus. In order to solve discharge in the MFD process, many researchers have studied influence factors (e.g., material weight, vacuum pressure, moisture content etc.) of microwave discharge. For example, Cao et al. (2006) investigated influence of vacuum pressure and material weight on critical discharge microwave power under variable feed-in area in the MFD process of winter-date. They found the degrees of three factors (vacuum pressure, material weight and feed-in area) affecting the critical discharge microwave power: feed-in area > vacuum pressure > material weight. The critical discharge microwave power increased with increasing feed-in area, vacuum pressure and material weight. Thus, the higher the discharge microwave power, the smaller the discharge potential. Duan et al. (2010a) showed different vacuum pressures and moisture contents control to avoid discharge phenomenon in MFD of sea cucumbers. It was found that corona discharge phenomenon can occur rapidly at vacuum pressure range (100–200 Pa) in the MFD process. The critical discharge microwave power was the least at the vacuum pressures about 150 Pa. The less possibility of corona discharge during MFD took place at the vacuum pressure range (50–100 Pa). The possibility of corona discharge increased with decreasing moisture content. Thus, the higher the moisture content of sea cucumbers, the higher the critical discharge microwave power. Duan et al. (2012) presented drying pressure (20, 40, 60, 80, 100, 150 and 300 Pa) and drying process (initial stage, middle stage and end stage) control to adjust critical discharge microwave power during MFD of apple slices. They observed that corona discharge phenomenon can occur at vacuum pressure range (80–200 Pa) in the MFD process. The critical discharge microwave power was the least at the vacuum pressures about 80 Pa. The corona discharge can rapidly occur at the initial and end stages due to low loss factors in the two stages, which caused low microwave energy dissipation (Kristiawan et al. 2011). Therefore, microwave power was adjusted basing on dielectric property of apple slices during MFD.

Temperature distribution studies during MFD

MFD application was limited due to the non-uniform heating problem resulting in non-uniform temperature distribution (Vadivambal and Jayas 2008). It was difficult to control the microwave field distribution and achieve uniform heating. The non-uniform temperature distribution not only affected the quality of dried products, but also brought about microbiological safety problems (Li et al. 2011). Some researchers have studied the temperature distribution at different stages during MFD of fruits and vegetables and tried to solve uniformity issue. For example, Jiang et al. (2012) used an infrared thermal imaging camera to observe temperature distribution during MFD of banana chips. In their experiment, they found uniform temperature distribution at sublimation drying stage and uniform temperature distribution at desorption primary stage during MFD of banana chips. They considered that melting of ice crystals can be not sublimated. On the other hand, Wang et al. (2012b) applied pulse-spouted bed to MFD process and presented temperature distributions during PSMFD of stem lettuce slices. They used a fiber optic thermometer to monitor temperature during PSMFD. It was found that pulse-spouted was good for improving uniformity during MFD compared to steady mode. Results showed that non-uniform temperature distribution still exist during PSMFD process. However, the temperature difference was very small in different stages during PSMFD of stem lettuce slices. Similarly, as reported by Jiang et al. (2015b), an infrared thermal imaging camera was used to evaluate the temperature distribution uniformity of banana cubes dried by PSMFD. There was good temperature distribution uniformity of banana cubes through observing infrared camera photos. However, when microwave power, spouting time and spouting interval time were not reasonably set, the temperature distribution of banana cubes was non-uniform. Thus, PSMFD can provide good uniformity at suitable conditions.

