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Review

Microwave processing techniques and their recent applications in the food industry

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ABSTRACT

Background: Microwave processing techniques have been extensively used in the food industry due to its significant reduction in cooking time and energy consumption. Microwave processing technologies such as microwave drying, heating and sterilizing play a significant role in food quality and safety control. However, few reviews have been published in recent years summarizing the latest developments in the application of microwave technology in the food industry.
Scope and approach: This review focuses on recent applications of microwave processing technologies including microwave drying, heating, and sterilizing in fruit (banana, apple, olive, sour cherries, pomegranate arils, blueberries, kiwifruit, aronia, strawberry, and grape tomato), vegetables (potato, bamboo shoot, purslane leaves, onion, green bean, pumpkin, eggplant, edamame, sea tangle, garlic, kale, red cabbage, tomato, cassava, lentils, chickpea, broccoli, Brussels sprouts, cauliflower, jalapeño peppers, and coriander foliage), and meat products (sardine fish, restructured silver carp slices, sea cucumber, beef semitendinosus muscle, bovine supraspinatus muscle, camel longissimus dorsi muscle, foal meat, bovine gluteus medium muscle, chicken steak, mature cows semimembranosus and semitendinosus muscles, kavurma (a ready-to-eat meat product), salmon, cod, drumettes, and beef slices), changes in product quality as affected with microwave processing are discussed in details, and future directions of research are presented.
Key findings and conclusions: Microwave drying has the advantages of low energy consumption and high efficiency as compared to conventional drying, while producing more porous structure of foods. Microwave drying usually combines with other conventional drying to enhance the quality of a food product. Compared with the traditional method, microwave heating or cooking can generally retain higher levels of bioactive components, antioxidant activity and attractive color of vegetables, while microwave cooking with water can cause a serious drop in nutrients due to leaching and thermal liability. Microwave sterilization has the capacity to completely inactivate microorganisms and effectively destroy enzyme activity, and less effect on antioxidant activity, texture and color of food products compared with conventional pasteurization.

1. Introduction

Microwaves are electromagnetic waves with the frequency varies from 300 MHz to 300 GHz (Chandrasekaran, Ramanathan, & Basak, 2013). The frequency of the microwave oven is defined to avoid interference with communications. The lower the microwave frequency, the better the penetration. Generally speaking, to balance efficiency and cost, home microwave frequency is 2.45 GHz,

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Nomenclature

L	Lightness (CIELab tristimulus color values)
a	Redness (CIELab tristimulus color values)
b	Yellowness (CIELab tristimulus color values)
Deff	Effective moisture diffusivity
R^2	Determination coefficient
RMSE	Root mean square error

while industrial microwave frequency is 915 MHz or 2.45 GHz. The microwave field is an alternating magnetic field, in which, polarity molecules from the original random thermal motion changes according to the orientation of the electric field direction (2.45 billion times per second) (Menéndez et al., 2010). The ability of food material to convert microwave energy into heat can be understood by its dielectric properties (Franco, Yamamoto, Tadini, & Gut, 2015; Curet, Rouaud, & Boillereaux, 2014). Dielectric properties show the nature of electrostatic energy saving and loss in the electric field, usually expressed as dielectric constant and dielectric loss. Non-uniformity is a characteristic of microwave processing. The microwave pattern is responsible for creating a hot spot and cold spot, and the hot spot is concentrated in a region where the electromagnetic field intensity is higher (Kumar, Saha, Sauret, Karim, & Gu, 2016). Therefore, it is important to improve the uniformity during microwaving. Microwaving has been enormously applied in the field of food processing such as drying, heating or cooking, pasteurization and preservation of foods (Chandrasekaran et al., 2013).

Like cooling (Sun & Hu, 2003; Wang & Sun, 2002a, 2002b; Sun & Wang, 2000; Sun, 1997; McDonald, Sun, & Kenny, 2000; Sun, & Brosnan, 1999; Zheng, & Sun, 2004; Wang & Sun, 2004) and freezing (Kiani, Zhang, Delgado, & Sun, 2011; Ma et al., 2015; Xie, Sun, Xu, & Zhu, 2015; Cheng, Sun, & Pu 2016; Pu, Sun, Ma, & Cheng, 2015; Cheng, Sun, Zhu, & Zhang, 2017, Xie, Sun, Zhu, & Pu, 2016), drying (Cui, Sun, Chen, & Sun, 2008; Yang, Sun, & Cheng, 2017; Pu, & Sun, 2016a) is a common processing method used in the food industry. In particular, microwave drying has many advantages, including lower shrinkage, lower bulk density, and higher rehydration ratio, dehydration rate and energy saving than traditional drying (Aydogdu, Sumnu, & Sahin, 2015; Duan, Zhang, Mujumdar, & Wang, 2010; Horuz & Maskan, 2015). However, more porous structure of foods caused by microwave drying occurs due to faster drying rate when compared with traditional drying (Aydogdu et al., 2015; Horuz & Maskan, 2015). In addition, overheating normally results in scorching and the production of off-flavors especially during the final stage of microwave drying (Horuz, Bozkurt, Karataş, & Maskan, 2017). Usually, in order to improve the drying rate and enhancing the quality of products, the microwave drying method and other traditional drying methods are employed in combination.

Microwave heating or cooking (Półtorak et al., 2015) can retain high levels of bioactive components, antioxidant activity and attractive color of vegetables, when cooking without water or with a small amount of water (Akdaş & Bakkalbaşı, 2016; Pellegrini et al., 2010; Tian et al., 2016; Xu et al., 2014). It can also decrease the anti-nutritional factors, meanwhile increase in in-vitro protein digestibility (Hefnawy, 2011; Xu et al., 2016; Yang, Hsu, & Yang, 2014). However, microwave cooking with massive water can cause a great drop in nutrients due to leaching and thermal liability (Dolinsky et al., 2015; de Lima et al., 2017).

Microwave sterilization can not only effectively reduce the potential microorganisms in food to ensure food safety, but can also inactivate the enzyme to maintain the nutrition of food (Chen et al., 2016; Marszałek, Mitek, & Skąpska, 2015). Increase in microwave power and time increases the effectiveness (Valero, Cejudo, & García-Gimeno, 2014). In addition, the non-uniformity of microwave sterilization can influence the quality of the product and shorten the shelf life.

Due to the above advantages, microwave processing techniques have been extensively used in the food industry. However, few reviews have been published in recent years summarizing the latest developments. Therefore, this review focuses on the applications of microwave processing technologies in the last few years. The technologies covered include microwave drying, heating or cooking, and sterilizing in vegetable, fruit and meat processing. Attentions are paid to the quality changes of food product after microwave processing and future research directions.

2. Microwave drying

2.1. Mechanism of microwave drying

Microwave drying, such as vacuum-microwave drying, hot air-microwave drying, microwave-far infrared combination drying, microwave-convective drying and microwave-freeze drying, is a complex process involving heat and mass transfer, which is based on the volumetric heating (Pu & Sun, 2015, 2016b, 2017; Cui, Xu, Sun, & Chen, 2005; Cui, Xu, & Sun, 2003, 2004a, 2004b). Vapor is generated inside a food item and then spread through internal pressure gradient. Because of the strong penetrability of microwave, food inside and outside are heated at the same time and the temperature of food rises simultaneously.

Microwave drying translates the high frequency electromagnetic energy into heat, thus liquid moisture is intensively evaporated and transported toward the food material surface (Li, Wang, & Kudra, 2011). In the process of microwave drying, two successive stages should be considered: liquid evaporation (Arballo, Campañone, & Mascheroni, 2010), and drying consisting of three stages including heating up, constant rate drying and falling rate drying (Bal, Kar, Satya, & Naik, 2010).

2.2. Moisture migration and distribution during drying process

During constant and falling rate-drying periods, effective moisture diffusion phenomenon shows an overall mass transport property of water in the food material, including liquid and vapor diffusion, vaporization-condensation, hydrodynamic flow and other possible mass transfer processes. The effective moisture diffusion coefficient is affected by many factors such as composition, moisture content, temperature, and the porosity of food material, which can be explained by the Fick's diffusion equation, and it is the only physical mechanism to transfer the water to surface.

In order to understand the moisture migration and distribution, Jiang, Zhang, Mujumdar, and Lim (2012) employed a nuclear magnetic resonance (NMR) spectroscopy to study banana dried by microwave-freeze drying, as the spin-spin relaxation time, which is the time of revocation of transverse magnetization, and peak area can reflect the nature and content of water. With spin-spin relaxation time increasing, the three peaks represent strongly bound water, bound water, and free water components, respectively. From Fig. 1, it can be seen that as the drying process continues, the area of the three peaks is smaller, which means that the moisture content of food is falling. At the same time, the relaxation time of the three peaks is close to 0, which means that the structure of water and food are closer. During banana chips dried by microwave-freeze drying, from the moisture content and drying rate curves, drying

