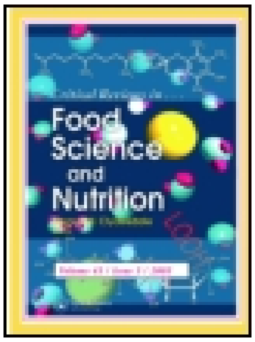

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REVIEW

Review of recent applications and research progress in hybrid and combined microwave-assisted drying of food products: Quality properties

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ABSTRACT

The growing concerns over product quality have increased demand for high quality dried food products and encouraged researchers to explore and producers of such products to implement novel microwave (MW)-assisted drying methods. This paper presents a critical review of the key principles and drawbacks of MW-assisted drying as well as needs for future research. In this article, recent research into application of microwaves as an alternative heat source, applications and progress in hybrid MW-assisted drying that rely on various drying media and combined two or three stages of MW-assisted drying for the preservation of food products is reviewed critically. The effect of different MW-assisted drying methods, conditions and initial pretreatments on the thermophysical properties, color, nutritional value and rehydration potential of dried food products is discussed in detail along with the discussion on how the material properties evolve and change in structure, color, and composition during MW-assisted drying and recent attempts at mathematical modeling of these changes made for different fruits and vegetables. It should be noted that most of the published results were obtained in laboratory-scale dryers. Pilot-scale testing is needed to bridge the gap between laboratory research and industrial applications to fulfill the potential for novel hybrid and combined MW-assisted drying methods and to expand their role in food processing.

KEYWORDS
Microwave-assisted drying; thermophysical properties; color; nutritional value; rehydration potential; mathematical models

Introduction

Drying of food products aims to transform perishable materials into stable products and at the same time: (i) reduce their moisture content and water activity, (ii) slow down the growth of bacteria, yeast and mold as well as undesirable enzymatic reactions, (iii) extend their shelf live, (iv) maintain their desired quality characteristics, (v) modify their texture attributes of different food products according to the potential consumer preferences (vi) make them available in times of shortage and at the regions far away from their place of origin, and (vii) make them more convenient in packaging, transporting, preserving, fabricating and further processing (Zhang et al. 2006; Zielinska, Sadowski, and Błaszczak 2015). One of the most used methods is hot air convective drying (HACD) in a stationary layer under natural and forced convection. HACD is commonly used because of its low construction cost and simple operation. However, it may result in deterioration of quality attributes such as color, texture, nutritional value or rehydration ability. Due to chemical or biochemical reactions, drying causes physical and structural modifications of the material tissue and transient thermal and moisture gradients develop tensional and compressional stresses that cause tissue breakage and fracture during drying (tensional stresses are greater than compressional ones, especially at the boundary of the dried material) (Lewicki and Pawlak 2005). Loss of water and segregation of components often cause rigidity, damage and disruption of cell walls, and even collapse of cellular tissue (Mattea, Urbicain, and Rotstein 1989). The most pronounced macroscopic modification is the shrinkage and deformation of dried food products (Mayor and Sereno 2004). Significant shrinkage of the material, damage of cytoplasmic membranes and compacting the ingredients of dry substance limit its application (Figiel 2007; Figiel 2009; Zielinska, Sadowski, and Błaszczak 2016). Microwave drying (MWD) has been attracting growing interest in dehydration of different food products (Li, Raghavan, and Orsat 2010a). This is due to the ability of microwaves to penetrate into dielectric materials and generate internal heat (Jia, Clements, and Jolly 1993). The heat generated inside the dried particle establishes a vapor pressure within the product and results in moisture being forced to the surface as well as preventing from occurring case hardening (Turner and Jolly 1991). A MWD system usually consists of a water or air-cooled

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magnetron, power supply and a waveguide assembly to carry the waves, a processing chamber in which the material is processed, system that monitors, measures and controls the drying process as well as a system that positions the product inside the drying chamber. Compared to hot air, drying rates and product quality are subsequently enhanced by microwaves. Microwaves used instead of hot air shorten drying time, limit oxidation and exert a positive influence on such properties of dried materials as density, porosity, mechanical and reconstitution properties, color and the content of bioactive compounds (Soysal et al. 2009; Leusink et al. 2010; Zielinska and Michalska 2016). The proper selection of such parameters as microwave power, microwave mode, temperature, drying rate, etc. may significantly improve the quality of dried products (Zielinska, Sadowski, and Błaszczak 2016). However, MWD is still not common in the agri-food industry. High initial capital investment and the complexity of microwave heating of highly hydrated products reduce their applicability at the industrial level. Additionally, MWD alone has some drawbacks, such as difficulties with material temperature controlling at the final stage of drying process and thus uneven heating, possible texture damage, and the limited penetration depth of the MW radiation into the food products (Zhang et al. 2006). In recent years, there is an increasing demand of producing high quality dried products. The key to improving the quality of dried products is to limit changes to their quality characteristics during drying processes. Hybrid and combined MW-assisted drying are newly emerging ways of drying and most of the applications need a systematic approach of study. This has motivated the researchers to investigate innovative hybrid and combined MW-assisted drying.

Hybrid MW-assisted drying used for food products preservation

Microwaves (MW) are usually applied in the whole drying process to assist or enhance conventional drying and form e.g. hybrid MW-assisted hot air convective drying (MWHACD), MW-assisted multiflash drying (MWMFD), MW-assisted spouted bed drying (MWSBD), MW-assisted inert medium fluidized bed drying (MWIMFBD), MW-assisted atmospheric freeze drying (MWAFD), MW-assisted vacuum drying (MWVD) or MW-assisted vacuum freeze drying (MWVFD). Hybrid MW-assisted drying may improve the quality of food materials which is far better than that achievable by the application of each method alone. MWHACD improves both drying efficiency and economic of the drying process. Microwaves combined with spouted bed drying (MWSBD) significantly improve the uneven heating of dried particles (Feng and Tang 1998). The uniformity in temperature distribution, as well as reduction of drying time can be achieved during e.g. MW-assisted inert medium fluidized bed drying (MWIMFBD) (Hu et al. 2017). MWVD allows to modify the structure of dried fruits and vegetables and produce crispy snacks of high quality and desirable texture (Zielinska, Sadowski, and Błaszczak 2016).

To save energy and avoid risk of overheating, microwaves can be applied intermittently (power on/power off mode) or in the final stage of drying process. These schemes can be carried out with airflow at atmospheric or under reduced pressure. Also, a temperature-controlled strategy, a MWD system with the ability of automatic temperature and power control or a MWD system that realizes drying process keeping drying rate constant can be the suitable methods in making dried food products (Li, Raghavan, and Orsat 2010b; Cao et al. 2017; Cuccurullo et al. 2018).

Combined MW-assisted drying used for food products preservation

Due to several limitations of existing hybrid MW-assisted drying methods, a number of combined MW-assisted drying methods, such as hot air convective drying and microwave-vacuum drying (HACD + MWVD), heat pump hot air convective drying and microwave-vacuum drying (HP HACD + MWVD), heat pump atmospheric freeze drying and microwave-vacuum drying (HP AFD + MWVD), freeze drying and microwave-vacuum drying (FD + MWVD), microwave-vacuum drying and freeze drying (MWVD + FD), vacuum infrared radiation drying and pulsed spouted bed microwave vacuum drying (VIRD + PSBMWVD), osmotic dehydration and microwave vacuum drying (OD + MWVD), osmotic dehydration and hot air convective drying and microwave vacuum drying (OD + HACD + MWVD), vacuum osmotic dehydration and microwave vacuum drying (VOD + MWVD) and microwave vacuum drying and osmotic dehydration and microwave vacuum drying (MWVD + OD + MWVD) has been developed to maximize the benefits of individual drying techniques and produce high quality dried products, in terms of material properties (Cui et al. 2008; Duan et al. 2008; Eikevik, Alves-Filho, and Bantle 2012; Zielinska et al. 2013; Zielinska, Sadowski, and Błaszczak 2016; Monteiro, Carciofi, and Laurindo 2016; Cao et al. 2017; Jiang et al. 2017; Junqueira, Corrêa, and Ernesto 2017). They consist of a multi-stage drying, including various drying techniques, where at least one stage is drying with the use of microwaves. With reference to the direction for future research in drying of food products, further development and improvement of MW-assisted drying methods is one of main directions (Zhang et al. 2006). It is clearly motivated by economic incentive to improve the MW-assisted drying processes to obtain a higher product quality at a lower cost in terms of energy consumption and environmental impact. Thus, different heat sources and drying methods can be used to overcome above mentioned drawbacks.

Figure 1 summarizes hybrid and combined MW-assisted drying methods applied recently for different food products. Table 1 shows recent applications of hybrid and combined MW-assisted drying for different food products, while Table 2 presents recent references regarding hybrid and combined MW-assisted drying of food products along with specified conditions of initial treatment, drying and rehydration opertions.

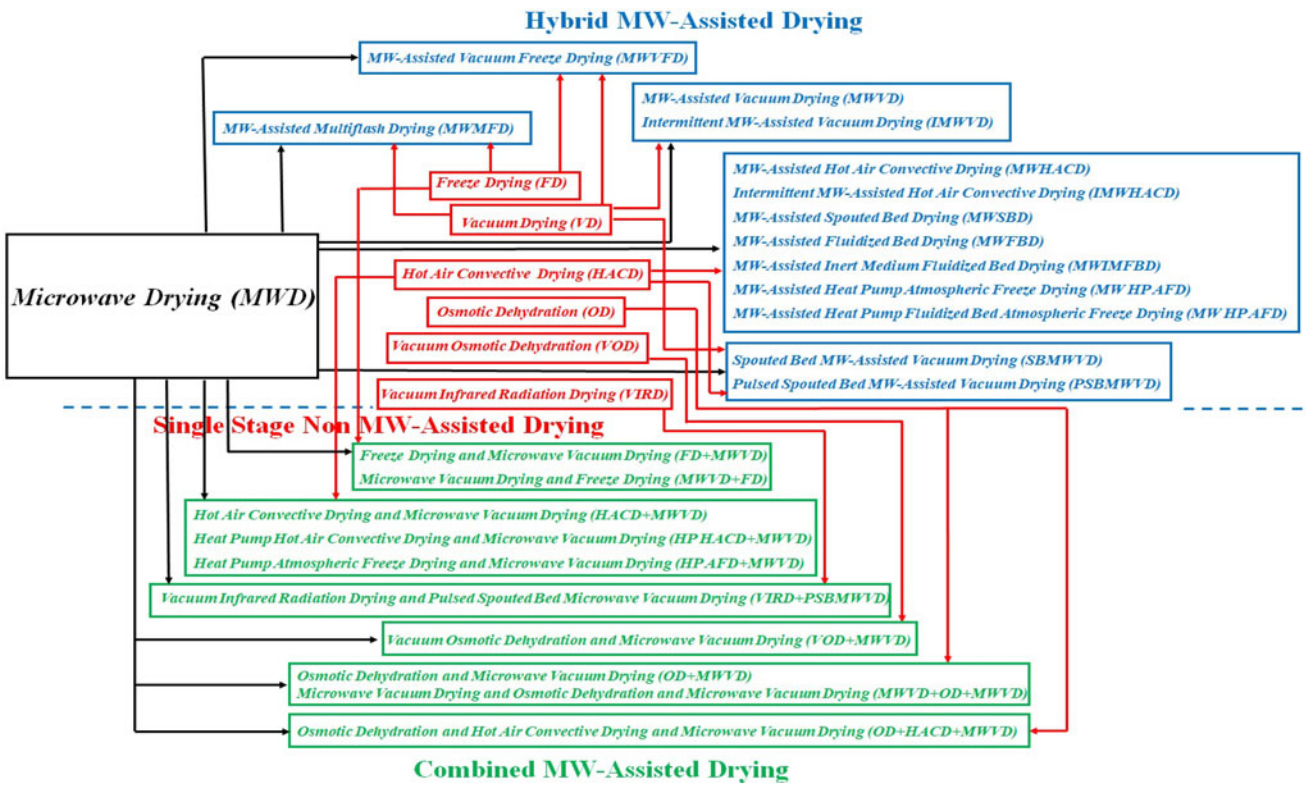

Figure 1. Hybrid and combined MW-assisted drying methods applied recently for different food products.

Quality parameters of food materials

The focus to date has been on improving the engineering aspects of MW-assisted drying to produce "engineered" products of desired material properties. Thorough understanding of the changes in material properties is essential for the development of novel MW-assisted drying processes and food products. Different MW-assisted drying methods may affect properties of high moisture food products. As it is common for material properties to change with the moisture removal from the material during drying, they play an important role in the design and prediction of heat and mass transfer processes during MW-assisted drying and determining the influence of drying methods on the quality properties of dried products. Structural and thermophysical properties that change during drying include mass-volume-area related properties involved in the heat transfer (Cui et al. 2008; Huang et al. 2011; Wang et al. 2013; Chong et al. 2014; Liu et al. 2017; Zielinska, Ropelewska, and Markowski 2017). Most of these properties indicate changes in the chemical composition and structural organization of dried products ranging from the micro to macroscopic level. The micro and macrostructure observations of surfaces and cross-sections of fruits and vegetables are often included to develop the knowledge on the effect of drying methods and conditions on the textural properties of dried samples. Also the morphological properties are reported for evaluating the effect of MW-assisted drying methods and conditions on the changes in the sample size and shape (Nahimana and Zhang 2011; Eikevik, Alves-Filho, and Bantle 2012). To estimate the degree to which the structure of different food products collapses during MW-assisted drying, many authors evaluate changes in mechanical properties (Bondaruk, Markowski, and Błaszczak 2007; Sunjka, Orsat, and Raghavan 2008; Stępień 2008; Setiady et al. 2009; Figiel 2009; Zhang, Zhang, and Mujumdar 2011; Bai-Ngew, Therdthai, and Dhamvithee 2011; Jiang et al. 2011; Mothibe et al. 2014; Zielinska, Sadowski, and Błaszczak 2015; Zielinska, Sadowski, and Błaszczak 2016). It is also reported that structural and thermophysical properties of fruits and vegetables change during drying and depend on the chemical composition, physical arrangement of the structure, phase distribution of a system, internal and external pore space represented by its porosity, etc. (Zielinska, Ropelewska, and Markowski 2017). Thus, the knowledge about the changes in heat transport properties of fruits during drying is needed to make heat transfer calculations and design of equipments for the drying and preservation of MW-assisted dried products. MW-assisted drying of food products may also affect the color and nutritional value of dried food products (Abbasi and Azari 2009; Soysal et al. 2009; Duan et al. 2010a; Leusink et al. 2010; Yan et al. 2010; Therdthai and Northongkom 2011; Wang et al. 2013; Pei et al. 2014; Huang and Zhang 2016; Liu et al. 2017). Not only MW-assisted drying, but also rehydration may lead to significant changes in mass of rehydrated products. The degree of changes in rehydration potential of MW-assisted dried products depends mainly on the drying method and operational conditions. If inadequately designed, irreversible cell dislocation, cellular rupture or loss of integrity of MW-assisted dried products may occur (Giri and Prasad 2007; Cui et al. 2008; Abbasi and Azari 2009; Setiady et al. 2009; Yan et al. 2010; Gaware, Sutar, and Thorat 2010; Jiang et al.

Table 1. Application of hybrid and combined MW-assisted drying in food processing.

Symbol	Product	References
MWD	Okra, Plum Slices, Pumpkin Slabs, Bamboo Shoot Slices, Olive Leaf, Apple Slices	Dadali, Apar, and Özbek (2007), Chayjan and Alaei (2016), Alibas (2007), Bal et al. (2011), Şahin et al. (2018), Cuccurullo et al. (2018)
MWHACD	Okra Slices, Tomatoes	Kumar, Prasad, and Murthy (2014), Kone et al. (2013)
IMWHACD	Bananas, Red Pepper, Pumpkin Slices	Pereira, Marsaioli, and Ahrné (2007), Soysal et al. (2009), Junqueira, Corrêa, and Ernesto (2017)
MW SBD	Carrot Slices	Yan et al. (2010)
MW FBD	Carrot Slices	Yan et al. (2010)
MW HP AFD	Whole Green Peas	Eikevik, Alves-Filho, and Bantle (2012)
MW HP FB AFD	Whole Green Peas	Eikevik, Alves-Filho, and Bantle (2012)
MWVD	Carrot Slices, Beetroot Slices, Mint Leaves, Fingerroots, Potato Slices, Whole Blueberries, Potato Cubes, Carrot Wafers, Apple Slices, Apple Cubes, Mixed Potato and Apple Paste, Whole Green Peas, Pineapple Discs, Mushroom Slices, Tomato Slices, Whole Strawberries, Strawberry Cubes, Cranberries, Okra, Onion Slices	Nahimana and Zhang (2011), Yan et al. (2010), Musielak and Kieca (2014), Therdthai and Zhou (2009), Therdthai and Northongkom (2011), Setiady et al. (2009), Setiady et al. (2007), Zielinska, Sadowski, and Błaszczak (2016), Zielinska, Sadowski, and Błaszczak (2015), Zielinska and Michalska (2016), Zielinska, Ropelewska, and Markowski (2017), Zielinska and Markowski (2016), Bondaruk, Markowski, and Błaszczak (2007), Markowski, Bondaruk, and Błaszczak (2009), Mothibe et al. (2014), Cui et al. (2008), Huang et al. (2011), Zielinska et al. (2013), Chauhan and Srivastava (2009), Correa et al. (2011), Giri and Prasad (2007), Gaware, Sutar, and Thorat (2010), Bórquez, Melo, and Saavedra (2015), Leusink et al. (2010), Jiang et al. (2017), Abbasi and Azari (2009)
IMWVD	Taro Slices	Zhang et al. (2017)
PSBMWVD	Okra, Stem Lettuce Slices, Apple Cubes, Carrot Cubes	Huang and Zhang (2016), Wang et al. (2013), Mothibe et al. (2014), Cao et al. (2017),
SBMWVD	Apple Cubes	Mothibe et al. (2014)
MWVFD	Mixed Potato and Apple Paste, Sea Cucumber, Banana Chips Slices, Onion Slices	Huang et al. (2011), Duan et al. (2010a), Jiang et al. (2013), Abbasi and Azari (2009)
PSBMWFD	Stem Lettuce Slices	Wang et al. (2013)
MWMFD	Bananas	Monteiro, Carciofi, and Laurindo (2016)
HACD + MWVD	Whole Blueberries, Blueberry Pomace, Apple Cubes, Frozen Cherries, Thawed Cherries, Pomegranate Arils, Okra, Pumpkin Slabs	Zielinska, Sadowski, and Błaszczak (2016), Zielinska, Sadowski, and Błaszczak (2015), Zielinska and Michalska (2016), Zielinska and Michalska (2018), Zielinska and Markowski (2016), Chong et al. (2014), Figiel (2007), Nowicka et al. (2015), Cano-Lamadrid et al. (2017), Jiang et al. (2017), Alibas (2007)
HP HACD + MWVD	Apple Cubes,	Chong et al. (2014)
HP AFD + MWVD	Whole Green Peas	Zielinska et al. (2013)
FD + MWVD	Button Mushroom Slices, Okra	Pei et al. (2014), Jiang et al. (2017)
MWVD + FD	Carrot Wafers, Apple Slices	Cui et al. (2008)
VIRD + PSBMWVD	Asparagus Cookies	Liu et al. (2017)
OD + MWVD	Quarters of Cranberry Fruits, Pineapple Discs, Carrot Cubes, Frozen Cherries, Thawed Cherries, Pomegranate Arils	Sunjka, Orsat, and Raghavan (2008), Correa et al. (2011), Changrue and Orsat (2009), Nowicka et al. (2015), Cano-Lamadrid et al. (2017)
OD + HACD + MWVD	Frozen Cherries, Thawed Cherries, Pomegranate Arils	Nowicka et al. (2015), Cano-Lamadrid et al. (2017)
VOD + MWVD	Whole Raspberries	Bórquez, Canales, and Redon (2010)
MWVD + OD + MWVD	Whole Cranberries	Zielinska et al. (2018)

2011; Huang et al. 2011; Nahimana and Zhang 2011; Jiang et al. 2013; Wang et al. 2013; Mothibe et al. 2014; Bórquez, Melo, and Saavedra 2015; Cuccurullo et al. 2018). Most of authors discuss the changes in the mass of rehydrated product which is only a net result of drying and rehydration and practically gives no information about the amount of water absorbed or soluble solids loss. A more in-depth analysis on the structural changes of food material during MW-assisted drying and rehydration includes quantification of soluble solids leach together with the imbibition of water into the dried material (Figiel 2007; Markowski, Bondaruk, and Błaszczak 2009; Therdthai and Northongkom 2011; Zielinska, Sadowski, and Błaszczak 2016).

Figure 2 presents quality properties of different food products that change during recently applied hybrid and/or combined MW-assisted drying methods.

Effect of methods and conditions on the quality parameters of MW-assisted dried food products

Structural and thermophysical properties

The most enhanced MWD systems for the preparation of high quality dehydrated fruits continuously adjust the MW power level in order to maintain the food material temperature above a target value. In this case, typical drying curves that exhibit high drying rates in the middle stage are obtained. One of the major disadvantages of this strategy is too rapid mass transport (Raghavan et al. 2010). This can lead to undesirable temperature increase in an early stage of drying and undesirable changes in food texture (Kone et al. 2013; Martynenko and Janaszek 2014). In response to these issues, a MWD system that can realize drying process keeping drying rate constant can be applied. Among others,

Table 2. Recent references (since 2007) regarding MW-assisted drying methods and conditions used for food products.

References	Processes	Conditions	Products
Alibas (2007)	MWD	MW Power: 160, 350 W	Pumpkin Slabs (5 × 50 × 20 mm)
	HACD + MWD	Air Temperature: 50, 75 °C, Air Velocity of 1 m/s, Technical Features: 230 V, 50 Hz, and 2650 W with a Frequency of 2450 MHz	
Bai-Ngew, Therdthai, and Dhamvithee (2011)	Freezing + MWVD	Freezing Temperature: −18 °C; MW Power: 582, 824, 1085 W; MW Intensity: 3.88, 5.49 and 7.23 W/g; Pressure and Frequency: 13.33 kPa and 2450 MHz	Durian Slices (thickness: 1.5 mm)
	Chilling + MWVD	Chilling Temperature: 4 °C; MW Power: 582, 824, 1085 W; MW Intensity: 3.88, 5.49 and 7.23 W/g; Pressure and Frequency: 13.33 kPa and 2450 MHz	
Bal et al. (2011)	MWD	MW Power: 140, 210, 280 and 350 W,	Bamboo Shoot Slices (diameter: 35 mm, thickness: 3.4 mm)
		Technical Features: 230 V, 50 Hz, and 700 W with a Frequency: 2450 MHz	
Bondaruk, Markowski, and Błaszczak (2007)	Blanching + MWVD	Blanching Temperature: 95 °C, Solution: Distilled Water, Time: 4.5 minutes; MW Power Density: 6 W/g, Pressure: 6, 12, 18, 24 kPa	Potato Cubes (dimensions: 10 × 10 × 10 mm)
Bórquez, Melo, and Saavedra (2015)	Freezing + MWVD	Freezing Temperature/Time: −20 °C/3 hours, −80 °C/3 hours	Whole Strawberries (longest axis: 4 cm)
		Drying Temperature: 50 °C, Pressure: 6 kPa, MW Power: 119–700 W	Strawberry Cubes (dimensions: 10 × 10 × 10 mm)
	Rehydration	Solution: Distilled Water, Water Temperature: 20 °C, Time: 12 hours	
Bórquez, Canales, and Redon (2010)	VOD + MWVD	OD Solution: Sucrose Solution, OD Pressure: 1.33 kPa for 8 minutes and Atmospheric Pressure up to 4 hours; Solution Temperature: 20 °C; MWVD Pressure: 1.33 and 101.33 kPa, MW Power: 119, 462, and 700 W, Pulsed Mode (MW on-off) with Temperature Control by varying MW settings at Time Intervals from 30 to 150 seconds	Whole Raspberries (no mechanical treatment)
	MWVD	MW Power Modes: Constant MW Power at 360 W and reduced MW Power from the initial 360 to 240 W; Pressure: 4–6 kPa	
	HACD + MWVD	Air Temperature: 60 °C; ; Air Velocity: 0.8 m/s; Time: 4 hours; MW Power Modes: Constant MW Power at 360 W and reduced MW Power from the initial 360 to 240 W	
Calin-Sanchez et al. (2014)	OD + MWVD	OD Temperature: 45 °C; Solution: Chokeberry Concentrated Juice (40° Bx); Time: 2 hours; Ratio of Osmotic Solution to Chokeberry Fruits: 3:1; MW Power Modes: Constant MW Power at 360 W and reduced MW Power from the initial 360 to 240 W	Black Chokeberries (frozen by liquid nitrogen and thawed)
	OD + HACD + MWVD	OD Temperature: 45 °C; Solution: Chokeberry Concentrated Juice (40° Bx); Time: 2 hours; Ratio of Osmotic Solution to Chokeberry Fruits: 3:1; Air Temperature: 60 °C; ; Air Velocity: 0.8 m/s; Time: 90 minutes; MW Power Modes: Constant MW Power at 360 W and reduced MW Power from the initial 360 to 240 W	
Cao et al. (2017)	PSBMWVD	Airflow: Compressed Air of 0.15MPa; Pulsed-Spouted Period: 2 s every minute; Vacuum: 0.09 MPa	Carrots (cut into 5-mm cubes)
	HACD + MWVD	Hot Air Temperature: 60 °C, Time: 2 hours, Air Velocity: 0.6 m/s, MW power: 360–120 W	
Cano-Lamadrid et al. (2017)	OD + HACD + MWVD	Solution: 100 % Pomegranate, 50 % Pomegranate and 50 % Chokeberry, 50 % Pomegranate and 50 % Apple, 50 % Apple and 50 % Chokeberry, 75 % Apple and 25 % Chokeberry, Temperature: 45 °C, Time: 90 minutes;	Pomegranate (cut at the equatorial zone, manually separated arils)
		Hot Air Temperature: 60 °C, Time: 2 hours, Air Velocity: 0.6 m/s, MW power: 360–120 W	
Changrue and Orsat (2009)	MWVD	MW Input Power: 1 and 1.5W/G; MW Power Modes: Continuous, 45 s on/15 s off and 30 s on/30 s off; Vacuum Pressure: 8 kPa	Carrot (cut into 10 mm cubes)
	OD + MWVD	Mixed Osmotic Solution: 50 % wt/wt Sugar Concentration and 5% wt/wt Salt Concentration for 2 hours and 38 minutes; Ratio of Sample to Solution 1:5(wt/wt); MW Input Power: 1 and 1.5W/g; MW Power Modes: Continuous, 45 s on/15 s off And 30 S on/30 s off; Vacuum Pressure: 8 kPa	
Chauhan and Srivastava (2009)	Blanching + MWVD	Blanching Temperature: 98 °C; Solution: Distilled Water; Time: 3 minutes;	Green Peas

(*continued*)

Table 2. Continued.

References	Processes	Conditions	Products
		MW Power: 100, 200, 300 W; Vacuum: 50, 225, 400 mm Hg	
Chayjan and Alaei (2016)	MWD	MW Power: 90, 270, 450 and 630 W	Plum Slices (thickness: 1.5 mm)
Chong et al. (2014)	HACD + MWVD	Air Temperature: 70 °C, Air Flow Velocity: 1 m/s, MW Power: 240 W, Pressure: 4–6 kPa, Rotation Speed of the Drying Chamber: 6 rpm	Apple Cubes (dimensions: 15 x 15 x 15 mm)
	HP HACD + MWVD	Air Temperature: 35 °C, Relative Humidity of Air: 20 %, Air Flow Velocity: 4 m/s, MW Power: 240 W, Pressure: 4–6 kPa, Rotation Speed of the Drying Chamber: 6 rpm	
Changrue and Orsat (2009)	MWVD	MW Power Density: 1 W/g, Pressure: 8 kPa, Continuous Mode of Drying	Carrot Cubes (dimensions: 10 x 10 x 10 mm)
	OD + MWVD	Solution: Sucrose Solution, Concentration: 50° Brix, Solution Temperature: 20 °C, Ratio of Fruits to Sirup: 1:5, MW Power Density: 1.5 W/g, Pressure: 8 kPa, Pulsed Mode (MW on-off): 45/15, 30/30 Seconds	
Chauhan and Srivastava (2009)	Blanching	Temperature: 98 °C, Solution: Distilled Water, Time: 3 minutes	Green Peas (diameter: 8 mm)
	MWVD	MW Power: 100, 200, 300 W, Pressure: 50, 225, 400 mm Hg	
Correa et al. (2011)	MWVD	MW Power Density: 4 W/g, Pressure: 2.8 kPa	Pineapple Discs (diameter: 1.0 and 2.4 mm)
	OD + MWVD	OD Time: 0, 3 and 6 hours, Solution: Sucrose Solution, Concentration: 40, 50 and 60° Brix (with 1 % of Citric Acid and 0.2 % of Ascorbic Acid), Temperature of Solution: 20 °C, Ratio of Fruits to Sirup: 1:10, MW Power Density: 4 W/g, Pressure: 2.8 kPa	
Cuccurullo et al. (2018)	MWD	MWD Temperature: 60, 70 and 80 °C, Drying Rate: Constant	Apple Slices (thickness: 10 mm; diameter: 20 mm)
Cui et al. (2008)	MWVD	MW Power: 400 W, Pressure: 2.5 kPa	Carrot Slices (thickness: 8 mm, diameter: 40 mm)
	MWVD + FD	MW Power: 400 W, MWVD Pressure: 2.5 kPa, Freezing Temperature: −25 °C, Heating Plate Temperature: 30 °C, FD Pressure: 0.2 kPa	Apple Slices (20 × 20 × 8 mm)
	Rehydration	Solution: Water, Water Temperature: 50 °C, Time: 50 minutes	
Dadali, Apar, and Özbek (2007)	MWD	MW Power: 180, 360, 540, 720, and 900 W; Technical Features: 230 V, 50 Hz, and 2650 W with a Frequency of 2450 MHz	Okra (trimmed barest slice from the stem end)
Duan et al. (2008)	MWFD	MWFD Temperature: −20 °C; MWFD Time: 8 hours, MW Power: 2.3 W/g, Pressure: 100 Pa, Cold Trap Temperature: −40 °C,	Sea Cucumber (length: 12 cm, thickness: 5 mm)
	UA-OD + MWFD	Ultrasound Application Duration: 30 min, Ultrasound Power: 240 W, Brine Concentration: 20 %, OD Time: 4 hours, OD Temperature: 24 °C, MWFD Temperature: −20 °C; Time: 8 hours, MW Power: 2.3 W/g, Pressure: 100 Pa, Cold Trap Temperature: −40 °C	
	Rehydration	Solution: Distilled Water, Water Temperature: 25 °C, Time: 2 hours	
Duan et al. (2010a)	MWFD	Temperature: −20 °C; Time: 8 hours, MW Power: 1.6, 2, and 2.3 W/g, Pressure: 50 Pa, Cold Trap Temperature: −40 °C	Sea Cucumber (length: 12 cm, thickness: 5 mm)
Eikevik, Alves-Filho, and Bantle (2012)	Freezing + MW HP AFD	Freezing Temperature: −30 °C; Drying Air Temperature: −6, −3, 0 °C, Relative Humidity of Air: 20.4–22.7%, Condition: Fixed Bed with Air Flow Velocity: 2.7 m/s, MW Power: 140, 280 W, Product Load: 2000 g	Whole Green Peas (no mechanical treatment)
	Freezing + MW HP FB AFD	Freezing Temperature: −30 °C; Drying Air Temperature: −6, −3, 0 °C, Relative Humidity of Air: 22.5 %, Condition: Fluidized Bed with Air Flow Velocity: 4.5 m/s, MW Power: 140, 280 W, Product Load: 1000 and 2000 g	
Figiel (2007)	HACD + MWVD	Air Temperature: 55 °C, Air Flow Rate: 4 m/s, Time of Convective Pre-Drying: 40, 100 and 160 minutes, Finish-Drying with the MW Power: 240, 480 and 720 W, Pressure: 4–6 kPa	Apple Cubes (dimensions: 10 × 10 × 10 mm)
Figiel (2009)	MWVD	MW Power: 240, 480 and 720 W; 30 s Mw pulses followed by 5 s breaks; Pressure: 4–6 kPa	Garlic Cloves (55 mm height and 70 mm diameter) halved or sliced into 4 mm pieces

(*continued*)

Table 2. Continued.

