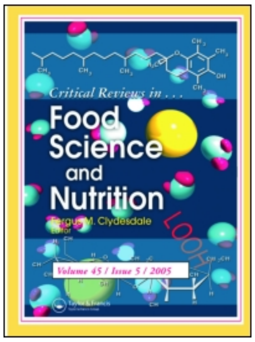

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Recent developments in high-quality drying of vegetables, fruits, and aquatic products

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ABSTRACT
Fresh foods like vegetables, fruits, and aquatic products have high water activity and they are highly heat-sensitive and easily degradable. Dehydration is one of the most common methods used to improve food shelf-life. However, drying methods used for food dehydration must not only be efficient and economic but also yield high-quality products based on flavor, nutrients, color, rehydration, uniformity, appearance, and texture. This paper reviews some new drying technologies developed for dehydration of vegetables, fruits, and aquatic products. These include: infrared drying, microwave drying, radio frequency drying, electrohydrodynamic drying, etc., as well as hybrid drying methods combining two or more different drying techniques. A comprehensive review of recent developments in high-quality drying of vegetables, fruits and aquatic products is presented and recommendations are made for future research.

KEYWORDS
Hybrid drying; high-quality; new developments; vegetables; fruits; aquatic products

Introduction

In general, food high-quality drying can be defined as a special drying technology, which protects qualities of fresh foods such as color, flavor, nutrients, rehydration, appearance, and uniformity during drying process. Some high-efficiency, energy-saving, and environment friendly drying technologies such as solar drying, heat pump drying, superheated steam drying, freeze drying as well as multistage combined drying have gradually replaced traditional drying technologies to concurrently shorten drying time and improve product quality (Wang et al., 2011b). Field assisted methods have been attempted for newer drying techniques which include electromagnetic heating (infrared), dielectric heating (radio frequency and microwave), inductive heating, and ohmic heating as well as heating in external fields such as pulsed electric field, ultrasound and ultraviolet light (Vishwanathan et al., 2010). While applications of microwave and infrared radiation for food dehydration are established to some extent, utilization of other techniques such as radio frequency drying and microwave-assisted pulse-spouted bed freeze-drying has gained momentum only in the recent past.

Raw vegetables, fruits, and aquatic products have high water activity and are highly susceptible to mechanical damage, microbial spoilage and environmental conditions thus perishable (Huang and Zhang, 2012). Water is one of the most important components of foods, affecting fat oxidation, microbiological growth, flavor and texture of dried food products. Food material exposed to environment loses or gains water to adjust its proper moisture content to an equilibrium state with the environment of relative humidity (Fan et al., 2005). Dehydration is one of the most common processes used to improve food storage stability, since it considerably decreases water activity of material, reduces microbiological activity and also is required to minimize physical and chemical changes of material (Mayor and Sereno, 2004). This processes can be broadly classified as thermal drying, osmotic drying and mechanical dewatering, based on water-removing method (Duan et al., 2005). Nowadays, drying has been successfully applied to food products due to reduction of moisture content to desirable level leading to safe storage over a long period and substantial reduction in weight and volume resulting in lower costs of package, storage, and transportation (Taheri-Garavand et al., 2011). Traditionally, foods like vegetables, fruits, and aquatic products are dried in open sunlight which is weather-dependent and contamination-prone (Goyal et al., 2008). In order to achieve consistent quality of dried product, industrial dryers like solar and convective dryers should be used (Kingsly et al., 2007; Oztop and Akpinar, 2008). However, the major disadvantages of convective drying are low energy efficiency and lengthy drying times during falling rate period of drying because of low thermal conductivity in inner sections of foods (Pan et al., 2008b). It is also well known that hot air drying results in much physical or chemical quality degradation (Swasdisevi et al., 2009).

Therefore, unsuitable drying process can induce degradation (e.g., oxidation, loss of color, or loss of nutritional-functional properties) and structural changes in the food (e.g., shrinkage, loss of texture, or causing variation in its original microstructure), such physical and chemical changes can render the food

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product unacceptable to consumers (Miranda et al., 2009). So, development of drying technologies is important for food and agro-products and new, high-quality, and consumer-attractive dehydrated foods are necessary to widen product availability and diversify markets. The present demand of high-quality dehydrated products in the market requires dried foods to maintain nutritional and organoleptic properties of initial fresh products at very high levels (Mayor and Sereno, 2004). Above all, new drying technologies are needed for dried products with better quality control, environment friendly, higher energy efficiency, lower cost, and safer operation (Mujumdar and Law, 2010).

The objectives of this article are to present an overview of the recent developments in the high-quality drying of vegetables, fruits and aquatic products. It also examines the relative advantages of those technologies in maintaining the quality of dried foods and highlights prospect of further research and possible industrial applications.