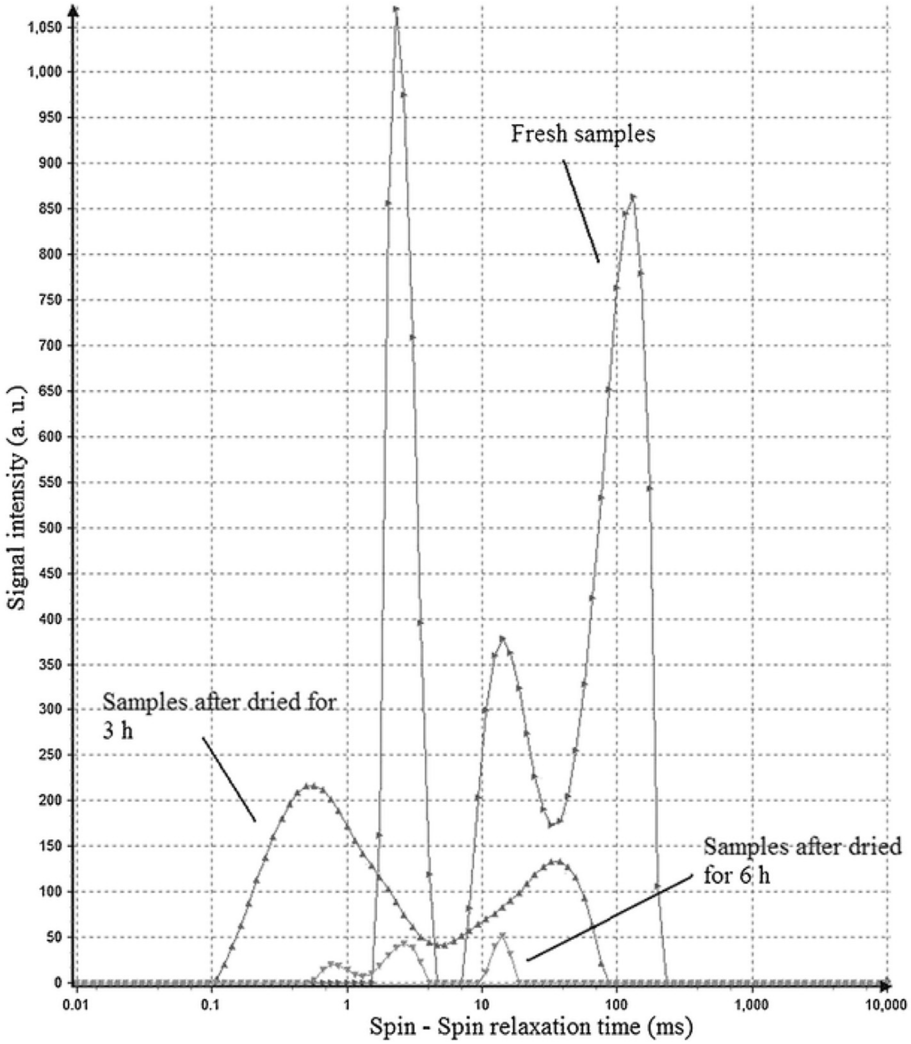

Fig. 1. Spin-spin relaxation times (T2) of different banana chips dried by MFD (Jiang et al., 2012).

for 3 h was the demarcation point of the sublimation drying stage (Jiang et al., 2012). At the sublimation drying stage, most of the free water and bound water was removed, while during the desorption drying stage, the unfrozen water could also be removed. Wang, Zhang, and Mujumdar (2010) investigated potato slices dried by microwave-freeze drying and showed that the sublimation period could last for about 4 h, followed by the desorption phase, during which, microwave drying had a lower drying rate, because the dielectric constant of ice is smaller than water. Jiang, Zhang, and Mujumdar (2010) showed that during sublimation drying, water could absorb microwave energy, leading to hot spots. Partial melting in the frozen area could thus cause very uneven heating. The ice melts into liquid water with microwave input could block pore and lead to the expansion of the food structure (Jiang et al., 2010), as evidenced by Wang, Zhang, and Arun (2013), who showed that restructured fish slices from silver carp were expanded by microwave-vacuum drying (4, 6, and 8 mm thickness), compared to other drying methods such as air drying, freeze drying and vacuum drying (4 mm thickness), which had different degrees of contraction.

In the process of microwave drying, effective moisture diffusion coefficient plays an important role as mass transfer is the key to the dehydration process. Table 1 summarizes some relevant studies. From Table 1, it can be seen that with the increase of the microwave power, Deff increases accordingly during microwave drying. For example, by increasing the microwave output power from 180 W to 900 W, Deff of purslane leaves dried by microwave drying increased from 5.913×10^{-11} m^2/s to 1.872×10^{-10} m^2/s (Demirhan & Özbek, 2010). A higher microwave power usually results in a more porous structure and increases the temperatures of the food material. In addition, high temperatures usually cause the denaturization of cell membranes and phase transitions, greatly damaging the samples. Bound water in damaged tissues is easier to be removed as compared with that in less damaged tissues during microwave drying. In order to predict the microwave drying process, various models have been used to fit the experimental data. However, based on Table 1, it seems that the Midilli et al. model is a robust model for describing microwave drying processes.

2.3. Effects of microwave drying on food quality attributes

The quality of food products has some changes during microwave drying. These changes include optical properties such as color and appearance, sensory properties such as odor, taste and flavor, structural properties such as density, porosity and specific volume, textural properties, rehydration properties such as rehydration rate and rehydration capacity, and nutritional characteristics such as vitamins and proteins.

Table 1
Effective moisture diffusivity of foods during microwave drying.

Material	Power (W)	Deff (m^2/s)	Change	Simulation model	R^2	References
Bamboo shoot slices	140–350	4.153×10^{-10} –22.835×10^{-10}	↑	Wang and Singh model	0.985	Bal et al. (2010)
Sardine fish	200–500	7.158×10^{-8} –3.408×10^{-7}	↑	Midilli et al. model	0.999	Darvishi et al. (2013)
Purslane leaves	180–900	5.913×10^{-11} –1.872×10^{-10}	↑	Midilli et al. model	0.997	Demirhan and Özbek (2010)
Onion slices	328–557	2.59×10^{-7} –5.08×10^{-7}	↑	Page model	0.995	Demiray, Seker, and Tulek (2016)
Apple slices	200–600	3.93×10^{-7} –2.27×10^{-6}	↑	Midilli et al. model	0.999	Zarein et al. (2015)
Green Bean Slices	180–800	1.387×10^{-8} –3.724×10^{-8}	↑	Midilli et al. model	0.999	Doymaz, Kipcak, and Piskin (2016)
Olive pomace	170–510	3.55×10^{-9} –20.47×10^{-9}	↑	Midilli et al. model	0.999	Sadi and Meziane (2015)

'↑' means that with the increase in microwave power, Deff increases accordingly.

Many investigations have been conducted on the changes of food products in nutritional characteristics during microwave drying. Nawirska-Olszańska, Stępień, and Biesiada (2017) showed that at the power of 100 W, the content of total polyphenols, bioactive compounds (chlorophyll *a*+*b*, carotenoids) and anti-oxidative properties of pumpkin slices dried by fountain-microwave were greater than that using the power of 250 W, and their results differed statistically. This was an opposite of the conclusion reported by Al Juhaimi et al. (2016), who showed that with a decrease in microwave power from 540 W to 180 W, the total phenolic contents and antioxidant activity values of apple slices deteriorated. The possible reason might be that in a small range of power (100 W - 250 W), increasing microwave power could cause rapid increase in temperature, and a temperature too high could destroy the nutrients of foods. However, when the microwave power showed a large change (180 W - 540 W), higher microwave power could shorten the heating time, thus improving the retention rate of nutrients preferably. Wojdyło, Figiel, Lech, Nowicka, and Oszmiański (2013) indicated that when sour cherries processed by vacuum-microwave drying, the contents of phenolic compounds, antioxidant activity, and color that is related to anthocyanins content were lower when drying at high temperature than those at low temperature. Similar results were reported for apple slices dried by intermittent microwave-convective air drying by Aghilinategh, Rafiee, Hosseinpur, Omid, and Mohtasebi (2015). In microwave drying, a higher temperature could destroy the nutrients of foods to a greater extent, especially heat sensitive components.

Textural and rehydration properties are also affected during microwave drying. Nawirska-Olszańska et al. (2017) showed that during fountain-microwave drying of pumpkin slices, a high microwave power resulted in decreased compression work, which was due to the partial dissolution of the middle lamellae of the samples. In addition, Sarimeseli (2011) demonstrated that the rehydrating capacity of coriander leaves processed by microwave drying decreased as the microwave power output increased (180–900 W), which may be attributed to cellular break down of the leaves during the drying process. This is in agreement with those reported by Horuz and Maskan (2015). Therefore, microwave drying at low microwave power should be able to maintain more tissue integrity of the food material than microwave drying at high microwave power.

On the other hand, the effects of microwave drying, microwave-vacuum drying, and microwave-far infrared combination drying were also reported on textural and rehydration properties as compared with other drying method including hot-air drying, freeze drying and vacuum drying. Eggplant slices dried by microwave-far infrared combination drying and pomegranate (*Punica granatum* L.) arils dried by microwave drying produced more porous structure than those treated by hot-air drying with faster drying rate, which greatly destroyed the integrity of the tissue (Aydogdu et al., 2015; Horuz & Maskan, 2015). Moreover, the low bulk density correlated well with a low degree of shrinkage. Therefore, eggplant slices and pomegranate (Punica granatum L.) arils processed by microwave drying could achieve lower shrinkage and bulk densities and higher rehydration ratio than hot-air drying method (Aydogdu et al., 2015; Horuz & Maskan, 2015). The maximum compression force of edamame subjected to microwave drying was lower than that from hot-air drying (Lv, Zhang, Bhandari, Yang, & Wang, 2017). Furthermore, Zielinska, Sadowski, and Błaszczak (2015) showed similar results about the hardness, chewiness and gumminess of blueberries (Vaccinium corymbosum L.), which were several times lower by microwave-vacuum drying than by hot-air drying, and Wang et al. (2013) indicated that restructured silver carp slices dried by microwave-vacuum drying had higher rehydration ratio as well as lower water holding capacity, hardness, springiness, cohesiveness, and chewiness than other dying methods such as air drying, freeze drying and vacuum drying. Generally speaking, compared with other drying methods such as hot-air drying, freeze drying and vacuum drying, microwave assisted drying including microwave drying (Horuz & Maskan, 2015; Lv et al., 2017), microwave-vacuum drying (Wang et al., 2013; Zielinska et al., 2015) and microwave-far infrared combination drying (Aydogdu et al., 2015) could cause greater damage on the cohesive forces between cells, producing more porous structure, thus having low bulk density, low degree of shrinkage and higher rehydration ratio of the dried food products.