References	Processes	Conditions	Products
Figiel (2010)	HACD + MWVD	Air Temperature: 60 °C; Air Velocity: 1.8 m/s; MW power: 240, 360, 480 W; Pressure: 4–6 kPa	Beetroots (cut into 10 mm Cubes)
Gaware, Sutar, and Thorat (2010)	MWVD	Product Temperature 40–45 °C, MW Power: 300–600 W, Pressure: 8 kPa	Tomato Slices (thickness: 6 mm)
	Rehydration	Solution: Water, Solution Temperature: 25 °C, Time: 1440 minutes	
Giri and Prasad (2007)	MWVD	MW Power: 150 and 250 W, Pressure: 10–20 kPa	Mushroom Slices (thickness: 7.5 and 12.5 mm)
	Rehydration	Solution: Distilled Water, Solution Temperature: 30 and 100 °C, Time: 3 h (30 °C) and 10 minutes (100 °C)	
	MWHACD	MW power:120, 150, and 180 W; Air temperature: 60 °C	
Horuz, Jaafar, and Maskan (2017)	Ultrasonication + MWHACD	Output Power: 300 W; Ultrasonic Density: 0.011 W/ cm^3; Ratio of Tomatoes to Tap Water: 1:4; Bath Temperature: 26.4 °C; Time of Ultrasonic Waves: 0, 20, 40 min; MW power:120, 150, and 180 W; Air temperature: 60 °C	Tomato Slices (thickness: 0.7 mm; length: 54 mm; width 19 mm)
	Rehydration	Solution: Distilled Water, Solution Temperature: 30 °C	
Huang et al. (2011)	MWFD	Freezing Temperature/Time: −30 °C/1 hour, and then −60 °C; Pressure: 0.1 kPa, Cold Trap Temperature: −40 °C MW Power Density: 1.6 W/g	Mixed Potato And Apple Paste (sheet or slices thickness: 3 mm, dimensions of slices: 2.5 × 1.25 × 0.3 cm)
	MWVD	MW Power Density: 4 W/g, Pressure: 25,5 kPa, Rotation Speed of Turntable: 5 rpm	
	Rehydration	Solution: Water, Water Temperature: 20 °C	
Huang and Zhang (2016)	Blanching + MWVD	Blanching Temperature: 95 °C, Blanching Solution: Water, Blanching Time: 5 min; Microwave Power: 0.1–0.8 kW	Okra
	Blanching + PSBMWVD	Blanching Temperature: 95 °C, Blanching Solution: Water, Blanching Time: 5 min; Microwave Power: 0.1–1.0 kW	
Jiang et al. (2011)	MWVD	MW Power Level: 1 W/g ; Pressure: 100 Pa	Potato and Banana slices (thickness about 2 cm) steamed for 5 min and 15 min, respectively; blended banana:potato in ratio (w/w): 3:7, 1:1 and 7:3
	MWFD	MW Power Levels: 2, 2.5 and 3 W/g ; Temperature of The Cold Trap: −40 to −45 °C	
Jiang et al. (2013)	Freezing + MWFD	Freezing Temperature: −50 °C; Cold Trap Temperature: −35 to −40 °C, Pressure: 100 Pa, Microwave Power in Primary Drying Stage: 1.0 W/g, Secondary Drying Stage: 1.0, 1.5, 2 W/g	Banana Chips Slices (thickness: 3 mm)
	Rehydration	Solution: Distilled Water, Water Temperature: 25 °C; Time: 5 minutes	
	MWVD	Blanching Solution: Water, Blanching Temperature: 100 °C; Blanching Time: 150 seconds; Vacuum: 70 kPa, Microwave Power: 1536 W with a Pulse Ratio (PR) Regulation, PR of 1.5 (10 seconds on, 5 seconds off) until the completion of drying	
Jiang et al. (2017)	FD + MWVD	Blanching Solution: Water, Blanching Temperature: 100 °C; Blanching Time: 150 seconds; Freezing Temperature: −30 °C, Absolute Pressure: 20 Pa, Heating Plate Temperature: 25 °C, Cold Trap Temperature: –50 °C for 10 hours (until the moisture content of the samples is lower than 80 g/100 g wb.), Microwave Power: 1536 W with a Pulse Ratio (PR) regulation, PR of 1.5 (10 seconds on, 5 seconds off), Vacuum: 70 kPa	Okra (trimmed tops and tips of the blanched okra)
	HACD + MWVD	Blanching Solution: Water, Blanching Temperature: 100 °C; Blanching Time: 150 seconds; Air Temperature: 70 °C, Air Velocity of 1.5 m/s for 2 hours until the moisture content is lower than 60 g/100 g wb., Microwave Power: 1536 W with a Pulse Ratio (PR) regulation, PR of 1.5 (10 seconds on, 5 seconds off), Vacuum: 70 kPa	
Junqueira, Corrêa, and Ernesto (2017)	MWD	MW power: 780 W	Pumpkin Slices (peeled, seeds removed, length: 2.00 cm, width: 2.00 cm, thickness: 0.50 cm)
	IMWHACD	Air Temperature: 30, 60 °C; air velocity: 2.22, 4.44 m s^{-1}; MW power: 780 W; time of microwave drying: 60 s, time of convective drying: 60 s	

(*continued*)

Table 2. Continued.

References	Processes	Conditions	Products
Kone et al. (2013)	MWHACD	No MW Power Control: MW Power Densities: 1.5, 2 and 2.5 W/g; Air Temperature: 40 °C Automatic MW Power Control: MW Power Densities: 3,5 and 7 W/g, Air Temperature: 40 °C	Potato Cubes (half cut)
Korzeniowska et al. (2011)	MWVD	MW Power: 360 W, Pressure: 4–6 kPa, Rotation Speed of Cylinder: 6 rev/min	Pumpkin Slices (thickness: 5 mm, diameter: 18 mm)
	OD + MWVD	OD Time: 6 hours, Solution: Sucrose Solution, Concentration: 20, 40 and 60 %, Temperature of Solution: 40 °C, Ratio of Osmotic Solution to Pumpkin Slices: 3:1, MW Power: 360 W, Pressure: 4–6 kPa, Rotation Speed of Cylinder: 6 rev/min	
Kumar, Prasad, and Murthy (2014)	Blanching + MWHACD	Blanching Temperature: 95 °C, Blanching Solution: Water, Blanching Time: 5 minutes; MW Power: 0.5–2.5 W/g, Air Temperature: 40–70 °C, Air Velocity: 1–2 m/s	Okra Slices (thickness: 2 cm)
Lech et al. (2015)	MWVD	MW Power: 120, 240, 360, and 480 W, Pressure: 4–6 kPa	Beetroot Slices (diameter: 18 mm, thickness: 9.6, 6.3, 3.35, and 2.6 mm, specific surface area: 429, 541, 827, and 998 m^2/m^3)
	OD + MWVD	Solution: Chokeberry Juice Concentrated to 40° Bx, Temperature: 50 °C, Time: 2 hours, Ratio of Osmotic Solution to Beetroot Slices: 3:1, MW Power: 120, 240, 360, and 480 W, Pressure: 4–6 kPa	
Leusink et al. (2010)	MWVD	Pressure: 30 mm Hg, MW Power: 1.8 kW, Time: 0–35 minutes followed by MW Power: 1.2 KW, Time: 20–25 minutes	Cranberries (stored at −25 °C until use)
Liu et al. (2017)	VIRD	Temperature: 70 °C, Pressure: −0.09 MPa,	
	PSBMWVD	MW Power: 2.5 W/g, Pulse-Spout Period: 2 s, Interval: 28 s, First Drying Stage without Spouting: 20 min at Pressure of −0.09 MPa, Recovery Time: 10 s; Second Stage of Drying: Vacuum Pressure inside Chamber: −0.07 MPa to −0.09 MPa	Asparagus Cookies (cut into slices, diameter: 9 mm, thickness: 10 mm; blanched for 3 min in 95 °C water; ground for 4 min; slurry was then concentrated for 12 min using MWVD at 2.5 W/g to around 85% (w.b.) moisture content
	VIRD + PSBMWVD	Temperature: 70 °C, Pressure: −0.09 MPa, MW Power: 2.5 W/g, Pulse-Spout Period: 2 s, Interval: 28 s, First Drying Stage without Spouting: 20 min at Pressure of −0.09 MPa, Recovery Time: 10 s; Second Stage of Drying: Vacuum Pressure inside Chamber: −0.07 MPa to −0.09 MPa	
	Rehydration	Solution: Distilled Water, Water Temperature: 25 °C; Time: 10 minutes	
Markowski, Bondaruk, and Błaszczak (2009)	Blanching + MWVD	Blanching Temperature: 95 °C, Solution: Distilled Water, Time: 4.5 minutes; MW Power: 480 W, Pressure: 6, 12, 18, 24 kPa	Potato Cubes (dimensions: 10 × 10 × 10 mm)
Mierzwa, Kowalski, and Kroehnke (2017)	MWHACD	Air temperature: 58 °C, Airflow Velocity: 1.6 m/s, MW Power: 100 W, IR: 250 W. Relative Humidity of Air: 20 and 22 %	Carrot Slices (diameter: 35, height: 5 mm)
	UA-OD + MWHACD	Temperature: 30 °C; Acoustic Waves of Frequency: 25 kHz; Intensity: >1 W/cm^2; Solution: Aqueous Solutions of Analytically Pure Fructose; Solution to Sample Mass Ratio: 4:1; Time: 30, 120 minutes; Air Temperature: 58 °C, Airflow Velocity: 1.6 m/s, MW Power: 100 W, IR: 250 W. Relative Humidity of Air: 20 and 22 %	
Monteiro, Carciofi, and Laurindo (2016)	MWVD	MW Power: 400 W, 700 W, 1000 W, Vacuum 4–8 kPa	Bananas slices (peeled, without fruit ends, thickness of 5 mm, average diameter of 27.6 ± 3.5 mm)
	MWMFD	Warming in the MW Field until 60 °C under Atmospheric Pressure, Vacuum 4–8 kPa, MW Power: 400 W, 700 W, 1000 W; The Number of Heating-Vacuum Pulse Cycle: 3	
Mothibe et al. (2014)	VD	Pressure: 7.5 kPa; Temperature: 70 °C	Apple Cubes (dimension: 5 mm)
	MWVD	Pressure: 7.5 kPa; Rotation Speed of Turntable: 5 rpm; MW Power Levels: low (P1), medium low (P3), medium (P5), medium high (P7), high (P10)	
	PSBMWVD	Air Flow: $1 m^3/min$; MW Power: 2.4 W/g; Pulse-Spout Period: 3 s; Interval: 5 s; Vacuum: 7.5 kPa; Vacuum System with a Pumping Rate of $1 m^3/min$; Pressure: 7.5 kPa; Rotation Speed of Turntable: 5 rpm; MW Power Levels: low (P1), medium low (P3), medium (P5), medium high (P7), high (P10)	

(*continued*)

Table 2. Continued.

References	Processes	Conditions	Products
	SBMWVD	Temperature: 70 °C; Pressure: 7.5 kPa; Rotation Speed of Turntable: 5 rpm; MW Power Levels: low (P1), medium low (P3), medium (P5), medium high (P7), high (P10)	
Musielak and Kieca (2014)	MWVD	Pressure: 10–12 kPa, Two-Stage MW Power: Initial MW Power: 200, 250, 300 W, Criteria for Change in MW Power for 150 W: Moisture Ratio: 0.54;	Carrot Slices (diameter: 30 mm, thickness: 6 mm)
		Constant MW Power: 150, 200, 250, 300, 350 W; Periodic MW Power: 5 minutes Interval for MW Power: 200, 250, 300 W; Duration of Interval: 20, 25, 30 min for MW Power: 150 W	Beetroot Slices (diameter: 60 mm, thickness: 7 mm)
Nahimana and Zhang (2011)	Blanching + MWVD	Temperature: 90 °C, Solution: Water, Time: 4 minutes; Pressure: 4 kPa, MW Power Density: 1.3, 1.9, 2.5 W/g, Temperature in the Cabinet: 33 °C, Rotation Speed of Turntable: 5 rpm	Carrot Slices (thickness: 4 mm)
	Rehydration	Solution: Water, Temperature: Room Temperature and 100 °C, Time: 5 and 100 minutes	
Nowicka et al. (2015)	HACD + MWVD	Air Temperature: 50 °C, MW Power: 360 W, Pressure: 4–6 kPa	Frozen Sour Cherries (with stones, FS, without stones, FW)
	OD + HACD + MWVD	Solution: Apple Concentrate, Temperature: 40 °C, Time: 180 minutes, Air Temperature: 50 °C, MW Power: 360 W, Pressure: 4–6 kPa	Thawed Sour Cherries (with stones, TS, without stones, TW)
Pei et al. (2014)	Freezing + FD + MWVD	Freezing Temperature: −30 °C; Freezing Time: 8 hours, Cold Trap Temperature: −83 °C, Heating Plate Temperature: 20, 30, 40 °C, Pressure: 70, 100, 130 Pa, MW Power: 20, 40, 60 W/g, Pressure: 90 kPa; Material Layer Thickness: Single, Double, Triple	Button Mushroom Slices (thickness: 5 mm)
Pereira, Marsaioli, and Ahrné (2007)	OD + MWHACD	OD Solution: Sucrose Solution containing 1% Citric Acid and 0.6% Ascorbic Acid, Concentration: 50° Brix, Solution Temperature: 40 °C, Time: 90 min; Three Periods of Drying: Phase I (Output MW Power: 760 W; Input Air Flow at 80 °C and 5.7 m/s for 5 min; 2 kg/kg); Phase II (Output MW Power: 380 W; Input Air Flow at 50 °C and 3.3 m/s; 70 °C and 3.3 m/s; 70 °C and 5.7 m/s; 0.67 kg/kg); Phase III (Output MW Power: 0 W, 76 W, 150 W or 230 W; Input Air Flow at 50 °C and 3.3 m/s; 70 °C and 3.3 m/s; 70 °C and 5.7 m/s up to the Final Moisture Content of 0.17 kg/kg)	Bananas slices (peeled, thickness: 10 mm)
Şahin et al. (2018)	MWD	MW Power: 300, 400, and 500 W, Atmospheric Pressure: 2.45 GHz, Solid Mass: 1.5, 2, and 2.5 G, Drying Time: 4, 5, and 6 min	Fully Expanded Fresh Olive Leaves
Setiady et al. (2007)	Blanching + MWVD	Temperature: 98 °C, Solution: Water, Time: 2 minutes; MW Power Density: 1 W/g, Pressure: 5 kPa, Temperature: 50, 60, 70 °C, Time: 60, 90, 120, 150 minutes	Potatoe Slices (thickness: 3.175 mm)
Setiady et al. (2009)	Blanching + MWVD	Temperature: 98 °C, Solution: Tap Water, time: 2 minutes; MW Power Density: 1 W/g, Pressure: 2.27 kPa	Potato Slices (thickness: 3 mm)
	Rehydration	Solution: Water, Water Temperature: 98 °C/70 °C, Time: 30 minutes	
Soysal et al. (2009)	MWHACD	Air temperature: 35, 55, 60, 65 and 75 °C; Air Flow Speed: 1.5 m/s; MW Power: 0, 597.20 and 697.87 W	Red Pepper Slices (length: 2.5 cm, width: 2.0 cm)
	IMWHACD	Air Temperature: 35, 55, 60, 65 and 75 °C; Air Flow Speed: 1.5 m/s; MW Power: 0, 597.20 and 697.87 W; Pulsed Mode: 30 s on–30 s off, 30 s on–45 s off, 30 s on–60 s off, and 30 s on–90 s off; The Corresponding Pulse Ratios for on-off Timings: 2.0, 2.5, 3.0. 4.0	
Stępień (2008)	Blanching + MWVD	Solution: Water, Temperature: 95 °C, Time: 3 minutes, MW Power: 480 W, Pressure: 4–10 kPa	Carrot Cylinders (diameter: 20 mm, height: 5 mm)
	OD + MWVD	OD Time: 24 hours, Solution: 5% Solution of NaCl, MW Power: 480 W, Pressure: 4–10 kPa	
Sunjka, Orsat, and Raghavan (2008)	OD + MWVD	OD Time: 24 hours, Solution: High Fructose Corn Sirup, Solution Concentration: 77° Bx, Temperature: 23 °C, Ratio Of Sirup to Fruit: 2:1, Continuous and Pulsed Mode (MW on-off): 30/30, 30/45 seconds, MW Power Density: 1, 1.25, 1.5 W/G, Pressure: 3.4, 18.6, 33.8 kPa	Cranberries (cut in quarters)
Therdthai and Northongkom (2011)	MWVD	MW Power: 2880, 3360 W; Pressure: 13.33 kPa	Fingerroot Slices (peeled, sliced along the length, dimension of 50 × 4 × 1 mm)

(*continued*)

Table 2. Continued.

References	Processes	Conditions	Products
Therdthai and Zhou (2009)	MWVD	MW Power Density: 8.0, 9.6, 11.2 W/g, Pressure: 13.33 kPa	Mint Leaves (no mechanical treatment)
Tsuruta et al. (2015)	MWVD	MW Power: 100 W; Pressure: 5 kPa ; Rotation Speed of the Drying Chamber: 3 rpm	Radishes, Carrots (3 cm cubic samples)
Yan et al. (2010)	Blanching + MWVD	Blanching Solution: Water, Blanching Temperature: 90 °C, Blanching Time: 10 minutes; MW Power Density: 2.4 W/g, Pressure: 5 kPa	Carrot Slices (dimensions: 8 × 8 × 8 mm)
	Blanching + MWFBD	Blanching Solution: Water, Blanching Temperature: 90 °C, Blanching Time: 10 minutes; MW Power Density: 2.0 W/g, Pressure: 1 kPa, Cold Trap Temperature: −40 ˚C	
	Blanching + MWSBD	Blanching Solution: Water, Blanching Temperature: 90 °C, Blanching Time: 10 minutes; Air Temperature: 50 °C, MW Power Density: 2.0 and 3.5 W/g	
	Rehydration	Solution: Water, Solution Temperature: 50 °C	
Wang, Zhang, and Mujumdar (2010)	Blanching + MWFD	Water Blanching Temperature: 100 °C; Blanching Time: 5 min; Vacuum: 100 Pa; Temperature of the cold trap: −40 °C; MW power: 1.6 W/g	Potato Slices (4 mm slices with a diameter of 40 mm)
	Calcium Treatment + MWFD	Solution: 0.5% Calcium Chloride; Time: 10 min; Vacuum: 100 Pa; Temperature of the Cold Trap: −40 °C; Heating Shelf Temperature: 55 °C MW Power: 1.6 W/g	
Zhang, Zhang, and Mujumdar (2011)	Blanching + MWVD	Water Blanching Temperature: 90–95 °C, Blanching Time: 4 minutes; MW Power Density: 2.2, 2.0, 1.8 W/g, Maximum Vacuum Pressure: −0.095 MPa, Rotation Speed of the Drying Chamber: 10 rpm, Microwave Frequency was 2,450 MHz. The Maximum Vacuum Pressure: −0.095 MPa.	Wild Cabbage Chips (thickness of about 3 to 5 mm)
	Blanching + MWFD	Water Blanching Temperature: 90–95 °C, Blanching Time: 4 minutes; Freezing Temperature: −70 °C, Freezing Time: 5 hours, Absolute Pressure: 100 Pa, Cold Trap Temperature: −40 °C	
Zhang et al. (2017)	IMWVD	MW Power Density: 8 W/g, on-off Timing: 1 min on–3 min off, Pulse Ratio for on-off Timing: 4.0	Taro Slices (thickness: 4 mm, size of slices was 3 × 3 × 0.4 cm^3)
	Blanching + IMWVD	Water Blanching Temperature: 100 °C, Blanching Time: 2 minutes; MW Power Density: 8 W/g, on-off Timing: 1 min on–3 min off, Pulse Ratio for on-off Timing: 4.0	
		Blanching + Freezing + IMWVD	Water Blanching Temperature: 100 °C, Blanching Time: 2 minutes; Temperature of Freezing: –20 °C, Time: 12 hours; MW Power Density: 8 W/g, on-off Timing: 1 min on–3 min off, Pulse Ratio for on-off Timing: 4.0
	Blanching + Immersion in Maltodextrin Solution + IMWVD	Water Blanching Temperature: 100 °C, Blanching Time: 2 minutes, Maltodextrin Solution: 2 % *w/v*), Time: 40 minutes; MW Power Density: 8 W/g, on-off Timing: 1 min on–3 min off, Pulse Ratio for on-off Timing: 4.0	
	Blanching + Immersion in Maltodextrin	Solution + Freezing + IMWVD	Water Blanching Temperature: 100 °C, Blanching Time: 2 minutes; Maltodextrin Solution: 2 % *w/v*), Time: 40 minutes; Temperature of Freezing: –20 °C, Time: 12 hours; MW Power Density: 8 W/g, on-off Timing: 1 min on–3 min off, Pulse Ratio for on-off Timing: 4.0
Zielinska and Markowski (2016)	MWVD	MW Power Density: 1 W/G, Pressure: 4–6 kPa	Whole Blueberries (no mechanical treatment)
	HACD + MWVD	Air Temperature: 60 and 80 °C, MW Power Density: 1 W/g, Pressure: 4–6 kPa, Intermittent Moisture Content after Hot Air Pre-Drying: 2 and 4 kg H_20/kg DM	
Zielinska and Michalska (2016)	Freezing + MWVD	Convective Freezing Temperature: −18 °C; MW Power Density: 1.3 W/g, Pressure: 4–6 kPa, Rotation Speed of the Drying Chamber: 6 rpm	Whole Blueberries (no mechanical treatment)
	Freezing + HACD + MWVD	Convective Freezing Temperature: −18 °C; Air Temperature: 60 and 90 °C, Intermittent Moisture	

(*continued*)

Table 2. Continued.

References	Processes	Conditions	Products
		Content after Hot Air Pre-Drying Step ≈ 2 kg $H_2$0/kg DM, MW Power Density: 1.3 W/g, Pressure: 4–6 kPa, Rotation of the Drying Chamber: 6 rpm	
Zielinska and Michalska (2018)	Freezing + MWVD	Convective Freezing Temperature: −18 °C; Freezing Time: No Longer than 1 Week; MW Power Density: 1.3 W/g, Pressure: 4–6 kPa, Rotation Speed of the Drying Chamber: 6 rpm	Blueberry Pomace
	Freezing + HACD + MWVD	Convective Freezing Temperature: −18 °C; Freezing Time: No Longer than 1 Week; Air Temperature: 60 and 90 °C, Intermittent Moisture Content after Hot Air Pre-Drying Step ≈ 2 kg $H_2$0/kg DM, MW Power Density: 1.3 W/g, Pressure: 4–6 kPa, Rotation of the Drying Chamber: 6 rpm	
Zielinska, Sadowski, and Błaszczak (2015)	MWVD	MW Power Density: 1 W/g, Pressure: 4–6 kPa; Rotation Speed of the Drying Chamber: 6 rpm	Whole Blueberries (no mechanical treatment)
	Freezing + MWVD	Convective Freezing Temperature: −20 °C; MW Power Density: 1 W/g, Pressure: 4–6 kPa; Rotation Speed of the Drying Chamber: 6 rpm	
	HACD + MWVD	Air Temperature: 60 and 80 °C, MW Power Density: 1 W/g, Pressure: 4–6 kPa, Intermittent Moisture Content after Hot Air Pre-Drying Step: 2 and 4 kg $H_2$0/kg DM	
	Freezing + HACD + MWVD	Convective Freezing Temperature: −20 °C; Air Temperature: 60 and 80 °C, MW Power Density: 1 W/g, Pressure: 4–6 kPa, Intermittent Moisture Content after Hot Air Pre-Drying Step: 2 and 4 kg $H_2$0/kg DM	
Zielinska, Sadowski, and Błaszczak (2016)	MWVD	MW Power Density: 1 W/g, Pressure: 4–6 kPa; Rotation Speed of the Drying Chamber: 6 rpm	Whole Blueberries (no mechanical treatment)
	HACD + MWVD	Air Temperature: 60 and 80 °C, MW Power Density: 1 W/g, Pressure: 4–6 kPa, Intermittent Moisture Content after Hot Air Pre-Drying Step: 2 and 4 kg $H_2$0/kg DM	
	Rehydration	Solution: Distilled Water, Solution Temperature: 21 °C, Time: 5 minutes	
Zielinska et al. (2013)	Freezing + MWVD	Freezing Temperature: −20 °C; MW Power: 100 W, Pressure: 3 kPa, Rotation of the Drying Chamber: 6 rpm	Whole Green Peas (no mechanical treatment)
	Freezing + HP AFD + MWVD	Freezing Temperature: −20 °C; Air Temperature: −5 °C, Relative Humidity of Air: 20 and 50 %, Air Flow Rate: 4.5 m/s, MW Power: 100 W, Pressure: 3 kPa; Rotation Speed of the Drying Chamber: 6 rpm	
	Freezing + HP HACD + MWVD	Freezing Temperature: −20 °C; Air Temperature: 30 °C, Relative Humidity of Air: 20 and 50 %, Air Flow Rate: 4.5 m/s, MW Power: 100 W, Pressure: 3 kPa; Rotation Speed of the Drying Chamber: 6 rpm	
	Rehydration	Solution: Water, Water Temperature: 95 °C; Time: 10 minutes	
Zielinska, Ropelewska, and Markowski (2017)	MWVD	MW Power Density: 0.75 W/g, Pressure: 4–6 kPa	Whole Cranberries (no mechanical treatment)
Zielinska et al. (2018)	MWVD	MW Power: 100, 150, 200, 300, 450, 500 W, Pressure: 5 kPa, Rotation Speed of the Drying Chamber: 6 rpm	Whole Cranberries
	Freezing + MWVD	Convectional Freezing: Temperature: −18 °C, Time: 24 hours;	
Cryogenic Freezing: Liquid Nitrogen with Boiling Point of −195.9 °C; Time: 1 minute; MW Power: 100, 150, 200, 300, 450, 500 W, Pressure: 5 kPa, Rotation Speed of the Drying Chamber: 6 rpm			

HACD, hot air convective drying; MWD, microwave drying; MWHACD, microwave-hot air convective drying; FD, freeze drying; VFD, vacuum freeze drying; MWFD, microwave freeze drying; VD, vacuum drying; MWVD, microwave-vacuum drying; MWMFD, microwave multi-flash drying; MWSD, microwave spouted bed drying; PSMWVD, pulse-spouted microwave vacuum drying; OD, osmotic dehydration under atmospheric pressure; VOD, osmotic dehydration under reduced pressure; UA-OD, ultrasound assisted osmotic dehydration; MWOD, microwave-osmotic dehydration; HPD, heat pump drying; HP HACD, heat pump hot air convective drying; HP AFD, heat pump atmospheric freeze drying; HP FB AFD, heat pump fluidized bed atmospheric freeze drying; MW HP AFD, microwave assisted heat pump atmospheric freeze drying; MW HP FB AFD, microwave assisted heat pump fluidized bed atmospheric freeze drying.

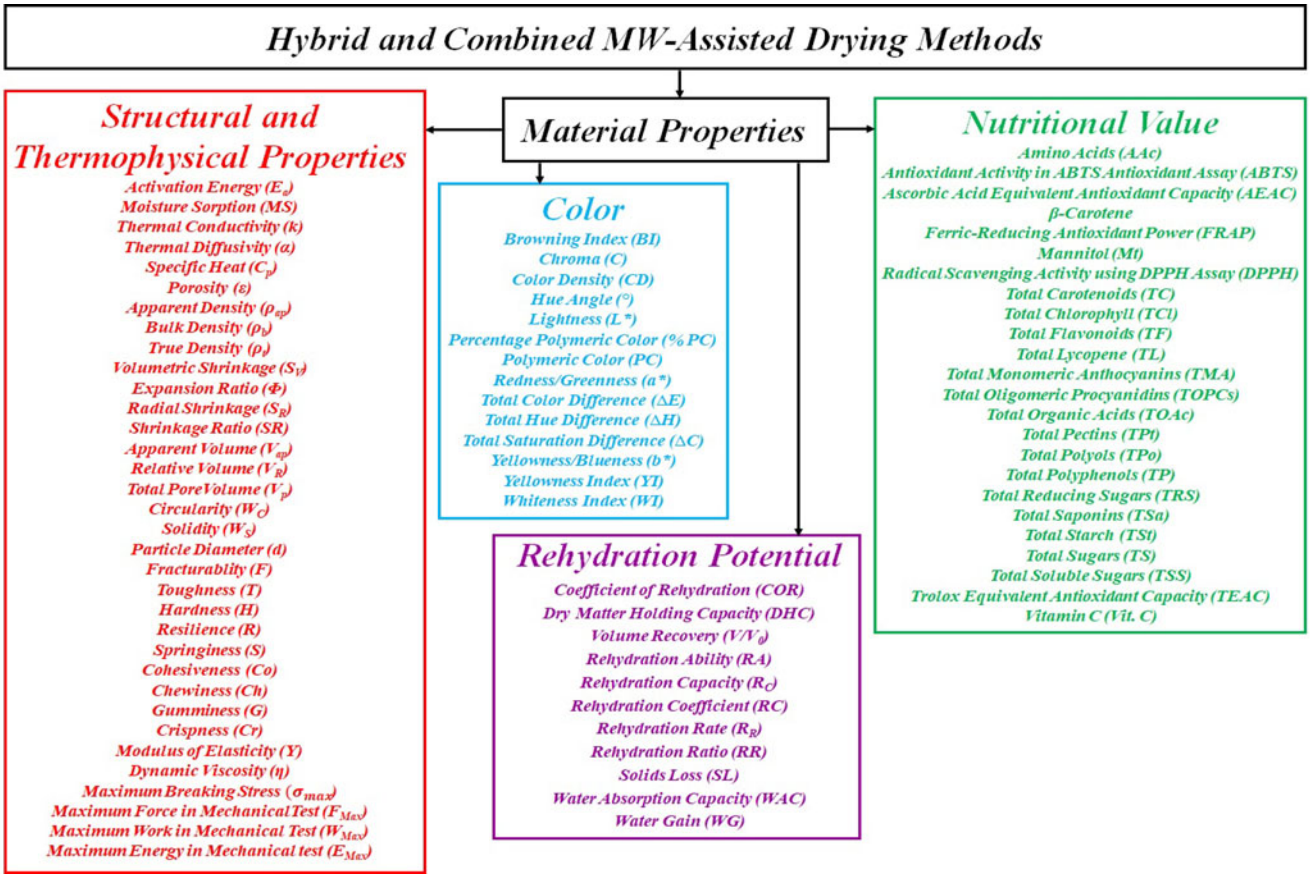

Figure 2. Quality properties of different food products that change during recently applied hybrid and/or combined MW-assisted drying methods.

pulsed mode, automatic on/off temperature level or microwave density control should be set in order to meet key requirements for food quality. The resultant benefits of operating at constant drying rates include e.g. an improvement of texture of dried apples (Cuccurullo et al. 2018). Additionally, the system with MW power control results in improved texture of the dried products compared to the tomatoes dried without MW power control (Kone et al. 2013).