High-quality drying methods of vegetables, fruits, and aquatic products based on six aspects

Generally, the quality of dehydrated food product is mainly determined by the following six parameters. (1) Retention of flavor substances which greatly influence organoleptic quality of dried products (Chin et al., 2008). (2) Retention of nutrients, especially heat-sensitive and oxygen-sensitive substances like vitamins A, C, and thiamine (Sagar and Suresh, 2010). (3) Inhibition of browning to keep desirable color which is closely associated with factors such as freshness, desirability and food safety (Arabhosseini et al., 2009). (4) Rehydration, which represents the ability of restoring fresh product properties when dried material is in rehydration solution (Contreras et al., 2012). (5) In addition, quality uniformity is also very important for dried products, which can be measured on the basis of temperature, moisture content, color difference, shrinkage, and so on (Wang et al., 2012d). (6) Appearance and texture which are results of complex interactions among food components at macro-structural and microstructural levels.

Study of high-quality drying technologies is critical to maintain these quality attributes of food for its high moisture content, heat-sensitive, and easy degradation characteristics. Recent researches on six aspects of quality of products dried by different methods are presented in Table 1. From this table, pretreatment methods and suitable drying processes and conditions can improve the quality of dried products. Pretreatments like blanching and dipping are benefit to color, rehydration, and nutritional content of products upon drying. Sometimes, rapid drying retains more heat-sensitive nutrients like vitamin C. According to many references, freeze-drying is one of dehydration methods with final products of highest quality compared with the other methods (Abbasi and Azari, 2009). However, this method always needs a long time and high cost. Thus, many researches on combined freeze drying with other drying method were studied to improve drying rate and reduce energy consumption on the premise of high product quality. In addition, the drying uniformity is closely related to product quality, especially for dielectric dried products. The improvement of drying uniformity of microwave energy was undergone by magnetron arrangement (Wang et al., 2013a), rotating turntable (Geedipalli et al., 2007), starting microwave power in spouted bed (Yan et al., 2010b) and in pulse-spouted bed (Wang et al., 2012d).

Some high-quality drying techniques suitable for vegetables, fruits, and aquatic products

Common hot-air drying typically requires about two thirds of total drying time for removing the final one-third moisture content. Moreover, it may destroy thermo-labile components and cause solute migration and formation of a crust (Xu et al., 2004). So, more and more high-quality drying techniques suitable for vegetables, fruits, and aquatic products have been studied.

Air impingement drying

Air impingement drying has been successfully used in paper and textile industries because of rapid drying rate (Lujan-Acosta et al., 1997). During its processing, the air impinges on product surface at high velocity, and removes the boundary layer of moisture and cold air, thus greatly promoting heat transfer and reducing drying time (Moreira, 2011; Anderson and Singh, 2006). Impingement drying of corn tortillas (Lujan-Acosta et al., 1997), potato chips (Moreira, 2011), carrot cubes (Xiao et al., 2010a), yam slices (Xiao et al., 2012), and grapes (Xiao et al., 2010b) has been investigated.

Fluidized-bed drying (FBD)

Fluidized-bed drying (FBD) plays an important role in drying of granular materials owing to its good performance, low investment, and robustness of respective equipment (Peglow et al., 2011). This drying technique provides good mixing as well as excellent heat and mass transfer between materials and drying medium. It not only gives higher drying rate but also has been proved to yield high-quality dried materials in some cases (Wang et al., 2012a). FBD is particularly available for drying granular food stuff, such as waxy rice (Jaiboon et al., 2011), soybean (Dondee et al., 2011), sliced potato (Lozano-Acevedo et al., 2011), milky mushroom slices (Arumuganathan et al., 2009), maize (Janas et al., 2010), carrots (Zielinska and Markowski, 2010), olive pomace (Meziane, 2011).

Low-pressure superheated steam drying (LPSSD)

Superheated steam drying (SSD) also has been applied to many food products successfully during the past decade. The advantages of SSD include environment-friendly method, prevention of fire and explosion hazards, low energy consumption, high-drying rate, and high quality of dried products under certain conditions (Sa-adchom et al., 2011). However, there still exist some limitations when applying SSD to dry heat-sensitive materials (Nimmol et al., 2007b). So a concept of using superheated steam at reduced pressure (low-pressure superheated steam, LPSS) to dry heat- and oxygen-sensitive products has been tested and shown to be effective in preserving both

Table 1. Recent studies on six aspects of quality of products dried by different drying methods.