The energy consumption of microwave drying has also been widely studied in order to obtain a minimum energy consumption under the experimental conditions. Darvishi, Azadbakht, Rezaeiasl, and Farhang (2013) observed that when microwave power was 500 W, sardine fish dried by microwave drying obtained a minimum energy consumption at four different microwave powers (200, 300, 400 and 500 W), Han et al. (2016) found that sea tangle dried with preheating for 20 min in a microwave dryer followed by drying at 100 °C in a far-infrared dryer consumed the least energy consumption with only 4.78 kJ/kg water, while Zarein, Samadi, and Ghobadian (2015) reported that the energy efficiency of apple slices processed by microwave drying was 54.34% at power level of 600 W and 17.42% at 200 W. As reducing the microwave power generally increases the drying time, it is thus not easy to assess the changing trend of energy consumption. For example, increasing the microwave output power could shorten the microwave drying time of sardine fish, which was as high as 51% (Darvishi et al., 2013). In addition, compared with freeze drying, sea cucumber treated by microwave drying saved 32% energy (Duan et al., 2010). Calín-Sánchez, Figiel, Wojdyło, Szarycz, and Carbonell-Barrachina (2013) also found that garlic slices dried by a combined method consisting of convective pre-drying followed by vacuum-microwave drying required less energy consumption than processed by the traditional convective drying. Therefore, it is evident that microwave drying and vacuum-microwave drying consume less energy than freeze drying and convective drying because the microwave is directly applied to the material and there is no additional thermal loss, so the thermal efficiency is high.

The improvements of foods processed by the microwave drying are listed in Table 2. Reducing vacuum-microwave drying power from 480 W to 120 W could be recommended for drying sour cherries with respect to the retention of maximum contents of total phenolics, especially anthocyanins, maximum antioxidant capacity, as well as minimum color change (Wojdyło et al., 2013). Considering better color, shrinkage, rehydration capacity and drying time, the optimum microwave drying condition for pomegranate (Punica granatum L.) arils was established at 350 W (Horuz & Maskan, 2015). Considering the drying time, discoloration, rehydration ratio, and energy consumption during combined microwave and far-infrared ray drying, the optimal drying condition for achieving high quality sea tangle was 15 min of preheating in a microwave dryer and drying at 100 °C in a far-infrared dryer (Han et al., 2016). The optimum condition of intermittent microwave-convective drying for apple slices was 1.78 m/s (air velocity), 40 °C (air temperature), 4.48 (pulse ratio), and 600 W (microwave power) (Aghilinategh et al., 2015). Therefore, it can be noted that different optimal drying conditions should be obtained for drying different types of foods.

3. Microwave heating

3.1. Mechanism of microwave heating

Conventional heating relies on heat conduction and convection. However, microwave heating, such as microwave-convective heating and combination of microwave, convection, and radiant heating, is based on volumetric heating, which heats the foods instantaneously (Kappe, 2013). The electric field component of the microwave induces the rotation of dipoles in foods and the heat is generated by the friction of molecules (Aguilar-Reynosa et al., 2017).

Polar molecules cannot synchronously oscillate with a magnetic field and have a short delay. The delay converts magnetic energy into translational energy, thus gradually decreases the amplitude of the microwave. Penetration is a kind of ability that the electromagnetic wave gets through the interior of foods. Electromagnetic waves travel from the surface of food and spread inside. Because the energy is absorbed and then translated into thermal energy, thus microwave carries the energy in the form of index attenuation. Penetration depth, which is dependent on food composition, is defined as the distance from the surface of the product before the intensity decays to 1/e (approximately 37%) of the original value (Vadivambal & Jayas, 2008). The hot spot and cold spot are found to be due to the standing wave (Kumar et al., 2016). The hot spot is concentrated in the region of high electric field intensity.

Table 3 summarizes the temperature distribution models during microwave heating. Uneven heating is an intrinsic characteristic of the microwave heating and achieving heating uniformity is a challenge in microwaving, which could be overcome by employing a feedback control loop to control the heating process. Therefore, it is important to know the temperature distribution of the foods in the process of microwave heating.

3.2. Effects of microwave heating on chemical components of food products

In microwave heating, changes associated with chemical components of food products are mainly related to the cook loss, antioxidant activity, bioactive components, and anti-nutritional components including trypsin inhibitor, haemagglutinin activity, tannins, saponins and phytic acid. Chang et al. (2011) reported the relationships between perimysium granulation, endomysium granulation, thermal denaturation and shrinkage of collagen and temperature (Fig. 2), and showed that during microwave heating and water bath heating, the higher the internal endpoint temperature or the longer the heating time of beef semitendinosus muscle, the higher the insoluble collagen contents were obtained, which could be accounted for the thermal denaturation and shrinkage of collagen. Musto, Faraone, Cellini, and Musto (2014) indicated that during microwave heating, cooking loss increased significantly with time, and consequently with increasing endpoint core temperatures of bovine supraspinatus muscle. In addition, cooking loss of the camel longissimus dorsi muscle were significantly affected by thermal treatment, being higher after microwaving (~43%) and lower after roasting (~34%) and braising (~30%), which could be attributed to the high loss of water and fat caused by protein denaturation and disintegration of the texture matrix with microwave treatment (Yarmand, Nikmaram, Emam Djomeh, & Homayouni, 2013). This is similar to that reported by Domínguez, Gómez, Fonseca, and Lorenzo (2014), who showed that the total loss percentage of foal meat treated by microwave heating (32.5%) was higher than by grilling (22.5%), frying (23.8%) and roasting (26.7%). Therefore, during microwave cooking, protein denaturation and cooking loss of foods increase with the increase in heating time or temperature, and the total cooking loss is higher than other cooking methods such as grilling, frying, roasting and braising due to no crust formed during microwave cooking.

Many investigations have been conducted on antioxidant activity and retention of bioactive components of vegetables with microwave heating. Akdaş and Bakkalbaşı (2016) reported that microwave treatment without water was suitable for cooking kale as the retention of ascorbic acid, total carotenoids, and total chlorophylls of kale was 89.4%, 99.8%, 44.7%, respectively. Tian et al. (2016) observed losses of total phenolics (negligible), total

Table 2
The optimal microwave drying parameters of different foods.

Material	Drying method	Power	Time	Air		Other	References
				Temperature	Velocity		
Pomegranate arils	Microwave drying	350 W	–	–	–	–	Horuz and Maskan (2015)
Sea tangle	Combination of microwave and far-infrared drying	–	15 min	–	0.8 m/s	Far-infrared of 100 °C	Han et al. (2016)
Apple slices	Microwave-convective drying	600 W	–	40 °C	1.78 m/s	Pulse ratio of 4.48	Aghilinategh et al. (2015)
Sour cherries	Vacuum-microwave drying	Reduction from 480 W to 120 W	–	–	–	Pressure between 4 and 6 kPa	Wojdyło et al. (2013)

Table 3
The temperature distribution model of foods during microwave heating.

Simulation method	Simulation object	Validation method	Validation	Reference
Physics-based computational temperature profiles modeling under combination of heating modes such as microwaves, convection, and radiant heating	TX151 powder with water (1:10 parts by weight)	Temperature distribution was measured by magnetic resonance imaging (MRI)	Good matching	Rakesh, Seo, Datta, McCarthy, and McCarthy (2010)
Using finite difference time domain under microwave heating	Gellan gel cylinder	Temperature distribution was measured by optical fiber sensor at 12 discrete points	The RMSE values ranged from 0.53 to 4.52 °C, with an average value of 2.02 °C	Pitchai, Birla, Subbiah, Jones, and Thippareddi (2012)
Modeling of heat and mass transfer during intermittent microwave-convective drying (IMCD) of multiphase porous media	Apple slice	Moisture content and temperature distribution were recorded after each cycle	$R^2 = 0.9906$	Kumar et al. (2016)
Decoupled-models for modeling microwave heating of frozen and fresh materials	Mashed potato	Temperature distribution was measured by the fiber-optic sensors at six locations	The averaged RMSE values were 5.2 °C (fresh) and 6.6 °C (frozen)	Chen, Pitchai, Jones, and Subbiah (2015)