Dielectric property studies during MFD

The dielectric properties of fruits and vegetables took place the changes in the MFD process (Duan et al. 2012). It is essential to study dielectric properties dependency of chemical composition such as sugar, salt, and moisture contents so as to improve drying rate and microwave heating uniformity during MFD process (Wang et al. 2010a; Wang et al. 2011a). Dielectric properties can be represented by a relative complex permittivity, which is expressed as $\varepsilon = \varepsilon'$-$\varepsilon$", where ε' is the dielectric constant and ε" is the dielectric loss factor. A large number of studies on dielectric properties of fruits and vegetables have been reported during MFD. Different methods were used to change the dielectric properties. For instance, Wang et al. (2010a) reported that dielectric properties of instant vegetable soup during MFD can be improved by adding three food ingredients (NaCl content, sucrose content and sodium glutamate content). Furthermore, it was found that drying rate and product quality can be improved. This is due to the condiments changed the dielectric properties of the material and improved the microwave absorbing capacity. Similarly, Wang et al. (2011a) discussed the change of the dielectric properties of re-structured potato slices during MFD. After adding salt and sucrose, both ε' and ε'' can be increased at the temperature range from -25 to -5 °C. The salt addition can increase significantly dielectric properties of the potato slices compared to sucrose addition. This is due to the increase of ionic loss for salt addition and the low ionic conductivity of sucrose. On the other hand, Wang et al. (2012) used two blanching methods (boiling water and microwave) to improve the dielectric properties of stem lettuce cubes during MFD. Results showed that the ε' and ε'' of stem lettuce cubes by microwave blanching decreased markedly in comparison to that of boiling water ones. This is due to a lot of ions and soluble components in stem lettuce cubes by microwave blanching. Therefore, microwave blanching can change dielectric property to enhance the MFD process. Duan et al. (2012) presented that dielectric property of apple slices can be changed during MFD by adjusting moisture content and temperature. Results showed that loss factor decreased fast when both moisture content and temperature were low. This is due to dipole loss of water, and an increase in temperature caused an increase in mobility of ions and conductivity. The similar results were reported by Jiang et al. (2014a), they used a network analyser to study dielectric properties of banana chips during MFD process. The ε' and ε'' of banana chips were very high at initial drying stage due to the melt of surface ice crystals. The ε' and ε'' decreased markedly at desorption drying stage. This is due to the low moisture content ($<10\%$) resulting in the high mass transfer resistance of vapor. Therefore, the change of dielectric properties is beneficial to control the microwave energy transfer in MFD process.

Application of pretreatment to MFD

Some pretreatment methods (e.g. ultrasound, osmotic dehydration, blanching, nanoscale silver coating, vacuum-cooling etc.) prior to MFD of food products were used (Zhang et al. 2017, Wray and Ramaswamy 2015b). Ultrasound can produce a rapid series of alternative compressions and expansions (sponge effect) in solid media resulting in the formation of microscopic channels for easy removal of moisture (Amami et al. 2017). Osmotic dehydration is a process that is widely used for partial removal of water from high moisture products (Wang et al. 2010b). Blanching of vegetables and fruits is also an important pretreatment process in the industrial production. Blanching is mainly used to disrupt enzyme activity, increase cell membrane permeability and inhibit microbial growth (Wang et al. 2012d; Latorre et al. 2013; Liu et al. 2014). Nanoscale silver can penetrate into cells and inactivate enzymes (Duan et al. 2008a). Vacuum cooling can quickly remove heat after blanching of the material (Song et al. 2016). Some researchers have been reported on pretreatment to improve the MFD process as shown in Table 2. From Table 2, pretreatment methods are used to enhance quality of food products such as fruits and vegetables during MFD. Pretreatments are beneficial to color, texture, rehydration and nutritional content of products (Duan et al. 2008b). Pretreatments can accelerate the drying rate, which can retain more heat-sensitive nutrients like vitamin C. On the other hand, pretreatments can reduce energy consumption, which can decrease drying process cost (Wang et al. 2011b). Pretreatments can also improve the safety of food products, which is helpful to stable storage of dried products (Duan et al. 2008a). Therefore, pretreatment can enhance the MFD process.

Table 2. Application of different pretreatment methods in the MFD.

Materials	Pretreatment methods	Conclusions	References
Sea cucumber	Ultrasound assisted osmotic dehydration with salt solution	The ultrasound assisted osmotic dehydration can reduced the drying time by about 2 h and obtain good quality in MFD.	Duan et al. 2008b
	Nanoscale silver coating	MFD combined with nanoscale silver coating had a good sterilization effect.	Duan et al. 2008a
Apple slices	Calcium ion impregnation	Calcium ion can improve structure, dehydration rate and shrinkage ratio of apple slices during MFD.	Wu et al. 2010
Potato chips	Osmotic dehydration with salt or sucrose solution	Osmotic pretreatment obtained good quality and shorten total drying time during MFD.	Wang et al. 2010b
	Calcium ions soaking and blanching	Calcium ion treatment and blanching can maintain the shape changes during MFD.	Wang et al. 2010c
Carrot slices	Vacuum cooling	Vacuum cooling pretreatment can reduce the drying time and power consumption, and improve retention rate of vitamin C.	Wang et al. 2011b
Stem lettuce cubes	Blanching	Microwave blanching can keep good quality and improve MFD rate.	Wang et al. 2012d

Influence of MFD on the quality of vegetables and fruits

Drying causes changes in the nutritional value and physical properties of food products (Sagar and Kumar 2010; Zheng et al. 2010; Zheng et al. 2015; Szadzińska et al. 2016; Zhang et al. 2016; Ostermann-Porcel et al. 2016). Numerous studies have been conducted to evaluate the effects of microwave-assisted freeze-drying on the physical, chemical microstructure characteristics and safety describing the quality of products being dried.