Quality Indicators	Drying methods	Materials	References	Conclusions
Flavor	Freeze-drying (FD), Oven-drying (OD)	Grape skin	(De Torres et al., 2010)	FD method was less aggressive than OD methods.
	Microwave drying (MD), silica gel drying (SGD), oven drying (OD)	Ginger	(Huang et al., 2012a)	The volatiles of SGD ginger were similar to those of fresh ginger, and MD ginger had a higher content of zingiberene and satisfactory dehydration efficiency.
	FD + MVD, MVD + FD, FD	Apple slices	(Huang et al., 2012b)	Aroma retention in FD + MVD samples was better than MVD + FD products and worse than FD samples.
Nutrition	MVD, MFD, MWSD	Carrot pieces	(Yan et al., 2010a)	The highest retention of carotene and vitamin C was observed in MFD carrot pieces and no significant differences were observed between MVD and MWSD products.
	FD + MVD, MVD + FD, FD	Apple slices	(Huang et al., 2012b)	The contents of reducing sugars, total pectin and lower total phenols: FD + MVD > FD > MVD + FD.
	HAD, VD, VFD	Ganoderma lucidum	(Fan et al., 2012)	Vacuum freeze drying was an appropriate and effective treatment for obtaining the polysaccharide from G. lucidum.
Color	HAD, MD	Apricots	(García-Martínez et al., 2013)	The use of microwave energy, either in combination or not with mild-hot air, may be recommended to obtain dried apricots, without needing to apply sulfur pretreatment.
	HAD, VD, LSSSD	Cabbage	(Phungamngoen et al., 2013)	Dried blanched (blanching in hot water for 4 min or blanching with saturated steam for 2 min) samples exhibited greener and darker color than the dried acetic acid pretreated (soaking in 0.5% (v/v) acetic acid for 5 min) and untreated samples.
	FD, MFD	banana chips	(Jiang et al., 2013)	Compared with FD, the MFD method that increased the heating powder in the secondary drying stage could potentially be an effective method to reduce the energy consumption without seriously sacrificing the color of the end product.
Rehydration	HAD	Red Pepper	(Doymaz and Kocayigit, 2012)	Samples pre-treated with ethyl oleate and citric acid solutions before drying had higher rehydration ratio compared with untreated samples.
	Microwave drying coupled with air drying	Apricot and apple	(Contreras et al., 2012)	Vacuum impregnation pretreatment and microwave application to air drying allow us to obtain a dried product with a better rehydration capacity.
	Explosion puffing drying	Mango chips	(Zou et al., 2013)	The nonpretreated samples had a higher glass transition temperature, expansion ratio and rehydration ratio and lower hardness and crispness values than the osmotic pretreated samples.
Uniformity	MWD		(Geedipalli et al., 2007)	The carousel (i.e. a rotating turntable in microwave ovens) helps in increasing the temperature uniformity of the food by about 40%.
	MWD	Carrot	(Wang et al., 2013a)	The drying uniformity was influenced by magnetron location and quantity.
	MVD, MFD, MWSD	Carrot pieces	(Yan et al., 2010a)	Color of MWSD products was very uniform.
	MSFD	Stem lettuce slices	(Wang et al., 2012d)	Microwave freeze-dried products in the pulse-spouted mode dried more uniformly as compared to those dried in steady spouted bed mode.
	MSVD	Stem lettuce slices	(Wang et al., 2013b)	MSVD products were found to be more uniform compared to those obtained in a conventional rotating turntable MW dryer.
Appearance and Texture	MFD, FD, MVD, VD	Re-structured mixed potato with apple chips	(Huang et al., 2011)	The crispness and hardness of MFD mixed chips were both higher than those of FD chips. The crispness of MVD chips was higher than that of VD chips and the hardness of MVD chips was lower than that of VD chips.
	MVD, MFD, MWSBD	Re-structured purple-fleshed sweet potato Granules	(Liu et al., 2012)	Maximum penetration force of MWSBD-treated sample was lowest. MWSBD may be an alternative way to MWFD with measurements to maintain the anthocyanin level.
	SIRFD	Banana	(Pan et al., 2008b)	The sample processed with SIRFD had much higher crispness than the samples processed with regular freeze-drying. Drying method and acid dip had a significant effect on crispness of the final product.

physical and chemical properties of many food products, such as cabbage (Phungamngoen et al., 2013), potato chips (Pimpaporn et al., 2007; Kingcam et al., 2008), carrot (Devahastin et al., 2004), mangosteen rind (Suvarnakuta et al., 2011), banana (Nimmol et al., 2007a), and fish meal (Nygaard and Hostmark, 2008).