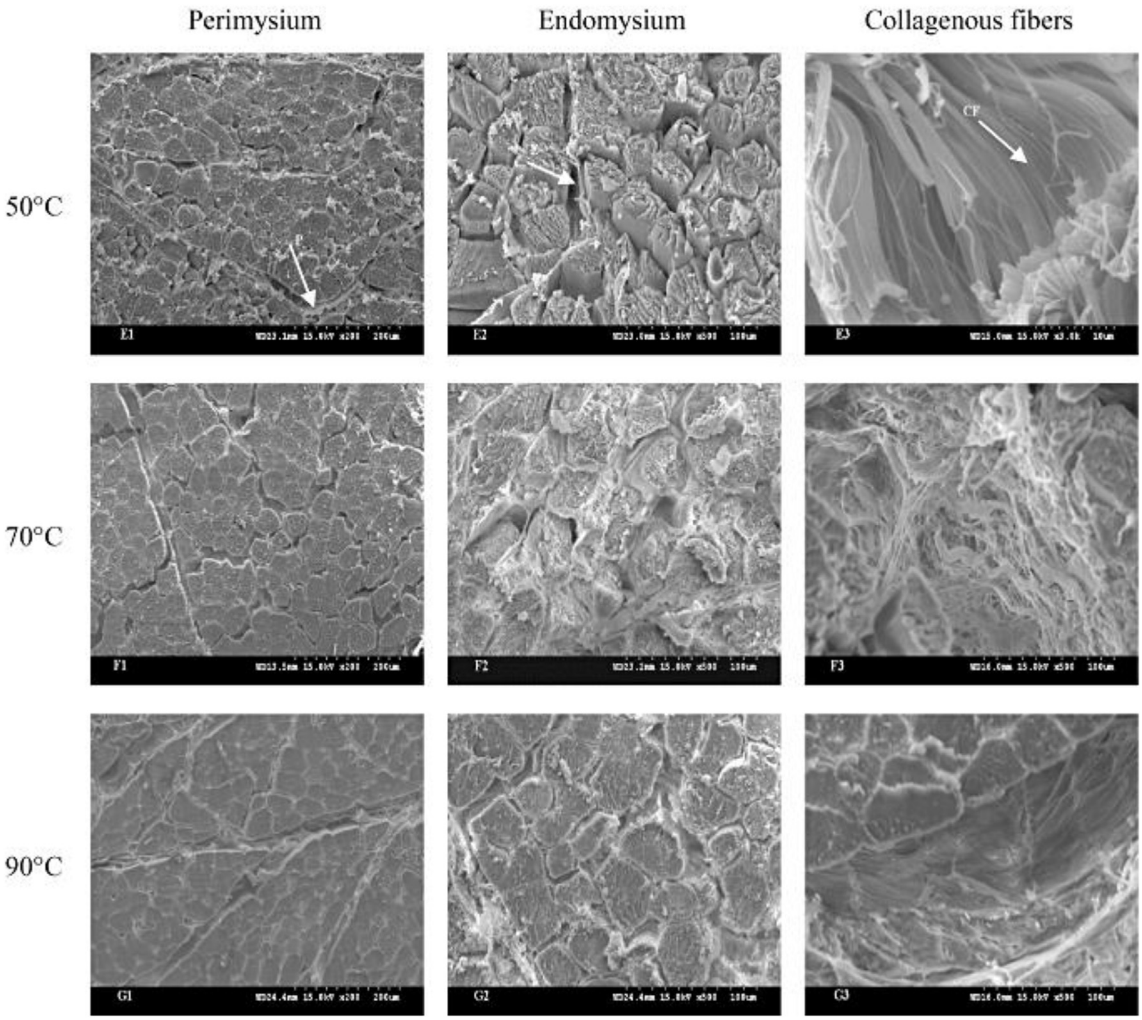

Fig. 2. Scanning electron microscope (SEM) photographs of intramuscular connective tissue for beef semitendinosus muscle heated to endpoint temperature: 50c (e1, e2, e3); 70c (f1, f2, f3); and 90c (g1, g2, g3) during microwave heating. Magnification were: E1→G1 (×200), E2→G2 (×500), E3 (×3000), F3, G3 (×500). P, perimysium; E, endomysium; CF: collagenous fibers (Chang et al., 2011).

anthocyanin (14.01%) and chlorogenic acid (20.01%) after microwaving purple-fleshed potatoes without water were much lower than stir-frying, baking, air-frying and frying. Xu et al. (2014) reported that there was negligible change in total phenolic content and no significant loss of vitamin C of red cabbage (adding 10 mL water to 300 g sample) after microwave heating, whereas obvious changes were observed on losses after stir-frying and boiling. The retention of bioactive components of vegetables processed by microwave is higher than those processed by other cooking methods because of shorter heating time, and without the pretreatment of soaking (Tian et al., 2016; Xu et al., 2014). Therefore, microwave cooking should be done without water or with a small amount of water for retaining antioxidant activity and bioactive components.

However, when massive water is added to foods during microwave heating, the retention of nutrients drops greatly. Dolinsky et al. (2015) found that microwave cooking with water was not recommended to cook selected vegetables owing to significant reduction in the contents of polyphenols (soluble polyphenol and hydrolysable polyphenol) of kale (reduction of 23.4%), tomato (reduction of 21.9%), and green beans (reduction of 22.9%), while steaming with little osmotic exchanges was more suitable for maintaining higher levels of their polyphenol concentrations. This observation was similar to that reported by de Lima et al. (2017), who showed that cassava (adding 500 g water to 500 g sample) treated by steaming retained more phenolic compounds (retention of 236.1%) and antioxidant activity (retention of 308.6%) than by microwaving (retention of 164.4% of phenolic and 273.4% of antioxidant activity). For bioactive substances of vegetables, microwave cooking increased the retention rate to varying degrees because water may cause a softening and rupture of the lignocellulosic structure, enabling those soluble bioactive substances to be released from the food matrix, while increasing the loss owing to leaching and thermal liability.

Studies were also performed on the changes of anti-nutritional factors, including trypsin inhibitor, haemagglutinin activity, tannins, saponins and phytic acid due to microwave heating. Hefnawy (2011) showed that the anti-nutritional factors in lentils were significantly reduced (a reduction of 93.3% for trypsin inhibitor, 34.4% for tannins and 39.2% for phytic acid) after microwave treatment. Moreover, microwave treatment improved the in-vitro protein digestibility and protein efficiency ratio of lentils (Hefnawy, 2011), which was in agreement with Deng, Padilla-Zakour, Zhao, and Tao (2015), who observed that the phytic acid, trypsin inhibitor activity, tannin and saponin of buckwheat were lowered by 33.4%, 13%, 27.5%, 20.1%, respectively, as well as protein digestibility was increased by 3.6% after microwave heating. Yang et al. (2014) noticed that trypsin inhibitors of soybeans were most effectively reduced (76.92% reduction for black soybeans, 97.91% reduction for yellow soybeans) by microwaving. In addition, Xu et al. (2016) reported that chickpea with the treatment of soaking followed by microwave cooking significantly increased in-vitro protein digestibility (increase ratio of 24.4%), and the contents of phytate and tannin levels were reduced by 25.3% and 39.8%, respectively. Therefore, microwave cooking could effectively decrease the anti-nutritional factors and increase in-vitro protein digestibility of foods.

3.3. *Effects of microwave heating on sensory attributes of food products*

During microwave heating, the changes associated with sensory attributes of food products can reflect in texture and color properties. Food color changes during thermal processing can be influenced by degradation of pigments, oxidation of ascorbic acid, enzymatic browning, and non-enzymatic browning (Ling, Tang, Kong, Mitcham, & Wang, 2014).

On one hand, effects on texture properties of foods during microwave heating were studied. Yarmand et al. (2013) noticed that after microwave heating, the compression force of the camel longissimus dorsi muscle was more than twice than that of the raw meat because of less solubilization of collagen. Półtorak et al. (2015) showed that the shear force value and the shrinkage rate of bovine gluteus medium muscle roasted in a microwave-convection oven were significantly higher than those roasted with traditional convection heating. In addition, Jouquand et al. (2015) found that beef burgundy prepared by microwaving perceived tougher texture than by convection oven. However, Choi et al. (2016) observed that the hardness of chicken steak cooked by a microwave oven was lower than that cooked with boiled and grilling. Moreover, Muñoz, Achaerandio, Yang, and Pujolà (2017) found a significant decrease in the shear force for potato tubers after microwaving because microwaving weakened the cohesive forces between cells. The above contradictive results might be related to different types of foods and different conditions of the heat treatments. Changing the conditions of heat treatment and food samples can change the texture properties. For example, marination with 10% injected brine solution (5.6% salt, 4% sodium lactate, 5% lactose, and 0.5% ascorbate) was used successfully to enhance the tenderness of Semimembranosus and Semitendinosus muscles from Friesian mature cows cooked by microwave (Pérez-Juan, Kondjoyan, Picouet, & Realini, 2012).

On the other hand, many investigations on the color of foods including vegetables and meats with microwave heating were reported. Pellegrini et al. (2010) showed that comparing with boiling and steaming, microwave heating was the best cooking method for maintaining the color of both fresh and frozen brassica vegetables (broccoli, Brussels sprouts, and cauliflower). In addition, comparing with other treatments such as boiling and steaming, kale subjected to microwave heating was awarded the highest scores for the value of b, which depended on chlorophylls and the formation of pheophytin (Akdaş & Bakkalbaşı, 2016; Armesto, Gómez-Limia, Carballo, & Martínez, 2016). Generally speaking, vegetables cooked in microwave can receive the highest scores for color. Armesto et al. (2016) showed that fresh kale had greater color intensity L after microwave cooking for 20 min (from 40.26 to 34.55) and 30 min (from 40.26 to 33.26). Similar results were reported by dos Reis et al. (2015), who observed that microwave cooking significantly decreased the L value of fresh cauliflower (from 56.7 to 49.4) and fresh broccoli (from 46.1 to 39.9). However, Zhong, Dolan, and Almenar (2015) found that the L value the frozen broccoli increased after microwaving (from ~21 to ~24) and Xu et al. (2014) observed that the L value of red cabbage was slightly enhanced with microwave treatment (from 26.57 to 28.99). The difference between these results could be attributed to the longer cooking times used for microwaving by Armesto et al. (2016), and fresh foods used by dos Reis et al. (2015).

The denaturation of proteins affects the changes in color. An increased reflection of light arising from light scattering by denatured proteins causes lesser lightness, while thermal denaturation of myoglobin and other proteins causes lesser redness. Therefore, during microwave heating of foods, an increase in microwave power would reduce the exposure time, leading to the obvious reduction in the denaturation of myoglobin and other proteins. For example, Półtorak et al. (2015) observed that bovine gluteus medium muscle treated by microwave-convection heating at 100% microwave intensity had lesser lightness, higher redness and lesser yellowness than those treated at 30% microwave intensity. Similarly, Pérez-Juan et al. (2012) reported that Semitendinosus muscles from Friesian mature cows cooked by microwaving at 654 W had lesser lightness, higher redness and lesser yellowness than those at 182 W. Özcan and Bozkurt (2015) also found that kavurma (one of ready-to-eat meat products) processed by microwaving possessed lesser lightness, higher redness and lesser yellowness with increase of cooking time. Therefore, microwave heating of meats should cause lesser lightness, higher redness and lesser yellowness by increasing microwave power levels or time of microwave cooking.