The development of internal stresses during drying and shrinkage of food materials depends on the MW power. It is reported that the application of high microwave power (780 W) causes the development of greater internal stresses during drying and enlarged shrinkage of pulsed vacuum osmodehydrated pumpkin slices subjected to MWD. In this case, convective drying at high temperatures better prevents shrinkage of pumpkin slices (the outer parts dry quickly, become rigid and their fixed tissue volume does not contract quickly) (Schulze, Hubbermann, and Schwarz 2014; Junqueira, Corrêa, and Ernesto 2017). Increasing air temperature and air velocity may have a positive effect on MWHACD time and dried product quality. However, the effect is not as great as this associated with MW power (Pereira, Marsaioli, and Ahrné 2007).

Intermittent MW-assisted hot air convective drying (IMWHACD) is longer than MWHACD. It results in higher quality of dried products than those obtained using HACD. However, it should be conducted at low drying air temperature and MW power level with relatively long power-off time. For example, IMWHACD conducted at 35 °C is preferred over HACD when production of high quality red pepper with better physical properties and texture of dried food products is considered (Soysal et al. 2009). Additionally, an increase in air temperature, at the same air velocity during IMWHACD may result in higher shrinkage of pumpkin slices (Junqueira, Corrêa, and Ernesto 2017).

Microwave (volumetric) heating under reduced pressure results in vapor formation inside the food materials at relatively low temperatures, leading to an expanded porous structure and limited shrinkage of material to be dried. Generally, lab scale MWVD with continuous MW modes are used to dry food materials. However, MWVD with pulsed mode and automatic on/off temperature level can be used e.g. for production of dried strawberries with similar shape and texture as the fresh fruits (Bórquez, Melo, and Saavedra 2015). MWVD ensures lower shrinkage of the dried potatoes than HACD (Markowski, Bondaruk, and Błaszczak 2009). It also reduces shrinkage of apples and creates porous products with a honeycomb-like network (Setiady et al. 2009). Vapor bubbles increase total pressure gradient inside the dried meant leaves and significantly enhance dried material porosity (Therdthai and Zhou 2009). MWVD potatoes retain porous cell structure (porosity of MWVD samples is 20 times higher than that of HACD potatoes and slightly lower than FD ones) (Setiady et al. 2009). Also, MWVD is the best for drying of black chokeberries in terms of their porosity, bulk density and hardness (Calin-Sanchez et al. 2014). MWVD seems to be an effective method for producing dried snacks characterized by hard and crispy texture and considerable resistance to stress associated with manufacturing, packaging, storage, and delivery. Cranberries processed by MWVD are characterized by significantly greater hardness, gumminess, and chewiness in comparison with HACD samples. HACD produced brittle fruit that were difficult to store and transport and were not fully suitable for direct consumption (Zielinska, Markowski, and Zielinska 2019). MWVD can also be suitable for production of non-fried crispy and low-fat fruit and vegetable snacks. MWVD can be used to produce crispy porous potatoes, while HACD harder and more brittle products and FD spongy and soft ones (Setiady et al. 2009). Due to crispy and porous texture, the force required to cause an assumed deformation of MWVD snacks is significantly lower than that dried by HACD and in the same range as that of conventionally fried chips (Bondaruk, Markowski, and Błaszczak 2007; Bai-Ngew, Therdthai, and Dhamvithee 2011). The crispness of MWVD apple chips is higher and the taste more desirable than that of VD ones (MW application increases the content of water soluble pectins and decreases protopectin fraction in apple and results in a more rigid structure of dried chips than that of VD ones) (Huang et al. 2011; Contreras et al. 2005). Also, MWVD significantly changes thermal properties of food products. However, the research on the thermal properties of MW-assisted dried fruits and vegetables remains scarce. As they are significantly influenced by the temperature and moisture content of the material subjected to MWVD, their changes with moisture content and material temperature should be thoroughly discussed in the literature. It is reported, that MWVD cranberries are characterized by significantly lower values of thermal conductivity and specific heat, and higher thermal diffusivity than raw fruits (Zielinska, Ropelewska, and Markowski 2017). As the porosity of MWVD cranberries is 86%, the thermal conductivity of such porous food materials lies above the upper Hashin-Shtrikman bound. However, it still remains within the Wiener bounds and is consistent with the theory of thermal conductivity of heterogenous materials validated for particulate materials (Carson 2015; Wang et al. 2008). The measured values of thermal diffusivity of MWVD cranberries and the values derived from Parallel and Maxwell-Eucken with air dispersed (ME1) models are consistent with the literature data for different fruits (Hobani and Al-Askar 2000; Rahman and Al-Saidi 2009).

Among the drying conditions, the MW power, vacuum, MW mode, drying temperature, drying rate and drying time are reported to have significant influence on the quality of MW-assisted dried food products (Sunjka, Orsat, and Raghavan 2008; Chauhan and Srivastava 2009; Jiang et al. 2013; Calin-Sanchez et al. 2014; Chong et al. 2014; Zielinska and Markowski 2016). The higher is the MW power, the greater are the changes in the physical properties of food materials. For example, higher MW energy absorbed by material per unit time results in higher internal pressure, more porous structure and lower bulk density of MWVD re-structured lychee mixed with purple sweet potato snacks (Qiao, Huang, and Xia 2012). Also, high MW power prevents shrinkage and case hardening of MWVD mint leaves (Therdthai and Zhou 2009) and enlarges the V_R of MWVD garlic (Figiel 2009). In addition to MW power, also the system pressure may significantly affect the properties of dried food products. A higher vacuum favors the vaporization of water and ensures better texture parameters of dried potato cubes (Bondaruk, Markowski, and Błaszczak 2007). On the other hand, the pressure level in the drying chamber does not influence the texture parameters of dried cranberries (Sunjka, Orsat, and Raghavan 2008). The changes in properties of dried food products may also be influenced by the combined effect of MW power, system pressure as well as MW mode. The combined effect of higher MW power and vacuum results in higher linear shrinkage ratios, although the former one is dominant (Chauhan and Srivastava 2009). The samples dehydrated at higher MW power have lower apparent density ratios because they have more porous structures, as evident by their higher linear shrinkage ratios. At higher MW power, the drying rates are higher due to the generation of more heat at greater depths, resulting in escape of water vapor at a faster rate without causing much collapse in the cellular structure of green peas (Chauhan and Srivastava 2009).

MWFD may also be suitable for production of non-fried fruit and vegetable chips (Huang et al. 2011). MWFD produces sea cucumbers with similar texture as FD products (Duan et al. 2008). However, compared to a conventional FD system, which dries layer after layer starting from the outside, the microwave system generates heat within the product itself so that sublimation is taking place within the product volume. MWFD produces mixed potato and apple chips of higher crispness and hardness than those of FD ones (Huang et al. 2011). Additionally, MW application results in an expanded porous structure of mixed chips, which explains the increased crispness of MWFD mixed chips. The familiar honeycomb network can be observed in the MWFD sample. FD samples reveal a clear porous structure, but the honeycomb number is less than that of MWFD. Compared to MWVD and VD, MWFD and FD chips are characterized by the lower bulk densities. MWFD yields potato/banana re-structured chips of three times lower hardness than MWVD and allows to maintain the original shape of chips during drying (Jiang et al. 2011). Restructured wild cabbage chips made by MWFD and MWVD have crisper structure, whereas those made by HACD have dense structure. The fracturability of MWFD is the lowest and followed by MWVD and HACD. Additionally, MWFD restructured wild cabbage chips retain their initial shape, whereas MWVD samples are puffed (Zhang, Zhang, and Mujumdar 2011).

Another interesting alternative is MWMFD, which allows selecting the gas expansion procedure for reducing shrinkage and creating new structure and texture in dehydrated fruit and vegetable chips. During MWMFD, the water suddenly evaporates at each vacuum pulses, locally blowing-up, expanding the gas phase and pushing the solid matrix. This kind of structure results in irregular force deformation curves, which is characteristic for crispy products. By applying successive cycles of heating and vacuum pulses in a microwave field, larger pores, higher porosity and crispness of dried bananas than MWVD and FD fruits can be produced (Monteiro, Carciofi, and Laurindo 2016).

There are also some reports on the benefits of PSBMWVD over other drying methods and its positive effect on the physical properties of the dried products (Wang et al. 2013; Jiang et al. 2013; Mothibe et al. 2014). An online temperature-detection-assisted control system of PSBMWVD allows to obtain high quality of dried carrot cubes, in terms of their physical and mechanical properties (Cao et al. 2017). Among the apples dried by PSBMWVD, SBMWVD, MWVD, fruits dried in pulsed-spouted bed have the most uniform structure (Mothibe et al. 2014). The collisions between the sample slices and the drying chamber wall during PSBMWVD result in a decreased shrinkage ratio compared to MWVD (Wang et al. 2013). The shape of stem lettuce slices dried using PSBMWVD is nearly circular. Shrinkage of PSBMWVD okra is significantly greater than that of MWVD, and both are higher than those dried by FD (Huang and Zhang 2016). In case of FD samples, the ice sublimates into water vapor to escape under vacuum condition, the space of the originally frozen water is remained, so the total shrinkage of FD is lower than that of PSBMWVD and MWVD ones. Additionally, the shrinkage of PSBMWVD okra is significantly greater than that of MWVD samples. It is due to the change of periodical pressure and collisions of dried particles with the wall of the drying chamber. Nevertheless, PSBMWVD may prevent local overheating of samples and improve uniformity of drying. PSBMWVD and MWVD okra samples have higher hardness and fracturability compared to FD ones. The lowest hardness force and strength of FD samples may be because material remains frozen during drying, no heat damage occurs, and the removal of ice crystals leaves a porous honeycomb-type structure (Huang and Zhang 2016). PSBMWVD stem lettuce slices result in slightly lower shrinkage than MWVD samples (Wang et al. 2013). Stem lettuce slices do not puff during both PSBMWVD and MWVD. The cells of PSBMWVD and MWVD stem lettuce slices are tightly linked and the cell boundary disappear compared to those dried by FD with clear edge and smooth surface, indicating greater shrinkage during PSBMWVD and MWVD stem lettuce slices than in FD. Also, the cell surface structure of PSBMWVD stem lettuce slices is more compact than those dried by MWVD. This might be due to periodical pressure changes that cause the samples spatial movement in the drying chamber, which result in collision between the sample slices and the drying chamber wall. Additionally, pressure changes inside and outside the drying sample lead to extrusion between cells, resulting in a compact microstructure (Wang et al. 2013). PSBMWVD as well as MWFD banana cubes show an expansion trend, while FD fruits show a trend of minor shrinkage (Jiang et al. 2013). MW-assisted drying results in expanded texture due to the low chamber pressure, and thus relatively high internal vapor pressure. PSBMWVD samples show a lower expansion ratio than MWFD. The expansion of banana cubes dried with MWFD or PSBMWVD lead to a frothy texture and decrease the fracturability of these samples compared to FD ones, meaning that they are more brittle (Jiang et al. 2013).

Also, the application of MW HP AFD and MW HP FB AFD is suggested for drying of vegetables, such as green peas, that are used as ingredients in ready-to-go instant soups. MW HP FB AFD leads to higher decrease in particle size of green peas than MW HP AFD (Eikevik, Alves-Filho, and Bantle 2012). Due to the higher heat and mass transfer rates, drying in a fluid bed causes higher mechanical stresses than drying in a fixed bed. The peas dried in a fixed bed at $-6\,^{\circ}C$ show the least decrease in particle size, followed by the product dried at $-3\,^{\circ}C$ and $0\,^{\circ}C$.

HACD + MWVD causes considerably lower shrinkage of dried material than HACD. Thus, it is recommended as a potential method for drying such food products as blueberries, apples and beetroots (Figiel 2007; Figiel 2010; Zielinska, Sadowski, and Błaszczak 2016). HACD + MWVD results in volume expansion and puffing, while HACD alone results in structure collapse. Due to the puffing phenomenon that occurred in the structure of material subjected to HACD + MWVD, the breaking force of beetroots is significantly lower than those dried by HACD alone meaning that beetroots are more susceptible to local cracking than HACD samples (Figiel 2010). HACD + MWVD as well as MWVD produce more porous blueberries than HACD (Zielinska, Sadowski, and Błaszczak 2015). Despite this, microcracks and microfissures are clearly seen on the surfaces of MWVD berries. Compared to HACD and MWVD, HACD + MWVD minimizes surface cracking. Nevertheless, deep grooves in mesocarp tissue of MWVD and HACD + MWVD samples, collapsing mesocarp, and seed relocation can be observed during dehydration (Zielinska, Sadowski, and Błaszczak 2016). In comparison with HACD fruit, blueberries dried by MWVD and HACD + MWVD are characterized by lower endurance than blueberries dried by HACD (Zielinska, Sadowski, and Błaszczak 2016). It could be attributed to the porous structure of dried samples, puffing phenomenon, limited changes in the cell structure and limited shrinkage. High MW power may reduce shrinkage of HACD + MWVD apples and beetroots (Figiel 2007; Figiel 2010).

The changes in physical attributes of food products subjected to HACD + MWVD can also be related to the conversion point of combined MW-assisted drying. The shorter convective drying stage results in an increased volume and decreased shrinkage of beetroots dried by combined HACD + MWVD, while longer convective drying stage results in local hardening of the surface layer, which makes puffing difficult (Figiel 2010). Also, HACD + MWVD with hot air pre-drying at the temperature of $60\,^{\circ}C$ until the achievement of moisture content of about 4 kg H_2O/kg DM produces berries with lower shrinkage than HACD + MWVD at the same hot air temperature until the achievement of moisture content of about 2 kg H_2O/kg DM. Contrary, HACD + MWVD with hot air pre-drying at the temperature of $80\,^{\circ}C$ until the achievement of moisture content of about 4 kg H_2O/kg DM produces berries with higher shrinkage than HACD + MWVD at the same hot air temperature until the achievement of moisture content of about 2 kg H_2O/kg DM (Zielinska, Sadowski, and Błaszczak 2016). As shown above, proper combination order, temperature and conversion point of HACD + MWVD should be selected for particulate food products to minimize physicochemical changes and maintain the high quality of dried products, in terms of their texture and physical properties.

Increasing air temperature in the convective phase of HACD + MWVD may significantly decrease volume changes of blueberries (Zielinska, Sadowski, and Błaszczak 2016). HACD + MWVD with hot air pre-drying at the temperature of 80 °C until the achievement of moisture content of about 2 kg H_2O/kg DM produces berries with the largest volume. This combination stabilizes the surface structure of berries by case hardening in the initial convective stage of drying, which promotes puffing in the final stage of MWVD. By contrast, HACD + MWVD with hot air pre-drying at 60 °C until the achievement of moisture content of about 2 kg H_2O/kg DM does not promote puffing or significant changes in sample size in the final stage of MWVD.

Among other combined MW-assisted drying methods, MWVD + FD and FD + MWVD are often used for fruit and vegetables preservation (Cui et al. 2008; Huang et al. 2012). MWVD + FD produces carrots and apples that exhibit similar texture to FD ones, with a slightly higher shrinkage, but without marked warp and still attractive external appearance (Cui et al. 2008). The hardness and crispness of MWVD + FD of apple slices are higher than those dried by FD + MWVD and FD. The hardness of FD + MWVD of apple slices is lower and crispness is higher than those dried by FD (Huang et al. 2012). This corresponds with the content of water soluble pectins (WSP) (the content of WSP in FD apple slices is higher than FD + MWVD samples and lower than MWVD + FD samples). Thus, the higher content of WSP in dried apple slices the more rigid structure is obtained. The texture of apple slices dried by FD + MWVD is crispier and thus more preferred than MWVD + FD (Huang et al. 2012). FD + MWVD samples reveal an unclear porous structure because of the significant shrinkage of the cell walls. Due to the great shrinkage of cell walls, the porous structure of MWVD + FD sample disappears. Fast drying rate during MWVD + FD results in cell collapse. During FD + MWVD, the free water is moved from samples at the end of FD process and a general structure is formed during initial FD. Then the effect of fast drying rate at MWVD stage on structure is smaller than that during MWVD + FD. The greater cell collapse is observed in MWVD + FD samples than FD + MWVD ones. MWVD + FD apple slices show dense structure with cell walls compactly stacked on top of each other resulting in a rigid structure.

Among different combined methods, HP FB AFD + MWVD is recommended as a method with high potential for drying of green peas of desired texture (Zielinska et al. 2013). In HP FB AFD + MWVD, the solid state of water, with restricted movement in comparison to liquid water, protects the original structure and preserves the shape of green peas with significantly lower volume reduction than HACD. The shrinkage of HP FB AFD + MWVD of green peas is higher than MWVD samples and lower than that dried by HACD. Even the shrinkage of samples dried by HP FB AFD + MWD is higher than MWVD ones, the samples still show the flat external appearance without marked warping and surface cracking. MWVD samples are characterized by a structure with minimum deformation in respect to non-dried particles. MWVD creates a large vapor pressure in the center of the dried particles, allowing rapid moisture movement to the vacuum and preventing structural damage. Puffing phenomenon creates a porous structure of green peas, thus reducing the density and shrinkage of final products. Many pores are observed on the cross-section area of MWVD and HP FB AFD + MWVD samples. MWVD samples have much more uniform structure than the samples dried by HP FB AFD + MWVD, where some cavities and disrupting of the continuity of the cellular structure is observed. Due to sublimation of frozen water, HP FB AFD + MWVD leads to porous structure of dried green peas, while HACD samples present concave appearance with wrinkled seed coat and much more shrunken cotyledon (Zielinska et al. 2013).

Also, HP HACD + MWVD is one of the most suitable drying technique to produce crispy and healthy apple snack of nice texture and appearance (Chong et al. 2014). HP HACD + MWVD as well as HACD + MWVD produce apples with significantly higher hardness and chewiness than samples dehydrated without microwaves. The increased hardness results from the rapid mass transfer during MWVD that damages the membrane and cell structure of the fruits and causes puffing (Chong et al. 2014).

The feasibility and application of VIRD + PSBMWVD as a potential mean for dehydration of asparagus cookies is also recommended (Liu et al. 2017). The expansion ratio of VIRD + PSBMWVD is significantly higher than that of PSBMWVD ones. The collisions between samples and drying chamber wall have adverse effect on the expansion ratio. Also, the pulsation of inlet air breaks the vacuum environment, and causes higher deformation of dried particles. The hardness and fracturability of VIRD + PSBMWVD products is higher than that of PSBMWVD ones, which indicates crisper texture of samples dried without IR radiation. It results from crust formation, which occurs due to the absorption of IR energy on the sample surface (Liu et al. 2017).

Color

MW-assisted drying results in lower color degradation than HACD (Therdthai and Zhou 2009; Bondaruk, Markowski, and Błaszczak 2007; Setiady et al. 2009; Cui et al. 2008; Zielinska, Sadowski, and Błaszczak 2016; Zielinska and Michalska 2016; Leusink et al. 2010; Soysal et al. 2009).

MWD systems were developed to obtain nice overall appearance and color of pumpkin and apple slices (Alibas 2007; Cuccurullo et al. 2018). It is reported that color changes during MWD depend e.g. on the MW power or drying rate. The greater color changes of pumpkin slabs during MWD are related to a decrease in MW power (Alibas 2007). Additionally, operating at constant evaporation rate helps to reduce product hotspots and decrease color changes of MWD apple slices caused by non-enzymatic browning (Cuccurullo et al. 2018). MWHACD can be used to obtain high quality of red pepper, in terms of their color and overall appearance (Soysal et al. 2009). IMWHACD samples are characterized by higher brightness, redness and yellowness than the samples subjected to MWHACD. The darker appearance of MWHACD samples than IMWHACD ones results from the non-enzymatic browning reactions that occur during MWHACD (Soysal et al. 2009). Drying at high MW power has often more negative effect on the optical properties of final products than drying at low MW power. The increase in MW power results in decrease in L^*, b^*, *BI*, chroma and hue angle, and increase in a^* and ΔE of bamboo shoot slices (Bal et al. 2011). Also, higher MW power results in greater color changes of okra slices subjected to MWHACD (Kumar, Prasad, and Murthy 2014). Additionally, higher MW power causes a rapid rise in product temperature leading to charring of the osmotically dehydrated MWHACD bananas (Pereira, Marsaioli, and Ahrné 2007). Contrary, the color of OD + MWHACD banana slices does not depend on the MW power (Pereira, Marsaioli, and Ahrné 2007). Based on the above observations, it is necessary to control the MW power during the final drying stage in order to avoid temperature runaway and color deterioration. The MW power control system during MWHACD of food products can be used in order to solve the problem of hot spots on the surface of dried food products, e.g. tomato slices (Kone et al. 2013). Optical properties of MW-assisted dried food products may also depend on the mode of drying. IMWHACD produces high quality dried red pepper with better color than continuous mode (Soysal et al. 2009). Beside MW power and MW mode, hot air temperature and velocity may influence color of MWHACD food products. For example, the significant increase in redness of pumpkin slices is caused by increase in air velocity (Junqueira, Corrêa, and Ernesto 2017). A lower air temperature and a higher air velocity can cause cooling on the product surface. This interaction should be explored to improve product appearance and to decrease the quantity of charred pieces (Pereira, Marsaioli, and Ahrné 2007).

MWVD seems to be good alternative to the convective drying of cranberries, in terms of the color of final products (Zielinska and Zielinska 2019). However, drying process should be conducted at low MW powers, i.e. from 100 to 300 W. MWVD provides products with slight chlorophyll degradation. For example, MWVD mint leaves are light green/yellow, while HACD mint leaves occurs dark green/brown. The limited color changes during MWVD of mint leaves are related to the lower material temperature, shorter drying time and limited oxidation than during HACD (Therdthai and Zhou 2009). Due to the shorter drying time, MWVD better prevents color damage of potato cubes than HACD and leads to lighter potato slices than HACD (Bondaruk, Markowski, and Błaszczak 2007; Setiady et al. 2009). Flavonoids are easily released from MWVD fingerroots to the surrounding water due to a porous structure of samples, whereas HACD causes hardening of samples, which impedes the release of flavonoids into the water (the water after rehydration of MWVD samples is more yellow than in case of HACD ones) (Therdthai and Northongkom 2011). Higher MW power results in greater color changes of cranberries, carrots and beetroots subjected to MWVD (Sunjka, Orsat, and Raghavan 2008; Musielak and Kieca 2014). Higher MW power pronounces the carrot slices scorching and the appearance of dark spots in the final stage of MWVD (Nahimana and Zhang 2011). The color of MWVD potato cubes is better preserved when the pressure in drying chamber is higher. A vacuum level of 24 kPa ensures slighter color changes than vacuum level of 6, 12, and 18 kPa (Bondaruk, Markowski, and Błaszczak 2007).

Due to high temperature of material in the final stages of drying and a low amount of water, the surface scorching may be the reason for the color losses during MWVD of food products (Nahimana and Zhang 2011). Unfavorable effect of MWVD on color of dried products resulting from decreasing moisture content and increasing sample temperature can also be observed for okra and plums (Dadali, Apar, and Özbek 2007; Chayjan and Alaei 2016). The nonuniformity of MW absorption may induce the overheating of MWVD material, mainly in the last stage of drying. Thus, PSBMWVD can be used instead of MWVD to cause lower discoloration of stem lettuce slices during drying (Wang et al. 2013). PSBMWVD also results in better color of apple cubes than SBMWVD, MWVD and VD (Mothibe et al. 2014).

The overheating and some local charring can be eliminated or limited by using MWFD instead of MWVD (Yan et al. 2010). MWFD can produce dried food products of such high quality, in terms of their color, as FD. For example, MWFD and FD produce sea cucumbers of comparable color (Duan et al. 2010a). Also, there are no significant differences between color of MWFD and FD potato and apple chips, except for the blueness of MWFD products which is more desired than that of the FD chips. The blueness of MWVD and VD chips is higher than that of the MWFD and FD. Due to MW application and shorter drying times, the blueness of the MWFD and MWVD chips is higher than FD and VD ones (Huang et al. 2011). MWFD and MWVD of potato/apple chips result in higher b^* values than FD and VD ones, while MWVD and VD chips are characterized by higher L^* and b^* values than MWFD and FD ones. It means that the application of microwaves shortens the drying time, and thus causes lower color losses. However, freezing does not prevent color losses during dehydration of food products (Huang et al. 2011). There is no significant difference in lightness of MWVD and VD chips. However, VD chips turn red due to the browning reaction during the long drying process. As in case of MWVD, the overheating may occur during MWFD of some food products and cause the appearance of heat spots, and hence local charring, darkening of material and higher color degradation of dried chips than FD (Huang et al. 2011). Fortunately, there are no reports on burning in commercial FD and MWFD (Abbasi and Azari 2009). However, burning and Millard reactions may occur during MWD and MWVD. To reduce the color changes of banana chips during drying, PSBMWVD can be used instead of MWFD (Jiang et al. 2013). Due to enhanced MW absorption, higher MW power in MWFD results in local over-heating and caramelization or burning of banana chips (Jiang et al. 2013). The color degradation increases with an increase in MW power density in the final stage of MWFD.

Also, MW HP AFD may have favorable effect on the color preservation of green peas. Green peas dried by MW HP AFD (fixed bed) at −6 °C and −3 °C show only a minor color reduction. The higher color changes of green peas dried at 0 °C are related to the higher air temperature and the partial thawing of food products (Eikevik, Alves-Filho, and Bantle 2012). Additionally, the green peas dried in a fluid bed show higher color reduction than in a fixed bed, which might be related to the mechanical stress (Eikevik, Alves-Filho, and Bantle 2012). It means that fluidization does not prevent color losses during MW HP FB AFD of food products (Eikevik, Alves-Filho, and Bantle 2012).

Combined HACD + MWVD may significantly reduce the color changes during dehydration of food products compared to HACD. Blueberries dried by HACD + MWVD are less red than HACD fruits (Zielinska, Sadowski, and Błaszczak 2016). It means that shorter time of exposure to oxygen and high temperature allows to limit transformation of anthocyanin pigments into brown compounds that probably occurs in the final stage of HACD (Zielinska, Sadowski, and Błaszczak 2016).

Combined MWVD + FD allows to obtained only slightly darker carrot slices than FD samples, while MWVD ones are significantly darker (Cui et al. 2008).

Additionally, HP HACD + MWVD results in lighter apple cubes than those dried by HACD + MWVD. Greater color changes of apple cubes during HACD + MWVD than HP HACD + MWVD are due to higher material temperature which favors enzymatic browning, caramelization effect or protein denaturation (Chong et al. 2014). Due to the higher content of chlorophyll, HP FB AFD + MWVD as well as HP FB HACD + MWVD green peas exhibit smaller changes in color, saturation, and hue than MWVD and HACD ones (Zielinska et al. 2013). Low material temperature during HP FB AFD as well as reduced pressure and thus lower material temperature during final MWVD allow to obtain smaller changes in color, saturation and hue of green peas than HACD and MWVD (Zielinska et al. 2013). Due to the long exposure time to higher temperatures and thus formation of undesirable gray-brown compounds such as pheophorbide or pheophytin, MWVD and HACD result in darker samples than HP FB AFD + MWVD as well as HP FB HACD + MWVD.

FD + MWVD, HACD + MWVD, MWVD and FD cause lower ΔE changes and result in the lighter okras than HACD (Jiang et al. 2017). The lowest color changes during FD and FD + MWVD of okras result from the reduced level of oxygen, low drying temperature and thus limited enzymatic browning reaction. Slightly higher values of ΔE of MWVD samples result from overheating and the appearance of heat spots. Due to shorter drying time, HACD + MWVD decreases ΔE and increases L^* values of okra compared to HACD. Compared to MWVD, the combined FD + MWVD drying leads to shortening of the drying time and reduction of uneven drying (Jiang et al. 2017).

The use of VIRD + PBSMWVD reduces the color changes of asparagus cookies in comparison to VIRD (Liu et al. 2017). Combined VIRD + PBSMWVD limits the surface scorching phenomenon. However, VIRD + PBSMWVD results in higher changes than PSBMWVD.

Nutritional value

Heat treatment can be effective in increasing the TP content of different food products (Izli 2017). The increase in TP content in dried samples may occur because the drying treatments accelerate bound phenolic compounds as part of the breakdown of cellular constituents (Chang et al. 2006). In this study, the increase could be explained by the degradation of complex phenolic tannins by heat, which cause more phenolics to be extracted. In addition, the increase in TP content could be explained by the formation of Maillard reaction products, which would cause new phenolic compounds to form from precursors during thermal treatments (Que et al. 2008; Sultana et al. 2012). The increase in TP content of dried samples can be observed during MWD of date fruits (Izli 2017). Among HACD, FD and MWD, the highest TP content is noted for date fruits dried by MWD at 120 W (Izli 2017). The highest TP in MWD dates might be because of the high temperatures reached in the dried fruits during MWD, which could cause greater cell disruption and lead to rupturing that releases the content of TP compounds.