Freeze drying (FD)

Freeze drying is a method in which water is removed from material by sublimation (Lewicki, 2006). This drying process is conventionally divided into three stages: pre-freezing of wet material, primary drying stage (sublimation of frozen solvent under vacuum), and secondary drying stage (desorption of residual bound water from material matrix) (Nastaj and Ambrożek, 2006; Nastaj and Witkiewicz, 2009). To improve storage stability of dried products, residual water after the primary drying stage may further be removed by desorption in the secondary drying stage (Nam and Song, 2007). Low temperature and pressure below the triple point of water render excellent quality to freeze-dried products. Thus, this process generates minor changes in color, flavor, chemical composition and texture and its product quality is considered as the highest of any dehydration techniques (Nawirska et al., 2009). As freeze-drying is a very time-consuming and therefore expensive process, it is of major importance for industry to maximize process efficiency (De Beer et al., 2007).

Infrared radiation drying

Medium and far Infrared radiation (IR) sources (wavelengths of 2–100 μm) have been investigated for drying agricultural products (Pan et al., 2008a), which also has been considered as a potential method for obtaining high-quality dried food stuffs (Vishwanathan et al., 2010). The radiation impinges on exposed food surfaces and penetrates to convert into an internal heating with molecular vibration of the material (Pan et al., 2008b). The use of IR for dehydrating foods could reduce drying time, increase energy efficiency, maintain uniform drying temperature in food, as well as kill microorganism and inhibit enzymatic reaction to some extent, and therefore produce better-quality products (Krishnamurthy et al., 2008).

Dielectric drying

The electromagnetic energy of microwave and radio frequency can directly interact with foods interior to quickly raise center temperature, because most foods as dielectric materials can store electric energy and convert it into heat (Sisquella et al., 2014). Compared to conventional drying, dielectric heating has a more rapid rise-up time to target temperature owning to its phenomenon of volumetric heating (Wang et al., 2006).

Microwave drying

Microwave (MW), a relatively mature technology in drying food, can penetrate materials and heat products without supplemental thermal gradients, which contributes to heat transfer during dehydration (Jiang et al., 2010b). Microwave energy at 915 and 2450 MHz can be absorbed by water-containing materials or other “lossy” substances, such as carbohydrate and some organics, and thus can be converted to heat (Karaaslan and Tunçer, 2008). However, MW heating has several drawbacks, such as inherent nonuniformity, limited penetration depth, and “puffing” phenomenon (Zhang et al., 2006).

Radio frequency drying

The need to achieve fast and effective thermal treatment has resulted in the increased use of radio frequency (RF) energy to heat foods (Sisquella et al., 2014). RF energy generates heat volumetrically within wet material based on combined mechanisms of dipole rotation and conduction effects which speed drying process (Marshalla and Metaxasa, 1999). The free-space wavelength in the RF range is 20–360 times longer than that of commonly used MW frequencies, allowing RF energy to penetrate foods more deeply and provide better heating uniformity in materials than microwave energy (Wang et al., 2012b). Therefore, RF (13.56, 27.12, and 40.68 MHz for industrial applications) thermal processes have the potential to reduce thermal quality degradation in drying food (Luechapattanaporn et al., 2005). However, major challenges with adopting RF heating in the food industry are still nonuniform heating and runaway heating, which cause overheating in corners, edges, and center parts, especially in foods of intermediate and high water content (Alfaifi et al., 2014).

Electrohydrodynamic drying (EHD)

Electrostatic field treatment applied in drying is less known than conventional drying technologies based on conduction, radiation, or other types of heat transfer (Esehaghbeygi and Basiry, 2011). Electrohydrodynamic drying, a novel nonthermal drying technique, is an attractive candidate for drying heat-sensitive materials (Ahmedou et al., 2009). This drying method uses a high electric field which consists of one or multiple point electrode and a plate electrode to improve its drying rate (Li et al., 2006). Allen and Karayiannist (1995) proposed that three major means for EHD to enhance single-phase convective heat transfer are by flow of “corona wind”, by electrophoresis, and by dielectrophoretic forces. The decreasing temperature in EHD process is partly due to rapid evaporative cooling and also reduced entropy because of dipole orientation in electric field. Compared with convective and freeze drying, EHD drying systems have a simpler design and therefore consume less energy (Bajgai et al., 2006). A few studies have been implemented to investigate the effect of corona discharge on dehydration of some foods, like okara cake (Li et al., 2006), rapeseed (Basiry and Esehaghbeygi, 2010), tomato slices (Esehaghbeygi and Basiry, 2011), sea cucumber (Bai et al., 2013), scallop muscle (Bai et al., 2012a), and shrimps (Bai and Sun, 2011).