4. Microwave sterilization

4.1. Mechanism of microwave sterilization

The purpose of sterilization is to improve the safety and extend the shelf life of foods. Microwave pasteurization or sterilization can be explained by various mechanisms, such as selective heating, electroporation, cell membrane rupture and magnetic field coupling (Kozempel, Annous, Cook, Scullen, & Whiting, 1998). For example, due to the microwave selective heating, microbial bodies can reach a higher temperature than the surrounding fluid, leading to faster microbial destruction. For the electroporation mechanism, the electrical potential across the cell membrane can generate pores in cells, resulting in the leakage of cellular material. On the other hand, in the magnetic field coupling mechanism, vital components of the cell such as protein or DNA coupled in the magnetic field can be destroyed.

4.2. Effects of microwave sterilization on microorganisms

Microwave radiation including water-assisted microwave heating and microwave sterilization can be used to control potential microorganisms in foods. Table 4 shows the inactivation of pathogens in foods during microwave sterilization. Microwave sterilization can reduce the colony count of microbes in foods. Moreover, increasing microwave power and sterilization temperature, or extending the sterilization time could improve the effectiveness of microwave sterilization (Valero et al., 2014).

Microwave sterilization can substantially reduce the microorganisms in foods. Generally speaking, different types of foods usually inoculate with different types and levels of microorganisms, which further shows the requirements for different microwave sterilization conditions. De La Vega-Miranda, Santiesteban-López, López-Malo, and Sosa-Morales (2012) observed a 5.12 log reduction of *Salmonella typhimurium* on jalapeño pepper at 3 × 10^8 CFU/g using the water-assisted microwave treatment at 950 W to reach temperature at 63 °C for 25 s, and a 4.45 log reduction of *Salmonella typhimurium* on coriander foliage at 3 × 10^8 CFU/g at 63 °C for 10 s. Under the same microwave sterilization conditions (power and temperature), there was a difference between the effect of sterilization on jalapeño pepper and coriander foliage. In another work, Valero et al. (2014) reported that the inactivation rates of Salmonella enteritidis (6.30 log CFU/g) in a potato omelet under microwave heating at 300 W, 450 W, 600 W were 0.17 s^{-1}, 0.34 s^{-1}, 0.67 s^{-1}, respectively. It is noticed that the higher the power level, the faster the inactivation during microwave sterilization. This was similar to those reported by Lu, Turley, Dong, and Wu (2011) and Benlloch-Tinoco, Pina-Pérez, Martínez-Navarrete, and Rodrigo (2014). Lu et al. (2011) indicated that during microwave sterilization, after 50 s heating at the high power level of 700 W, more than 2.05 log reduction of *Salmonella enterica* (an initial titer of 10^7 CFU/mL) was obtained on grape tomatoes, while heating for 50 s at the medium power level of 350 W, more than 1.70 log reduction was achieved. Benlloch-Tinoco et al. (2014) also showed that the $D_{60\ ^{\circ}C}$ values of the inactivation of *L. monocytogenes* in a kiwifruit puree at 1000 W, 900 W and 600 W were 17.04 s, 17.35 s, 42.85 s, respectively.

In addition, microwave radiation dose play an important role in determining the thoroughness of inactivation. It has been proved that microorganisms can be completely inactivated if microwave radiation dose reaches a certain level. For example, the complete inhibition of bacteria (*E. coli*, *Salmonella enteritidis* and *Enterococcus* spp.) viability at 10^6 - 10^7 MPN/g and spores (*Clostridium sporogenes*) viability at 10^6–10^7 CFU/g on salmon and cod were observed using the microwave treatment with the lethal doses of 430 kJ/g and 1900 kJ/g, respectively (Bauza-Kaszewska, Skowron, Paluszak, Dobrzański, & Śrutek, 2014). Therefore cell responses depend on the microwave power levels, and the hypothesis of a specific electromagnetic threshold effect is probably related to the temperature increase (Rougier, Prorot, Chazal, Leveque, & Leprat, 2014).

On the other hand, studies were also performed to examine the effects of temperatures on complete microwaving inhibition of microorganisms. For example, Zeinali, Jamshidi, Khanzadi, and Azizzadeh (2015) showed that chicken meats (drumettes), inoculated with *Listeria monocytogenes* (an initial titer of 1.6 × 10^6 CFU/mL), were subjected to the microwave radiation and by enhancing the surface temperature of drumettes to higher than 74 °C (after the end of 60 s of the exposure time), the superficial contamination of drumettes could be completely eliminated, because there was a significant correlation between the bacterial population and the temperature of the samples ($p < 0.001$, $r = -0.879$). Jamshidi, Seifi,

Table 4
The inactivation of pathogens in the foods during microwave-assisted sterilizing.

Material	Pathogen	Concentration of the pathogen	Sterilization method	Sterilization condition	Inactivation of pathogens	References
Jalapeño peppers	*Salmonella typhimurium*	3 × 10^8 CFU/g	Water-assisted microwave heating	At 950 W to reach 63 °C for 25 s	5.12 log reduction	De La Vega-Miranda et al. (2012)
Coriander foliage	*Salmonella typhimurium*	3 × 10^8 CFU/g	Water-assisted microwave heating	At 950 W to reach 63 °C for 10 s	4.45 log reduction	De La Vega-Miranda et al. (2012)
Grape tomatoes	*Salmonella enterica*	The initial titer of inoculums (25 μL) is 10^7 CFU/mL	Microwave heating	At high power level of 700 W for 50 s At medium power level of 350 W for 50 s	More than 2.05 log reduction More than 1.70 log reduction	Lu et al. (2011)
Salmon and cod	*E. coli*, *Salmonella enteritidis*, *Enterococcus* spp. and *Clostridium* spores	10^6-10^7 MPN/g (bacteria) and 10^6 −10^7 CFU/g (spores)	Microwave radiation	About 430 kJ/g (but only 140 kJ/g for *Salmonella Enteritidis* and *E. coli*) for bacteria About 1900 kJ/g for spores	Theoretical complete inactivation	Bauza-Kaszewska et al. (2014)
Drumettes	*Listeria monocytogenes*	The initial titer of inoculums is 1.6 × 10^6 CFU/mL	Microwave radiation	More than 74 °C (after the end of 60 s exposure time)	Elimination of the superficial contamination	Zeinali et al. (2015)
Fresh beef slices	*E. coli* O157:H7	3.2 × 10^7 CFU/cm^2	Microwave radiation	More than 70 °C (after the end of 30 s of the exposure time)	Elimination of the superficial contamination	Jamshidi et al. (2010)
Potato omelet	*Salmonella enteritidis*	6.3 log CFU/g	Microwave radiation	40 s treatment at 800 W	4.80 log reduction	Valero et al. (2014)

and Kooshan (2010) also observed the complete inhibition of *E. coli* O157:H7 (at the level of 3.2×10^7 CFU/cm^2) on fresh beef slices using the microwave treatment with the surface temperature of more than 70 °C (after the end of 30 s of the exposure time), due to the significant correlation between the bacterial population and the temperature of the samples ($p < 0.0001$, $r = -0.973$).

4.3. Effects of microwave sterilization on quality attributes of food products

The effects of microwave sterilization on food quality attributes studied mainly include bioactive substances, antioxidant activity, enzyme activity, texture and color. Piasek et al. (2011) found that the loss of total anthocyanins in aronia subjected to the microwave sterilization ranged from 39.7% to 59.1%, which was lower than those (66.1%–99.8%) treated by thermal processing at 100 °C. In another work, Marszałek et al. (2015) showed that microwave heating was lesser destructive for strawberry purée than conventional heating, because the lowest losses of total content of polyphenols (5.7%), total content of anthocyanins (19.2%) and vitamin C (3.4%) in strawberry purée under continuous microwave heating at 90 °C (at atmospheric pressure) for 10 s were achieved, which were lower than those (14.0%, 60.2% and 61.7%, respectively) with traditional heating at 90 °C for 15 min. This is because the microwave exposure time (7 s for aronia, 10 s for strawberry purée) was far less than thermal processing time (1–5 h for aronia, 15 min for strawberry purée) (Marszałek et al., 2015; Piasek et al., 2011). For bioactive substances of foods, microwave sterilization normally shows no obvious changes owing to the short exposure time. In addition, Lu et al. (2011) found that the losses of ascorbic acid content and lycopene content of grape tomato after microwave heating were less than 6.83% and 13.52%, respectively. Therefore, microwave sterilization has no significant effects on bioactive substances and antioxidant activity of foods.

For the enzyme activity of the food products, microwave sterilization can cause inactivation. Umudee, Chongcheawchamnan, Kiatweerasakul, and Tongurai (2013) observed the interruption of enzymatic lipolysis reaction in oil palm fruits by microwave sterilization. Chen et al. (2016) noticed that the activity of wheat germ lipase decreased by 60% and 100% after microwave radiation when the temperatures were up to 45 and 60 °C, respectively. Marszałek et al. (2015) found that the activity of polyphenol oxidase and peroxidase on strawberry purée decreased by 98% and 100%, respectively, after microwave radiation at 120 °C. The enzyme, mostly consisting of protein, is easily damaged by microwave processing, microwave sterilization is beneficial to the maintenance of the quality of foods by effective decrease in enzyme activity.

For textural and color properties of food products, microwave sterilization normally shows minor effects. Table 5 summarizes the texture and color of foods before and after the proposed microwave sterilization. Lu et al. (2011) showed no significant changes in the firmness of grape tomato (ranging from 2.43 to 2.82 N), with lower values after treatment. The firmness of jalapeño pepper and coriander also remained no significant changes after microwave heating, which was decreased from 10.93 N to 9.29 N, and was increased from 6.17 N to 8.21 N, respectively (De La Vega-Miranda et al., 2012). Generally speaking, when the time of microwave sterilization is short, its effects on texture are minor, for example, when microwave sterilization was less than 1 min, the texture of the grape tomato, jalapeño pepper and coriander remained with no significant difference (De La Vega-Miranda et al., 2012; Lu et al., 2011). However, lengthy microwave sterilization could lower the texture properties. On the other hand, for effects on color, De La Vega-Miranda et al. (2012) reported that the color of jalapeño pepper was significantly affected by microwave sterilization with the lightness (L) decreasing from 30.38 to 24.35 and from 25.98 to 19.61 for coriander. However, Lu et al. (2011) indicated that all color parameters (L, a and b) of grape tomato did not show significant changes after microwave heating treatments. The difference between these results could be attributed to the green vegetable used by De La Vega-Miranda et al. (2012) and red vegetables used by Lu et al. (2011). The color of the red vegetables was closely related to the lycopene, which showed no significant changes after microwave heating.