Physical parameters quality of vegetables and fruits dried by MFD mainly include color, texture and rehydration compliance and so on. The color change is important physical parameter of dried products from the consumer point of view. Another relevant physical quality parameter is food texture. Proper texture parameters of the product are required due to tactile sensation or bite ability. Rehydration compliance can reflect the physical and chemical changes that occurred during drying (Huang et al. 2011). Chemical quality parameters of vegetables and fruits mainly include nutrients and vitamin retention during MFD. Recent studies on physical and chemical quality parameters of vegetables and fruits dried by MFD were shown in Table 3. From this table, reasonable drying method and pretreatment can improve quality of vegetables and fruits at suitable drying condition. The quality parameters (e.g. color change, hardness and fracturability, rehydration ratio, β-carotene, anthocyanin and vitamin C etc.) of vegetables and fruits dried by MFD were similar to FD and better than other drying methods. As we all known, FD is the best drying method to obtain good quality of products (Wang et al. 2010c). However, FD required a long time and high cost. FD assisted by microwave can accelerate drying rate and maintain quality parameters. Therefore, MFD can achieve high efficiency and high quality.

The microstructure changes of the product induced during MFD, which is beneficial for understanding process mechanisms. The microstructure changes mainly include destruction of cell membrane and cell wall (Wang et al. 2010c). Some researchers analyzed microstructure changes to evaluate the drying processing of fruits and vegetables. For example, Jiang et al. (2010b) found that the cell walls of banana chips disappeared at the primary drying stage of MFD, but it showed no influence on the final product.

Table 3. Recent studies on physical and chemical quality parameters of vegetables and fruits dried by MFD.

Quality parameters	materials	Methods	Main results	References
Color	Banana slices	Drying stage (pre-freeze stage, primary and secondary drying stage)	The color change of the primary drying stage banana chips varied greatly.	Jiang et al. 2010b
		Drying method (MFD, FD and pulse-spouted microwave vacuum drying)	The color of FD was better that that of MFD and pulse-spouted microwave vacuum drying.	Jiang et al. 2014b
	Restructured mixed potato with apple chips	Drying method (MFD, FD microwave vacuum drying and vacuum drying)	The color changes between MFD and FD were not markedly different. The L* values were also not markedly different between microwave vacuum drying and vacuum drying.	Huang et al. 2011
	Restructured wild cabbage chips	Drying method (MFD, microwave vacuum drying and hot air drying)	The cabbage chips dried by MFD can obtained better color compared to microwave vacuum drying and hot air drying	Zhang et al. 2011
Texture	Banana slices	Maturity (low, medium, high sugar content); Microwave power (1.5–2.2 W/g)	The hardness and fracturability of MFD was good at high sugar content and 2 W/g.	Jiang et al. 2010a
	Restructured mixed potato with apple chips	Drying method (MFD, FD microwave vacuum drying and vacuum drying)	The crispness and hardness of MFD were higher than those of FD, which were lower than microwave vacuum drying and vacuum drying.	Huang et al. 2011
	Banana/potato restructured chips	Drying method (MFD, microwave vacuum drying); Proportion (1:1, 3:7, 7:3); Microwave power (2–3 W/g)	The hardness and fracturability of MFD were high at high potato content and 2.5 W/g, which were lower than that of microwave vacuum drying.	Jiang et al. 2011
Rehydration	Apple slices	Drying method (MFD, FD)	The rehydration ratios of MFD and FD had no significant difference.	Duan et al. 2012
	Potato slices	Pretreatment (blanching); Drying method (MFD, FD)	The rehydration ratios of MFD and FD blanched potato slices were up to twice than that of unblanched ones.	Wang et al. 2010c
	Carrot pieces	Drying method (MFD, FD, microwave-assisted vacuum drying and microwave-assisted spouted bed drying)	The rehydration ratio of carrot pieces dried by MFD was nearly the same compared to that of FD and better than that of microwave-assisted vacuum drying and microwave-assisted spouted bed drying.	Yan et al. 2010
Nutrition	Carrot pieces	Drying method (MFD, microwave-assisted vacuum drying and microwave-assisted spouted bed drying)	The retention of β-carotene and vitamin C of MFD were higher than those of microwave-assisted vacuum drying and microwave-assisted spouted bed drying	Yan et al. 2010
	Apple slices	Microwave power (1.2–2 W/g)	Protopectin and total pectin content decreased with increasing microwave power during MFD.	Wu et al. 2010
	Potato slices	Pretreatment (blanching); Drying method (MFD, FD)	The sugar and starch losses of MFD were similar to those of FD.	Wang et al. 2010c
	Restructured purple-fleshed sweet potato granules	Drying method (MFD, microwave-assisted vacuum drying and microwave-assisted spouted bed drying)	The anthocyanin level of MFD was higher than that of microwave-assisted vacuum drying and microwave-assisted spouted bed drying.	Liu et al. 2012