MWVD may result in lower degradation of nutritional value than HACD (Zielinska and Zielinska 2019). MWVD produces potatoes of slightly higher starch and total sugars contents than HACD (Bondaruk, Markowski, and Błaszczak 2007). However, both MWVD and HACD result in disintegration of cell walls and starch granules. Also, the AA and TMA content of MWVD cranberries are significantly higher than HACD ones. Due to the higher AA and TMA content, MWVD cranberries are more desired by consumers than HACD ones (Leusink et al. 2010). Higher nutritional value of MWVD products than HACD ones is related to the lower material temperature during drying, shorter drying time and limitation of the oxidation reaction (Bondaruk, Markowski, and Błaszczak 2007; Leusink et al. 2010; Cui et al. 2008; Jiang et al. 2017).

Occasionally, unfavorable effect of high temperature during MWVD on nutritional value of food products is reported (Nahimana and Zhang 2011). MWVD of carrot slices results in thermal and oxidative degradation of carotenoids. The thermal destruction of bioactive compounds during MWVD may result from temperature increase in the final stage of MWVD, nonuniformity of microwave absorption and therefore the appearance of overheating of material and some charring in the last stage of drying (Yan et al. 2010). The content of nutritional components of MWVD food products may be lower e.g. than FD ones. Among MWVD, PSBMWVD and FD, MWVD and PSBMWVD of okra result in significantly lower amount of TCl, vit. C and TF than FD. It can be caused by uncontrolled increase in material temperature in the final stage of MWVD which causes local overheating and scorching (Huang and Zhang 2016). The content of nutritional components of MWVD food products may even be lower than HACD ones (Duan et al. 2010b). For example, the contents of AA, TP and TEAC of HACD sea cucumbers are higher than those obtained for MWVD products (Duan et al. 2010a). MWVD at low MW powers, i.e. from 100 to 300 W, seems to be good alternative to HACD of berries, in terms of bioactive compounds, i.e. TP, TF, TMA and FRAP values (Zielinska and Zielinska 2019).

Another interesting alternative is MWFD which allow to prevent significant changes in nutritional value of e.g. sea cucumbers (Duan et al. 2010a). Among carrot slices dried by MWFD, MWVD and MWSBD, the MWFD products are characterized by the highest β – carotene and vit. C contents (Yan et al. 2010).

Also, combined HP HACD + MWVD can be used to speed up the convective drying process and obtain dried food products of high nutritional value. It is reported that HP HACD + MWVD apple cubes are characterized by higher nutritional value, i.e. TP and DPPH, than HACD + MWVD samples (Chong et al. 2014).

Combined FD + MWVD as well as MWVD + FD can also be good alternatives to obtain dried food products of high nutritional value comparable with FD ones and significantly higher than HACD ones. It should b pointed out that FD + MWVD results in higher nutritional value of dried apple slices than MWVD + FD (Huang et al. 2012). The β – carotene losses during MWVD + FD and MWVD of food products are much lower than during HACD. The oxidative degradation of the carotene during MWVD + FD and MWVD of carrots is greatly reduced due to higher dehydration rate, shorter drying time and lower oxygen availability than during HACD (Cui et al. 2008). FD + MWVD and FD okra samples have significantly higher TF and TP contents than MWVD ones. As the heat generation during MWVD is more intense than in FD + MWVD, it induces higher thermal degradation of TP and TF (Jiang et al. 2017).

Due to the Maillard reactions, the contents of TRS decrease during FD + MWVD and FD of button mushroom slices. Higher content of AAc in FD + MWVD than in FD products result from the shorter drying time of FD + MWVD than FD. The AAc content increases during the sublimation period in FD, probably due to the proteolysis, and decreases during the desorption period of FD and MWVD in FD + MWVD, probably because of the Strecker degradation of AAc and the Maillard reaction between AAc and TRS. Lower contents of TSS and TPo in FD + MWVD button mushroom slices than in FD ones result from the decomposition under the influence of instantaneous high temperature produced by microwaves. The content of Mt, which constitutes major soluble sugar/polyol, increases during the sublimation period of FD and FD in FD + MWVD. It is caused by an increase in the sample temperature that activated the enzymes responsible for the metabolism of macromolecule sugars. Desorption period of FD and MWVD in FD + MWVD results in a decrease in Mt content due to the thermal decomposition caused by higher material temperature. The increase in TOAc content during the sublimation period of FD is attributed to enzymes activation and ions of TOAc formation, while the decrease in TOAc content in desorption period of MWVD in FD + MWVD is caused by decarboxylation (Pei et al. 2014).

The degradation of TP, TMA contents and TEAC ABTS of whole blueberries is lower during MWVD and HACD + MWVD than HACD. MWVD and HACD + MWVD reduce the time when the material is in contact with oxygen and therefore, cause lower changes in bioactive compound of blueberries than HACD. HACD + MWVD blueberries have higher TMA content and the TEAC ABTS values than HACD and MWVD. Relatively high hot air temperature in the first stage of combined HACD + MWVD results in surface hardening, and thus limited juice leakage and simultaneous loss of bioactive compounds. Lower air temperature and prolonged exposure to oxygen in the first convective stage of drying result in much greater degradation of TMA and TEAC ABTS (Zielinska and Michalska 2016). It should be noted that a reverse effect is observed for blueberry pomace, what points to the influence of the material structure on the content of TP in the dried products. HACD + MWVD of blueberry pomace brings desired outcomes for TP content only when relatively low hot air drying temperature is applied during initial convective drying stage (Zielinska and Michalska 2018).

The changes in nutritional value of dried food products during MW-assisted drying are associated with changes in MW power. Among different MW power (150, 200, 250, 300, and 350 W), MWVD with constant MW power of 200 W and pressure inside the dryer at 10–12 kPa results in carrot slices with the best nutritional value (Musielak and Kieca 2014). In case of carrot slices, only the lowest MW power gives an undamaged product of high nutritional value. Changing of MW power during MWVD may result in higher nutritional value of dried food products. The MW power may change in time intervals. However, the use of interval conditions either has a small influence on the process time and does not provide satisfactory quality of the dried samples. In case of MWVD at periodic MW powers, products dried by MW power of 300 W with 5 minutes intervals and MW power of 150 W with 20 minutes intervals are characterized by the highest nutritional value (Musielak and Kieca 2014). The initial drying can also be performed with higher MW power and then the process can be continued with the lower one. This method may short the drying time and give high quality of dried material. MWVD of carrot slices at two-stage MW power (300 W and 150 W) results in the highest content of β – carotene in dried products (Musielak and Kieca 2014).

Also, different changes in nutritional value of dried food products can be observed under different pressure level during MW-assisted drying. The content of TSt and TS of potato cubes is higher at higher pressure during MWVD. A vacuum level of 24 kPa ensures high level of TSt and TS preservation (Bondaruk, Markowski, and Błaszczak 2007).

Additionally, temperature during drying may affect the nutritional value of dried products. Among different drying methods, HP HACD + MWVD results in the highest content of TP in dried apple cubes (Chong et al. 2014). It can be explained by the fact that the air temperature during initial hot air drying stage of HP HACD + MWVD is significantly lower than e.g. HACD + MWVD. Such a low drying temperature (approx. 35 °C) allows native TOPCs of apple help inhibit polyphenol oxidase activity. Higher temperature (approx. 70 °C) during other MW-assisted drying processes, causes depolymerization of TOPCs and results in decomposition and depolymerization of TP compounds and thus lower antioxidant activity of dried apple cubes (Chong et al. 2014). Among different combined MW-assisted drying methods, HACD at 90 °C + MWVD produces blueberries of high nutritional value, i.e. strong AA and high TMA content (Zielinska and Michalska 2016). However, lower drying temperature during initial HACD stage proves to be desirable for preservation of bioactive compounds of blueberry pomace (Zielinska and Michalska 2018).

Rehydration potential

The application of adequately designed MWVD can be an adequate method to improve rehydration characteristics of dried products and obtain products with significantly higher rehydration potential than that of HACD ones (Giri and Prasad 2007; Nahimana and Zhang 2011; Bórquez, Melo, and Saavedra 2015; Therdthai and Zhou 2009; Gaware, Sutar, and Thorat 2010; Setiady et al. 2009). Compared to MW-assisted drying without temperature control, MW system that realizes drying process keeping drying rate constant results in significant improvement of rehydration potential of dried products (Cuccurullo et al. 2018). The supremacy of the MWVD over HACD as a method that enables production of dried products characterized by the porous microstructure is confirmed by high values of WAC, DHC and RA of MWVD potatoes (Markowski, Bondaruk, and Błaszczak 2009). An improvement in RR of MWVD mushrooms and fingerroots over HACD is also observed (Giri and Prasad 2007; Therdthai and Northongkom 2011). Generally, the higher rehydration potential of MWVD products is attributed to the lower material temperature and higher internal pressure during MWVD than HACD. Low drying temperature helps to reduce structure changes and limit case hardening of carrots (Nahimana and Zhang 2011). Additionally, high internal pressure that occurs in MWVD products generates expanded and puffed structure that helps to obtain higher values of COR of MWVD than HACD products (Nahimana and Zhang 2011). Also, high values of RC of MWVD strawberries with the ability of automatic temperature control indicates their low microstructure damage. As a result of vapor expansion within the product, MWVD with the ability of automatic temperature control yields an open structure and low shrinkage of strawberries that improve the accessibility and effective water diffusivity during rehydration and result in high RC values (Bórquez, Melo, and Saavedra 2015).

MWVD tomato slices have lower RR than those dried by FD (Gaware, Sutar, and Thorat 2010). MWVD and HACD potatoes have similar WHC values and almost two times lower values of RR than that of FD ones (Setiady et al. 2009). Also, MWVD blueberries are characterized by the lowest moisture content, rehydration ratio, water gain and solids loss compared to HACD and HACD + MWVD samples (Zielinska, Sadowski, and Błaszczak 2016). HACD, MWVD as well as HACD + MWVD blueberries suffer structure collapse and significant shrinkage during drying and do not achieve complete rehydration. Most probably, the juice and seeds that exuded from berries during MWVD form a thick and sticky layer on the outer surface of rehydrated fruits. The layer is impermeable to water, and it prevents solids from leaving the interior of the fruit. Water-soluble substances are retained inside the berries during MWVD rehydration, and solids are eluted only from the outer surface. Significant loss of dry substance components of blueberries during rehydration is also related to the loss of blueberries firmness (Zielinska, Sadowski, and Błaszczak 2016). As rapid evaporation of water from MWVD berries leads to exudation of juice from the interior and the formation of a barrier for water gain during rehydration, appropriate combination of HACD + MWVD may decrease the initial rate of water evaporation and result in lower cellular and structural disruption of HACD + MWVD samples and higher RC values of rehydrated whole blueberries in comparison with MWVD and HACD (Zielinska, Sadowski, and Błaszczak 2016; Zielinska and Markowski 2016). Also apples dried by HACD + MWVD are characterized by a remarkably higher WAC index than apples dried by HACD (Figiel 2007). As above, HACD + MWVD can be beneficial e.g. for dried fruits added to breakfast cereals consumed with milk within minutes of mixing (Zielinska and Markowski 2016).

The application of microwaves greatly improves the rate of FD. Thus, MWFD of sea cucumbers is not only shorten than the FD processing time, but also produce products with similar microstructural characteristics to the FD sea cucumbers and high RR values. The structure of MWFD sea cucumbers facilitates rapid and almost complete rehydration when water is added to the dried material (Duan et al. 2010a). Also, the values of RR of MWFD potato/banana chips immediately reach their highest values and are significantly higher than that of MWVD ones (Jiang et al. 2011). MWFD removes water through sublimation, keeping the original shape of the dried potato/banana chips very well and creating a porous structure, which increase RR (Jiang et al. 2011). Also, onion slices dried by MWFD possess higher RR than those dried by MWVD (Abbasi and Azari 2009). Rapid microwave energy absorption causes rapid evaporation of water, creating a flux of rapidly escaping vapor that helps in preventing shrinkage and case hardening, thereby improving rehydration characteristics. Additionally, the values of RR of MWVD and MWFD restructured potato and apple chips are significantly higher than that dried by VD and FD (Huang et al. 2011).

Combined MWVD + FD can be an alternative method to obtain apple and carrot slices of high rehydration properties comparable with FD ones and significantly higher than HACD ones. It can be explained by the fact that the surface micro holes and capillaries of MWVD + FD and FD samples look similar. Due to the puffed texture, MWVD samples exhibit higher RC than MWVD + FD and FD samples (Cui et al. 2008).

Not only MWVD and MWFD, but also MWSBD meets major requirements of consumers in terms of rehydration properties of dried material (Yan et al. 2010). The highest initial RR occurs during MWFD of carrots compared to MWVD and MWSBD ones. However, there are no significant differences between RR of MWFD, MWVD and MWSBD carrots after a long rehydration time. Also, PSBMWVD bananas and steam lettuce slices show the impressive rehydration ability (Jiang et al. 2013; Wang et al. 2013). In the first minute of rehydration both MWFD and PSBMWVD samples show even better rehydration ability than FD ones. After long rehydration time, FD samples show higher RA values because of the more porous structure compared with MWFD or PSBMWVD samples. The structural collapse during MWFD or PSBMWVD leads to higher compactness of the solid structure and hence higher thickness of the solids that surrounds the pores, which prevents high water accessibility through the solids and causes lower RC values. PSBMWVD and MWVD apples show similar RA, much higher than VD and lower than SBMWVD. Even though, all samples cannot reach the original moisture content of fresh fruits (Mothibe et al. 2014).

PSBMWVD and MWVD products do not recover their structural properties after rehydration. This may be due to the fact that irreversible physicochemical changes occur during drying and the solutes leaking from damaged cells migrate to the surface, form a crust and result in a relatively dense surface structure (Wang et al. 2013). The MW energy results in greater changes in the structure and composition of stem lettuce tissue during drying compared to VD. During MW drying, especially in the initial drying stage, apart from the heat required for drying, a significant increase in the electrical conductivity of stem lettuce slices is observed, indicating that there are more mobile ions formed in the samples being dried due to interactions of the ions with the electromagnetic field. The larger interactions of ions with polymers during MWVD and PSBMVD processes stiffen the structure and restrict polymer hydration and swelling during rehydration compared to VD processes. The RC of the samples dried using PSBMVD is higher than that of the samples dried using MWVD. The small injuries occur in the structure and composition of stem lettuce tissue due to lower sample temperature and better drying uniformity during PSBMVD compared to MWVD (Wang et al. 2013).

PSBMWVD and MWVD okra show lower rehydration potential than FD samples (Huang and Zhang 2016). The shorter drying time and more uniform heating cause less intense physical and chemical changes that occur in the dried material and result in higher RR of PSBMWVD samples than MWVD ones. MWVD samples may suffer some irreversible physicochemical changes, such as solutes leakage from damaged cells, their migration to the surface and formation of a crust. Such changes may result in a relatively compact surface structure and thus, lower values of RR of MWVD samples than PSBMWVD ones.

There are only a few research studies on the kinetics of moisture uptake and soluble solids loss (Therdthai and Zhou 2009; Giri and Prasad 2007; Gaware, Sutar, and Thorat 2010; Nahimana and Zhang 2011; Setiady et al. 2009; Markowski, Bondaruk, and Błaszczak 2009; Zielinska and Markowski 2016). Optimally designed MWVD can produce dried foods with higher values of RC than HACD (Figiel 2010). Due to less dense structure, MWVD of mint leaves and mushroom slices yields significantly higher rehydration rates than HACD (Therdthai and Zhou 2009; Giri and Prasad 2007). However, MWVD and HACD of tomato result in lower rate of rehydration than FD (Gaware, Sutar, and Thorat 2010). The rate of water gain and solids loss during rehydration are the highest during the initial phase of rehydration. The voids of MWVD samples are rapidly filled with water and therefore MWVD resulted in greater initial rehydration rate than HACD samples. Higher rehydration ratio of MWVD samples in early stage results from the lower shrinkage due to lower material temperature during drying and shorter drying time or reduced changes to the cell structure and limited case hardening that promotes rehydration. After immediate voids refilling, rehydration of MWVD samples continues at reduced rate (Giri and Prasad 2007). In the middle time, the inverse situation occurs, with the predominance of HACD samples. After a long period of rehydration, MWVD and HACD samples converge to the same values of RR (Nahimana and Zhang 2011). In comparison with HACD and MWVD, HACD + MWVD of blueberries leads to significantly higher rates of initial and successive rehydration. MWVD blueberries reveal the presence of a thick and sticky layer on the surface of dried fruits that could be the main factor limiting water gain during rehydration. Also, the lowest initial rate of solids loss is observed during rehydration of MWVD samples. Most probably, juice exuding from fruits during MWVD form a thick layer on the surface of blueberries, which prevents solids from leaving the interior of fruits during rehydration. Water soluble solids are retained inside the samples during rehydration, whereas solids attached to the sample surface are eluted from the outer layer during rehydration (Zielinska and Markowski 2016).

Besides of the imbibition of water into the dried material and the loss of soluble solids, changes in color, structure and nutritional value of the plant tissue take place during rehydration. The knowledge on the structural changes of dried products during rehydration should help to optimize MW-assisted drying and rehydration conditions and obtain high quality rehydrated products in terms of their overall appearance (size, shape, volume), texture (hardness, springiness, cohesiveness, gumminess, chewiness, resilience) or structure (porosity, density). There is, however, limited number of research reports on the nutritional value, structural, optical, textural and mechanical properties of rehydrated MW-assisted dried products (Setiady et al. 2009; Markowski, Bondaruk, and Błaszczak 2009; Zielinska et al. 2013; Zielinska, Sadowski, and Błaszczak 2016). MWVD potatoes do not lose their textural integrity after rehydration. Their structure can retain more water and exhibit a higher volume increase following rehydration. The uneven surface appearance of MWVD rehydrated potatoes result from the puffed structure created by vacuum drying. MWVD potatoes are significantly softer, less springy, gummy, chewy, and resilient after rehydration than HACD samples. Contrary, FD samples are significantly softer, less gummy, chewy, cohesive, resilient and fragile after rehydration then MWVD ones and consequently easily torn apart and loss textural integrity (Setiady et al. 2009). MWVD potatoes recover up to 94% of the volume of a raw sample, while that of dried HACD up to 51% of their original volume (Markowski, Bondaruk, and Błaszczak 2009). However, MWVD and HACD + MWVD cause extensive damage to the structure of blueberries and do not allow their complete rehydration. Rehydrated fruits are softer, less chewy and gummy than raw ones and H, Ch and G of dried berries are approximately one order of magnitude lower than that of raw samples. Also, high values of ΔE indicate significant changes in blueberry color caused by drying and rehydration (Zielinska, Sadowski, and Błaszczak 2016). Also, rehydrated green peas dried by MWVD and HP FB AFD + MWVD are much softer than green peas in their fresh form and do not recover their original mechanical strength after rehydration (Zielinska et al. 2013).

MW power may affect the rehydration potential of food products. The increase in MW power during MW-assisted drying of apple slices increases the values of WAC, DHC and RA (Figiel 2007). An increase in MW power also induces increase in AC values of garlic (Figiel 2009). Additionally, higher MW power results in higher RR values of MW-assisted dried cranberries (Sunjka, Orsat, and Raghavan 2008), potato/banana re-structured chips (Jiang et al. 2011) and okra (Kumar, Prasad, and Murthy 2014). The improved rehydration characteristics can be attributed to the development of high internal pressure and greater internal stresses during drying at higher MW power. The immediate absorption of MW energy generates large internal heat and causes rapid evaporation of water, creating a flux of rapidly escaping vapor that can cause opening of pores in the structure and prevent the shrinkage and case hardening phenomena (Sharma and Prasad 2001; Giri and Prasad 2007). However, excessively high MW power may decrease the values of RR. The high MW power leads e.g. to hardening of MWFD sea cucumbers, melting of ice, and significant shrinkage of dried products (Duan et al. 2010a). Also, higher MW power results in lower RC values of dried tomatoes (Horuz, Jaafar, and Maskan 2017).

The pressure level has even higher effect on the rehydration characteristics of dried mushroom slices than MW power and sample thickness (Giri and Prasad 2007). The increase/decrease in system pressure may have both positive/negative effect on the rehydration potential of MW-assisted dried food products. For example, the lower is the system pressure applied in MWVD, the higher are the values of RR of mushroom slices (Giri and Prasad 2007). It can be due to the fact that as the pressure level decreases, the values of RR increase, owing to the increased drying rate and creation of pores that are induced by vacuum conditions (Kiranoudis, Tsami, and Maroulis 1997). However, the ability of dried potato cubes to absorb water is higher at higher pressure during MWVD. A vacuum level of 24 kPa ensures the best overall quality of dried potato cubes, i.e. slighter color changes of the product accompanied by its higher ability to absorb water, good texture (Bondaruk, Markowski, and Błaszczak 2007). No significant differences are observed between WAC, DHC and RA as well as V_R of potatoes dried at different pressures under MWVD conditions (Markowski, Bondaruk, and Błaszczak 2009).

The values of RR of dried products can be significantly affected by MW power, system pressure and MW mode. Drying with higher overall MW input and longer MW power off time combined with low system pressure offers the best conditions e.g. for rehydration of dried cranberries. Longer MW power off time provides enough time for cranberry to redistribute moisture, while higher vacuum creates effective environment for the preservation of berry tissue (Sunjka, Orsat, and Raghavan 2008). However, there are no significant changes in rehydration potential of carrot cubes dried under different MW mode and MW power (Changrue and Orsat 2009).

RR of MWHACD okra increases with increase in hot air temperature and air velocities (Kumar, Prasad, and Murthy 2014). Contrary, air temperature and air velocity do not influence R_C values of IMWHACD pumpkin slices (Junqueira, Corrêa, and Ernesto 2017). Also, the water temperature influences RR of MWVD tomato slices. The reduced RR at 100 °C compared to that at 25 °C is observed due to solids loss in boiling water (Gaware, Sutar, and Thorat 2010).

The application of higher temperature in the first stage of HACD + MWVD results in higher values of R_C and RR of blueberries (Zielinska and Markowski 2016). The higher water absorption of samples dried by HACD + MWVD with a hot air pre-drying step at the temperature of 80 °C until the achievement of a moisture content of about 2 kg H_2O/kg DM than MWVD or HACD ones can be explained by the fact that it produces fruits with the lowest shrinkage, the highest porosity, and produces rehydrated blueberries with the largest volume (Zielinska, Sadowski, and Błaszczak 2016).

The significant findings regarding the effect of hybrid and combined MW-assisted drying methods on the quality parameters of food products are summarized in Table 3. The detailed findings on the effect of MW power, vacuum, MW mode, drying temperature and drying time on the properties of MW-assisted dried food products are presented in Table 4.

Table 3. Effect of hybrid and combined MW-assisted drying methods on the quality properties of dried food products.

References	Processes	Product	Properties		Significant Findings
Abbasi and Azari (2009)	MWD MWVD MWFD	Onion Slices	Physical	Microstructure	There were no significant differences in microstructure of fresh and MWFD and FD onion slices.
			Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*)	FD and MWFD resulted in lower a^* values of onion slices than MWVD and MWD. The b^* values representing yellowness increased as a result of the lack of Millard reaction conditions in the commercial FD and MWFD.
			Rehydration Potential	Rehydration Ratio (RR)	Onion slices dried by commercial FD and MWFD possessed higher RR than those dried by MWD and MWVD.
Bai-Ngew, Therdthai, and Dhamvithee (2011)	Freezing Chiling MWVD	Durian Chips	Physical	Microstructure	MWVD dried samples were characterized by the microstructure comparable to the commercial fried durian chips.
			Mechanical	Hardness (H)	The hardness of MWVD durian chips was in the same range as that of conventionally fried ones.
Bondaruk, Markowski, and Błaszczak (2007)	Blanching MWVD	Potato Cubes	Physical	Microstructure	MWVD resulted in puffed potato characterized by porous microstructure with a net of open cavities.
			Mechanical	Maximum Force (F_{Max}) and Maximum Energy (E_{Max}) Required to Compress Sample	F_{Max} and E_{Max} were the lowest for MWVD material.
			Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Yellowness Index (YI)	Drying caused an increase in L^* and a^* in comparison with the reference sample. The decrease in b^* and YI values was observed for potato cubes dried by MWVD and HACD.
			Nutritional Value	Total Starch (TSt), Total Sugars (TS), Total Reducing Sugars (TRS)	MWVD potatoes had lower losses of nutritional value than HACD ones.
Bórquez, Melo, and Saavedra (2015)	MWVD	Whole strawberries	Rehydration Potential	Rehydration Coefficient (RC)	The values of RC indicates that MWVD did not cause great damage to the microstructure of strawberries.
Cao et al. (2017)	PSBMWVD	Carrot Cubes	Physical	Shrinkage Ratio (SR), Hardness (H)	An online temperature-detection-assisted control system of PSBMWVD was applied. A linear temperature-controlled strategy and a three-step temperature-controlled strategy improved product quality in terms of its texture and heating non-uniformity compared to constant temperature control, but need greater energy consumption and longer drying time.
Chayjan and Alaei (2016)	MWD	Plum Slices	Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE), Chroma (C), Hue Angle ($h°$), Browning Index (BI)	MWD caused a decrease in L^* and hue angle, and an increase in a^*, b^*, ΔE, chroma and BI of plum slices.
Chong et al. (2014)	HACD + MWVD HP HACD + MWVD	Apple Cubes	Mechanical	Hardness (H), Springiness (S), Cohesiveness (Co), Chewiness (Ch)	Hardness of apple cubes finish-dried by MWVD was higher than that dried by other methods. This method was

(*continued*)

Table 3. Continued.

References	Processes	Product	Properties		Significant Findings
					preferred to produce dried apples with harder and crispy texture such as some snack food. HP HACD apples were characterized by the lowest H values. HP HACD was found to be the most suitable drying method for producing soft dried fruits. Higher values of Ch were obtained for apples finally dried by MWVD with HACD or HP HACD as a pre-drying step.
			Optical	Lightness (L^*), Redness/ Greenness (a^*), Yellowness/ Blueness (b^*)	HP HACD + MWVD apple cubes were the brightest and HACD + MWVD apples were the darkest. Low temperature drying provided brighter, less red and yellow dried apples. HACD + MWVD produced dried apples with golden yellow and golden light brown colors (high a^* and b^* values).
			Nutritional Value	Total Polyphenols (TP), Radical Scavenging Activity using DPPH assay (DPPH), Antioxidant Activity (AA)	HP HACD + MWVD apples had the highest TP content and AA. TP content of HACD + MWVD apples was the lowest. TP content was correlated with DPPH. Samples with lower amount of TP had lower AA. DPPH of HP HACD + MWVD apples was the highest and that of HACD + MWVD ones was the lowest.
Cuccurullo et al. (2018)	MWD	Apple Slices	Physical	Texture	Compared to MW-assisted drying without temperature control, a MW system that realizes drying process keeping drying rate constant improves the texture of dried apples.
			Optical	Whiteness Index (*WI*)	The constant drying rate did not affect *WI* index of MWD apple slices, with respect to reference sample dried at controlled temperature. However, the changes caused by non enzymatic browning, showed a significant decrease by operating at constant drying rate.
			Nutritional Value	Total Polyphenols (TP)	Enzymatic browning was a consequence of phenolic compounds' oxidation by polyphenol oxidase (PPO), which triggered the generation of dark pigments.
			Rehydration Potential	Rehydration Ratio (RR)	Compared to MW-assisted drying without temperature control, a MW system that realizes drying process keeping drying rate constant improves RR of dried apples.
Cui et al. (2008)	MWVD MWVD + FD	Carrot Slices, Apple Slices	Physical	Volumetric Shrinkage (S_V)	S_V of samples dried by MWVD + FD was higher than that of FD samples and lower than HACD samples.
			Mechanical	Maximum Force Measured in Puncture Test (F_{Max})	MWVD + FD carrot and apple slices were softer than HACD samples.
			Optical	Lightness (L^*), Redness/ Greenness (a^*),	FD carrot slices had the highest lightness, redness, and

(*continued*)

Table 3. Continued.

References	Processes	Product	Properties		Significant Findings
				Yellowness/ Blueness (b^*)	yellowness. MWVD + FD slices had slightly lower values of color parameter. The value of L^*, a* and b^* of carrots were not only attributed to the presence of carotenes but also affected by the density of samples.
			Nutritional Value	Total Carotene (TC), Vitamine C (vit. C)	The TC and vitamin C losses were comparable for FD, MWVD + FD and MWVD but TC and total vitamin C contents, as well as CR and vitamin C retention were the highest for FD samples.
			Rehydration Potential	Rehydration Capacity (RC)	The values of RC of MWVD + FD are comparable with FD or MWVD ones and significantly higher than HACD ones.
Dadali, Apar, and Özbek (2007)	MWD	Okra	Optical	Lightness (L^*), Redness/ Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE), Chroma (C), Hue Angle ($h°$), Browning Index (BI)	MWD resulted in a decrease in L^* and b^* values, and an increase in a* and ΔE of okra.
Duan et al. (2010a)	MWFD	Sea Cucumber	Mechanical	Hardness (H)	There was no obvious difference between the FD and MWFD sea cucumbers in terms of their microstructure.
			Optical	Lightness (L^*), Redness/ Greenness (a^*), Yellowness/ Blueness (b^*),	There was no significant difference between MFD and FD samples in terms of their color.
			Rehydration Potential	Rehydration Ratio (RR)	FD and MWFD sea cucumbers had clearly higher porosity than HACD sea cucumbers, thus resulting in higher rehydration ability.
			Nutritional Value	Amino Acids (AAc)	There was no significant difference between total content of AAc of FD and MWFD sea cucumbers.
Eikevik, Alves-Filho, and Bantle (2012)	Freezing MW HP AFD MW HP FB AFD	Green Peas	Physical	Particle Diameter (d)	The diameter of green peas dried with MW was lower than for the products dried without MW.
			Optical	Lightness (L^*), Redness/ Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE)	Green peas dried by MW HP FB AFD showed significantly higher reduction in color than MW HP AFD.
			Rehydration Potential	Rehydration Ratio (RR), Water Gain (WG), Solids Loss (SL)	Blueberries dried by HACD + MWVD were characterized by the highest RR and WG. MWVD blueberries imbibed smaller amount of water and lost smaller amount of solids during rehydration than berries dried by HACD and combined HACD + MWVD methods.
Gaware, Sutar, and Thorat (2010)	MWVD	Tomato Slices	Rehydration Potential	Rehydration Ratio (RR), Rehydration Kinetic	FD tomato slices had higher RR than MWVD slices.
Giri and Prasad (2007)	MWVD	Mushroom Slices	Rehydration Potential	Rehydration Ratio (RR)	An improvement in RR of dried mushroom by MWVD was observed over HACD.
Huang et al. (2011)	Freezing MWFD MWVD	Potato And Apple Re-Structured Chips	Physical	Microstructure, Density (ρ)	MW application resulted in an expanded porous structure (low ρ) of potato and apple re-structured chips. The consumer acceptance of

(*continued*)

Table 3. Continued.