Recent combined drying technologies suitable for vegetables, fruits, and aquatics

Nowadays some new techniques such as MW-, IR-, and RF-assisted drying have been applied to shorten drying time and improve final quality of dried products (Köse and Erentürk, 2010). Many different combinations of drying methods were used to avoid disadvantages of single drying method such as long drying time, high power consumption, or low product quality (Huang et al., 2012b). Combined drying methods include parallel and tandem drying. Parallel drying uses two or more drying methods which are implemented simultaneously, such as most field assist drying methods. Tandem drying involves the use of one drying method followed by one or more other drying methods (Huang and Zhang, 2012), recent researches are shown in Table 2.

Table 2. Applications of multistage combined drying for vegetables, fruits, and aquatic products.

Combining orders	Materials	Conversion Points	Advantages	References
VFD + AD	Bamboo shoots	24.4% (d.b.)	Sensory, nutrition, cell structure and rehydration ratio were superior to these of single AD drying; Gross energy consumption was 21% lower than that of single FD drying.	(Xu et al., 2005)
VFD + AD	Strawberries	31.98% (w.b.)	Lower cost than VFD.	(Xu et al., 2006)
IR + FD	Banana	20% and 40% weight reductions	Higher drying rate than FD and producing high crispy banana chips.	(Pan et al., 2008b)
FD + MVD	Apple slices	37.12% (w.b.)	Better appearance, with a savings of 39.20% in invalid energy consumption	(Huang et al., 2009)
MVD + FD	Carrot and apple chips	48%, 37% (w.b.)	Higher drying rate than FD and carotene and vitamin C retention, rehydration capacity, color retention, and texture were close to FD.	(Cui et al., 2008)
HP-FB-AFD + MVD	Green peas	2.07 ± 0.11 kg/kg (d.b.)	Minimal shrinkage (20%) and desirable porous inner structure.	(Zielinska et al., 2013)
SSD + HAD	Logan	200% (d.b.)	Better color	(Somjai et al., 2009)
EHD + FD	Sea cucumber	40 ± 1% (d.b.)	Less drying time and has lower energy consumption, lower shrinkage, higher rehydration rate and higher protein content	(Bai et al., 2012b)

HP-FB-AFD: heat pump-fluidized bed atmospheric freeze drying.

Parallel combined drying

RF-related combined drying

Radio frequency assisted hot air drying (RFHAD). According to Thomas (1996), RF heats all parts of the product mass and evaporates the water at relatively low temperature. It is suggested that limitation of heat transfer in convective drying with hot air alone can be overcome by combining RF heat with conventional convective drying (Patel and Kar, 2012). A schematic diagram of RFHAD dryer (SO 6B, Monga Strayfield, Pune, Maharashtra, India) with two built-in hot air blowing system under RF applicator and a controller for temperature and air flow is presented in Figure 1. Roknul et al. (2014) reported that the RFHAD yielded a uniform drying and the quality of the RFHAD samples was better than hot air drying, infrared drying, and microwave-assisted hot air drying.

Radio frequency assisted heat pump drying (RFHPD). Marshalla and Metaxasa (1999) combined RF energy with heat pump batch drier, and showed several improvements resulting from the combined drying process. This RFHPD reduces discoloring of dried products, especially those that are highly susceptible to surface color change. Also, cracking caused by stress due to uneven shrinkage during drying, can be eliminated by RF assisted drying (Patel and Kar, 2012). The schematic diagram of RF-assisted heat pump dryer has been given in Figure 2.

MW-related combined drying

There are some strategies to increase energy efficiency in MW drying such as using a combination of MW and traditional drying systems, applying microwave under vacuum (MVD) (Wang et al., 2012e), combining microwave heating with freeze drying (MFD) (Jiang et al., 2010a), and applying intermittent/