The structure changes of banana chips dried by MFD were similar to that of FD. The similar results were reported by Wang et al. (2012d), the microstructure of stem lettuce cubes dried by MFD were also similar to that of FD. On the other hand, Huang et al. (2011) presented that the microstructure of re-structured mixed potato with apple chips dried by MFD had familiar honeycomb network. The microstructure of mixed chips showed clearly porous structure but the honeycomb number was less than that of MFD due to microwave heating resulting in expanded porous structure formation of dried product. Jiang et al. (2014a) obtained that the cell structure of banana chips had notable change at desorption stage during MFD. Therefore, MFD can provide good microstructure of dried product.

The product safety is the major factor which determines the product's suitability and market value. The microorganism is responsible for many deteriorative processes, thus it is extremely important to reduce their activity. Some researchers showed that MFD process can cause a reduction in microbial content of dried product. For instance, Duan et al. (2007) showed that sterilization of cabbage dried by MFD had an obvious effect compared to that of FD. This is due to the fact that the thermal effect and biological effect of microwave could cause microorganism death. On the other hand, Duan et al. (2008a) presented that microwave freeze drying combined with nanoscale silver coating treatment can decrease microorganism number due to the effects of high microwave power, high temperature and nanoscale silver resulting in low microorganism number. Therefore, MFD or its combination with antibacterial agents has sterilization effect to increase the shelf life.

Conclusion

Basing on the literature, it is clear that MFD can replace FD in many applications. MFD shortens the overall drying time and reduces net energy consumption. Moreover, MFD can ensure the similar product quality as conventional FD. MFD indicated a smaller reduction of some nutrient elements of food products. Meanwhile, MFD affects some physical properties of vegetables and fruits such as color change, hardness and rehydration. From the microorganism analysis, the reduction of the microorganism was observed for samples dried by MFD. However, there are still some problems needing further research to successfully introduce MFD to industrial applications. The future research trends and challenges in this area can be as follows: 1. Novel non-thermal technologies such as ultrasounds, high pressure processing, pulsed electric fields should be applied to improve quality of heat-sensitive fruits and vegetables in MFD process. 2. The design of computer software needs innovative research to simulate microwave freeze drying process, which is beneficial for optimizing process parameters and predicting temperature and moisture distribution. 3. The mode of drying process should be studied in the MFD. For example, multi-stage continuous drying can be controlled to improve efficiency and reduce energy consumption. 4. AS the microwave field keeps changing during the drying process, microwave field should be further studied to improve the microwave freeze drying theory.

Acknowledgments

We acknowledge the financial support from National Key R&D Program of China (Contract No. 2017YFD0400901), Jiangsu Province (China) Agricultural Innovation Project(Contract No. CX(17)2017), Jiangsu Province (China) "Collaborative Innovation Center for Food Safety and Quality Control"Industry Development Program, Jiangsu Province (China) Infrastructure Project (Contract No. BM2014051) all of which enabled us to carry out this study.

Funding

National Key R&D Program 510 of China (Contract No. 2017YFD0400901), Jiangsu Province (China) Agricultural Innovation Project (Contract No. CX (17) 2017), Jiangsu Province (China) "Collaborative Innovation Center for Food Safety and Quality Control" Industry Development Program, Jiangsu Province (China) Infrastructure Project (Contract No. BM2014051).

References

Abbasi, S., and S. Azari 2009. Novel microwave–freeze drying of onion slices. *Int. J. Food Sci. Technol.* 44:974–979.

Argyropoulos, D., A. Heindl, and J. Müller 2011. Assessment of convection, hot-air combined with microwave-vacuum and freeze-drying methods for mushrooms with regard to product quality. *Int. J. Food Sci. Technol.* 46:333–342.

Ambros, S., S. A. W. Bauer, L. Shylkina, P. Foerst, and U. Kulozik 2016. Microwave-vacuum drying of lactic acid bacteria: Influence of process parameters on survival and acidification activity. *Food Bioprocess Technol.* 9:1901–1911.

Amami, E., W. Khezami, S. Mezrigui, L. S. Badwaik, A. K. Bejar, C. T. Perez, and N. Kechaou 2017. Effect of ultrasound-assisted osmotic dehydration pretreatment on the convective drying of strawberry. *Ultrason. Sonochem.* 36:286–300.