5. Conclusions and future trends

Compared to conventional drying, microwave drying shows lower energy consumption with products having better sensory attributes. However more porous structure occurs in foods. As for microwave heating, with increasing in microwave power, hot air-microwave heating can effectively reduce the final water content and the recovery rate, but accordingly increase the shrinkage, dehydration rate and rehydration rate of the samples. Microwave cooking has the ability to maintain high antioxidant activity, retain high contents of bioactive components for vegetables, and improve the in-vitro protein digestibility of food products by significantly reducing anti-nutritional factors, however significant losses in nutrients could happen if cooking with massive water. Microwave sterilization can be effectively used to ensure microbiological safety of food products. It exhibits no obvious changes in antioxidant activity, color and bioactive components owing to the destruction of enzyme activity and a short exposure time.

Although microwave has been widely used in food processing, it is necessary to strengthen further investigations in certain areas. The non-uniformity of microwave field is a long-standing technical barrier to achieving uniform processing of foods, which can generally lead to hot or cold spots in foods. Research should be

Table 5
Color and texture of foods before and after the proposed microwave sterilizing.

Material	Sterilization method	Texture	Color			Reference
			L	*a*	*b*	
Grape tomatoes	Microwave heating for 0 s	2.82 ± 0.23a N/mm	27.90 ± 0.98a	12.50 ± 0.96a	11.17 ± 0.84a	Lu et al. (2011)
	Microwave heating for 50 s at medium power	2.43 ± 0.43 bN/mm	26.73 ± 0.40a	12.10 ± 0.69a	10.60 ± 1.56a	
	Microwave heating for 50 s at high power	Not detected	26.77 ± 1.16a	11.93 ± 0.35a	11.23 ± 0.35a	
Jalapeño peppers	Before treatment	Firmness 10.93 ± 1.33 N	30.48 ± 0.65	−8.51 ± 0.57	8.28 ± 0.51	De La Vega-Miranda et al. (2012)
	Water-assisted microwave heating at 950 W to reach 63 °C for 25 s	Firmness 9.29 ± 1.92 N	24.35 ± 0.64	−5.67 ± 0.47	5.75 ± 0.60	
Coriander foliage	Before treatment	Firmness 6.17 ± 1.58 N	25.98 ± 0.19	−5.66 ± 0.18	7.18 ± 0.19	De La Vega-Miranda et al. (2012)
	Water-assisted microwave heating at 950 W to reach 63 °C for 10 s	Firmness 8.21 ± 1.58 N	19.61 ± 0.06	−5.99 ± 0.09	5.68 ± 0.09	

Data with different letters (a, b) are significantly different ($p < 0.05$).

continued in this area to minimize the negative effects on food quality and safety. Low temperature cooking can retain a high level of food nutrients, however information on using microwave to achieve low temperature cooking is scarce, and thus further efforts can be made to understand and utilize the technique. Microwave has the unique characteristics of high efficiency processing, and its combination with other conventional processing methods can normally effectively overcome the disadvantages of the conventional techniques, and therefore, future research can focus on developing novel combined processing techniques for enhancing processing efficiency while maintaining product quality and safety. In addition, the existence or non-existence of the non-thermal effect in microwave sterilization is still under debating, and more studies to be conducted may be able to shed more light on this topic and clear any doubts.

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References

Aghilinategh, N., Rafiee, S., Hosseinpur, S., Omid, M., & Mohtasebi, S. S. (2015). Optimization of intermittent microwave-convective drying using response surface methodology. *Food Science & Nutrition, 3*(4), 331–341.

Aguilar-Reynosa, A., Romaní, A., Rodríguez-Jasso, R. M., Aguilar, C. N., Garrote, G., & Ruiz, H. A. (2017). Microwave heating processing as alternative of pretreatment in second-generation biorefinery: An overview. *Energy Conversion and Management, 136*, 50–65.

Akdaş, Z. Z., & Bakkalbaşı, E. (2016). Influence of different cooking methods on color, bioactive compounds, and antioxidant activity of kale. *International Journal of Food Properties*, 1–11.

Al Juhaimi, F., Uslu, N., Bozkurt, D., Ghafoor, K., Babiker, E. E., & Özcan, M. M. (2016). Effects of oven and microwave drying on phenolic contents and antioxidant activities in four apple cultivars. *Quality Assurance and Safety of Crops & Foods, 8*(1), 51–55.

Arballo, J. R., Campañone, L. A., & Mascheroni, R. H. (2010). Modeling of microwave drying of fruits. *Drying Technology, 28*(10), 1178–1184.

Armesto, J., Gómez-Limia, L., Carballo, J., & Martínez, S. (2016). Effects of different cooking methods on some chemical and sensory properties of Galega kale. *International Journal of Food Science & Technology, 51*(9), 2071–2080.

Aydogdu, A., Sumnu, G., & Sahin, S. (2015). Effects of microwave-infrared combination drying on quality of eggplants. *Food and Bioprocess Technology, 8*(6), 1198–1210.

Bal, L. M., Kar, A., Satya, S., & Naik, S. N. (2010). Drying kinetics and effective moisture diffusivity of bamboo shoot slices undergoing microwave drying. *International Journal of Food Science & Technology, 45*(11), 2321–2328.

Bauza-Kaszewska, J., Skowron, K., Paluszak, Z., Dobrzański, Z., & Śrutek, M. (2014). Effect of microwave radiation on microorganisms in fish meals. *Annals of Animal Science, 14*(3), 623–636.

Benlloch-Tinoco, M., Pina-Pérez, M. C., Martínez-Navarrete, N., & Rodrigo, D. (2014). Listeria monocytogenes inactivation kinetics under microwave and conventional thermal processing in a kiwifruit puree. *Innovative Food Science & Emerging Technologies, 22*, 131–136.

Calín-Sánchez, Á., Figiel, A., Wojdyło, A., Szarycz, M., & Carbonell-Barrachina, Á. A. (2013). Drying of garlic slices using convective pre-drying and vacuum-microwave finishing Drying: Kinetics, energy consumption, and quality studies. *Food and Bioprocess Technology, 7*(2), 398–408.

Chandrasekaran, S., Ramanathan, S., & Basak, T. (2013). Microwave food processing—a review. *Food Research International, 52*(1), 243–261.

Chang, H. J., Xu, X. L., Li, C. B., Huang, M., Liu, D. Y., & Zhou, G. H. (2011). A comparison of heat-induced changes of intramuscular connective tissue and collagen of beef semitendinosus muscle during water bath and microwave heating. *Journal of Food Process Engineering, 34*(6), 2233–2250.

Chen, Z., Li, Y., Wang, L., Liu, S., Wang, K., Sun, J., et al. (2016). Evaluation of the possible non-thermal effect of microwave radiation on the inactivation of wheat germ lipase. *Journal of Food Process Engineering*, 1–11.

Chen, J., Pitchai, K., Jones, D., & Subbiah, J. (2015). Effect of decoupling electromagnetics from heat transfer analysis on prediction accuracy and computation time in modeling microwave heating of frozen and fresh mashed potato. *Journal of Food Engineering, 144*, 45–57.

Cheng, Lina, Sun, Da-Wen, Zhu, Zhiwei, & Zhang, Zi (2017). Emerging techniques for assisting and accelerating food freezing processes: A review of recent research progresses. *Critical Reviews in Food Science and Nutrition, 57*(4), 769–781.

Cheng, Jun-Hu, Sun, Da-Wen, & Pu, Hongbin (APR 15 2016). Combining the genetic algorithm and successive projection algorithm for the selection of feature wavelengths to evaluate exudative characteristics in frozen-thawed fish muscle. *Food Chemistry, 197*, 855–863. Part: A.

Choi, Y. S., Hwang, K. E., Jeong, T. J., Kim, Y. B., Jeon, K. H., Kim, E. M., et al. (2016). Comparative study on the effects of boiling, steaming, grilling, microwaving and superheated steaming on quality characteristics of marinated chicken steak. *Korean Journal for Food Science of Animal Resources, 36*(1), 1–7.

Cui, Zheng-Wei, Sun, Li-Juan, Chen, Wei, & Sun, Da-Wen (FEB 2008). Preparation of dry honey by microwave-vacuum drying. *Journal of Food Engineering, 84*(4), 582–590.

Cui, Z. W., Xu, S. Y., & Sun, Da-Wen (2003). Dehydration of garlic slices by combined microwave-vacuum and air drying. *Drying Technology, 21*(7), 1173–1184.

Cui, Z. W., Xu, S. Y., & Sun, Da-Wen (2004a). Microwave-cacuum drying kinetics of carrot slices. *Journal of Food Engineering, 65*(2), 157–164.

Cui, Z. W., Xu, S. Y., & Sun, Da-Wen (2004b). Effect of microwave-vacuum drying on the carotenoids retention of carrot slices and chlorophyll retention of Chinese Chive Leaves. *Drying Technology, 22*(3), 561–574.

Cui, Z. W., Xu, S. Y., Sun, Da-Wen, & Chen, W. (2005). Temperature changes during microwave-vacuum drying of sliced carrots. *Drying Technology, 23*(5), 1057–1074.

Curet, S., Rouaud, O., & Boillereaux, L. (2014). Estimation of dielectric properties of food materials during microwave tempering and heating. *Food and Bioprocess Technology, 7*(2), 371–384.

Darvishi, H., Azadbakht, M., Rezaeiasl, A., & Farhang, A. (2013). Drying characteristics of sardine fish dried with microwave heating. *Journal of the Saudi Society of Agricultural Sciences, 12*(2), 121–127.