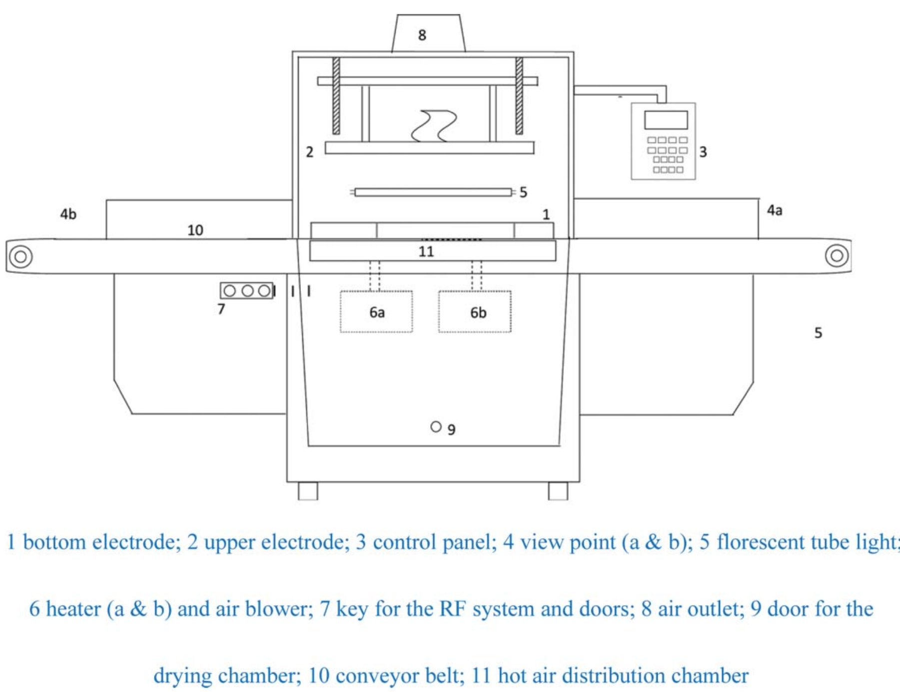


Figure 1. A schematic diagram of hot air-assisted radio frequency dryer (Roknul et al., 2014). 1 bottom electrode; 2 upper electrode; 3 control panel; 4 view point (a & b); 5 florescent tube light; 6 heater (a & b) and air blower; 7 key for the RF system and doors; 8 air outlet; 9 door for the drying chamber; 10 conveyor belt; 11 hot air distribution chamber.

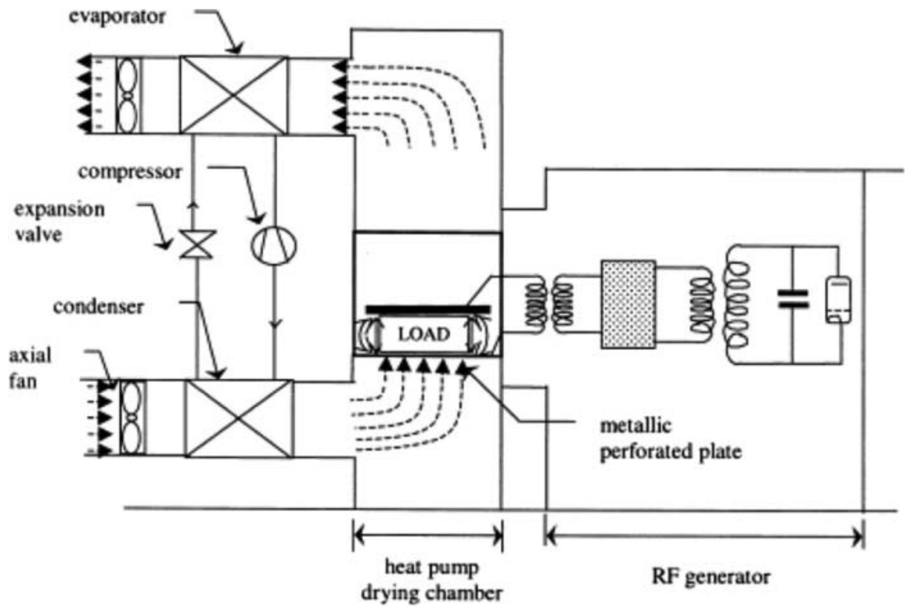


Figure 2. A schematic diagram of RF assisted heat pump dryer (Chua et al., 2002).

pulsed microwave instead of continuous MW (Arikan et al., 2011). How to embed MW energy in other drying is still a challenge, because different combinations will cause different drying characteristics and results. For instance, in early stage of MVD, food quality is almost maintained while in later stage, the temperature of sample with little available moisture might rapidly rise and the structure of dried food would be destroyed if MW power is not properly supplied (Cui et al., 2008). The uniformity of MVD products is influenced by many factors, such as vacuum cavity effects, product attributes, and their spatial location in the microwave cavity. So use of continuous MW generators and nonresonant multimode cavity, maintenance of good dielectric load in applicator, as well as reduction of wall losses and leakages were all benefited to efficiency and uniformity of MW driers (Wang et al., 2012c).