Bórquez, R., D. Melo, and C. Saavedra 2014. Microwave-vacuum drying of strawberries with automatic temperature control. *Food Bioprocess Technol.* 8:266–276.

Cui, Z. W., C. Y. Li, C. F. Song, and Y. Song 2008. Combined microwave-vacuum and freeze drying of carrot and apple chips. *Dry. Technol.* 26:1517–1523.

Cao, X., M. Zhang, Z. Fang, A. S. Mujumdar, H. Jiang, H. Qian, and H. Ai 2016. Drying kinetics and product quality of green soybean under different microwave drying methods. *Dry. Technol.* 35:240–248.

Cao, Y., S. Li, B. Yang, F. Zhao, D. Su, and Q. Zhao 2006. Experimental study of vacuum discharge in microwave freeze-drying process. http://www.icef11.org/content/papers/aft/AFT495.pdf.

Duan, X., M. Zhang, and A. S. Mujumdar 2007. Studies on the microwave freeze drying technique and sterilization characteristics of cabbage. *Dry. Technol.* 25:1725–1731.

Duan, X., M. Zhang, X. Li, and A. S. Mujumdar 2008a. Microwave freeze drying of sea cucumber coated with nanoscale silver. *Dry. Technol.* 26:413–419.

Duan, X., M. Zhang, X. Li, and A. S. Mujumdar 2008b. Ultrasonically enhanced osmotic pretreatment of sea cucumber prior to microwave freeze drying. *Dry. Technol.* 26:420–426.

Duan, X., M. Zhang, A. S. Mujumdar, and S. Wang 2010a. Microwave freeze drying of sea cucumber (*Stichopus japonicus*). *J. Food Eng.* 96:491–497.

Duan, X., M. Zhang, A. S. Mujumdar, and R. Wang 2010b. Trends in microwave-assisted freeze drying of foods. *Dry. Technol.* 28:444–453.

Duan, X., G. Y. Ren, and W. X. Zhu 2012. Microwave freeze drying of apple slices based on the dielectric properties. *Dry. Technol.* 30:535–541.

Duan, X., X. Yang, G. Ren, Y. Pang, L. Liu, and Y. Liu 2015. Technical aspects in freeze-drying of foods. *Dry. Technol.* 34:1271–1285.

Duan, X., S. S. Yan, F. L. Zeng, and G. Y. Ren 2016a. Simulation of heat and mass transfer during microwave freeze drying of white mushrooms based on dielectric property. *Modern Food Sci. Technol.* 32:177–182.

Duan, X., W. C. Liu, G. Y. Ren, L. L. Liu, and Y. H. Liu 2016b. Browning behavior of button mushrooms during microwave freeze-drying. *Dry. Technol.* 34:1373–1379.

Fan, L., S. Ding, Y. Liu, and L. Ai 2012. Dehydration of crude protein from Ginkgo biloba L. by microwave freeze drying. *Int. J. Biol. Macromol.* 50:1008–1010.

Huang, L., M. Zhang, A. S. Mujumdar, D. Sun, G. Tan, and S. Tang 2009. Studies on decreasing energy consumption for a freeze-drying process of apple slices. *Dry. Technol.* 27:938–946.

Huang, L., M. Zhang, A. S. Mujumdar, and R. Lim 2011. Comparison of four drying methods for re-structured mixed potato with apple chips. *J. Food Eng.* 103:279–284.

Huang, J., and M. Zhang 2015. Effect of three drying methods on the drying characteristics and quality of okra. *Dry. Technol.* 34:900–911.

Jiang, H., M. Zhang, and A. S. Mujumdar 2010a. Microwave freeze-drying characteristics of banana crisps. *Dry. Technol.* 28:1377–1384.

Jiang, H., M. Zhang, and A. S. Mujumdar 2010b. Physico-chemical changes during different stages of MFD/FD banana chips. *J. Food Eng.* 101:140–145.

Jiang, H., M. Zhang, A. S. Mujumdar, and R. X. Lim 2011. Comparison of the effect of microwave freeze drying and microwave vacuum drying upon the process and quality characteristics of potato/banana re-structured chips. *Int. J. Food Sci. Technol.* 46:570–576.

Jiang, H., M. Zhang, A. S. Mujumdar, and R. X. Lim 2012. Analysis of temperature distribution and SEM images of microwave freeze drying banana chips. *Food Bioprocess Technol.* 6:1144–1152.

Jiang, H., M. Zhang, Y. Liu, A. S. Mujumdar, and H. Liu 2013. The energy consumption and color analysis of freeze/microwave freeze banana chips. *Food Bioprod. Process.* 91:464–472.