References	Processes	Product	Properties		Significant Findings
					texture of MWFD and MWVD chips was higher than that of FD and VD.
			Mechanical	Hardness (H), Crispness (Cr)	The values of H and Cr of MWFD mixed chips were both higher than those subjected to FD. MWVD chips had lower H and higher Cr than those subjected to VD.
			Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*)	Application of MW increased b^* values of chips. The b^* values of MWVD and VD chips were higher than that of the MWFD and FD. The overall appearance of MWFD and FD chips was significantly higher than that of MWVD and VD.
			Rehydration Potential	Rehydration Ratio (RR)	RR of MWFD and FD potato and apple restructured chips reached highest value after ten seconds. MWVD and VD chips required very long rehydration times to reach their highest RR. The highest RR for MWVD and VD chips were lower than that of MWFD and FD chips. MW heating resulted in higher RR of mixed chips than that without such volumetric heating.
Huang et al. (2012)	FD + MWVD MWVD + FD	Apple Slices	Physical	Microstructure	Samples dried by FD + MWVD reveal an unclear porous structure because the cell walls shrink significantly. The porous structure of the sample dried by the MWVD + FD disappeared due to the great shrinkage of cell walls.
			Mechanical	Hardness (H), Crispness (Cr)	The hardness and crispness of FD + MWVD samples were lower and higher, respectively, than for the FD samples. The hardness and crispness of MWVD + FD samples were both higher than FD samples.
			Nutritional Value	Total Sugars (TS), Total Reducing Sugars (TRS), Total Polyphenols (TP), Total Pectins (TPt),	For the composition retention in dried samples, FD and FD + MWVD are better than MWVD + FD.
Huang and Zhang (2016)	Blanching MWVD PSBMWVD	Okra	Nutritional Value	Total Chlorophyll (TChl), Total Flavonoids (TF), Vitamine C (vit. C)	The contents of chlorophyll and vitamin C were the lowest for MWVD okra. In the case of flavonoids, no significant difference was observed between MWVD and PSBMWVD samples.
Jiang et al. (2011)	MWVD MWFD	Potato/Banana Re-Structured Chips	Rehydration Potential	Rehydration Ratio (RR)	MWFD potato/banana re-structured chips had higher RR than MWVD samples.
Jiang et al. (2013)	MWFD PSBMWVD	Banana Chips Slices	Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE)	MWFD caused the greater changes in color than FD. MWFD samples were darker than FD ones and they had the higher values of a^* and b^* parameters.
			Rehydration Potential	Rehydration Ratio (RR)	In the first minute of rehydration, both MWFD and PSBMWVD dried samples showed better rehydration ability than FD samples.

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Table 3. Continued.

References	Processes	Product	Properties		Significant Findings
					However, MWFD and PSBMWVD dried banana cubes had lower final values of RR than those dried by FD.
Jiang et al. (2017)	MWVD FD + MWVD HACD + MWVD	Okra	Optical	Lightness (L^*), Redness/ Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE)	All dried samples had higher a^* and lower b^* parameter than fresh okra. Application of MW decreased the ΔE values compared to HACD, and increased ΔE compared to FD. MWVD samples were characterized by lower value of ΔE than HACD and HACD + MWVD, and higher ΔE than FD and FD + MWVD.
			Nutritional Value	Total Flavonoids (TF), Total Polyphenols (TP), Ascorbic Acid Equivalent Antioxidant Capacity (AEAC), Ferric-Reducing Antioxidant Power (FRAP), Antioxidant Activity in ABTS Antioxidant Assay (ABTS)	The values of TFC, TPC, AEAC, FRAP and ABTS were the lowest for HACD okras and the highest for FD samples. Compared to HACD, HACD + MWVD caused an increase in TFC, TPC, AEAC, FRAP and ABTS. FD + MWVD samples had lower values of TFC, TPC, AEAC, FRAP and ABTS than FD ones.
Junqueira, Corrêa, and Ernesto (2017)	MWD MWHACD	Pumpkin Slices	Physical	Volumetric Shrinkage (S_V)	Compared to MWD and MWHACD, lower shrinkage of pumpkin slices was observed during HACD.
			Optical	Lightness (L^*), Redness/ Greenness (a^*), Yellowness/ Blueness (b^*)	Compared to HACD, the redness of pump kin slices was intensified by using microwaves.
			Rehydration Potential	Rehydration Coefficient (RC)	MW-assisted dried pumpkin slices presented higher shrinkage and lower RC values than HACD ones.
Leusink et al. (2010)	MWVD	Cranberries	Nutritional Value	Total Monomeric Anthocyanins (TMA), Antioxidant Activity (AA)	MWVD and FD resulted in a higher AA and TMA content than HACD cranberries.
Liu et al. (2017)	PSBMWVD VIRD VIRD + PSBMWVD	Asparagus Cookies	Physical	Expansion Ratio (φ), Fracturability (F)	The expansion ratio of PSBMWVD product was significantly lower than that of VIRD-PSBMVD samples. No significant difference in fracturability of PSBMWVD and VIRD-PSBMWVD samples was observed.
			Optical	Lightness (L^*), Redness/ Greenness (a^*), Yellowness/ Blueness (b^*)	Asparagus cookies dried by PSBMWVD and VIRD + PBSMWVD were greener than those dried by VIRD.
			Nutritional Value	Total Chlorophyll (TChl), Total Saponins (TSA)	PSBMWVD and VIRD + PSBMWVD resulted in the higher TChl and TS of asparagus cookies than VIRD.
Markowski, Bondaruk, and Błaszczak (2009)	Blanching MWVD	Potato Cubes	Physical	Volume (V), Microstructure, Macrostructure	MWVD led to expansion of dried potato cubes.
			Rehydration Potential	Water Absorption Capacity (WAC), Dry Matter Holding Capacity (DHC), Rehydration Ability (RA)	Higher WAC, DHC and RA values were observed for MWVD samples than HACD ones.
Mothibe et al. (2014)	MWVD PSBMWVD SBMWVD	Apple Cubes	Physical	Density (ρ)	The apparent density of VD apple cubes is higher from that produced using a microwave field. PSB MWVD gave products with the lowest apparent density.

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Table 3. Continued.

References	Processes	Product	Properties		Significant Findings
			Mechanical	Maximum Force to Break the Sample in Puncture Test (F_{Max})	MWVD apple cubes had significantly lower hardness than those dried by PSBMWVD, SBMWVD and VD.
			Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*)	PSBMWVD apple cubes had better color than those dried by SBMWVD, MWVD and VD. The L^* values of PSBMWVD and SBMWVD are significantly higher compared to those obtained by VD and MWVD. PSBMWVD and SBMWVD also gave products with significantly low a^* values. For b^* values, drying methods involving vacuum resulted in products with high values in the following order: PSBMWVD > VD > MWVD.
			Rehydration Potential	Rehydration Rate (R_R)	All samples could not rehydrate to the original moisture content of fresh fruits. PSBMWVD and MWVD apples showed similar rehydration ability, much higher than VD but lower than SBMWVD. Rehydration properties were found to be the best for SBMWVD samples.
Nahimana and Zhang (2011)	Blanching MWVD	Carrot Slices	Physical	Radial Shrinkage (S_R)	MWVD caused the carrot slices to undergo significant V_R.
			Morphological	Circularity Index (W_C), Solidity Index (W_S)	W_C and W_S reached their highest changes as early as the half drying time.
			Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Whiteness Index (*WI*)	MWVD caused significant increase in L^* and *WI* index and decrease in a^* and b^*.
			Rehydration Potential	Coefficient of Rehydration (COR), Rehydration Ratio (RR)	COR of MWVD carrots was greater than HACD ones. MWVD samples had greater initial RR than HACD samples. Then, the inverse situation occurred. After a long period of time (90 minutes), MWVD and HACD samples seemed to converge to the same values of RR.
			Nutritional Value	Total Carotenoids (TC)	MWVD caused significant degradation of carotenoids content.
Pei et al. (2014)	FD + MWVD	Button Mushroom Slices	Nutritional Value	Total Soluble Sugars (TSS), Total Polyols (TPo), Free Amino Acids (FAAc), Amino Acids (AAc)	FD + MWVD products were characterized by lower contents of TSS and polyols and higher contents of FAAc than FD ones. There were no differences in OAc contents of FD and FD + MWVD mushrooms.
Setiady et al. (2009)	Blanching MWVD	Potato Slices	Physical	Microstructure, Porosity (ε), Density (ρ)	MWVD produced crispy and porous potatoes. Porosity of MWVD potatoes was about 20 times that of HACD ones, and a half that of FD samples. Also density of MWVD potatoes was higher than FD samples, and lower than HACD ones.
			Mechanical	Maximum Force (F_{Max}) and Maximum Work (W_{Max}) to Fracture or Shatter the Sample	MWVD and HACD potato slices required more force to fracture or shatter than FD potatoes.

(*continued*)

Table 3. Continued.

References	Processes	Product	Properties		Significant Findings
			Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE)	FD and MWVD increased L^*, a^* and b^*, while HACD decreased L^* and increased a^* and b^* values. FD potatoes were characterized by the highest L^* and b^* values and that of MWVD ones were higher than that subjected to HACD.
			Rehydration Potential	Rehydration Ratio (RR), Hardness (H), Springiness (S), Cohesiveness (Co), Gumminess (G), Chewiness (Ch), Resilience (R_S), Microstructure	RR of FD potatoes was almost twice than that of MWVD and HACD samples. MWVD and HACD potatoes had similar rehydration properties. FD samples were significantly softer and less gummy, chewy, cohesive, and resilient than MWVD and HACD potatoes. FD potatoes were fragile, easily torn apart and tended to lose textural integrity after rehydration, while MWVD and HACD samples remained intact.
Soysal et al. (2009)	MWHACD IMWHACD	Red Pepper	Mechanical	Hardness (H), Fracturability (F)	The continuous MWHACD resulted in poor dried product quality, while intermittent MWHACD produced dried red pepper with better texture.
			Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*)	The continuous MWHACD resulted in poor dried product quality, while intermittent MWHACD produced dried red pepper with better color.
Therdthai and Northongkom (2011)	MWVD	Fingerroot	Physical	Texture	The structure of MWVD samples was porous.
			Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*)	After rehydration of MWVD samples, water presented higher yellowness than that of HACD samples.
			Rehydration Potential	Water Absorption Capacity (WAC), Dry Matter Holding Capacity (DHC), Rehydration Ability (RA)	WAC of MWVD samples was significantly higher than that of HACD samples. MWVD fingerroot sample contained less drying matter holding capacity than HACD sample.
Therdthai and Zhou (2009)	MWVD	Mint Leaves	Physical	Microstructure	MWVD mint leaves had a more porous and uniform structure than the HACD ones.
			Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE)	MWVD increased L^* and b^* values of mint leaves. MWVD mint leaves were light green-yellow.
Wang et al. (2013)	MWVD PSBMWVD	Stem Lettuce Slices	Physical	Shrinkage Ratio (SR), Apparent density (ρ_{ap})	The collision between the sample slices and the drying chamber wall during PSBMWVD resulted in a decreased SR compared to MWVD.
			Mechanical	Hardness (H)	The hardness of the rehydrated stem lettuce slices dried by PSBMWVD was higher than that of the sample dried by VD and MWVD.
			Optical	Total Color Difference (ΔE)	The pulsed spouted mode resulted in dried stem lettuce slices with low discoloration.
			Rehydration Potential	Rehydration Capacity (RC)	The pulsed spouted mode resulted in dried stem lettuce slices with high rehydration capacity.

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Table 3. Continued.

References	Processes	Product	Properties		Significant Findings
Yan et al. (2010)	Blanching MWVD MWFD MWSBD	Carrot Slices	Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE)	MWFD carrots had the best color. Other processes resulted in lower values of L^*. MWVD induced a decrease in b^*, while MWSBD induced a decrease in a^* and b^*. The color of carrots dried by MWFD and MWVD was close to those dried by FD.
			Nutritional Value	β – Carotene, Vitamine C. (vit. C)	Nutritional content of MWFD carrot pieces was the best due to the highest retention of carotene and vitamin C. The β – carotene content of MWFD carrot was close to fresh samples. Carotene content of MWVD and MWSBD carrot slices was equal to about 70 % of the value of fresh carrot. Vitamin C content of MWFD carrot slices was close to the vitamin C content of fresh samples. The vitamin C content of MWVD and MWSBD slices was significantly lower than that of MWFD.
			Rehydration Potential	Rehydration Ratio (RR)	MWFD carrots were characterized by the highest initial RR. After a period of time, there were no differences between RR of MWFD, MWVD and MWSBD carrots.
Zielinska and Michalska (2016)	MWVD HACD + MWVD	Whole Blueberries	Mechanical	Hardness (H), Gumminess (G), Chewiness (Ch)	MWVD and HACD + MWVD significantly increased H, Ch and G of frozen/thawed blueberries. H, Ch and G of MWVD or HACD + MWVD berries were several times lower in comparison with HACD berries.
			Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE) Redness/Blueness Ratio (a^*/b^*), Color Density (CD), Polymeric Color (PC), Percentage Polymeric Color (% PC)	Drying significantly influenced a^*, b^* and a^*/b^* values. Redness of blueberries increased, while blueness decreased. ΔE^* between dried and control sample was found to be significant, but recognizable only by a qualified observer. The lowest increase in % PC was indicated for blueberries dried using HACD 90 °C + MWVD.
			Nutritional Value	Total Polyphenols (TP), Total Monomeric Anthocyanins (TMA), Trolox Equivalent Antioxidant Capacity (TEAC)	Dried blueberries had reduced TPC, TMA and TEAC values. HACD (90 °C) + MWVD blueberries had the highest TMA content and the strongest antioxidant capacity.
Zielinska and Michalska (2018)	MWVD HACD + MWVD	Blueberry Pomace	Optical	Color Density (CD) Polymeric Color (PC), Percent Polymeric Color (% PC), Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*)	MWVD and HACD + MWVD increased significantly CD of blueberry pomace when compared to non-dried samples. The greatest amount of polymeric compounds was indicated after MWVD of blueberry pomace. HACD + MWVD resulted in higher values of PC than in HACD, proving that MWVD

(*continued*)

Table 3. Continued.

References	Processes	Product	Properties		Significant Findings
					was mainly responsible for the formation of polymeric compounds. MWVD and HACD + MWVD resulted in much lower values of % PC than for HACD.
			Nutritional Value	Total Polyphenols (TP) Content, Total Monomeric Anthocyanins (TMA) Content, Trolox Equivalent Antioxidant Capacity (TEAC)	Among different drying methods, MWVD resulted in the lowest losses of TP, TMA and TEAC of blueberry pomace.
Zielinska, Ropelewska, and Markowski (2017)	MWVD	Whole Cranberries	Physical	Porosity (ε), Volume (V), Density (ρ)	HACD and MWVD significantly increased ε and decreased V and ρ of cranberries.
			Thermal	Thermal Conductivity (k), Thermal Diffusivity (α), Specific Heat (C_p)	MWVD fruits were characterized by lower values of λ and C_p, and higher values of α than raw cranberries.
Zielinska, Sadowski, and Błaszczak (2015)	Freezing MWVD HACD + MWVD	Whole Blueberries	Physical	Volumetric Shrinkage (S_V), Porosity (ε), Density (ρ)	HACD + MWVD promoted most efficient drying in terms of enhanced product quality determined by porosity, density and shrinkage of dried blueberries.
			Mechanical	Hardness (H), Springiness (S), Cohesiveness (Co), Gumminess (G), Chewiness (Ch)	HACD + MWVD promoted most efficient drying in terms of enhanced product quality determined by hardness, chewiness and gumminess of dried blueberries.
Zielinska, Sadowski, and Błaszczak (2016)	Freezing MWVD HACD + MWVD	Whole Blueberries	Physical	Macrostructure, Volume Recovery (V/V_0), Porosity (ε), Density (ρ)	HACD, MWVD and HACD + MWVD followed by rehydration caused extensive damage to the structure of blueberries. HACD + MWVD with hot air pre-drying at 60 °C until the achievement of moisture content of about 4 kg H_20/kg DM, followed by rehydration, produced the largest berries.
			Mechanical	Hardness (H), Springiness (S), Cohesiveness (Co), Gumminess (G), Chewiness (Ch)	Rehydrated fruits were softer, less chewy and gummy than raw ones and H, Ch and G of raw berries were approximately one order of magnitude higher than that of rehydrated ones.
			Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*) Total Color Difference (ΔE)	Most drying methods significantly decreased L^* values (the only exception was HACD at 60 °C). All drying methods increased a^* and b^* values. MWVD and HACD + MWVD caused limited color changes in comparison with HACD. After rehydration, berries dried by HACD at 60 °C were significantly darker and redder than fruits dried by other methods. High values of ΔE between raw and dried samples indicated significant color changes during MWVD and HACD + MWVD of blueberries.

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Table 3. Continued.

References	Processes	Product	Properties		Significant Findings
Zielinska et al. (2013)	MWVD HP FB AFD + MWVD	Green Peas	Physical	Microstructure, Macrostructure, Density (ρ), Porosity (ε), Volumetric Shrinkage (S_V)	MWVD generated products with the highest ε, the lowest ρ and S_V. However, HP FB AFD + MWVD satisfied important requirements, such as high product quality in terms of textural properties of dried products. MWVD and HP FB AFD + MWVD led to porosity development.
			Mechanical	Maximum Force to Compress Dried Samples (F_{Max}), Maximum Force to Compress Rehydrated Samples (F_{Max})	Mechanical resistance of green peas has not been influenced by drying method. Rehydrated samples were much softer than green peas in their fresh form and did not recover their original mechanical strength.
			Morphological	Circularity Index (W_C)	No significant changes in morphological parameters of green peas were observed during HP AFD.
			Optical	Total Color Difference (ΔE), Total Saturation Difference (ΔC), Total Hue Difference (ΔH)	Green peas turned lighter and yellower during drying. No significant changes in color were observed during HP AFD. HP AFD + MWVD resulted in smaller changes in color, saturation and hue of green peas than single stage HACD or MWVD.

MWVD, microwave-vacuum drying; HACD, hot air convective drying; FD, freeze drying; VD, vacuum drying; MWVD + FD, microwave-vacuum drying and freeze drying; HACD + MWVD, combined hot air convective drying and microwave-vacuum drying; MWFD, microwave freeze drying; HP AFD + MWVD, combined heat pump atmospheric freeze drying and microwave-vacuum drying; HP FB AFD + MWVD, combined heat pump fluidized bed atmospheric freeze drying and microwave-vacuum drying; HP HACD + MWVD, combined heat pump hot air convective drying and microwave-vacuum drying; MW HP AFD, microwave heat pump atmospheric freeze drying; MW HP FB AFD, microwave heat pump fluidized bed atmospheric freeze drying; MWD, microwave drying; FD + MWVD, freeze drying and microwave-vacuum drying; MWVD + FD, microwave-vacuum drying and freeze drying; MWSBD, microwave spouted bed drying; MWHACD, microwave hot air convective drying; PSBMWVD, pulsed spouted bed microwave-vacuum drying; SBMWVD, spouted bed microwave-vacuum drying.

Effect of pretreatments on the quality parameters of MW-assisted dried food products

Structural and thermophysical properties

Quality of MW-assisted dried products that gain consumer attraction can be affected by initial pretreatments, such as freezing/thawing, chilling, blanching, osmotic dehydration, ultrasonication (Stępień 2008; Bai-Ngew, Therdthai, and Dhamvithee 2011; Zielinska, Sadowski, and Błaszczak 2015; Mierzwa, Kowalski, and Kroehnke 2017; Eikevik, Alves-Filho, and Bantle 2012; Zielinska and Michalska 2016; Wang, Zhang, and Mujumdar 2010; Zhang et al. 2017). Proper pretreatment may inactivate enzymes and, then minimize possible deterioration reactions during drying and subsequent storage. It may also result in the initial moisture content reduction, structure modification, and therefore reduction of drying time and improvement of material quality (Deng et al. 2019).

Depending on the product used, convective freezing may have positive or negative effect on the physical attributes of MW-assisted dried food products. Compared to MWVD without initial pretreatment, a combination of freezing and MWVD is a better method for durian chips preservation (Bai-Ngew, Therdthai, and Dhamvithee 2011). Among others, freezing before MWVD tends to reduce the hardness of the dried chips. Due to rapid water evaporation from the ice-crystal state under MWVD conditions, MWVD of frozen durian chips also allows to create more porous structure of final products than drying without initial freezing pretreatment (Bai-Ngew, Therdthai, and Dhamvithee 2011). Contrary, the combination of freezing/thawing and MWVD or HACD + MWVD adversely affects the physical attributes of whole blueberries (Zielinska, Sadowski, and Błaszczak 2015). Freezing of whole berries before drying causes severe damage to the inner parts of berry fruits, i.e. large irregular ice crystals formed during freezing induce considerable texture modification and result in a significant decrease of cuticle thickness and the mechanical strength of berry skin in puncture and cutting tests. This allows for significant reduction of drying time (even by 29%) and specific energy consumption of drying (even by 27%) in comparison with MW-assisted drying without initial pretreatment. However, it lowers the quality of MWVD or HACD + MWVD berries by producing harder, more chewy and gummy fruits (Zielinska, Sadowski, and Błaszczak 2015).

Water blanching is used to modify mechanical and rheological properties and tenderize the texture of MW-assisted dried food products. Certain fruits and vegetables, such as carrots may benefit from being blanched before being MW-assisted dried. Water blanching of carrots results in significant increase in the dry matter resistance to compression and decreases the strength of the dry material to cutting

Table 4. Effect of drying conditions on the quality properties of hybrid and combined MW-assisted dried food products.

References	Processes	Product		Properties	Significant Findings
Alibas (2007)	MWD HACD + MWD	Pumpkin Slabs	Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Chroma (C), Hue Angle (h°)	The application of lower MW power of 160 W during MWD resulted in higher changes in color parameters than 350 W. The optimum conditions during HACD + MWD i.e. MW power of 350 W and 50 °C caused the lowest color changes.
Bai-Ngew, Therdthai, and Dhamvithee (2011)	Freezing Chilling MWVD	Durian Chips	Mechanical	Hardness (H)	An increase in MW power level from 3.88 to 5.49 W/g tended to reduce the hardness of the durian chips. Further increase to 7.23 W/g created hot spots and increase in the breaking resistance.
Bal et al. (2011)	MWD	Bamboo Shoot Slices	Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE), Chroma (C), Hue Angle (h°), Browning Index (BI)	Higher MW power resulted in higher color loss of bamboo shoot slices.
Bondaruk, Markowski, and Błaszczak (2007)	Blanching MWVD	Potato Cubes	Mechanical	Texture	A vacuum level of 24 kPa was most appropriate for potato drying and resulted in the best texture parameters of dried products.
			Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Yellowness Index (YI)	MWVD at pressure of 24 kPa resulted in the best color of dried potato cubes.
			Nutritional Value	Total Starch (TSt), Total Sugars (TS), Total Reducing Sugars (TRS)	Among different drying conditions, MWVD at 12, 18 and 24 kPa resulted in the highest content of starch, TS and RS of dried potatoes.
Calin-Sanchez et al. (2014)	MWVD HACD + MWVD OD + HACD + MWVD	Black Chokeberries	Physical	True Density (ρ_t), Bulk Density (ρ_b), Porosity (ε), Total Pore Volume (V_p)	Compared to drying at constant MW power, the values of ρ_t of MWVD and OD + HACD + MWVD black chokeberries were significantly lower when MW power was controlled during drying. The values of ε for drying with the use of MW power adjustment were significantly higher for HACD + MWVD and lower for OD + HACD + MWVD fruits compared to drying at constant MW power. MW power adjustment resulted in increase in V_p of MWVD and HACD + MWVD fruits and decrease in V_p of OD + HACD + MWVD fruits in comparison to drying at constant MW power.
Changrue and Orsat (2009)	MWVD OD + MWVD	Carrot Cubes	Rehydration Potential	Coefficient of Rehydration (COR)	The mode of drying and MW power had no influence on COR values of carrot cubes.
Chauhan and Srivastava (2009)	Blanching MWVD	Green Peas	Physical	Shrinkage Ratio (SR)	MWVD of green peas at MW power of 237.31 W and a 360.22 mm Hg vacuum were found to be optimum drying conditions.
Chong et al. (2014)	HACD + MWVD HP HACD + MWVD	Apple Cubes	Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*)	The drying using heat pump (HP HACD + MWVD) resulted in brighter apple cubes than drying without heat pump (HACD + MWVD).
			Nutritional Value	Total Polyphenols (TP), Antioxidant Activity (AA)	The lower degradation of nutritional value was in the case of drying in lower temperature caused by heat pump.

(*continued*)

Table 4. Continued.

References	Processes	Product	Properties		Significant Findings
Duan et al. (2010a)	MWFD	Sea Cucumbers	Rehydration Potential	Rehydration Ratio (RR)	The increase in MW power from 1.6 to 2.3 W/g caused reduction in RR of sea cucumbers.
Eikevik, Alves-Filho, and Bantle (2012)	Freezing MW HP AFD MW HP FB AFD	Green Peas	Physical	Particle Diameter (d)	Green peas dried in a fixed bed at −6 °C showed the least decrease in particle diameter, followed by the product dried at −3 °C and 0 °C. The highest decrease in particle diameter was obtained for peas were dried in the fluid bed. The quality of the product dried by HP AFD at −6 and −3 °C was not significantly reduced due to the application of MW radiation.
			Optical	Lightness ($L*$), Redness/Greenness ($a*$), Yellowness/Blueness ($b*$), Total Color Difference (ΔE)	Drying at higher temperature and in the presence of MW radiation resulted in higher degradation of color of green peas.
Figiel (2007)	HACD + MWVD	Apple Cubes	Physical	Relative Volume (V_R)	An increase in V_s and decrease in shrinkage of apple cubles were correlated to the increase in MW power.
			Rehydration Potential	Water Absorption Capacity (WAC), Dry Mater Holding Capacity (DHC), Rehydration Ability (RA)	Apples dried by HACD + MWVD were characterized by a remarkably higher WAC than apples dried without microwaves. Apples pre-dried with hot air for a shorter period and finish-dried at a higher MW power were characterized by significantly higher DHC and RA as compared with samples dried without microwaves or other combined methods. Mostly, an increase in MW power caused more significant increase in rehydration potential.
Figiel (2009)	MWVD	Garlic Cloves, Halves and Slices	Physical	Relative Volume (V_R)	Increasing MW power increased V_R of MWVD garlic.
			Mechanical	Breaking Stress (σ_{max})	Increasing MW power caused an increase in compressive strength of MWVD garlic cloves.
			Rehydration Potential	Absorption Capacity (AC)	Generally, increased MW power induced increase in AC.
Figiel (2010)	HACD + MWVD	Beetroots	Physical	Relative Volume (V_R), Volumetric Shrinkage (S_V)	Both, increasing the MW power and decreasing HACD pre-drying time increased V_R and decreased S values of dried beetroots.
			Rehydration Potential	Absorption Capacity (AC)	Increasing the MW power and decreasing HACD pre-drying time resulted in increase in AC values of dried beetroots.
Gaware, Sutar, and Thorat (2010)	MWVD	Tomato slices	Rehydration Potential	Rehydration Rate (RR)	Increasing temperature of water resulted in decrease in RR and decrease in rehydration time required for reconstitution of tomato slices.
Giri and Prasad (2007)	MWVD	Mushroom Slices	Rehydration Potential	Rehydration Ratio (RR)	RR depended mainly on pressure level, while sample thickness and MW power had less effect on the values of RR. RR was positively correlated with MW power, and negatively correlated with the pressure.
Horuz, Jaafar, and Maskan (2017)	Ultrasonication MWHACD	Tomato Slices	Rehydration Potential	Rehydration Capacity (RC)	The increase in MW power resulted in a decrease in RC values of dried tomatoes.
Jiang et al. (2011)	MWVD MWFD Rehydration	Potato/Banana Re-Structured Chips	Mechanical	Hardness (H) Fracturability (F)	An increase in MW power density from 2 to 3 W/g resulted in significant decrease in hardness and fracturability of MWFD banana/potato re-structured chips.

(*continued*)

Table 4. Continued.

References	Processes	Product		Properties	Significant Findings
			Rehydration Potential	Rehydration Rate (RR)	Among different drying methods, the chips dried at MW power of 2 W/g were characterized by the highest RR. The lowest values of RR were found for samples dried at 2.5 W/g.
Jiang et al. (2013)	MWFD	Banana Chips Slices	Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE)	Higher MW power resulted in the higher color loss, which was expressed in an increase in ΔE, a^* and b^* values, as well as a decrease in L^*.
Junqueira, Corrêa, and Ernesto (2017)	IMWHACD	Pumpkin Slices	Physical	Volumetric Shrinkage (S_V)	An increase in drying temperature during IMWHACD from 30 to 60 °C caused increase in S values of pumpkin slices.
			Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*)	The significant increase in a^*/a^*_0 was caused by increase in air velocity.
			Rehydration Potential	Coefficient of Rehydration (COR)	Drying at different air temperatures and air velocities did not cause significant changes in COR of dried samples.
Kone et al. (2013)	MWHACD	Tomato Slices	Physical	Microstructure	Strategy with the control of MW power density allowed better control of the material temperature in the final stage of drying and thus better texture of tomato slices than strategy without MW power density control. Strategy without MW power control results in severe tissue shrinkage and structure collapse, while the reduced shrinkage in strategy with MW power control was observed. The more porous structure was possibly linked to a massive and fast vaporization during strategy with MW power control.
			Mechanical	Maximum Force (F_{Max}) to Penetrate Sample	Strategy with MW power control by intermittence produced a less firm tomato (good dried structure) compared to strategy with automatic MW power control.
			Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*)	MWHACD using MW power density control to improve quality of dried products has been successful, since the formation of black spots on dried tomatoes, linked to strongly uneven heating and drying, was avoided. Strategy with the control of MW power density led to obtaining color parameters of dried tomatoes close to those of fresh ones.
			Nutritional Value	Total Lycopene (TL)	MWHACD with MW power control allowed retention of more lycopene in the desired final product as opposed to MWHACD without MW power control.
Kumar, Prasad, and Murthy (2014)	MWHACD	Okra Slices	Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE)	MW power and air temperature had significant effect on the color change of okra slices during MWHACD. The higher degradation of color of dried okra was observed at higher MW power and higher air temperature. Among all process variables, air temperature had maximum effect on the color change of okra slices during MWHACD.

(*continued*)

Table 4. Continued.