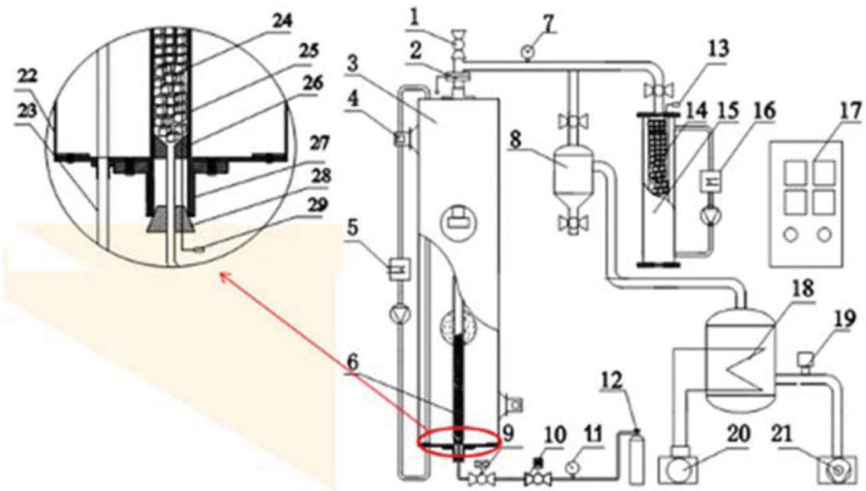
Microwave-enhanced spouted bed drying (MSBD). A microwave-enhanced spouted bed can produce more uniform drying. In spouted bed dryers, uniform exposure of product to microwave energy is achieved by pneumatic agitation. Fluidization also facilitates heat and mass transfers due to a constant renewed boundary layer at particle surface. Therefore, a combined fluidized or spouted bed is considered as an effective way to solve the uneven problem of MW drying (Yan et al., 2010b; Yan et al., 2013).

MVD in deep-bed drying and pulsed spouted microwave-vacuum drying (PSMVD). In vacuum condition, the contact between material and oxygen is limited and drying process can be undergone at low temperature (Nawirska et al., 2009). Vacuum expands air and water vapor present in the food and then forms a puffed structure, thus providing a large area-to-volume ratio for enhancing heat and mass transfer (Lee and Kim, 2009). Deep-bed drying in MW cavity can increase process efficiency and reduce running cost. Yet it needs to be well controlled to maintain good quality of final product (Hu et al., 2007). In the last few decades, many researchers have improved the uniformity of microwave drying, seen in Table 1. Lastly, Wang et al. (2013b) improved MVD uniformity by introducing a pulse pneumatic agitation in a laboratory system and found that PSMVD was more uniform and faster (reduced by 50% total drying time) compared to conventional rotating turntable microwave-dried ones.

Microwave-assisted pulse-spouted bed freeze-drying (PSMFD). Microwave freeze drying (MFD), i.e. FD assisted with MW heating, combines the advantages of FD and MW heating. Some research results showed that MFD can reduce 40% drying time compared with FD and provide similar quality (Jiang et al., 2010a, 2010b; Wang et al., 2010a, 2010b, 2010c). Aside from accelerating the drying rate, some researches show that MFD process can cause a reduction in microbial content of dried product (Duan et al., 2007). However, MFD products cannot hold their shape as well as FD ones, many problems still need to be resolved in practice (Jiang et al., 2010b). Four main technical problems of MFD were identified, including corona discharge, nonuniform heating, impedance matching, and efficiency of applicators (Duan et al., 2010b; Wang et al., 2012c). Wang et al. (2012d) improved drying uniformity of FD using microwave heating by introducing pneumatic pulse agitation in a laboratory system (Figure 3). Results showed that pulse-spouted bed mode resulted in dried stem lettuce slices with lower discoloration, more uniform and compact microstructure, higher rehydration capacity as well as greater hardness after rehydration over shorter drying time relative to those obtained in a steady spouting condition.

IR-related combined drying

Combination of IR radiation with convective heating or vacuum is considered to be more efficient over radiation or hot air heating alone (Pan et al., 2008b). A few reports have suggested that combing far-infrared radiation (FIR) with other dehydration techniques could shorten drying time, improve nutritional, sensorial, and functional properties of dried products, such as,



1 feeding ball valve; 2 plate valve with 3-mm diameter hole; 3 and 22 microwave heating cavity; 4 magnetron; 5 and 16 circulating water unit; 6 drying chamber for MFD and PSMFD; 7 and 11 pressure gauge; 8 solid–gas separator; 9 gas flow electromagnetic valve; 10 gas flow adjustable valve; 12 nitrogen gas source; 13 and 29 fiber optic temperature sensor; 14 and 24 sample; 15 drying chamber with a jacket for FD; 17 control panel; 18 vapor condenser; 19 vacuum pressure transducer; 20 refrigerator unit; 21 vacuum pump unit; 23 water load pipe; 25 Teflon tube; 26 gas distributer; 27 fixed unit for drying chamber holder; 28 silicon rubber stopper.