Jiang, H., M. Zhang, A. S. Mujumdar, and X. L. Rui 2014a. Changes of microwave structure/dielectric properties during microwave freeze-drying process banana chips. *Int. J. Food Sci. Technol.* 49:1142–1148.

Jiang, H., M. Zhang, A. S. Mujumdar, and R. X. Lim 2014b. Comparison of drying characteristic and uniformity of banana cubes dried by pulse-spouted microwave vacuum drying, freeze drying and microwave freeze drying. *J. Sci. Food Agric.* 94:1827–1834.

Jiang, N., C. Liu, D. Li, and Y. Zhou 2015a. Effect of blanching on the dielectric properties and microwave vacuum drying behavior of Agaricus bisporus slices. *Innov. Food Sci. Emerg. Technol.* 30:89–97.

Jiang, H., M. Zhang, A. S. Mujumdar, and R. X. Lim 2015b. Drying uniformity analysis of pulse-spouted microwave–freeze drying of banana cubes. *Dry. Technol.* 34:539–546.

Jiang, N., C. Liu, D. Li, Z. Zhang, C. Liu, D. Wang, L. Niu, and M. Zhang 2017. Evaluation of freeze drying combined with microwave vacuum drying for functional okra snacks: Antioxidant properties, sensory quality, and energy consumption. *LWT-Food Sci. Technol.* 82:216–226.

Kristiawan, M., V. Sobolik, L. Klíma, and K. Allaf 2011. Effect of expansion by instantaneous controlled pressure drop on dielectric properties of fruits and vegetables. *J. Food Eng.* 102:361–368.

Lombraña, J. I., I. Zuazo, and J. Ikara 2001. Moisture diffusivity behavior during freeze drying under microwave heating power application. *Dry. Technol.* 19:1613–1627.

Li, Z. Y., R. F. Wang, and T. Kudra 2011. Uniformity issue in microwave drying. *Dry. Technol.* 29:652–660.

Liu, P., M. Zhang, and A. S. Mujumdar 2012. Comparison of three microwave-assisted drying methods on the physiochemical, nutritional and sensory qualities of re-structured purple-fleshed sweet potato granules. *Int. J. Food Sci. Technol.* 47:141–147.

Latorre, M. E., M. F. de Escalada Plá, A. M. Rojas, and L. N. Gerschenson 2013. Blanching of red beet (*Beta vulgaris* L. var. conditiva) root. Effect of hot water or microwave radiation on cell wall characteristics. *LWT-Food Sci. Technol.* 50:193–203.

Liu, P., A. S. Mujumdar, M. Zhang, and H. Jiang 2014. Comparison of three blanching treatments on the color and anthocyanin level of the microwave-assisted spouted bed drying of purple flesh sweet potato. *Dry. Technol.* 33:66–71.

Li, R., L. Huang, M. Zhang, A. S. Mujumdar, and Y. C. Wang 2014. Freeze drying of apple slices with and without application of microwaves. *Dry. Technol.* 32:1769–1776.

Mujumdar, A. S., and C. L. Law 2010. Drying technology: Trends and applications in postharvest processing. *Food Bioprocess Technol.* 3:843–852.

Motavali, A., G. H. Najafi, S. Abbasi, S. Minaei, and A. Ghaderi 2013. Microwave-vacuum drying of sour cherry: comparison of mathematical models and artificial neural networks. *J. Food Sci. Technol.* 50:714–722.

Monteiro, R. L., B. A. M. Carciofi, and J. B. Laurindo 2016. A microwave multi-flash drying process for producing crispy bananas. *J. Food Eng.* 178:1–11.

Nastaj, J. F., K. Witkiewicz, and B. Wilczyńska 2008. Experimental and simulation studies of primary vacuum freeze-drying process of random solids at microwave heating. *Int. Commun. Heat Mass Tran.* 35:430–438.

Nastaj, J. F., and K. Witkiewicz 2009. Mathematical modeling of the primary and secondary vacuum freeze drying of random solids at microwave heating. *Int. J. Heat Mass Tran.* 52:4796–4806.

Onwude, D. I., N. Hashim, and G. Chen 2016. Recent advances of novel thermal combined hot air drying of agricultural crops. *Trends Food Sci. Technol.* 57:132–145.

Ostermann-Porcel, M. V., A. N. Rinaldoni, L. T. Rodriguez-Furlan, and M. E. Campderros 2016. Quality assessment of dried okara as a source of production of gluten-free flour. *J. Sci. Food Agric.* 97:2934–2941.