De La Vega-Miranda, B., Santiesteban-López, N. A., López-Malo, A., & Sosa-Morales, M. E. (2012). Inactivation of Salmonella Typhimurium in fresh vegetables using water-assisted microwave heating. *Food Control, 26*(1), 19–22.

Demiray, E., Seker, A., & Tulek, Y. (2016). Drying kinetics of onion (Allium cepa L.) slices with convective and microwave drying. *Heat and Mass Transfer*, 1–11.

Demirhan, E., & Özbek, B. (2010). Drying kinetics and effective moisture diffusivity of purslane undergoing microwave heat treatment. *Korean Journal of Chemical Engineering, 27*(5), 1377–1383.

Deng, Y., Padilla-Zakour, O., Zhao, Y., & Tao, S. (2015). Influences of high hydrostatic pressure, microwave heating, and boiling on chemical compositions, antinutritional factors, fatty acids, in vitro protein digestibility, and microstructure of buckwheat. *Food and Bioprocess Technology, 8*(11), 2235–2245.

Dolinsky, M., Agostinho, C., Ribeiro, D., Rocha, G. D. S., Barroso, S. G., Ferreira, D., et al. (2015). Effect of different cooking methods on the polyphenol concentration and antioxidant capacity of selected vegetables. *Journal of Culinary Science & Technology, 14*(1), 1–12.

Domínguez, R., Gómez, M., Fonseca, S., & Lorenzo, J. M. (2014). Effect of different cooking methods on lipid oxidation and formation of volatile compounds in foal meat. *Meat Science, 97*(2), 223–230.

Doymaz, I., Kipcak, A. S., & Piskin, S. (2016). Microwave drying of green bean slices: Drying kinetics and physical quality. *Czech Journal of Food Sciences, 33*, 367–376.

Duan, X., Zhang, M., Mujumdar, A. S., & Wang, S. (2010). Microwave freeze drying of sea cucumber (Stichopus japonicus). *Journal of Food Engineering, 96*(4), 491–497.

Franco, A. P., Yamamoto, L. Y., Tadini, C. C., & Gut, J. A. W. (2015). Dielectric properties of green coconut water relevant to microwave processing: Effect of temperature and field frequency. *Journal of Food Engineering, 155*, 69–78.

Han, C. S., Kang, T. H., Lee, J. H., Won, J. H., Cho, B. H., & Cho, S. C. (2016). Drying characteristics of sea tangle using combination of microwave and far-infrared dryer. *Journal of Biosystems Engineering, 41*(1), 43–50.

Hefnawy, T. H. (2011). Effect of processing methods on nutritional composition and anti-nutritional factors in lentils (Lens culinaris). *Annals of Agricultural Sciences, 56*(2), 57–61.

Horuz, E., Bozkurt, H., Karataş, H., & Maskan, M. (2017). Drying kinetics of apricot halves in a microwave-hot air hybrid oven. *Heat and Mass Transfer*, 1–11.

Horuz, E., & Maskan, M. (2015). Hot air and microwave drying of pomegranate (*Punica granatum* L.) arils. *Journal of Food Science and Technology, 52*(1), 285–293.

Jamshidi, A., Seifi, H. A., & Kooshan, M. (2010). The effect of short-time microwave exposures on Escherichia coli O157: H7 inoculated onto beef slices. *African Journal of Microbiology Research, 4*(22), 2371–2374.

Jiang, H., Zhang, M., & Mujumdar, A. S. (2010). Physico-chemical changes during different stages of MFD/FD banana chips. *Journal of Food Engineering, 101*(2), 140–145.

Jiang, H., Zhang, M., Mujumdar, A. S., & Lim, R. X. (2012). Analysis of temperature distribution and sem images of microwave freeze drying banana chips. *Food and Bioprocess Technology, 6*(5), 1144–1152.

Jouquand, C., Tessier, F. J., Bernard, J., Marier, D., Woodward, K., Jacolot, P., et al. (2015). Optimization of microwave cooking of beef burgundy in terms of nutritional and organoleptic properties. *LWT - Food Science and Technology, 60*(1), 271–276.

Kappe, C. O. (2013). How to measure reaction temperature in microwave-heated transformations. *Chemical Society Reviews, 42*(12), 4977–4990.

Kiani, Hossein, Zhang, Zhihang, Delgado, Adriana, & Sun, Da-Wen (NOV 2011). Ultrasound assisted nucleation of some liquid and solid model foods during freezing. *Food Research International, 44*(9), 2915–2921.

Kozempel, M. F., Annous, B. A., Cook, R. D., Scullen, O. J., & Whiting, R. C. (1998). Inactivation of microorganisms with microwaves at reduced temperaturas. *Journal of Food Protection, 61*(5), 582–585.

Kumar, C., Saha, S. C., Sauret, E., Karim, A., & Gu, Y. (2016). Mathematical modelling of heat and mass transfer during intermittent microwave-convective drying (IMCD) of foods. Proceedings of the 10th Australasian heat and mass transfer Conference: Selected, peer reviewed papers. *School of Chemistry, Physics and Mechanical Engineering, Queensland University of Technology*, 171–176.

de Lima, A. C. S., da Rocha Viana, J. D., de Sousa Sabino, L. B., da Silva, L. M. R., da Silva, N. K. V., & de Sousa, P. H. M. (2017). Processing of three different cooking methods of cassava: Effects on in vitro bioaccessibility of phenolic compounds and antioxidant activity. *LWT - Food Science and Technology, 76*, 253–258.

Ling, B., Tang, J., Kong, F., Mitcham, E. J., & Wang, S. (2014). Kinetics of food quality changes during thermal processing: A review. *Food and Bioprocess Technology, 8*(2), 343–358.

Li, Z. Y., Wang, R. F., & Kudra, T. (2011). Uniformity issue in microwave drying. *Drying Technology, 29*(6), 652–660.

Lu, Y., Turley, A., Dong, X., & Wu, C. (2011). Reduction of Salmonella enterica on grape tomatoes using microwave heating. *International Journal of Food Microbiology, 145*(1), 349–352.

Lv, W., Zhang, M., Bhandari, B., Yang, Z., & Wang, Y. (2017). Analysis about drying properties and vacuum impregnated qualities of edamame (Glycine Max (L.) Merrill). *Drying Technology*. http://dx.doi.org/10.1080/07373937.2016.1231201.

Ma, Ji, Pu, Hongbin, Sun, Da-Wen, Gao, Wenhong, Qu, Jia-Huan, & Ma, Kai-Yue (FEB 2015). Application of Vis-NIR hyperspectral imaging in classification between fresh and frozen-thawed pork Longissimus Dorsi muscles. *International Journal of Refrigeration-Revue Internationale Du Froid, 50*, 10–18.

Marszałek, K., Mitek, M., & Skąpska, S. (2015). Effect of continuous flow microwave and conventional heating on the bioactive compounds, colour, enzymes activity, microbial and sensory quality of strawberry purée. *Food and Bioprocess Technology, 8*(9), 1864–1876.

Menéndez, J. A., Arenillas, A., Fidalgo, B., Fernández, Y., Zubizarreta, L., Calvo, E. G., et al. (2010). Microwave heating processes involving carbon materials. *Fuel Processing Technology, 91*(1), 1–8.

McDonald, K., Sun, D.-W., & Kenny, T. (2000). Comparison of the quality of cooked beef products cooled by vacuum cooling and by conventional cooling. *Lebensmittel-Wissenschaft Und-Technologie-Food Science and Technology, 33*(1), 21–29.

Muñoz, S., Achaerandio, I., Yang, Y., & Pujolà, M. (2017). Sous vide processing as an alternative to common cooking treatments: Impact on the starch profile, color, and shear force of potato (*Solanum tuberosum* L.). *Food and Bioprocess Technology*, 1–11.

Musto, M., Faraone, D., Cellini, F., & Musto, E. (2014). Changes of DNA quality and meat physicochemical properties in bovine supraspinatus muscle during microwave heating. *Journal of the Science of Food and Agriculture, 94*(24), 785–791.

Nawirska-Olszańska, A., Stępień, B., & Biesiada, A. (2017). Effectiveness of the fountain-microwave drying method in some selected pumpkin cultivars. *LWT - Food Science and Technology, 77*, 276–281.

Özcan, A. U., & Bozkurt, H. (2015). Physical and chemical attributes of a ready-to-eat meat product during the processing: Effects of different cooking methods. *International Journal of Food Properties, 18*(11), 2422–2432.

Pellegrini, N., Chiavaro, E., Gardana, C., Mazzeo, T., Contino, D., Gallo, M., et al. (2010). Effect of different cooking methods on color, phytochemical concentration, and antioxidant capacity of raw and frozen brassica vegetables. *Journal of Agricultural and Food Chemistry, 58*(7), 4310–4321.

Pérez-Juan, M., Kondjoyan, A., Picouet, P., & Realini, C. E. (2012). Effect of marination and microwave heating on the quality of Semimembranosus and Semitendinosus muscles from Friesian mature cows. *Meat Science, 92*(2), 107–114.

Piasek, A., Kusznierewicz, B., Grzybowska, I., Malinowska-Pańczyk, E., Piekarska, A., Azqueta, A., et al. (2011). The influence of sterilization with EnbioJet® Microwave Flow Pasteurizer on composition and bioactivity of aronia and blueberried honeysuckle juices. *Journal of Food Composition and Analysis, 24*(6), 880–888.

Pitchai, K., Birla, S. L., Subbiah, J., Jones, D., & Thippareddi, H. (2012). Coupled electromagnetic and heat transfer model for microwave heating in domestic ovens. *Journal of Food Engineering, 112*(1), 100–111.