References	Processes	Product	Properties		Significant Findings
			Rehydration Potential	Rehydration Ratio (RR)	Air temperature and MW power had significant effect on RR. Rehydration properties were better for okra samples dried at higher than lower MW power. RR increased with increase in hot air temperature and air velocities.
Markowski, Bondaruk, and Błaszczak (2009)	Blanching MWVD	Potato Cubes	Physical	Volume (V), Microstructure, Macrostructure	MWVD at 6 kPa was found to be the optimal drying condition for potato cubes, ensuring porous microstructure, low shrinkage and high rehydration potential.
			Physical	Microstructure	The optimal conditions, i.e. MW power at 480 W and the pressure in the drying chamber at 6 kPa were found to produce dried potato with a porous microstructure.
			Rehydration Potential	Rehydration Ability (RA), Volume Recovery (V_R)	The optimal conditions, i.e. MW power at 480 W and the pressure in the drying chamber at 6 kPa were found to produce dried potato with a high V_R after rehydration and a high RA.
Monteiro, Carciofi, and Laurindo (2016)	MWVD MWMFD	Banana	Physical	Apparent Density (ρ_{ap}), Porosity (ε), Microstructure	An increase in MW power from 400 to 1000 W did not cause the significant changes in microstructure, density and porosity of MWVD and MWMFD bananas.
Musielak and Kieca (2014)	MWVD	Carrot Slices, Beetroot Slices	Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE)	Increasing MW power caused an increase in color changes of MWVD beetroot and carrot slices. In the case of drying at two-stage MW power, the lowest values of ΔE were observed for carrot slices dried by MW power of 250/150 W and beetroot slices dried by 300/150 W (MW power was changed after reaching moisture ratio of 0.54). For drying with periodic MW power, the lowest values of ΔE were observed for carrot slices dried by 200 W (5 minutes intervals) and 150 W (30 minutes intervals), and for beetroot slices dried by 200 W (5 minutes intervals) and 150 W (20 minutes intervals).
			Nutritional Value	β – Carotene	MWVD of carrot slices at two-stage MW power (MW power at 300/150 W (MW power was changed after reaching moisture ratio of 0.54) resulted in the highest content of β – carotene. MWVD with constant MW power of 200 W resulted in products with the best nutritional value. In case of MWVD at periodic MW powers, the highest results were observed for MW power of 300 W (5 minutes intervals) and 150 W (20 minutes intervals).
Nahimana and Zhang (2011)	Blanching MWVD	Carrot Slices	Physical	Radial Shrinkage (S_R), Circularity (W_C), Solidity (W_S)	There were no changes between V_R of final products dried by different MW power. W_C and W_S reached their highest changes as early as the half drying time. In the second half of drying, insignificant changes were recorded.

(continued)

Table 4. Continued.

References	Processes	Product		Properties	Significant Findings
			Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Whiteness Index (WI)	The higher was MW power the higher color loss (increase in L^*, and decrease in a^*, b^*) was observed. The highest increase in WI index was observed in core dried by the highest MW power.
Pereira, Marsaioli, and Ahrné (2007)	OD + MWHACD	Bananas	Physical	Porosity (ε), Apparent Volume (V_{ap})	Increasing MW power from 75 to 225 W resulted in decrease in apparent volume and porosity of dried samples. An increase in the air temperature (from 50 to 70 °C) caused a significant increase in values of V_{ap} and ε in the case of drying at 75 W and 150 W. An increase in the air velocity from 3.3 to 5.7 m/s during drying had a negative impact on V_{ap} and ε.
			Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE)	MW power, air velocity and temperature during OD + MWHACD of banana slices did not significantly effect the values of L^*, a^*, b^* and ΔE. However, higher MW power caused an increase in the number of charred pieces.
Qiao, Huang, and Xia (2012)	MWVD	Re-Structured Lychee Mixed With Purple Sweet Potato Snacks	Physical	Bulk Density (ρ_b)	Increasing microwave power from 2 to 8 W/g resulted in decrease in ρ_b of mixed chips.
Soysal et al. (2009)	MWHACD IMWHACD	Red Pepper	Physical	Hardness (H)	Among different drying methods and conditions, the intermittent microwave-convective drying at 35 °C with a Pulse Ratio (PR) of 3.0 at 597.20 W produced the highest quality dried red pepper in terms of their texture.
			Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), a^*/b^* Index	Among different drying methods and conditions, the intermittent microwave-convective drying at 35 °C with a Pulse Ratio (PR) of 3.0 at 597.20 W produced the highest quality dried red pepper in terms of their color.
Sunjka, Orsat, and Raghavan (2008)	OD + MWVD	Cranberries (Cut In Quarters)	Mechanical	Young's Modulus (Y), Toughness (T)	MW power and modes had significant effect on E values and insignificant effect on T values. Pressure did not show any effect on E and T values. Cranberries dried by MWVD at MW power level of 1.25 and 1.5 W/g and power on-off time 30/45 s resulted in soft, chewy product of good textural characteristics (low stiffness, low E value).
			Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Hue Angle ($h°$), Chroma (C), Total Color Difference (ΔE)	An increase in MW power had significant effect on L^*, a^*, $h°$, C and ΔE. Pressure did not show any effect on cranberry color. MWVD at MW power level of 1.25 and 1.5 W/g, power on-off time 30/45 s and vacuum level of 3.4 kPa resulted in color of dried cranberries similar to fresh ones. The burned fruits accounted for 5–15% of the total mass of dried sample.
			Rehydration Potential	Rehydration Ratio (R_R)	MWVD at MW power level of 1.25 W/g, power on-off time 30/45 s and vacuum level of 3.4 kPa offered good rehydration properties of cranberries.

(*continued*)

Table 4. Continued.

References	Processes	Product		Properties	Significant Findings
Therdthai and Zhou (2009)	MWVD	Mint Leaves	Physical	Microstructure	Increase in MW power resulted in increasing evaporation rate and thus prevented shrinkage and case hardening of mint leaves.
			Rehydration Potential	Rehydration Rate (R_R)	MWVD of mint leaves at 9.6 and 11.2 W/g yielded significantly higher R_R than HACD at 60 °C and 70 °C.
Zhang, Zhang, and Mujumdar (2011)	MWVD MWFD	Wild Cabbage Chips	Mechanical	Fracturability (F)	As the MW power increased from 1.8 to 2.2 W/g during MWVD and MWFD the fracturability of restructured cabbage chips decreased. It was related to the increase in the brittleness of dried chips.
Zielinska and Michalska (2016)	MWVD HACD + MWVD	Whole Blueberries	Mechanical	Springiness (S)	Springiness of samples dried by HACD at 90 °C as well as combined HACD at 90 °C + MWVD did not differ statistically from the springiness of control sample, while samples processed under different conditions were much more resilient.
			Nutritional Value	Total Polyphenols (TP), Total Monomeric Anthocyanins (TMA), Trolox Equivalent Antioxidant Capacity (TEAC),	HACD at 90 °C + MWVD blueberries had the highest TMA content and the strongest antioxidant capacity.
Zielinska and Michalska (2018)	MWVD HACD + MWVD	Blueberry Pomace	Optical	Color Density (CD), Polymeric Color (PC), Percent Polymeric Color (% PC), Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*)	HACD at 60 °C + MWVD caused higher changes in CD of blueberry pomace then HACD at 90 °C + MWVD, while HACD at 90 °C + MWVD caused higher changes in % PC of blueberry pomace then HACD at 60 °C + MWVD.
			Nutritional Value	Total Polyphenols (TP), Total Monomeric Anthocyanins (TMA), Trolox Equivalent Antioxidant Capacity (TEAC)	HACD at 60 °C + MWVD allowed to obtain a product with a higher content of TP, TMA and a stronger antioxidant capacity than HACD at 90 °C + MWVD.
Zielinska, Sadowski, and Błaszczak (2016)	Freezing MWVD HACD + MWVD	Whole Blueberries	Physical	Volumetric Shrinkage (S_V), Porosity (ε), Density (ρ)	HACD + MWVD with hot air pre-drying step at 80 °C until the achievement of moisture content of ≈ 2 kg H_20/kg DM was the most efficient drying method in terms of enhanced quality of whole blueberries determined by S_V, ε, ρ.
			Mechanical	Hardness (H), Gumminess (G), Chewiness (Ch)	HACD + MWVD with hot air pre-drying step at 80 °C until the achievement of moisture content of ≈ 2 kg H_20/kg DM was the best drying method for the appropriate H, Ch and G of dried blueberries.
			Rehydration Potential	Rehydration Ratio (RR), Water Gain (WG), Solids Loss (SL), Macrostructure, Volume Recovery (V/V_0)	Blueberries dried by HACD + MWVD with hot air pre-drying at 80 °C until the achievement of moisture content of about 2 kg H_20/kg DM were characterized by the highest RR and WG. HACD + MWVD with hot air pre-drying at 60 °C until the achievement of moisture content of about 4 kg H_20/kg DM, followed by rehydration, produced the largest berries.

(*continued*)

Table 4. Continued.

References	Processes	Product		Properties	Significant Findings
Zielinska and Markowski (2016)	Freezing MWVD HACD + MWVD	Whole Blueberries	Rehydration Potential	Rehydration Capacity (RC), Rehydration Rate (RR)	HACD + MWVD with hot air pre-drying step at 80 °C led to the highest RC and RR. Blueberries pre-dried by hot air until the achievement of lower moisture contents were characterized by a higher RR in comparison with the fruits dried until the achievement of higher moisture contents.

HACD, hot air convective drying; MWHACD, microwave hot air convective drying; MWVD, microwave-vacuum drying; HACD + MWVD, combined hot air convective drying and microwave-vacuum drying, OD + MWVD, osmotic dehydration combined with microwave-vacuum drying; MW HP AFD, microwave assisted heat pump atmospheric freeze drying; MW HP FB AFD, microwave assisted heat pump fluidized bed atmospheric freeze drying; HP AFD, heat pump atmospheric freeze drying; HP FB AFD, heat pump fluidized bed atmospheric freeze drying; MWMFD, microwave multi-flash drying; VIRD + PSMWVD, vacuum infrared radiation and pulse-spouted microwave vacuum drying.

force compared to that of the dry matter obtained from material that is not pretreated before MWVD. The high temperature blanching makes the cell walls of carrots subjected to the blanching and MWVD elastic, i.e. the values of the modulus of elasticity of carrots subjected to the blanching and MWVD are twice as high as those of the modulus of elasticity of the MWVD samples that are not blanched (Stępień 2008). In some cases, blanching negatively affects the textural properties of MW-assisted dried products. Due to the rigidity structure of starch gel, blanching of potato slices significantly increases the hardness of MWFD and FD products. Due to the relatively high drying rate and uniformity of MW heating, blanched and MWFD samples are significantly harder than the FD ones (Wang, Zhang, and Mujumdar 2010). Additionally, blanching of taro slices before IMWVD causes significant increase in bulk density of samples in comparison with other pretreatment methods. High values of bulk density of blanched taro slices are related to the enhanced shrinkage and less porous structure than unblanched samples. Blanching also leads to significant decrease of hardness of taro slices which is related to the decrease of amylose content after pretreatment (Zhang et al. 2017).

To modify texture of MW-assisted dried food products, blanching is often combined with other initial pretreatments, such as freezing or immersion in maltodextrin solution (Wang, Zhang, and Mujumdar 2010; Zhang et al. 2017). Blanching of potato slices results in an uptake of water and a change in starch granules structure. Due to the expanding starch granules that cause an increase in pressure inside the cells, tissues of blanched potato slices are more vulnerable to freezing damage compared to the unblanched samples and suffer more damage during MWFD and FD than untreated potatoes (Wang, Zhang, and Mujumdar 2010). During sublimation phase, cells deformation and swelling occur due to the growth of ice crystals. Further freezing of blanched potatoes results in irregular cells arrangement, cavities and cells separation. During desorption phase, more intercellular voids appear. It can be explained by the fact that the ice crystals formed during freezing push the gelatinized starch towards the cell wall. Furthermore, blanching results in the softening of potato tissues which is associated with the loss of turgor due to membrane disruption and solubilization and depolymerization of pectic polymers that are involved in cell-cell adhesion. Compared to unblanched and frozen samples, more impairment and disruption of cell walls occur in MWFD and FD samples that were blanched and frozen. Blanching combined with freezing or immersion in maltodextrin solution or both immersion in maltodextrin solution and freezing causes the changes in: amylose content, amylose to amylopectin ratio, mechanical properties, bulk density, porosity and thus structure of treated samples. Due to the decrease of amylose content, blanching combined with other treatments induces more significant decrease in porosity and hardness of IMWVD taro slices, and more significant increase in density and crispness of IMWVD taro slices in comparison with untreated samples (Zhang et al. 2017). As maltodextrin causes arrangements of taro starch granules and facilitates the leakage of amylose into water, blanching combined with immersion in maltodextrin solution even increases the changes in amylose content in comparison with blanching without other treatments. Most probably, maltodextrin interacts with pectin and other cellular wall components, destroys original cellular structure, and alters the surface stickiness of drops of fructose solutions which leads to crispier products (Zhang et al. 2017).

Calcium ions treatment of food products is useful way to avoid their changes in shape during MWFD. It also increases the thickness of the cell wall making potato tissue firmer (Wang, Zhang, and Mujumdar 2010).

The application of ultrasounds before MW-assisted drying is still under scientific investigation, and to our knowledge, there are no commercial applications of this technology in fruit and vegetables industry. It appears to have promising results, in terms of texture modification. High power ultrasounds cause desirable physical changes in different food product tissues due to cavitation and mechanical effect (Nowak et al. 2017). The ability to induce the mechanical effect and cavitation depend on the sound wave parameters, properties of the medium and state parameters (Williams 1983). Cavitation occurs through acoustical streaming which involves the creation of a local turbulence, microcirculation, microstreaming or microjets and has mechanical effect on the plant tissue (Nowak et al. 2017). Most commonly, waves with intensity in the range from 10 to 1000 W/cm^2 and frequencies in the range from 20 to 500 are used to induce microcavitation (Awad et al. 2012). It should be pointed out that improper use of ultrasounds may also result in irreversible changes, such as tissue disintegration or cell wall cracking. Application of ultrasounds before MWHACD of tomato slices improves their rehydration ability. Presumably, the positive effect of ultrasounds on the rehydration capacity is attributed to microscopic channels and high permeability of cell membranes generated due to ultrasound treatment (Horuz, Jaafar, and Maskan 2017).

Due to structural profiles developed in the plant tissue, osmotic dehydration (OD) has a great impact on the physical properties of the final MW-assisted dried product (Changrue and Orsat 2009; Bórquez, Canales, and Redon 2010; Correa et al. 2011; Mierzwa, Kowalski, and Kroehnke 2017). OD before MWVD decreases the MWVD carrots resistance to compression. OD + MWVD results in higher cutting strength and reduced compression strength of carrots when compared with carrots that are not subjected to OD before MWVD (Stępień 2008). OD + MWHACD better preserves the shape and texture of carrots than MWHACD itself (Mierzwa, Kowalski, and Kroehnke 2017). Compared to MWHACD carrots, the shrinkage and deformations of OD + MWHACD of carrots are considerably smaller and the material surface is not rough or hard. OD of beetroot slices in chokeberry juice before drying guarantees low shrinkage of MWVD products. Chokeberry juice does not contain as much sugar as pure sucrose solution, so it easily penetrates beetroot tissues and prevents they structural collapse during MWVD (Lech et al. 2015). Also, carrots processed by OD + MWVD are characterized by the lower shrinkage than those subjected to MWVD without initial OD treatment and their shrinkage is inversely proportional to the concentration of osmotic solution (Changrue and Orsat 2009). The impregnation of sugar and salt from the osmotic agent to the carrots strengthens the product's cell structure during MWVD and thus decreases the shrinkage and lowers collapse of cell structure. Due to the presence in the carrots' void spaces of solids from the osmotic agents, low shrinkage of OD + MWVD carrots provides low rehydration capacity of final products (Changrue and Orsat 2009). Additionally, the increase of solution concentration leads to less shrinkage of pineapples. Such behavior can be explained by the solid gain with the increase of the osmotic solution concentration. In osmotic dehydration, the empty spaces are occupied by molecular impregnation of the solute, which results in diminishing sample shrinkage (Correa et al. 2011). Compared to the samples dried without OD, OD + MWVD and OD + HACD + MWVD significantly affects the texture of dried products producing softer, crispier and less surface-hardened chokeberries than MWVD or HACD + MWVD without initial OD treatment. The increase in crispness of chokeberries can be related to the increase in their porosity and total pore volume (Calin-Sanchez et al. 2014). Additionally, OD + MWVD of pumpkin slices results in improved textural properties, high crispiness, low shrinkage, and low cohesiveness of final products (Korzeniowska et al. 2011). MWVD raspberries subjected to initial osmotic dehydration under reduced pressure (VOD) are characterized by undamaged structure with only a few fractures at the surface skin of dried products (Bórquez, Canales, and Redon 2010). However, OD before further drying produces dried sea cucumber with high hardness and low springiness related to stiffening of collagen due to salt osmosis (Duan et al. 2008).

Color

Convective freezing before MWVD of whole cranberries improved their overall appearance, whereas cryogenic freezing combined with MWVD produces dried berries with suboptimal overall appearance (Zielinska, Markowski, and Zielinska 2019). Convectively frozen berries dried by MWVD at low MW powers, i.e. from 100 to 300 W results in desirable color of fruits characterized by the highest lightness, redness and yellowness (Zielinska and Zielinska 2019). Convective freezing before MWVD of whole cranberries causes significant changes in the cellular structure of fruits and thus significantly increases redness and yellowness of dried cranberries. The most visible effect of freezing is the change in the properties of the cells, which become flaccid after thawing. The consequence of these changes is a greater leakage of natural juices from frozen fruits during MWVD than from untreated fruits. Additionally, freezing allows to prevent color of MW HP AFD and MW HP FB AFD of green peas (Eikevik, Alves-Filho, and Bantle 2012). Initial freezing before MW-assisted drying has even greater effect on the quality of final products, e.g. in terms of their color than the MW-assisted drying process itself (Zielinska and Michalska 2016).

Despite of the texture modification, blanching of material before MW-assisted drying significantly affects the quality of MW-assisted dried products in terms of their color and (Nahimana and Zhang 2011). MWVD and HACD cause color degradation of carrot slices and ample scorching, especially in carrot core tissue where distinctive dark spots are noticed. However, color losses under MWVD are generally lower than under HACD, where negative effects of heat and air on pigments are amplified by long drying times (Nahimana and Zhang 2011). Due to the starch gelatinization and the uptake of water during blanching, initial blanching decreases lightness of potato slices before MWFD and FD. However, the total color change of potato slices during MWFD and FD is smaller for blanched than unblanched potatoes (Wang, Zhang, and Mujumdar 2010). Also due to the gelatinization and hydrolysis of starch during blanching of taro slices, samples subjected to initial blanching before IMWVD were characterized by the lower lightness and redness and higher yellowness than untreated taro slices (Zhang et al. 2017). The samples pretreated with blanching and freezing and blanching, immersion in maltodextrin solution and freezing were characterized by significantly higher lightness than blanched taro slices. This phenomenon might be because combined pretreatments effectively increase the drying rate, shorten the drying time and decrease the oxidative browning reaction. Also, maltodextrin has an influence on the arrangement of gelatinized starch molecules and make the samples opaque.

Due to sugar gain, OD improves taste, external color and mechanical resistance of MWVD products. OD may better preserve the color of pineapple discs during MWVD and leads to the intensification of final product yellowness (Correa et al. 2011).

Nutritional value

Despite of the texture modification, blanching of material before MW-assisted drying significantly affects the quality of MW-assisted dried products in terms of their nutritional value (Nahimana and Zhang 2011). Water blanching of carrot slices significantly affects carotenoids leaching into the solution and thus reduction of carotenoids content in the final products. Blanching is also used as a pretreatment prior to MW-assisted drying to reduce the bioactive compounds losses and limit chemical reactions during drying of different agri-food products (Wang, Zhang, and Mujumdar 2010). However, leaching out of chemical components, such as vitamins and reducing sugars or gelatinization of starch granules are inevitable during thermal blanching of fruits and vegetables itself. Due to amylose solubility in hot water, blanching of taro slices before IMWVD results in general reduction of amylose level and change in amylose to amylopectin ratio (Zhang et al. 2017). Vit. C and RS losses are observed e.g. during blanching of potato slices before MWFD and FD (Wang, Zhang, and Mujumdar 2010). Nevertheless, blanched samples lose less vit. C during MWFD and FD than unblanched ones, and no further loss in RS during subsequent MWFD and FD of potato slices is noted. Additionally, leaching out of chemical components and gelatinization of starch granules of potato slices during blanching change dielectric properties of potatoes and thus decrease the drying rate of potato slices during MWFD (Wang, Zhang, and Mujumdar 2010).

OD results in leaching and gaining of nutritional components (Bórquez, Canales, and Redon 2010; Nowicka et al. 2015; Cano-Lamadrid et al. 2017). Sugar gain, pigments concentration, vit. C leaching, decrease in TP and TMA content, as well as AA is observed during OD of different food products, such as raspberries or pineapples. To minimize vit. C losses during OD, the reutilization of sucrose solution is suggested (Bórquez, Canales, and Redon 2010). Also, attempts are made to use other types of media that could affect the increase of nutrients of osmotically dehydrated material. Among different osmotic solutions, OD of pomegranate arils in pomegranate and pomegranate + chokeberry juices results in the highest anthocyanins content and antioxidant capacity of OD + HACD + MWVD products. It could be caused by the high content of TMA in used juices (Cano-Lamadrid et al. 2017). Up to date, also OD of sour cherries or pomegranate arils in apple juice before HACD + MWVD has been tested (Nowicka et al. 2015; Cano-Lamadrid et al. 2017). OD of sour cherries in apple juice before HACD + MWVD does not contribute to the increase in the content of TP and AA of the final products (Nowicka et al. 2015). Also, the use of apple juice with its high sugar content restricts the migration of anthocyanins from the chokeberry juice to the dried pomegranate arils (Cano-Lamadrid et al. 2017). Further research is needed to fully optimize this combined drying treatment.

Rehydration potential

Blanching of biological materials before MW-assisted drying influences their rehydration potential. For example, blanching of potato samples increases the rehydration capacity of MWFD and FD potatoes and is more effective than other treatments (Wang, Zhang, and Mujumdar 2010). High values of rehydration ratio of blanched and MWFD and FD potato slices can be explained by the higher water absorption and limited cell wall damages than in case of unblanched samples (Wang, Zhang, and Mujumdar 2010).

Calcium ions treatment of potatoes before MWFD and FD results in low rehydration capacity of final products (Wang, Zhang, and Mujumdar 2010). Calcium treatment is less effective than blanching because the infusion of calcium ions into the potato tissues bounds with pectin, increases cell rigidity and decreases water absorption during rehydration (Wang, Zhang, and Mujumdar 2010). A thickening of the cell wall can be observed due to the absorption of Ca^{2+} and the formation of calcium pectate, making the cell wall more resistant and stable.

UA-OD before further MWFD decreases the hardness and increases springiness of sea cucumbers and results in improved chewiness of dried products (Duan et al. 2008). Due to microscopic channels and high permeability of cell membranes generated by ultrasounds, ultrasound assisted OD before MWFD improves rehydration potential of sea cucumbers (Duan et al. 2008).

OD significantly affects rehydration potential of carrots, while MWVD did not influence the coefficient of rehydration. OD + MWVD of carrots results in lower shrinkage of final products than MWVD itself and then, results in lower values of coefficient of rehydration (Changrue and Orsat 2009). Most probably, OD + MWVD carrots' void spaces are packed with solids that migrate from the osmotic solution and results in lower values of coefficient of rehydration. The results are consistent with literature data (Correa et al. 2011).

Significant findings on the effect of freezing, blanching, calcium treatment, osmotic dehydration and ultrasounds on the quality properties of hybrid and combined MW-assisted dried food products are summarized in Table 5.

Prediction of changes in quality parameters of food products during MW-assisted drying

Structural and thermophysical properties

Complexity of structure and physiological response of different food product tissue to MW-assisted drying make it difficult to establish models for the development of thermophysical changes induced in the material structure by the MW-assisted drying process. However, modeling, design, and control of drying operations require and consider

Table 5. Effect of initial pretreatments on the properties of MW-assisted dried food products.

References	Processes	Product	Properties		Significant findings
Bai-Ngew, Therdthai, and Dhamvithee (2011)	MWVD Freezing + MWVD Chilling + MWVD	Durian Slices	Mechanical	Microstructure, Hardness (H)	Durian slices pretreated by freezing prior to MWVD had a significantly more porous sponge-like structure than samples non-treated before drying. MWVD durian chips subjected to initial freezing were characterized by the lower hardness than untreated ones or those subjected to initial chilling operation.
Bórquez, Canales, and Redon 2010	VOD + MWVD	Whole Raspberries	Physical	Macrostructure	VOD + MWVD allowed to obtain an undamaged dried raspberries of high quality in terms of their structure.
			Optical	Color	OD + MWVD allowed to obtain an undamaged dried raspberries of high quality in terms of their color.
			Nutritional Value	Total Sugars (TS), Vitamin C (vit. C)	OD caused an increase in TS and losses of vit. C
			Nutritional Value	Total Carotenoids (TC)	Blanching caused leaching of some carotenoids into the solution. MWVD of carrot slices incurred significant carotenoids losses. TC were higher in cortex than the core of MWVD carrot slices.
Calin-Sanchez et al. 2014	MWVD HACD + MWVD OD + MWVD OD + HACD + MWVD	Black Chokeberries	Physical	Porosity (ε), Pore Volume (V_p), Density (ρ)	OD + MWVD as well as OD + HACD + MWVD significantly increased ε and V_p of chokeberries compared to MWVD, HACD and HACD + MWVD without initial osmotic treatment.
			Mechanical	Crispness (C)	OD + MWVD as well as OD + HACD + MWVD of chokeberries are promising methods for crispy chips production as they significantly increased crispness of final products compared to MWVD and HACD + MWVD without initial osmotic treatment.
Cano-Lamadrid et al. (2017)	HACD + MWVD OD + HACD + MWVD	Pomegranate	Optical	Redness/Greenness (a^*)	OD using combination of pomegranate and chokeberry juices improved a^* of dried fruits.
			Nutritional Value	Total Anthocyanins (TA), Antioxidant Activity (AA)	OD using combination of pomegranate and chokeberry juices improved TA content and AA of dried fruits.
			Rehydration Potential	Rehydration Ratio (RR)	Osmotic dehydration in pomegranate and chokeberry concentrated juices improved the quality of dried pomegranate arils in terms of their rehydration rate.
Changrue and Orsat (2009)	MWVD OD + MWVD	Carrot Cubes	Physical	Texture, Shrinkage (S)	Lower shrinkage of MWVD carrots occurred when the process was coupled with OD treatment. OD made the end product softer than those dried without OD pretreatment.
			Optical	Redness/Greenness (a^*)	OD before MWVD results in dried carrots of greater redness.
			Rehydration Potential	Coefficient of Rehydration (COR)	Low shrinkage of OD + MWVD carrots provides low rehydration capacity of final products.
Changrue and Orsat (2009)	MWVD OD + MWVD	Strawberries	Physical	Texture, Shrinkage (S)	The results showed that the osmotic pretreatment did not help in terms of drying time and energy saving but provided a better texture and lower shrinkage of dried products.

(continued)

Table 5. Continued.

References	Processes	Product	Properties		Significant findings
			Optical	Color	The results showed that OD provided a better color of MWVD products.
			Rehydration Potential	Rehydration Capacity (RC)	The results showed that OD provided a higher RC values of MWVD products.
Correa et al. 2011	MWVD OD + MWVD	Pineapple Discs	Physical	Texture, Shrinkage (S)	OD reduced shrinkage of the samples while drying. OD also significantly affected the texture of product producing softer, less surface-hardened product compared to untreated ones.
			Optical	Lightness (L^*), Redness/ Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE)	OD preserved the color of the samples while drying. OD led to yellow intensification of the disk samples of pineapple. The increase in OD immersion time and product temperature led to sample browning.
			Rehydration Potential	Coefficient of Rehydration (COR)	In OD processes the empty spaces were filled with solute molecules, which led to the diminishing of rehydration capacity.
Duan et al. (2008)	MWFD OD + MWFD UA-OD + MWFD	Sea Cucumbers	Rehydration Potential	Rehydration Ratio (RR)	OD led to the lowest values of RR. Ultrasound pretreatment improved RR of non treated or osmotically dehydrated sea cucumbers.
Duan et al. 2008	MWFD OD + MWFD UA-OD + MWFD	Sea Cucumber	Physical	Texture, Shrinkage Ratio (S_R)	OD led to the highest shrinkage of MWFD sea cucumbers. Ultrasounds decreased shrinkage during MWFD of osmotically dehydrated products.
			Mechanical	Hardness (H), Springiness (S), Chewiness (Ch)	OD led to higher hardness and lower springiness of MWFD sea cucumbers than MWFD itself. UA-OD led to desired chewiness of final products.
			Rehydration Potential	Rehydration Ratio (RR)	Among different treatments, OD led to lowest rehydration ability of final products. UA-OD improves rehydration ratio of dried sea cucumbers.
Eikevik, Alves-Filho, and Bantle (2012)	MW HP AFD MW HP FB AFD	Whole Green Peas	Optical	Lightness (L^*), Redness/ Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE)	MW HP AFD at $-6\,^{\circ}C$ and $-3\,^{\circ}C$ resulted in the best product quality, whereas MW HP AFD at $0\,^{\circ}C$ resulted in the highest color reduction of green peas.
Horuz, Jaafar, and Maskan (2017)	MWHACD UA-MWHACD	Tomato Slices	Rehydration Potential	Rehydration Capacity (RC)	Ultrasounds improved RC compared to non-treated tomato slices.
Korzeniowska et al. 2011	MWVD OD + MWVD	Pumpkin	Mechanical	Crispness (C)	OD of pumpkin slices before their MWVD results in higher crispiness of final products than in case of MWVD ones.
Lech et al. 2015	MWVD OD + MWVD	Beetroot Slices	Physical	Texture, Shrinkage (S)	Beetroots osmotically dehydrated in chokeberry juice and then MWVD had high quality in terms of texture. Only samples pretreated in fruit juice and MWVD at 480/120W had unacceptable hardness and crispiness. All the osmotically pretreated samples were characterized by lower shrinkage during MWVD than the control sample.
			Nutritional Value	Total Phenolics (TP), Antioxidant Activity (AA)	OD in concentrated chokeberry juice significantly improved bioactive potential of MWVD beetroots.

(*continued*)

Table 5. Continued.