Pei, F., Y. Shi, A. M. Mariga, W. Yang, X. Tang, L. Zhao, X. An, and Q. Hu 2013. Comparison of freeze-drying and freeze-drying combined with microwave vacuum drying methods on drying kinetics and rehydration characteristics of button mushroom (*Agaricus bisporus*) Slices. *Food Bioprocess Technol.* 7:1629–1639.

Sagar, V. R., and P. S. Kumar 2010. Recent advances in drying and dehydration of fruits and vegetables: A review. *J. Food Sci. Technol.* 47:15–26.

Szadzińska, J., S. J. Kowalski, and M. Stasiak 2016. Microwave and ultrasound enhancement of convective drying of strawberries: Experimental and modeling efficiency. *Int. J. Heat Mass Tran.* 103:1065–1074.

Song, X., B. Liu, and G. K. Jaganathan 2016. Mathematical simulation on the surface temperature variation of fresh-cut leafy vegetable during vacuum cooling. *Int. J. Refrig.* 65:228–237.

Tao, Z., H. Wu, G. Chen, and H. Deng 2005. Numerical simulation of conjugate heat and mass transfer process within cylindrical porous media with cylindrical dielectric cores in microwave freeze-drying. *Int. J. Heat Mass Tran.* 48:561–572.

Vadivambal, R., and D. S. Jayas 2008. Non-uniform temperature distribution during microwave heating of food materials-A review. *Food Bioprocess Technol.* 3:161–171.

Valadez-Carmona, L., C. P. Plazola-Jacinto, M. Hernández-Ortega, M. D. Hernández-Navarro, F. Villarreal, H. Necoechea-Mondragón, A. Ortiz-Moreno, and G. Ceballos-Reyes 2017. Effects of microwaves, hot air and freeze-drying on the phenolic compounds, antioxidant capacity, enzyme activity and microstructure of cacao pod husks (*Theobroma cacao* L.). *Innov. Food Sci. Emerg. Technol.* 41:378–386.

Wang, Z. H., and M. H. Shi 1998. Microwave freeze drying characteristics of beef. *Dry. Technol.* 17:434–447.

Wang, W., and G. Chen 2003. Numerical investigation on dielectric material assisted microwave freeze-drying of aqueous mannitol solution. *Dry. Technol.* 21:995–1017.

Wu, H., Z. Tao, G. Chen, H. Deng, G. Xu, and S. Ding 2004. Conjugate heat and mass transfer process within porous media with dielectric cores in microwave freeze drying. *Chem. Eng. Sci.* 59:2921–2928.

Wang, W., and G. Chen 2005a. Theoretical study on microwave freeze-drying of an aqueous pharmaceutical excipient with the aid of dielectric material. *Dry. Technol.* 23:2147–2168.

Wang, W., and G. Chen 2005b. Heat and mass transfer model of dielectric-material-assisted microwave freeze-drying of skim milk with hygroscopic effect. *Chem. Eng. Sci.* 60:6542–6550.

Wang, W., and G. Chen 2007. Freeze drying with dielectric-material-assisted microwave heating. *AIChE J.* 53:3077–3088.

Wang, R., M. Zhang, A. S. Mujumdar, and J. C. Sun 2009. Microwave freeze-drying characteristics and sensory quality of instant vegetable soup. *Dry. Technol.* 27:962–968.

Witkiewicz, K., and J. F. Nastaj 2010. Simulation strategies in mathematical modeling of microwave heating in freeze-drying process. *Dry. Technol.* 28:1001–1012.

Wu, G. C., M. Zhang, A. S. Mujumdar, and R. Wang 2010. Effect of calcium ion and microwave power on structural and quality changes in drying of apple slices. *Dry. Technol.* 28:517–522.

Wang, R., M. Zhang, and A. S. Mujumdar 2010a. Effect of food ingredient on microwave freeze drying of instant vegetable soup. *LWT-Food Sci. Technol.* 43:1144–1150.

Wang, R., M. Zhang, and A. S. Mujumdar 2010b. Effect of osmotic dehydration on microwave freeze-drying characteristics and quality of potato chips. *Dry. Technol.* 28:798–806.

Wang, R., M. Zhang, and A. S. Mujumdar 2010c. Effects of vacuum and microwave freeze drying on microstructure and quality of potato slices. *J. Food Eng.* 101:131–139.

Wang, R., M. Zhang, A. S. Mujumdar, and H. Jiang 2011a. Effect of salt and sucrose content on dielectric properties and microwave freeze drying behavior of re-structured potato slices. *J. Food Eng.* 106:290–297.

Wang, H., Z. Hu, K. Tu, F. Wu, T. Zhong, and H. Xie 2011b. Application of vacuum-cooling pretreatment to microwave freeze drying of carrot slices. *Trans. CSAE* 27:358–363.