Półtorak, A., Wyrwisz, J., Moczkowska, M., Marcinkowska-Lesiak, M., Stelmasiak, A., Rafalska, U., et al. (2015). Microwave vs. convection heating of bovine gluteus medius muscle: Impact on selected physical properties of final product and cooking yield. *International Journal of Food Science & Technology, 50*(4), 958–965.

Półtorak, A., Wyrwisz, J., Moczkowska, M., Marcinkowska-Lesiak, M., Stelmasiak, A., Rafalska, U., Wierzbicka, A., & Sun, Da-Wen (2015). Microwave vs. convection heating of bovine gluteus medius muscle: Impact on selected physical properties of final product and cooking yield. *International Journal of Food Science and Technology, 50*(4), 958–965.

Pu, Hongbin, Sun, Da-Wen, Ma, Ji, & Cheng, Jun-Hu (JAN 2015). Classification of fresh and frozen-thawed pork muscles using visible and near infrared hyperspectral imaging and textural analysis. *Meat Science, 99*, 81–88.

Pu, Y.-Y., & Sun, Da-Wen (2015). Vis-NIR hyperspectral imaging in visualizing moisture distribution of mango slices during microwave-vacuum drying. *Food Chemistry, 188*, 271–278.

Pu, Yuan-Yuan, & Sun, Da-Wen (FEB 2016a). Prediction of moisture content uniformity of microwave-vacuum dried mangoes as affected by different shapes using NIR hyperspectral imaging. *Innovative Food Science & Emerging Technologies, 33*, 348–356.

Pu, Y.-Y., & Sun, Da-Wen (2016b). Prediction of moisture content uniformity of microwave-vacuum dried mangoes as affected by different shapes using NIR hyperspectral imaging. *Innovative Food Science and Emerging Technologies, 34*, 348–356.

Pu, Y.-Y., & Sun, Da-Wen (2017). Combined hot-air and microwave-vacuum drying for improving drying uniformity of mango slices based on hyperspectral imaging visualization of moisture content distribution. *Biosystems Engineering, 156*, 108–119.

Rakesh, V., Seo, Y., Datta, A. K., McCarthy, K. L., & McCarthy, M. J. (2010). Heat transfer during microwave combination heating: Computational modeling and MRI experiments. *AIChE Journal, 56*(9), 2468–2478.

dos Reis, L. C. R., de Oliveira, V. R., Hagen, M. E. K., Jablonski, A., Flôres, S. H., & de Oliveira Rios, A. (2015). Carotenoids, flavonoids, chlorophylls, phenolic compounds and antioxidant activity in fresh and cooked broccoli (Brassica oleracea var. Avenger) and cauliflower (Brassica oleracea var. Alphina F1). *LWT-Food Science and Technology, 63*(1), 177–183.

Rougier, C., Prorot, A., Chazal, P., Leveque, P., & Leprat, P. (2014). Thermal and nonthermal effects of discontinuous microwave exposure (2.45 gigahertz) on the cell membrane of Escherichia coli. *Applied and Environmental Microbiology, 80*(16), 4832–4841.

Sadi, T., & Meziane, S. (2015). Mathematical modelling, moisture diffusion and specific energy consumption of thin layer microwave drying of olive pomace. *International Food Research Journal, 22*(2), 494–501.

Sarimeseli, A. (2011). Microwave drying characteristics of coriander (*Coriandrum sativum* L.) leaves. *Energy Conversion and Management, 52*(2), 1449–1453.

Sun, D.-W. (MAR 1997). Solar powered combined ejector vapour compression cycle for air conditioning and refrigeration. *Energy Conversion and Management, 38*(5), 479–491.

Sun, D.-W., & Brosnan, T. (SEP 1999). Extension of the vase life of cut daffodil flowers by rapid vacuum cooling. *International Journal of Refrigeration-Revue Internationale Du Froid, 22*(6), 472–478.

Sun, D.-W., & Hu, Z. H. (JAN 2003). CFD simulation of coupled heat and mass transfer through porous foods during vacuum cooling process. *International Journal of Refrigeration-Revue Internationale Du Froid, 26*(1), 19–27. Article Number: PII S0140-7007(02)00038-5.

Sun, D.-W., & Wang, L. J. (NOV 2000). Heat transfer characteristics of cooked meats using different cooling methods. *International Journal of Refrigeration-Revue Internationale Du Froid, 23*(7), 508–516.

Tian, J., Chen, J., Lv, F., Chen, S., Chen, J., Liu, D., et al. (2016). Domestic cooking methods affect the phytochemical composition and antioxidant activity of purple-fleshed potatoes. *Food Chemistry, 197*, 1264–1270.

Umudee, I., Chongcheawchamnan, M., Kiatweerasakul, M., & Tongurai, C. (2013). Sterilization of oil palm fresh fruit using microwave technique. *International Journal of Chemical Engineering and Applications, 4*(3), 111–113.

Vadivambal, R., & Jayas, D. S. (2008). Non-uniform temperature distribution during microwave heating of foods—a review. *Food and Bioprocess Technology, 3*, 161–171.

Valero, A., Cejudo, M., & García-Gimeno, R. M. (2014). Inactivation kinetics for Salmonella Enteritidis in potato omelet using microwave heating treatments. *Food Control, 43*, 175–182.

Wang, L. J., & Sun, D.-W. (NOV 2002a). Modelling vacuum cooling process of cooked meat - part 1: analysis of vacuum cooling system. *International Journal of Refrigeration-Revue Internationale Du Froid, 25*(7), 854–861. Article Number: PII S0140-7007(01)00094-9.

Wang, L. J., & Sun, D.-W. (NOV 2002b). Modelling vacuum cooling process of cooked meat - part 2: mass and heat transfer of cooked meat under vacuum pressure. *International Journal of Refrigeration-Revue Internationale Du Froid, 25*(7), 862–871. Article Number: PII S0140-7007(01)00095-0.

Wang, L. J., & Sun, D.-W. (FEB 2004). Effect of operating conditions of a vacuum cooler on cooling performance for large cooked meat joints. *Journal of Food Engineering, 61*(2), 231–240.

Wang, Y. Q., Zhang, M., Mujumdar, Arun S., & Joseph Mothibe, kebitsamang (2013). Quality changes of dehydrated restructured fish product from silver carp (Hypophthalmichthys molitrix) as affected by drying methods. *Food and Bioprocess Technology, 6*(7), 1664–1680.

Wang, R., Zhang, M., & Mujumdar, A. S. (2010). Effects of vacuum and microwave freeze drying on microstructure and quality of potato slices. *Journal of Food Engineering, 101*(2), 131–139.

Wojdyło, A., Figiel, A., Lech, K., Nowicka, P., & Oszmiański, J. (2013). Effect of convective and vacuum–microwave drying on the bioactive compounds, color, and antioxidant capacity of sour cherries. *Food and Bioprocess Technology, 7*(3), 829–841.

Xie, Anguo, Sun, Da-Wen, Xu, Zhongyue, & Zhu, Zhiwei (JUL 1 2015). Rapid detection of frozen pork quality without thawing by Vis-NIR hyperspectral imaging technique. *Talanta, 139*, 208–215.

Xie, Anguo, Sun, Da-Wen, Zhu, Zhiwei, & Pu, Hongbin (SEP 2016). Nondestructive Measurements of Freezing Parameters of Frozen Porcine Meat by NIR Hyperspectral Imaging. *Food and Bioprocess Technology, 9*(9), 1444–1454.

Xu, Y., Cartier, A., Obielodan, M., Jordan, K., Hairston, T., Shannon, A., et al. (2016). Nutritional and anti-nutritional composition, and in vitro protein digestibility of Kabuli chickpea (*Cicer arietinum* L.) as affected by differential processing methods. *Journal of Food Measurement and Characterization, 10*(3), 625–633.

Xu, F., Zheng, Y., Yang, Z., Cao, S., Shao, X., & Wang, H. (2014). Domestic cooking methods affect the nutritional quality of red cabbage. *Food Chemistry, 161*, 162–167.

Yang, H. W., Hsu, C. K., & Yang, Y. F. (2014). Effect of thermal treatments on antinutritional factors and antioxidant capabilities in yellow soybeans and green-cotyledon small black soybeans. *Journal of the Science of Food and Agriculture, 94*(9), 1794–1801.

Yang, Qian, Sun, Da-Wen, & Cheng, Weiwei (JAN 2017). Development of simplified models for nondestructive hyperspectral imaging monitoring of TVB-N contents in cured meat during drying process. *Journal of Food Engineering, 192*, 53–60.

Yarmand, M. S., Nikmaram, P., Emam Djomeh, Z., & Homayouni, A. (2013). Microstructural and mechanical properties of camel longissimus dorsi muscle during roasting, braising and microwave heating. *Meat Science, 95*(2), 419–424.

Zarein, M., Samadi, S. H., & Ghobadian, B. (2015). Investigation of microwave dryer effect on energy efficiency during drying of apple slices. *Journal of the Saudi Society of Agricultural Sciences, 14*(1), 41–47.

Zeinali, T., Jamshidi, A., Khanzadi, S., & Azizzadeh, M. (2015). The effect of short-time microwave exposures on Listeria monocytogenes inoculated onto chicken meat portions. *Veterinary Research Forum, 6*(2), 173–176. Faculty of Veterinary Medicine, Urmia University, Urmia, Iran.

Zheng, L. Y., & Sun, D.-W. (DEC 2004). Vacuum cooling for the food industry - a review of recent research advances. *Trends in Food Science & Technology, 15*(12), 555–568.

Zhong, X., Dolan, K. D., & Almenar, E. (2015). Effect of steamable bag microwaving versus traditional cooking methods on nutritional preservation and physical properties of frozen vegetables: A case study on broccoli (Brassica oleracea). *Innovative Food Science & Emerging Technologies, 31*, 116–122.

Zielinska, M., Sadowski, P., & Błaszczak, W. (2015). Freezing/thawing and microwave-assisted drying of blueberries (*Vaccinium corymbosum* L.). *LWT - Food Science and Technology, 62*(1), 555–563.