References	Processes	Product	Properties		Significant findings
Mierzwa, Kowalski, and Kroehnke 2017	MWHACD UA-OD + MWHACD	Carrot Slices	Physical	Shape, Texture, Shrinkage (S)	The products pretreated with osmosis better retained their original shape and texture. The shrinkage and deformations were considerably smaller, the material surface was not rough or hard. Additionally, carrots pretreated with ultrasounds had the sweetest aroma in comparison with those dehydrated without ultrasound.
			Optical	Total Color Difference (ΔE)	OD and UA-OD positively influenced the color of MWHACD carrot slices.
Nahimana and Zhang (2011)	MWVD Blanching + MWVD	Carrot Slices	Optical	Lightness (L^*), Redness/ Greenness (a^*), Yellowness/Blueness (b^*), Whiteness Index (*WI*)	Blanching pretreatment degraded the color of carrot slices.
Nowicka et al. 2015	HACD + MWVD OD + HACD + MWVD	Sour Cherries	Nutritional Value	Total Polyphenols (TP), Antioxidant Activity (AA)	OD of sour cherries in apple juice before HACD + MWVD does not contribute to the increase in TP content and AA of the final products.
Stępień (2008)	Blanching + MWVD OD + MWVD	Carrot Cylinders	Mechanical	Maximum Work to Compress or Cut the Sample (W_{Max}), Moduls of Elasticity (Y), Dynamic Viscosity Coefficient (η)	Blanched and MWVD carrots were elastic and required a long chewing. Carrots subjected to OD before MWVD were hard and brittle. Carrots subjected to OD + MWVD were fragile and not elastic. Blanched and MWVD carrots can also resist greater loads during storage and transport than OD + MWVD samples.
Wang, Zhang, and Mujumdar (2010)	Blanching + MWFD Calcium treatment + MWFD	Potato Slices	Physical	Hardness (H)	Initial blanching significantly increased the hardness of MWFD and FD potatoes.
			Rehydration Potential	Rehydration Ratio (RR)	Dried blanched potato slices had much higher RR than the unblanched ones regardless of FD or MFD samples. The values of RR of MFD blanched potatoes were twice as much than that of the unblanched ones. Ca^{2+} treatment increased RR of dried potatoes.
			Nutritional Value	Vitamin C (vit. C), Total Reducing Sugars (TRS)	Blanched potatoes prior to drying significantly reduced the vitamin C and reducing sugar content.
Zhang et al. (2017)	IMWVD Blanching + IMWVD Blanching + Freezing + IMWVD Blanching + Immersion in Maltodextrin Solution + IMWVD Blanching + Immersion in Maltodextrin Solution + Freezing + IMWVD	Taro Slices	Physical	Porosity (ε)	All the pretreatments induced significant decrease of porosity of taro slices in comparison with untreated samples.
			Mechanical	Hardness (H), Crispness (C)	All the pretreatments induced significant decrease of hardness and increase of crispness of taro slices in comparison with untreated samples.
			Optical	Lightness (L^*), Redness/ Greenness (a^*), Yellowness/Blueness (b^*)	Initial blanching treatment decreased the lightness L^* and redness a^* of the taro slices and increased their redness b^*.
			Nutritional Value	Starch Content (SC)	Blanching of taro slices before IMWVD resulted in general reduction of amylose and amylopectin levels and change in amylase to amylopectin ratio
Zielinska and Michalska (2018)	MWVD Freezing + MWVD	Whole Cranberries	Optical	Lightness (L^*), Redness/ Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE), Total Hue Difference (ΔH), Total Saturation Difference (ΔC)	Convectionally frozen berries subjected to MWVD at 300 W were characterized by the highest lightness and redness.

(*continued*)

Table 5. Continued.

References	Processes	Product		Properties	Significant findings
Zielinska and Michalska (2016)	MWVD Freezing + MWVD HACD + MWVD Freezing + HACD + MWVD	Whole Blueberries	Optical	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Redness/Blueness Ratio (a^*/b^*), Total Color Difference (ΔE)	Freezing/thawing caused decrease in L*, and increase in a^* and b^* parameters in comparison to raw samples. Freezing/thawing of whole blueberries resulted in higher ΔE value than further drying of samples.
Zielinska, Sadowski, and Błaszczak (2015)	MWVD Freezing + MWVD HACD + MWVD Freezing + HACD + MWVD	Whole Blueberries	Physical	Shrinkage (S), Porosity (ε), Density (ρ)	Freezing/thawing did not exert a significant influence on S_V, ε and ρ of MW-assisted dried fruits.
			Mechanical	Hardness (H), Gumminess (G), Chewiness (Ch)	The combination of freezing/thawing and MW-assisted drying generated harder, more chewy and gummy fruits compared with those dried without initial pretreatment.

HACD, hot air convective drying; FD, freeze drying; MWHACD, microwave hot air convective drying; MWVD, microwave-vacuum drying; IMWVD, intermittent microwave-vacuum drying; MWFD, microwave freeze drying; HACD + MWVD, combined hot air convective drying and microwave-vacuum drying; OD + MWVD, osmotic dehydration combined with microwave-vacuum drying; OD + MWFD, osmotic dehydration combined with microwave-freeze drying; OD + HACD + MWVD, osmotic dehydration combined with hot air convective drying and microwave-vacuum drying; VOD + MWVD, osmotic dehydration under reduced pressure combined with microwave-vacuum drying; UA-OD + MWFD, ultrasound assisted osmotic dehydration combined with microwave-freeze drying; UA-OD + MWHACD, ultrasound assisted osmotic dehydration combined with microwave hot air convective drying; HP AFD, heat pump atmospheric freeze drying; MW HP AFD, microwave heat pump atmospheric freeze drying; HP FB AFD, heat pump fluidized bed atmospheric freeze drying; MW HP FB AFD, microwave heat pump fluidized bed atmospheric freeze drying.

changes in thermophysical properties of the dried products. Recently, some attempts at modeling shrinkage, density, and thermal conductivity changes during MW-assisted drying have been made for different fruits and vegetables, such as potatoes, carrots, radishes, cranberries, etc. (Figiel 2009; Setiady et al. 2009; Nahimana and Zhang 2011; Tsuruta et al. 2015). Setiady et al. (2009) derived a mathematical model to calculate true density of MWVD potato based on moisture content and a known solid density of dried potatoes. Four mathematical models were fitted to experimental data of S_R of MWVD carrot slices (Nahimana and Zhang 2011). The changes in V_R of garlic cloves, halves and slices with moisture content changes during MWVD were described using a square function (Figiel 2009). Also, two-dimensional numerical analysis was performed by using finite difference method (FDM) to understand the deformation mechanism during MW-assisted drying of radishes and carrots (Tsuruta et al. 2015). The transport phenomena were analyzed on the basis of the extended Darcy model for two-phase flow inside porous media with the use of a simplification of microwave heating. The model of Yang, Sakai, and Watanabe (2001) was utilized for the numerical simulation using a finite element method (FEM) for the shrinkage deformation during MWVD. The model assumed that the deformation behavior was elastoplastic within a small strain region and considered that the strain displacement was proportional to the moisture removal. The numerical shape and moisture distribution inside the MWVD vegetables agreed with the experimental results. Zielinska, Ropelewska, and Markowski (2017) determined thermal conductivity (k) of MWVD cranberries based on mathematical calculations. Fruits were treated as binary mixture of the condensed phase, which constituted of non-gaseous food components, i.e. water, protein, fat, carbohydrate, fiber and ash, as well as the gaseous (air) phase. Thermal conductivities of cranberries composed of a mixture of several constituents were calculated based on the known values of thermal conductivities of pure constituents and their volume fractions.

Color

There are several mathematical models applied to fit the experimental values of color parameters and nutritional value. Linear function is suitable to describe the changes in such parameters as L^* and b^* as well as ΔE with moisture changes during MWVD of Russet potatoes (Setiady et al. 2007). A second-order polynomial model and regression equation of color change were applied by Kumar, Prasad, and Murthy (2014) for fit to experimental values of ΔE of MWHACD okra slices. The model included the actual levels of air temperature, MW power and air velocity. Correa et al. (2011) used models for description of changes in L^*, a^*, b^* and ΔE during MWVD and OD + MWVD of pineapple discs. As the drying conditions such as sucrose concentration of osmotic solution, immersion time of osmotic dehydration and drying temperature significantly influence the changes in color parameters, they were included into the models. Bal et al. (2011) used zero kinetic model and first-order kinetic model for modeling the kinetic of color changes of bamboo shoot slices during MWD. The zero-order kinetic model and first-order kinetic model were also used by Dadali, Apar, and Özbek (2007) for description of color change kinetics of okra during MWD and by Chayjan and Alaei (2016) to fit to experimental data of color parameters of plum slices dried by MWD. Chayjan and Alaei (2016) also applied the first-order kinetic model, and the zero-order kinetic model. Additionally, the authors proposed a new model for mathematical determination of color changes as a function of drying time. The model included the initial value of color, the kinetic rate constant, drying time and the additional equation constant.

Nutritional value

During drying, the nutritional value of food material changes significantly. However, a very few studies addressed optimization of drying process in terms of the nutritional value of dried products (Şahin et al. 2018). A response surface method, using a central composite face-centered design (CCFD), was used to evaluate the effect of MWD on TP, TF, AA and OLE of olive leaves and to optimize the processing conditions. The second order model was used to predict the changes in AA values, the content of TP, TF, and OLE of MWD olive leaves (Şahin et al. 2018). The values of the determination coefficient (R^2) for TP (0.9982), TF (0.9981), AA (0.9972), and OLE (0.9981) indicate that the model adequately fits the relationship between the independent variables selected in the study. Moreover, the values of the adjusted determination coefficient ($R_a{}^2$) for TP (0.9965), TF (99.65), AA (0.9946), and OLE (0.9965) indicate that only 0.35, 0.35, 0.54, and 0.35% of the total variations of TP, TF, AA, and OLE, respectively, were not explained by the model. Moreover, low root mean squared deviations, i.e. RMSD = 0.0529, 0.0564, 0.0282, and 0.5838, show the strong correlations between the experimental and predicted results for TP, TF, AA, and OLE, respectively. The results of MWD under optimum conditions (Mass of sample: 2.085 g; Microwave power: 459.257 W; drying time: 6 min) has demonstrated to be the best among different drying methods used in the study. MWD under the optimum drying conditions allowed to achieve the maximum yields of TP (38.712 mg-GAE/g-DL), TF (35.658 mg-CE/g-DL), AA (25.216 mg-TEAC/g-DL), and OLE (203.561 mg/g-DL) in olive leaf.

Rehydration potential

The most important aspect of the rehydration operation is mathematical modeling of two main processes that take place simultaneously during rehydration of food products: water gain and solids loss. There is a general scarcity of research into the effect of MW-assisted drying on mass transfer kinetics in terms of water gain, solids loss, and effective moisture (solids) diffusivity during rehydration of different food products (Markowski, Bondaruk, and Błaszczak 2009; Gaware, Sutar, and Thorat 2010; Zielinska and Markowski 2016). In order to describe the kinetics of rehydration of MW-assisted dried products, Peleg's model was used to describe the water absorption kinetics during rehydration of MWVD tomato slices (Gaware, Sutar, and Thorat 2010), diffusive, Peleg's and Weibull's models were used to describe the changes in moisture contents during rehydration of MWVD potato cubes (Markowski, Bondaruk, and Błaszczak 2009), while first order kinetic and Peleg's models were used to describe the changes in rehydration capacity and loss of soluble solids during rehydration of blueberries subjected to MWVD and combined HACD + MWVD (Zielinska and Markowski 2016). Theoretical model based on Ficks second law of diffusion has been used to estimate the order of magnitude of the effective moisture diffusion of MWVD potato cubes (Markowski, Bondaruk, and Błaszczak 2009). As in the diffusion model, equilibrium moisture content was also considered as an additional parameter in the Peleg's and Weibull's models (Markowski, Bondaruk, and Błaszczak 2009). Such empirical formulas as Peleg's and first order kinetics models have been used to predict the mass of solids transferred from MWVD or HACD + MWVD blueberries into the solution, the mass of water absorbed by MWVD or HACD + MWVD blueberries over infinite time and the initial rate of rehydration or soluble solids leaching during rehydration of blueberries subjected to hybrid or combined MW-assisted drying processes (Zielinska and Markowski 2016).

The significant findings on modeling of MW-assisted dried food properties are presented in Table 6, while mathematical models used to describe changes in MW-assisted dried food properties are show in Table 7.

Concluding remarks

MWD alone has several limitations for experimental and commercial-scale applications, such as the non-uniformity of the electromagnetic field within the microwave cavity, the high penetration depth within the dielectric materials. Additionally, fast mass transport of the microwave power may alter the quality of dried food. To overcome these problems, materials to be dried should be in constant motion with a uniformity of power absorbed in the cavity to avoid any hot spots. Combined or hybrid MW-assisted drying techniques can also be employed. The paper presents a critical review on the effect of MW-assisted drying methods on the changes in material properties that occurred during drying of different food products under specified conditions. It focuses on recent trends related to hybrid and combined MW-assisted drying, drying process modeling and the needs and opportunities for future research and developments. In particular, it reviews the effect of drying methods, drying conditions and initial pretreatment on the structural and thermophysical properties, color, nutritional value and rehydration potential of MW-assisted dried food products. Significant progresses and beneficial evidences have been reported on hybrid MW-assisted drying methods, such as MWD, MWHACD, IMWHACD, MWSBD, MWFBD, MWIMFBD, MW HP AFD, MW HP FB AFD, MWVD, IMWVD, PSB MWVD, SB MWVD, MWFD, MWVFD, PSB MWFD, MW MFD, as well as combined (2 or 3 stage) drying methods, such as HACD + MWVD, HP HACD + MWVD, HP AFD + MWVD, FD + MWVD, MWVD + FD, VIRD + PSBMWVD, OD + MWVD, OD + HACD + MWVD, VOD + MWVD, MWOD + MWVD, MWVD + OD + MWVD. The MW-assisted drying techniques may become the trends of developing of drying technology in the future. However, further research and development efforst are still needed.

Future scope

Hybrid MW-assisted drying systems which consist of multiple heat sources have been continuously developing by the

Table 6. Recent references (since 2007) regarding the prediction of changes in food quality during hybrid and combined MW-assisted drying.

References	Processes	Modeled Value	Significant Findings
Bal et al. (2011)	MWD	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE), Chroma (C), Hue Angle ($h°$), Browning Index (BI)	The kinetics of a^* parameter, hue angle and ΔE were characterized by the zero-order model, and the values of L^*, b^*, C and BI were adequately defined by the first-order kinetic model. The kinetic rate constant decreased for L^*, b^*, BI, chroma and hue angle, and increased for a^* and ΔE parameters with increasing MW power. An increase in MW power caused the faster degradation rate of color due to high energy transfer to the product and an increase in its temperature.
Chayjan and Alaei (2016)	MWD	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE), Chroma (C), Hue Angle ($h°$), Browning Index (BI)	The zero-order kinetic model adequately fitted the values of a^*, b^*, ΔE, C and BI. The first-order kinetic model well described the changes in L^* and hue angle of plum slices. A new mathematical model for determination of color changes as a function of drying time was proposed. The new model better described the experimental data of color kinetics for all parameters than models of zero-order and first-order kinetics.
Correa et al. (2011)	MWVD OD + MWVD	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE), Volumetric Shrinkage (S_V)	Based on the data obtained from models, it was found that the increase in immersion time of osmotic dehydration and drying temperature caused the browning of samples. Additionally, an increase in drying temperature resulted in intensification of yellow and red color. Model describing the changes in b^* parameter indicated also that the decrease in solution concentration resulted in yellow intensification. Changes in ΔE parameter were directly proportional to immersion time of OD and inversely proportional to drying temperature.
Dadali, Apar, and Özbek (2007)	MWD	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE), Chroma (C), Hue Angle ($h°$), Browning Index (BI), Activation Energy for Color Change (E_a)	The zero-order kinetic model well fitted the experimental data of a^*, ΔE and hue angle. The first-order kinetic model adequately described the changes in L^*, b^*, C and BI of okra. The quadratic model was adequately applied to description of change kinetics of ΔE, C, $h°$, and BI, which depended on the ratio of the MW output. The activation energy for color change kinetic parameters was well described by the exponential expression based on Arrhenius's equation.
Figiel (2009)	MWVD	Relative Volume (V_R), Breaking Stress (σ_{Max})	V_R of garlic decreased until the critical moisture content was reached. No further change in volume of the slices was observed, although for whole cloves and halves a significant increase in sample volume was visible. Below critical moisture content, the pressure developed in the cells caused their walls to expand, enabling the material to gain in volume. There were no significant changes in σ_{Max} with the changes in moisture content of MWVD garlic until the critical value. Further decrease in moisture content of MWVD garlic caused significant increase in σ_{Max}. Further moisture removal resulted in increasing stiffening of their cell walls and increased σ_{Max} values of the material.
Gaware, Sutar, and Thorat (2010)	MWVD	Water Gain (WG)	Peleg's model adequately described rehydration kinetics of tomato slices over the range of experiments.
Kumar, Prasad, and Murthy (2014)	MWHACD	Total Color Difference (ΔE)	ΔE of okra slices were adequately described by a second-order polynomial model.
Markowski, Bondaruk, and Błaszczak (2009)	Blanching MWVD	Moisture Sorptions (MS)	Diffusive, Peleg's and Weibull's models effectively described the changes in MC during rehydration of MWVD potato cubes.
Nahimana and Zhang (2011)	Blanching MWVD	Radial Shrinkage (V_R)	The cubic model provided the best fit, while the worst fit was found for exponential model.
Şahin et al. (2018)	MWD	Total Polyphenols (TP), Antioxidant Activity (AA), Total Flavonoids (TF), Oleuropeins (OLE)	The second-order models were highly adequate for prediction of TPC, AA, TFC, and oleuropein of microwave dried olive leaf.

(*continued*)

Table 6. Continued.

References	Processes	Modeled Value	Significant Findings
Setiady et al. (2009)	Blanching MWVD	True Particle Density (ρ_p)	A derived model effectively described the changes in true density with moisture content of MWVD potato.
Setiady et al. (2007)	MWVD	Lightness (L^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE),	There was strong positive relation between L^*, b^*, and ΔE with moisture content. The correlation between L^* or b^* values and moisture content of the dried potatoes was described by linear function.
Tsuruta et al. (2015)	MWVD	Cubic Root of Volume Ratio ($\sqrt{\frac{V}{V_0}3}$)	By introducing a shrinkage coefficient of carrots and radishes defined with an experimental relationship between the cubic root of the volume ratio and the moisture content, FEM analyses were carried out. Coupled with the FDM analyses on the heat and moisture transport phenomena based on the extended Darcy model, the shrinkage deformation and moisture distribution were studied numerically. The simulation results show good agreement with the experimental measurements.
Zielinska and Markowski (2016)	Freezing MWVD HACD + MWVD	Rehydration Capacity (RC), Solids Loss (SL)	Both Peleg and the first-order-kinetic models effectively described the changes in RC and SL during rehydration of blueberries.
Zielinska, Ropelewska, and Markowski (2017)	MWVD	Thermal Conductivity (k)	The values derived from Parallel and Maxwell-Euken (with air dispersed) models were close to the measured values.

MWD, microwave drying; MWVD, microwave-vacuum drying; MWHACD, microwave hot air convective drying; HACD + MWVD, combined hot air convective drying and microwave-vacuum drying; OD, osmotic dehydration.

authors. Numerous combined MW-assisted drying technologies have also been developed for better utilization of microwave radiation in agri-food drying. The possible hybrids and combinations are nearly limitless, and their application is related to the product quality. The utilization of MW-assisted drying methods gives advantages in many aspects. The main advantages of hybrid and combined MW-assisted methods are: (i) the ability to create products with unique texture and physical characteristics, that cannot be replicated effectively with other drying methods without MW-assistance and (ii) high quality of final product in terms of material properties. However, they are still in the early stage of development, and usually used on small-scale for laboratory test.

Future research on MW-assisted drying should focus on the following areas:

1. *Pretreatments:* Fruits and vegetables are usually subjected to different pretreatments before drying to shorten the drying time, reduce the energy consumption and preserve the quality of dried products. The drying rate and material properties depend mainly on the pretreatment and drying methods and conditions. SSIB, HHAIB, MWB, OB, US, PEF and HHP may become the trends of developing of pretreatment technology in the future. However, they are all still in the early stage of development, and usually used on small-scale for test. To address the topic, more investigation is needed to explore the relationships between new pretreatments combined with different MW-assisted drying processes and final product quality. The knowledge on the changes in microstructure and physicochemical properties of products will allow to manage structure formation and tailor functional properties of food by selecting suitable pretreatment technologies and optimize the hybrid and combined MW-assisted drying conditions.
2. *Equipment:* 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 hybrid and combined MW-assisted drying.
3. *Drying conditions:* A large-scale industrial application of MW-assisted drying requires the detailed knowledge on the effect of various process parameters on the material properties and drying kinetics for proper design of system and equipment.
4. *Combination of different heat sources, types of dryers, combination order and conversion point:* Proper combination of different heat sources, types of dryers, combination order, and conversion point of hybrid and/or combined MW-assisted drying should be validated by experiment and selected for particulate food products to minimize changes in thermophysical properties, color, nutritional value and rehydration potentail of food materials and maintain the high quality of dried products.
5. *Optimization of hybrid and combined MW-assisted drying processes in terms of dried product quality:* Although several models have been established for optimization of a MW-assisted drying of selected number of materials in terms of the quality of dried product, there is still a lack of theoretical analyses, modeling, and simulation models for coupling between dried material properties and the drying conditions. The simulation models validated by experiments should predict the influence of the most important drying parameters such as MW power, pressure in the drying chamber, MW mode, drying temperature, drying rate and drying time on the

Table 7. Mathematical models used to describe the .changes in food material properties during MW-assisted drying.

References	Model name	Mathematical expression	Properties	Product
Bal et al. (2011)	Zero-Order Kinetic First-Order Kinetic	$C = C_0 \pm kt$ $C = C_0 \exp(\pm kt)$	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE), Chroma (C), Hue Angle ($h°$), Browning Index (BI), Activation energy for color change (E_a)	Bamboo Shoot Slices
Chayjan and Alaei (2016)	Zero-Order Kinetic First-Order Kinetic No name	$C = C_0 \pm kt$ $C = C_0 \pm kt$ $C = C_0 \exp(\pm kt^n) + at^n$	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE)	Plum Slices
Correa et al. (2011)	Second Order Polynomial	$Y = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \sum_{i<1}^{n} \beta_i X_i X_i + \sum_{i=1}^{n} \beta_{ii} X_i^2 \ + \ldots$	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE), Visual Quality (VQ), Coefficient of Rehydration (COR), Volumetric Shrinkage (S_V)	Pineapple Discs
Dadali, Apar, and Özbek (2007)	Zero-Order Kinetic First-Order Kinetic Second Order Polynomial Arrhenius's Equation	$C = C_0 \pm kt$ $C = C_0 \exp(\pm kt)$ $C_F = a + b\ \left(\frac{P}{m}\right) + c\ \left(\frac{P}{m}\right)^2$ $K = k_0 \exp\left(\frac{-E_a * m}{P}\right)$	Lightness (L^*), Redness/Greenness (a^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE), Chroma (C), Hue Angle ($h°$), Browning Index (BI), Activation Energy for Color Change (E_a)	Okra
Figiel (2009)	Quadratic Exponential	$V_R = a - bu + cu^2$ $\sigma_{max} = a + b\exp{-\frac{u}{c}}$	Relative Volume (V_R) Breaking Stress (σ_{max})	Garlic Cloves, Halves and Slices
Gaware, Sutar, and Thorat (2010)	Peleg's	$X(t) = X_0 + \frac{t}{k_1 + k_2 t}$	Moisture Sorption (MS)	Tomato Slices
Kumar, Prasad, and Murthy (2014)	Second Order Polynomial	$Y \ = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \sum_{i<1}^{n} \beta_i X_i X_i + \sum_{i=1}^{n} \beta_{ii} X_i^2 \ + \ldots$	Total Color Difference (ΔE), Hardness (H), Rehydration Ratio (RR)	Okra Slices
Markowski, Bondaruk, and Błaszczak (2009)	Peleg's Weibull's Diffusive	$X(t) = X_0 + \frac{t}{k_1 + k_2 t}$ $\frac{u - u_e}{u_0 - u_e} = \exp\left(-\left(\frac{t}{b}\right)^a\right)$ $\frac{u - u_e}{u_0 - u_e} = \frac{512}{\pi^6}\left[\sum_{i=1}^{\infty} \frac{1}{(2i-1)^2} exp\left(-(2i-1)^2 \pi^2 \frac{D_e t}{L^2}\right)\right]^3$	Moisture Sorption (MS)	Potato Cubes
Nahimana and Zhang (2011)	Exponential Rahman's Ratti's Cubic Model	$S_R = a\exp(bu)$ $S_R = 1 - a(u - u_0)$ $S_R = a + b\frac{u}{u_0}$ $S_R = au^3 + bu^2 + cu + d$	Radial Shrinkage (S_R)	Carrot Slices
Şahin et al. (2018)	Second Order Polynomial	$Y \ = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \sum_{i<1}^{n} \beta_i X_i X_i + \sum_{i=1}^{n} \beta_{ii} X_i^2 \ + \ldots$	Total Polyphenols (TP), Total Flavonoids (TF), Antioxidant Activity (AA), Oleuropeins (OLE)	Olive Leaf
Setiady et al. (2009)	No Name	$\rho_p = \frac{\rho_s}{1 - u\left(1 - \frac{\rho_s}{\rho_w}\right)}$	Particle Density (ρ_p)	Potatoes
Setiady et al. (2007)	Linear Function	$\Delta L* = a + bu \Delta E = a + bu \Delta b* = a + bu$	Lightness (L^*), Yellowness/Blueness (b^*), Total Color Difference (ΔE),	Russet potatoes
Tsuruta et al. (2015)	Model Of Yang, Sakai, and Watanabe (2001)	$d\varepsilon = d\varepsilon_m + d\varepsilon_s = d\varepsilon_m + S_V \cdot ds$	The Local Total Strains ($d\varepsilon$)	Radishes, Carrots
Zielinska and Markowski (2016)	Peleg's First Order Kinetic	$X(t) = X_0 + \frac{t}{k_1 + k_2 t}$ $\frac{dY_S}{dt} = -kY_S$	Moisture Sorption (MS)	Blueberries

(*continued*)

Table 7. Continued.

References	Model name	Mathematical expression	Properties	Product
Zielinska, Ropelewska, and Markowski (2017)	Serial	$k_e = \sum_i \frac{1}{\frac{\nu_i}{k_i}}$	Thermal Conductivity (k)	Cranberries
	Parallel	$k_e = \sum_i k_i \nu_i$		
	Maxwell-Euken (Air Dispersed)	$k_e = k_c \frac{2k_c+k_a-2(k_c-k_a)\varepsilon}{2k_c+k_a+(k_c-k_a)\varepsilon}$		
	Maxwell-Euken (Condensed Phase Dispersed)	$k_e = k_a \frac{2k_a+k_c-2(k_a-k_c)(1-\varepsilon)}{2k_a+k_c+(k_a-k_c)(1-\varepsilon)}$		
	Effective Medium Theory (EMT)	$\nu_c \frac{k_c-k_e}{k_c+2k_e} + \nu_a \frac{k_a-k_e}{k_a+2k_e} = 0$		

where: S_R, the radial shrinkage; V_R, the relative volume; σ_{max}, the breaking stress (MPa); $d\varepsilon$, the local total strains; $d\varepsilon_M$, the mechanical strains; $d\varepsilon_S$, the shrinkage strains; S_V, the volumetric shrinkage; ρ_p, the true particle density (kg/m^3); ρ_S, the density of solid (kg/m^3); ρ_W, the density of water (kg/m^3); ΔL^*, difference in lightness; Δb^*, difference in yellowness/blueness; ΔE, total color difference; k_e, k_i, k_c, k_a, the thermal conductivities of cranberries, i_{th} fraction of a cranberry, condensed matter in a cranberry and of the air contained in a cranberry, respectively (W/mK); v_i, v_c, v_a, the volume fractions of i_{th} constituent of a cranberry, condensed matter in a cranberry and of the air contained in a cranberry, respectively (m^3); Y, the dependent parameter also known as response; β_0, the intercept; β_i, the linear; β_{ii}, the second-order; Xi (i = 1–3) is the uncoded independent parameter; C, the value of any quality parameter C at a specified time; C_0, the initial value of any quality parameter C; C_F, the final value of any quality parameter C; t, the time (min); m, the weight of raw sample (g); P, the microwave output power (W); E_a, the activation energy (W/g); u, u_0, u_e, the instant, initial and equilibrium moisture contents (kg/kg$_{db}$); K, the kinetic rate constant of the quality parameter (1/min); Y_S, the mass of soluble solids (g); X(t), the mass of fraction Y (water or soluble solids) over time (g); X_0, the initial mass of fraction X (water or soluble solids) (g); D_e, the effective moisture diffusivity (m^2/s); L, the length of the edge of a cube (m); a, b, c, d, e, k, k_0, k_1, k_2, n, the model coefficients.

material properties, and help to improve the operational performance for different hybrid and combined MW-assisted drying processes.

6. *Material properties*: As the distribution of the electromagnetic fields is affected by the dielectric properties of the materials, the drying process should be controlled based on the changes of dielectric properties of the materials. The dielectric properties of the materials to be dried should be examined along with the factors affecting methods for measuring of the dielectric properties. Additionally, the concept of material properties and their evolution as a function of moisture content and material temperature during hybrid MW-assisted drying should be thoroughly analyzed. Also, in-depth knowledge about the changes in material properties during different stages of combined MW-assisted drying is required to develop combined MW-assisted methods that may preserve the most desirable characteristics of dried products, e.g. high porosity, and minimize or eliminate undesirable attributes, e.g. excessive shrinkage.
7. *Energy aspect:* There is a downside to the MWD alone, as it is a high energy consuming process. Hybrid and combined MW-assisted drying processes take advantages of e.g. conventional HACD and MWD alone. New hybrid and combined MW-assisted drying processes may be used to reduce energy consumption by combining different heat sources or drying techniques/modes in an appropriate manner. However, future studies are necessary for optimization of drying methods to predict the influence of e.g. MW power, pressure in the drying chamber, MW mode, drying temperature, drying rate, drying time, combination of different heat sources, types of dryers, combination order, and conversion point on the drying efficiency and help to improve the operational performances for different hybrid and combined MW-assisted drying processes.