Wang, Y., M. Zhang, A. S. Mujumdar, and K. J. Mothibe 2012a. Quality changes of dehydrated restructured fish product from silver carp (*Hypophthalmichthys molitrix*) as affected by drying methods. *Food Bioprocess Technol.* 6:1664–1680.

Wang, Y., M. Zhang, A. S. Mujumdar, and K. J. Mothibe 2012b. Microwave-assisted pulse-spouted bed freeze-drying of stem lettuce slices-effect on product quality. *Food Bioprocess Technol.* 6:3530–3543.

Wang, Y., M. Zhang, A. S. Mujumdar, and K. J. Mothibe 2012c. Experimental investigation and mechanism analysis on microwave freeze drying of stem lettuce cubes in a circular conduit. *Dry. Technol.* 30:1377–1386.

Wang, Y., M. Zhang, A. S. Mujumdar, K. J. Mothibe, and S. M. Roknul Azam 2012d. Effect of blanching on microwave freeze drying of stem lettuce cubes in a circular conduit drying chamber. *J. Food Eng.* 113:177–185.

Wang, Y., M. Zhang, A. S. Mujumdar, K. J. Mothibe, and S. M. Roknul Azam 2013a. Study of drying uniformity in pulsed spouted microwave-vacuum drying of stem lettuce slices with regard to product quality. *Dry. Technol.* 31:91–101.

Wang, Y., M. Zhang, B. Adhikari, A. S. Mujumdar, and B. Zhou 2013b. The application of ultrasound pretreatment and pulse-spouted bed microwave freeze drying to produce desalted duck egg white powders. *Dry. Technol.* 31:1826–1836.

Wray, D., and H. S. Ramaswamy 2015a. Novel concepts in microwave drying of foods. *Dry. Technol.* 33:769–783.

Wray, D., and H. S. Ramaswamy 2015b. Microwave-osmotic/microwave-vacuum drying of whole cranberries: Comparison with other methods. *J. Food Sci.* 80:E2792–802.

Yan, W. Q., M. Zhang, L. L. Huang, J. M. Tang, A. S. Mujumdar, and J. C. Sun 2010. Studies on different combined microwave drying of carrot pieces. *Int. J. Food Sci. Technol.* 45:2141–2148.

Zhang, M., J. Tang, A. S. Mujumdar, and S. Wang 2006. Trends in microwave-related drying of fruits and vegetables. *Trends Food Sci. Technol.* 17:524–534.

Zhang, J., M. Zhang, L. Shan, and Z. Fang 2007. Microwave-vacuum heating parameters for processing savory crisp bighead carp (*Hypophthalmichthys nobilis*) slices. *J. Food Eng.* 79:885–891.

Zhang, M., H. Jiang, and R. X. Lim 2010. Recent developments in microwave-assisted drying of vegetables, fruits, and aquatic products-drying kinetics and quality considerations. *Dry. Technol.* 28:1307–1316.

Zheng, X. Z., C. H. Liu, Z. Y. Chen, N. Y. Ding, and C. J. Jin 2010. Effect of drying conditions on the texture and taste characteristics of rough rice. *Dry. Technol.* 29:1297–1305.

Zhang, F., M. Zhang, and A. S. Mujumdar 2011. Drying characteristics and quality of restructured wild cabbage chips processed using different drying methods. *Dry. Technol.* 29:682–88.

Zielinska, M., P. Sadowski, and W. Błaszczak 2015. Freezing/thawing and microwave-assisted drying of blueberries (*Vaccinium corymbosum* L.). *LWT-Food Sci. Technol.* 62:555–563.

Zhang, M., H. Chen, A. S. Mujumdar, Q. Zhong, and J. Sun 2015. Recent developments in high-quality drying with energy-saving characteristic for fresh foods. *Dry. Technol.* 33:1590–1600.

Zheng, M., Q. Xia, and S. Lu 2015. Study on drying methods and their influences on effective components of loquat flower tea. *LWT-Food Sci. Technol.* 63:14–20.

Zhang, L., T. Liu, Y. Xue, C. Liu, H. Ru, M. Dong, and Z. Yu 2016. Effects of drying methods on the aroma components and quality of *Capsella bursa-pastoris* L. *J. Food Process Eng.* 39:107–120.

Zhang, M., H. Chen, A. S. Mujumdar, J. Tang, S. Miao, and Y. Wang 2017. Recent developments in high-quality drying of vegetables, fruits, and aquatic products. *Crit. Rev. Food Sci. Nutr.* 57:1239–1255.