Abbreviations

a^*	redness/greenness
AA	antioxidant activity
AAc	amino acids
AAD	ambient air drying
ABTS	antioxidant activity in ABTS antioxidant assay
AEAC	ascorbic acid equivalent antioxidant capacity
α	thermal diffusivity
b^*	yellowness/blueness
BI	browning index
C	chroma
Co	cohesiveness
Ch	chewiness
Cr	crispness
CD	color density
COR	coefficient of rehydration
C_p	specific heat
ΔC	total saturation difference
d	particle diameter
DHC	dry matter holding capacity
ε	porosity

Φ	expansion ratio
E_a	activation energy
E_{Max}	maximum energy
ΔE	total color difference
F	fracturability
F_{Max}	maximum force
FD	freeze drying
FD + MWVD	freeze drying and microwave vacuum drying
FRAP	ferric-reducing antioxidant power
G	gumminess
H	hardness
ΔH	total hue difference
h°	hue angle
HACD	hot air convective drying
HACD + MWVD	hot air convective drying and microwave vacuum drying
HHAIB	high humidity hot air impingement blanching
HHP	high hydrostatic pressure
HP AFD	heat pump atmospheric freeze drying
HP AFD + MWVD	heat pump atmospheric freeze drying and microwave vacuum drying
HPD	heat pump drying
HP FB AFD	heat pump fluidized bed atmospheric freeze drying
HP FB AFD + MWVD	combined heat pump fluidized bed atmospheric freeze drying and microwave-vacuum drying
HP HACD	heat pump hot air convective drying
HP HACD + MWVD	heat pump hot air convective drying and microwave vacuum drying
IMWHACD	intermittent microwave hot air convective drying
IMWVD	intermittent microwave vacuum drying
k	thermal conductivity
L^*	lightness
MS	moisture sorptions
Mt	mannitol
MWB	microwave blanching
MWFBD	microwave fluidized bed drying
MWFD	microwave freeze drying
MWHACD	microwave hot air convective drying
MWHP AFD	microwave heat pump atmospheric freeze drying
MW HP AFD	microwave assisted heat pump atmospheric freeze drying
MW HP FB AFD	microwave assisted heat pump fluidized bed atmospheric freeze drying
MWIMFBD	microwave assisted inert medium fluidized bed drying
MWMFD	microwave multi-flash drying
MWOD	microwave-osmotic dehydration
MWSBD	microwave spouted bed drying
MWSD	microwave spouted bed drying
MWVD	microwave vacuum drying
MWVFD	microwave vacuum freeze drying
MWVD + FD	microwave vacuum drying and freeze drying
MWVD + OD + MWVD	microwave vacuum drying and osmotic dehydration and microwave vacuum drying
η	dynamic viscosity coefficient
OB	Ohmic blanching
OD	osmotic dehydration under atmospheric pressure
OD + MWVD	osmotic dehydration and microwave vacuum drying
OD + HACD + MWVD	osmotic dehydration and hot air convective drying and microwave vacuum drying
OD + MWFD	osmotic dehydration combined with microwave-freeze drying
OLE	oleuropeins
PC	Polymeric color
PEF	pulsed electric field
% PC	percentage polymeric color
PR	pulse ratio
PSBMWVD	pulsed spouted bed microwave vacuum drying
PSBMWFD	pulsed spouted bed microwave freeze drying
PSMWVD	pulse-spouted microwave vacuum drying
ρ_{ap}	apparent density
ρ_b	bulk density
ρ_t	true density
RA	rehydration ability
RC	rehydration coefficient
RR	rehydration ratio
R_R	rehydration rate
R	resilience
S	springiness
SBMWVD	spouted bed microwave vacuum drying
SL	solids loss
S_V	volumetric shrinkage
S_R	radial shrinkage
SR	shrinkage ratio
SSIB	superheated steam impingement blanching
σ_{max}	maximum breaking stress
TC	total carotene
TChl	total chlorophyll
TEAC	trolox equivalent antioxidant capacity
TF	total flavonoids
TL	total lycopene
TMA	total monomeric anthocyanins
TOAc	total organic acids
TOPCs	total oligomeric procyanidins
TP	total polyphenols
TPt	total pectins
TPo	total polyols
TRS	total reducing sugars
TS	total sugars
TSa	total saponins
TSS	total soluble sugars
TSt	total starch
UA-OD	ultrasound assisted osmotic dehydration
UA-OD + MWFD	ultrasound assisted osmotic dehydration combined with microwave-freeze drying
UA-OD + MWHACD	ultrasound assisted osmotic dehydration combined with microwave hot air convective drying
US	ultrasonication
VD	vacuum drying
VFD	vacuum freeze drying
VIRD + PSMWVD	vacuum infrared radiation and pulse-spouted microwave vacuum drying
VIRD + PSBMWVD	vacuum infrared radiation drying and pulsed spouted bed microwave vacuum drying
V_{ap}	apparent volume
VOD	osmotic dehydration under reduced pressure
VOD + MWVD	vacuum osmotic dehydration and microwave vacuum drying
V_p	total pore volume
V_R	relative volume
V/V_0	volume recovery
WAC	water absorption capacity
W_C	circularity index
WG	water gain
WI	whiteness index

W_{Max}	maximum work
W_S	solidity index
Y	modulus of Elasticity
YI	yellowness index

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References

Abbasi, S., and S. Azari. 2009. Novel microwave-freeze drying of onion slices. *International Journal of Food Science & Technology* 44 (5):974–9. doi: 10.1111/j.1365-2621.2008.01774.x.

Alibas, I. 2007. Energy consumption and color characteristics of nettle leavers during microwave vacuum and convective drying. *Biosystems Engineering* 96 (4):495–502. doi: 10.1016/j.biosystemseng.2006.12.011.

Awad, T. S., H. A. Moharram, O. E. Shaltout, D. Asker, and M. M. Youssef. 2012. Applications of ultrasound in analysis, processing and quality control of food – A review. *Food Research International* 48 (2):410–27. doi: 10.1016/j.foodres.2012.05.004.

Bai-Ngew, S., N. Therdthai, and P. Dhamvithee. 2011. Characterization of microwave vacuum-dried durian chips. *Journal of Food Engineering* 104 (1):114–22. doi: 10.1016/j.jfoodeng.2010.12.003.

Bal, L. M., A. Kar, S. Satya, and S. N. Naik. 2011. Kinetics of color change of bamboo shoot slices during microwave drying. *International Journal of Food Science & Technology* 46 (4):827–33. doi: 10.1111/j.1365-2621.2011.02553.x.

Bondaruk, J., M. Markowski, and W. Błaszczak. 2007. Effect of drying conditions on the quality of vacuum-microwave dried potato cubes. *Journal of Food Engineering* 81 (2):306–12. doi: 10.1016/j.jfoodeng.2006.10.028.

Bórquez, R. M., E. R. Canales, and J. P. Redon. 2010. Osmotic dehydration of raspberries with vacuum pretreatment followed by microwave-vacuum drying. *Journal of Food Engineering* 99 (2):121–7. doi: 10.1016/j.jfoodeng.2010.02.006.

Bórquez, R., D. Melo, and C. Saavedra. 2015. Microwave-vacuum drying of strawberries with automatic temperature control. *Food and Bioprocess Technology* 8 (2):266–76. doi: 10.1007/s11947-014-1400-0.

Calin-Sanchez, A., A. Figiel, A. Wojdylo, M. Szarycz, and A. A. Carbonell-Barrachina. 2014. Drying of garlic slices using convective pre-drying and vacuum-microwave finishing drying: Kinetics, energy consumption, and quality studies. *Food and Bioprocess Technology* 7:398–408. doi: 10.1007/s11947-013-1062-3.

Cao, X., M. Zhang, H. Qian, and A. S. Mujumdar. 2017. Drying based on temperature detection-assisted control in microwave-assisted pulse-spouted vacuum drying. Journal of the Science of Food and Agriculture 97 (8):2307–15. doi: 10.1002/jsfa.8040.

Cano-Lamadrid, M., K. Lech, A. Michalska, M. Wasilewska, A. Figiel, A. Wojdyło, and Á. A. Carbonell-Barrachina. 2017. Influence of osmotic dehydration pre-treatment and combined drying method on physico-chemical and sensory properties of pomegranate arils, cultivar Mollar de Elche. *Food Chemistry* 232:306–15. doi: 10.1016/j.foodchem.2017.04.033.

Carson, J. K. 2015. Thermal conductivity measurement and prediction of particulate foods, international journal of food properties. *International Journal of Food Properties* 18 (12):2840–9. doi: 10.1080/10942912.2015.1016576.

Chang, C. H., H. Y. Lin, C. Y. Chang, and Y. C. Liu. 2006. Comparisons on the antioxidant properties of fresh freeze-dried and hot-air-dried tomatoes. *Journal of Food Engineering* 77 (3):478–85. doi: 10.1016/j.jfoodeng.2005.06.061.

Changrue, V., and V. Orsat. 2009. Osmotically dehydrated microwave vacuum drying of carrots. *Canadian Biosystems Engineering* 51:3.11–.19.

Chauhan, A. K. S., and A. K. Srivastava. 2009. Optimizing drying conditions for vacuum-assisted microwave drying of green peas (*Pisum sativum* L.). *Drying Technology* 27 (6):761–9. doi: 10.1080/07373930902828120.

Chayjan, R. A., and B. Alaei. 2016. New model for colour kinetics of plum under infrared vacuum condition and microwave drying. *Acta Scientiarum Polonorum. Technologia Alimentaria* 15 (2):131–44. doi: 10.17306/J.AFS.2016.2.13.

Chong, C. H., A. Figiel, C. L. Law, and A. Wojdyło. 2014. Combined drying of apple cubes by using of heat pump, vacuum-microwave, and intermittent techniques. *Food and Bioprocess Technology* 7 (4):975–89. doi: 10.1007/s11947-013-1123-7.

Contreras, C., M. E. Martín, N. Martínez-Navarrete, and A. Chiralt. 2005. Effect of vacuum impregnation and microwave application on structural changes which occurred during air-drying of apple. *LWT - Food Science and Technology* 38 (5):471–7. doi: 10.1016/j.lwt.2004.07.017.

Correa, J. L. G., S. R. S. Dev, Y. Gariepy, and G. S. V. Raghavan. 2011. Drying of pineapple by microwave-vacuum with osmotic pretreatment. *Drying Technology* 29 (13):1556–61. doi: 10.1080/07373937.2011.582558.

Cuccurullo, G., L. Giordano, A. Metallo, and L. Cinquanta. 2018. Drying rate control in microwave assisted processing of sliced apples. *Biosystems Engineering* 170:24–30. doi: 10.1016/j.biosystemseng.2018.03.010.

Cui, Z. W., C. Y. Li, C. F. Song, and Y. Song. 2008. Combined microwave-vacuum and freeze drying of carrot and apple chips. *Drying Technology* 26 (12):1517–23. doi: 10.1080/07373930802463960.

Dadali, G., D. K. Apar, and B. Özbek. 2007. Color change kinetics of okra undergoing microwave drying. *Drying Technology* 25:925–36. doi: 10.1080/07373930701372296.

Deng, L. Z., A. S. Mujumdar, Q. Zhang, X. H. Yang, J. Wang, Z. A. Zheng, Z. J. Gao, and H. W. Xiao. 2019. Chemical and physical pretreatments of fruits and vegetables: Effects on drying characteristics and quality attributes – A comprehensive review. *Critical Reviews in Food Science and Nutrition* 59 (9):1408–32.

Duan, X., M. Zhang, X. Li, and A. S. Mujumdar. 2008. Ultrasonically enhanced osmotic pretreatment of sea cucumber prior to microwave freeze drying. *Drying Technology* 26 (4):420–6. doi: 10.1080/07373930801929201.

Duan, X., M. Zhang, A. S. Mujumdar, and S. Wang. 2010a. Microwave freeze drying of sea cucumber (*Stichopus japonicus*). *Journal of Food Engineering* 96 (4):491–7. doi: 10.1016/j.jfoodeng.2009.08.031.

Duan, X., M. Zhang, A. S. Mujumdar, and R. Wang. 2010b. Trends in microwave-assisted freeze drying of foods. *Drying Technology* 28 (4):444–53. doi: 10.1080/07373931003609666.

Eikevik, T. M., O. Alves-Filho, and M. Bantle. 2012. Microwave-assisted atmospheric freeze drying of green peas: A case study. *Drying Technology* 30 (14):1592–9. doi: 10.1080/07373937.2012.700671.

Feng, H., and J. Tang. 1998. Microwave finish drying of diced apples in spouted bed. *Journal of Food Science* 63 (4):679–83. doi: 10.1111/j.1365-2621.1998.tb15811.x.

Figiel, A. 2007. Dehydration of apples by a combination of convective and vacuum-microwave drying. *Polish Journal of Food and Nutrition Sciences* 57 (4A):131–5.

Figiel, A. 2009. Drying kinetics and quality of vacuum-microwave dehydrated garlic cloves and slices. *Journal of Food Engineering* 94 (1):98–104.

Figiel, A. 2010. Drying kinetics and quality of beetroots dehydrated by combination of convective and vacuum-microwave methods. *Journal of Food Engineering* 98 (4):461–70.

Gaware, T. J., N. Sutar, and B. N. Thorat. 2010. Drying of tomato using different methods: Comparison of dehydration and rehydration kinetics. *Drying Technology* 28 (5):651–8. doi: 10.1080/07373931003788759.

Giri, S. K., and S. Prasad. 2007. Drying kinetics and rehydration characteristics of microwave-vacuum and convective hot-air dried mushrooms. *Journal of Food Engineering* 78 (2):512–21. doi: 10.1016/j.jfoodeng.2005.10.021.

Hobani, A. I., and S. R. Al-Askar. 2000. Effective thermal properties of dates. *Res. Bull* 92:5–20.

Horuz, E., H. J. Jaafar, and M. Maskan. 2017. Ultrasonication as pretreatment for drying of tomato slices in a hot air-microwave hybrid oven. *Drying Technology* 35 (7):849–59. doi: 10.1080/07373937.2016.1222538.

Hu, X., J. Kurian, Y. Gariepy, and V. Raghavan. 2017. Optimization of microwave-assisted fluidized bed drying of carrot slices. *Drying Technology* 35 (10):1234–48. doi: 10.1080/07373937.2016.1242014.

Huang, L. I., M. Zhang, A. S. Mujumdar, and R. X. Lim. 2011. Comparison of four drying methods for re-structured mixed potato with apple chips. *Journal of Food Engineering* 103 (3):279–84. doi: 10.1016/j.jfoodeng.2010.10.025.

Huang, L. I., M. Zhang, L. P. Wang, A. S. Mujumdar, and D. F. Sun. 2012. Influence of combination drying methods on composition, texture, aroma and microstructure of apple slices. *LWT - Food Science and Technology* 47 (1):183–8. doi: 10.1016/j.lwt.2011.12.009.

Huang, J., and M. Zhang. 2016. Effect of three drying methods on the drying characteristics and quality of okra. *Drying Technology* 34 (8):900–11. doi: 10.1080/07373937.2015.1086367.

Izli, G. 2017. Total phenolics, antioxidant capacity, colour and drying characteristics of date fruit dried with different methods. *Food Science and Technology* 37 (1):139–47.

Jia, X., S. Clements, and P. Jolly. 1993. Study of heat pump assisted microwave drying. *Drying Technology* 11 (7):1583–616. doi: 10.1080/07373939308916920.

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. *International Journal of Food Science & Technology* 46 (3):570–6. doi: 10.1111/j.1365-2621.2010.02523.x.

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 and Bioproducts Processing* 91 (4):464–72. doi: 10.1016/j.fbp.2013.04.004.

Jiang, N., Ch Liu, D. Li, Zh Zhang, Ch 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 Science and Technology* 82:216–26. doi: 10.1016/j.lwt.2017.04.015.

Junqueira, J. R. d J., J. L. G. Corrêa, and D. B. Ernesto. 2017. Microwave, convective, and intermittent microwave-convective drying of pulsed vacuum osmodehydrated pumpkin slices. Journal of Food Processing and Preservation 41 (6):e13250. doi:964 10.1111/jfpp.13250.

Kiranoudis, C. T., E. Tsami, and Z. B. Maroulis. 1997. Microwave vacuum drying kinetics of some fruits. *Drying Technology* 15 (10):2421–40. doi: 10.1080/07373939708917368.

Kone, K. Y., C. Druon, E. Z. Gnimpieba, M. Delmotte, A. Duquenoy, and J. C. Laguerre. 2013. Power density control in microwave assisted air drying to improve quality of food. *Journal of Food Engineering* 4:750–7. doi: 10.1016/j.jfoodeng.2013.06.044.

Korzeniowska, M., A. Figiel, K. Lech, M. Oziembłowski, and M. Szarycz. 2011. Sensory properties of pumpkintreated with sucrose osmotic solutions followed by vacuum-microwave drying. In *Product development and quality assurance*, eds. A. Jarmoluk, M. Oziembłowski, and A. Zimoch, 157–170. Wroclaw, Poland: UWP.

Kumar, D., S. Prasad, and G. S. Murthy. 2014. Optimization of microwave-assisted hot air drying conditions of okra using response surface methodology. Journal of Food Science and Technology 51 (2):221–32. doi: 10.1007/s13197-011-0487-9.

Lech, K., A. Figiel, A. Wojdyło, M. Korzeniowska, M. Serowik, and M. Szarycz. 2015. Drying kinetics and bioactivity of beetroot slices pretreated in concentrated chokeberry juice and dried with vacuum microwaves. *Drying Technology* 33 (13):1644–53. doi: 10.1080/07373937.2015.1075209.

Leusink, G. J., D. D. Kitts, P. Yaghmaee, and T. Durance. 2010. Retention of antioxidant capacity of vacuum microwave dried cranberry. *Journal of Food Science* 75 (3):311–6.

Lewicki, P. P., and R. P. Pawlak. 2005. Effect of osmotic dewatering on apple tissue structure. *Journal of Food Engineering* 66 (1):43–50. doi: 10.1016/j.jfoodeng.2004.02.032.

Li, Z., G. S. V. Raghavan, and V. Orsat. 2010a. Optimal power control strategies in microwave drying. *Journal of Food Engineering* 99 (3):263–8. doi: 10.1016/j.jfoodeng.2010.02.024.

Li, Z., G. S. V. Raghavan, and V. Orsat. 2010b. Temperature and power control in microwave drying. *Journal of Food Engineering* 97 (4):478–83. doi: 10.1016/j.jfoodeng.2009.11.004.

Liu, Z., M. Zhang, Z. Fang, B. Bhandari, and Z. Yang. 2017. Dehydration of asparagus cookies by combined vacuum infrared radiation and pulse-spouted microwave vacuum drying. *Drying Technology* 35 (11):1291–301. doi: 10.1080/07373937.2017.1330755.

Markowski, M., J. Bondaruk, and W. Błaszczak. 2009. Rehydration behavior of vacuum-microwave-dried potato cubes. *Drying Technology* 27 (2):296–305. doi: 10.1080/07373930802606600.

Martynenko, A., and M. A. Janaszek. 2014. Texture changes during drying of apple slices. *Drying Technology* 32 (5):567–77. doi: 10.1080/07373937.2013.845573.

Mattea, M., M. J. Urbicain, and E. Rotstein. 1989. Computer model of shrinkage and deformation of cellular tissue during dehydration. Chemical Engineering Sciences 44 (12):2853–9. doi: 10.1016/0009-2509(89)85095-X.

Mayor, L., and A. M. Sereno. 2004. Modelling shrinkage during convective drying of food materials: A review. *Journal of Food Engineering* 61 (3):373–86. doi: 10.1016/S0260-8774(03)00144-4.

Mierzwa, D., S. J. Kowalski, and J. Kroehnke. 2017. Hybrid drying of carrot preliminary processed with ultrasonically assisted osmotic dehydration. *Food Technology and Biotechnology* 55 (2):197–205.

Monteiro, R. L., B. A. M. Carciofi, and J. B. Laurindo. 2016. A microwave multi-flash drying process for producing crispy bananas. *Journal of Food Engineering* 178:1–11. doi: 10.1016/j.jfoodeng.2015.12.024.

Mothibe, K. J., C. Y. Wang, A. S. Mujumdar, and M. Zhang. 2014. Microwave-assisted pulse-spouted vacuum drying of apple cubes. *Drying Technology* 32 (15):1762–8. doi: 10.1080/07373937.2014.934830.

Musielak, G., and A. Kieca. 2014. Influence of varying microwave power during microwave-vacuum drying on the drying time and quality of beetroot and carrot slices. *Drying Technology* 32 (11):1326–33. doi: 10.1080/07373937.2014.924135.

Nahimana, H., and M. Zhang. 2011. Shrinkage and color change during microwave vacuum drying of carrot. *Drying Technology* 29 (7):836–47. doi: 10.1080/07373937.2011.573753.

Nowak, K. W., E. Ropelewska, A.E.D.A. Bekhit, and M. Markowski. 2017. Ultrasound applications in meat industry. In *Advances in meat processing technology*, edited by A. E. D. A. Bekhit, 1–30. Boca Raton, FL: CRC Press.

Nowicka, P., A. Wojdyło, K. Lech, and A. Figiel. 2015. Influence of osmodehydration pretreatment and combined drying method on the bioactive potential of sour cherry fruits. *Food and Bioprocess Technology* 8 (4):824–36. doi: 10.1007/s11947-014-1447-y.

Pei, F., Y. Shi, X. Gao, F. Wu, A. M. Mariga, W. Yang, L. Zhao, X. An, Z. Xin, F. Yang, and Q. Hu. 2014. Changes in non-volatile taste components of button mushroom (*Agaricus bisporus*) during different stages of freeze drying and freeze drying combined with microwave vacuum drying. *Food Chemistry* 165:547–54. doi: 10.1016/j.foodchem.2014.05.130.

Pereira, N. R., A. Marsaioli, and L. M. Ahrné. 2007. Effect of microwave power, air velocity and temperature on the final drying of osmotically dehydrated bananas. *Journal of Food Engineering* 81 (1):79–87. doi: 10.1016/j.jfoodeng.2006.09.025.

Qiao, F., L. I. Huang, and W. S. Xia. 2012. A study on microwave vacuum dried re-structured lychee (*Litchi chinensis* Sonn.) mixed with purple sweet potato (*Ipomoea batatas*) snack. *Food and Bioproducts Processing* 90 (4):653–8. doi: 10.1016/j.fbp.2012.05.002.

Que, F., L. Mao, X. Fang, and T. Wu. 2008. Comparison of hot air drying and freeze drying on the physicochemical properties and antioxidant activities of pumpkin (*Cucurbita moschata Duch.*) flours. International Journal of Food Science & Technology 43 (7):1195–201. doi: 10.1111/j.1365-2621.2007.01590.x.

Raghavan, G. S. V., Z. Li, N. Wang, and Y. Gariepy. 2010. Control of microwave drying process through aroma monitoring. *Drying Technology* 28 (5):591–9. doi: 10.1080/07373931003788049.

Rahman, M. S., and G. S. Al-Saidi. 2009. Thermal diffusivity of foods: Measurement, data, and prediction. In *Food properties handbook*, edited by M. S. Rahman. 2nd ed., 649–97. Boca Raton, FL: CRC Press.

Şahin, S., E. Elhussein, M. Bilgin, J. M. Lorenzo, F. J. Barba, and S. Roohinejad. 2018. Effect *of* drying method *on* oleuropein, total phenolic content, flavonoid content *and* antioxidant activity *of* olive *(Olea europaea)* leaf. *Journal of Food Processing and Preservation* 42:1–10.

Setiady, D., C. Clary, F. Younce, and B. A. Rasco. 2007. Optimizing drying conditions for microwave-vacuum (mivac®) drying of russet potatoes (Solanum tuberosum). *Drying Technology* 25 (9):1483–1489.

Setiady, D., J. Tang, F. Younce, B. A. Swanson, B. A. Rasco, and C. D. Clary. 2009. Porosity, color, texture, and microscopic structure of russet potatoes dried using microwave vacuum, heated air, and freeze drying. *Applied Engineering in Agriculture* 25 (5):719–24.

Sharma, G. P., and S. Prasad. 2001. Drying of garlic (*allium sativum*) cloves by microwave-hot air combination. *Journal of Food Engineering* 50 (2):99–105. doi: 10.1016/S0260-8774(00)00200-4.

Schulze, B., E. M. Hubbermann, and K. Schwarz. 2014. Stability of quercetin derivatives in vacuum impregnated apple slices after drying (microwave vacuum drying, air drying, freeze drying) and storage. *LWT - Food Science and Technology* 57 (1):426–33. doi: 10.1016/j.lwt.2013.11.021.

Soysal, Y., Z. Ayhan, O. Eştürk, and M. F. Arıkan. 2009. Intermittent microwave-convective drying of red pepper: Drying kinetics, physical (color and texture) and sensory quality. *Biosystems Engineering* 103 (4):455–63. doi: 10.1016/j.biosystemseng.2009.05.010.

Stępień, B. 2008. Effect of vacuum-microwave drying on selected mechanical and rheological properties of carrot. *Biosystems Engineering* 99 (2):234–8. doi: 10.1016/j.biosystemseng.2007.10.013.

Sultana, B., F. Anwar, M. Ashraf, and N. Saari. 2012. Effect of drying techniques on the total phenolic contents and antioxidant activity of selected fruits. *Journal of Medicinal Plants Research* 6 (1):161–7.

Sunjka, P. S., V. Orsat, and G. S. V. Raghavan. 2008. Microwave/vacuum drying of cranberries (*Vacccinium macrocarpon*). American Journal of Food Technology 3 (2):100–8. doi: 10.3923/ajft.2008.100.108.

Therdthai, N., and H. Northongkom. 2011. Characterization of hot air drying and microwave vacuum drying of fingerroot (*Boesenbergia pandurata*). *International Journal of Food Science & Technology* 46 (3):601–7. doi: 10.1111/j.1365-2621.2010.02525.x.

Therdthai, N., and W. Zhou. 2009. Characterization of microwave vacuum drying and hot air drying of mint leaves (*Mentha cordifolia Opiz ex Fresen*). *Journal of Food Engineering* 91 (3):482–9. doi: 10.1016/j.jfoodeng.2008.09.031.

Tsuruta, T., H. Tanigawa, and H. Sashi. 2015. Study on shrinkage deformation of food in microwave–vacuum drying. *Drying Technology* 33 (15–16):1830–1836.

Turner, I. W., and P. G. Jolly. 1991. Combined microwave and convective drying of a porous material. *Drying Technology* 9 (5):1209–69. doi: 10.1080/07373939108916749.

Wang, J., J. K. Carson, M. F. North, and D. J. Cleland. 2008. A new structural model of effective thermal conductivity for heterogeneous materials with co-continuous phases. *International Journal of Heat and Mass Transfer* 51 (9–10):2389–97. doi: 10.1016/j.ijheatmasstransfer.2007.08.028.

Wang, R., M. Zhang, and A. S. Mujumdar. 2010. Effects of vacuum and microwave freeze drying on microstructure and quality of potato slices. *Journal of Food Engineering* 101 (2):131–9. doi: 10.1016/j.jfoodeng.2010.05.021.

Wang, Y., M. Zhang, A. S. Mujumdar, and K. J. Mothibe. 2013. Microwave-assisted pulse-spouted bed freeze-drying of stem lettuce slices – Effect on product quality. *Food and Bioprocess Technology* 6 (12):3530–43. doi: 10.1007/s11947-012-1017-0.

Williams, A. R. 1983. *Ultrasound: Biological effects and potential hazards*. New York, NY: Academic Press.

Yan, W. Q., M. Zhang, L. L. Huang, J. Tang, A. S. Mujumdar, and J. C. Sun. 2010. Studies on different combined microwave drying of carrot pieces. *International Journal of Food Science & Technology* 45 (10):2141–8.

Yang, H., N. Sakai, and M. Watanabe. 2001. Drying model with nonisotropic shrinkage deformation undergoing simultaneous heat and mass transfer. *Drying Technology* 19 (7):1441–60. doi: 10.1081/DRT-100105299.

Zhang, M., J. Tang, A. S. Mujumdar, and S. Wang. 2006. Trends in microwave related drying of fruits and vegetables. *Trends in Food Science and Technology* 17 (10):524–34. doi: 10.1016/j.tifs.2006.04.011.

Zhang, Z., Q. Wei, C. Liu, D. Li, C. Liu, and N. Jiang. 2017. Comparison of four pretreatments on the drying behaviour and quality of taro (*Colocasia esculenta* L. *Schott*) slices during intermittent microwave vacuum-assisted drying. *Drying Technology* 35 (11):1347–57. doi: 10.1080/07373937.2017.1323761.

Zhang, F., M. Zhang, and A. S. Mujumdar. 2011. Drying characteristics and quality of restructured wild cabbage chips processed using different drying methods. *Drying Technology* 29 (6):682–8. doi: 10.1080/07373937.2010.525729.

Zielinska, M., P. Zapotoczny, O. Alves-Filho, T. M. Eikevik, and W. Blaszczak. 2013. Microwave vacuum-assisted drying of green peas using heat pump and fluidized bed: A comparative study between atmospheric freeze drying and hot air convective drying. *Drying Technology* 31 (6):633–42. doi: 10.1080/07373937.2012.751921.

Zielinska, M., P. Sadowski, and W. Błaszczak. 2016. Combined hot air convective drying and microwave-vacuum drying of blueberries *(Vaccinium corymbosum* L.): Drying kinetics and quality characteristics. *Drying Technology* 34 (6):665–84. doi: 10.1080/07373937.2015.1070358.

Zielinska, M., P. Sadowski, and W. Błaszczak. 2015. Freezing/thawing and microwave-assisted drying of blueberries (*Vaccinium corymbosum* L.). *LWT - Food Science and Technology* 62 (1):555–63. doi: 10.1016/j.lwt.2014.08.002.

Zielinska, M., and M. Markowski. 2016. The influence of microwave-assisted drying techniques on the rehydration behavior of blueberries (*Vaccinium corymbosum* L.).). *Food Chemistry* 196:1188–96. doi: 10.1016/j.foodchem.2015.10.054.

Zielinska, M., and A. Michalska. 2016. Microwave-assisted drying of blueberry (*Vaccinium corymbosum* L.) fruits: Drying kinetics, polyphenols, anthocyanins, antioxidant capacity, colour and texture. *Food Chemistry* 212:671–80. doi: 10.1016/j.foodchem.2016.06.003.

Zielinska, M., and A. Michalska. 2018. The influence of convective, microwave vacuum and microwave-assisted drying on blueberry pomace physicochemical properties. *International Journal of Food Engineering* 14 (3):0170332. doi: 10.1515/ijfe-2017-0332.

Zielinska, M., E. Ropelewska, and M. Markowski. 2017. Thermophysical properties of raw, hot-air and microwave-vacuum dried cranberry fruits (*Vaccinium macrocarpon* L.). *LWT - Food Science and Technology* 85:204–11. doi: 10.1016/j.lwt.2017.07.016.

Zielinska, M., and D. Zielinska. 2019. Effects of freezing, convective and microwave-vacuum drying on the content of bioactive compounds and color of cranberries. *LWT - Food Science and Technology* 104:202–9. doi: 10.1016/j.lwt.2019.01.041.

Zielinska, M., M. Markowski, and D. Zielinska. 2019. The effect of freezing on the hot air and microwave vacuum drying kinetics and texture of whole cranberries. *Drying Technology*. doi: 10.1080/07373937.2018.1543317.