Figure 3. A schematic diagram of freeze-drying system for PSMFD, MFD, and FD (Wang et al., 2012d) 1 feeding ball valve; 2 plate valve with 3-mm diameter hole; 3 and 22 microwave heating cavity; 4 magnetron; 5 and 16 circulating water unit; 6 drying chamber for MFD and PSMFD; 7 and 11 pressure gauge; 8 solid–gas separator; 9 gas flow electromagnetic valve; 10 gas flow adjustable valve; 12 nitrogen gas source; 13 and 29 fiber optic temperature sensor; 14 and 24 sample; 15 drying chamber with a jacket for FD; 17 control panel; 18 vapor condenser; 19 vacuum pressure transducer; 20 refrigerator unit; 21 vacuum pump unit; 23 water load pipe; 25 Teflon tube; 26 gas distributer; 27 fixed unit for drying chamber holder; 28 silicon rubber stopper.

convective drying with infrared heat source for carrots (Mihoubi et al., 2009) and apples (Witrowa-Rajchert and Rząca, 2009), combined far-infrared and vacuum drying for bananas (Swasdisevi et al., 2009) and strawberries (Shih et al., 2008), and combined hot air impingement and infrared drying for potato chips (Supmoon and Noomhorm, 2013).

Heat pump in combination with far-infrared radiation drying (FIRHPD). IR radiation partly overcomes inherent problem of uniformity due to heat pump drying. Therefore, HP in combination with FIR drying is an efficient method for reducing drying time with improved nutritional, sensorial, and functional properties of dried products, such as squid fillets (Deng et al., 2011b) and longan fruits (Nathakaranakule et al., 2010).

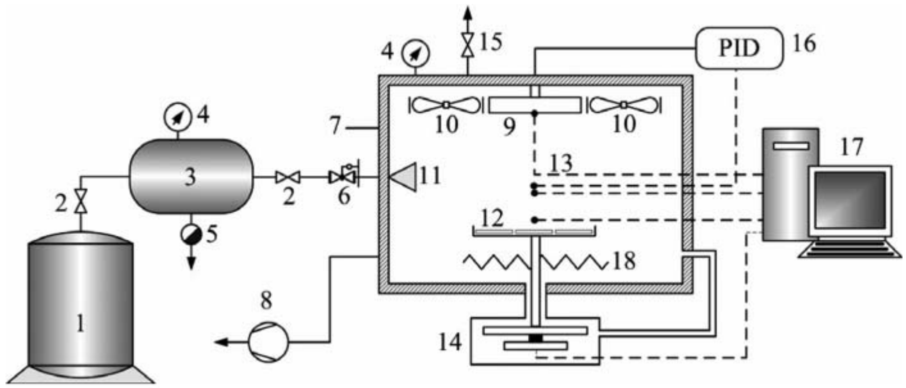
Combined far-infrared radiation and low-pressure superheated steam drying (FIRLPSSD). Nimmol et al. (2007b) proposed that combining low-pressure superheated steam drying with far-infrared radiation was suitable for heat-sensitive materials owning to relatively low temperature operating at reduced pressure. A schematic diagram of FIRLPSSD system has been shown in and Figure 4. This drying system can also be considered as a combined far-infrared and vacuum drying when vacuum pump is open and vacuum break-up valve is off (Nimmol et al., 2007b).

Combination of infrared radiation with freeze-drying (IRFD). A sequential infrared radiation and freeze-drying (SIRFD) method has been investigated in some studies as a means for reducing drying time and energy consumption producing high quality, crispy texture of vegetables and fruits, such as dried sweet potato (Lin et al., 2005), banana chips (Pan et al., 2008b), strawberry slices (Shih et al., 2008), and blueberries (Shi et al., 2008).

Combined near-infrared radiation and fluidized-bed drying (NIRFBD). Near infrared radiation (NIR), which has the wavelength between 0.75–3 μm, should be potential for combining fluidized-bed within food drying and solving the barrier of hot-air fluidized-bed drying (Dondee et al., 2011). Previous research by Sandu (1986) reported that NIR energy suddenly impinged upon material surface and its penetration depth into most grains was approximately 1 mm under the surface (Meeso et al., 2007).

UV-related combined drying

Ultraviolet drying is especially used in the field of printing and packaging industry where fast drying is required. It is also



1 boiler; 2 steam valve; 3 steam reservoir; 4 pressure gauge; 5 steam trap; 6 steam regulator; 7 drying chamber; 8 vacuum pump; 9 far-infrared radiator; 10 electric fans; 11 steam inlet and distributor; 12 sample holder; 13 thermocouples; 14 load cell; 15; vacuum break-up valve; 16 PID controller; 17 PC with data acquisition card; 18 electric heater.

Figure 4. A schematic diagram of far-infrared radiation assisted drying system (Nimmol et al., 2007b) 1 boiler; 2 steam valve; 3 steam reservoir; 4 pressure gauge; 5 steam trap; 6 steam regulator; 7 drying chamber; 8 vacuum pump; 9 far-infrared radiator; 10 electric fans; 11 steam inlet and distributor; 12 sample holder; 13 thermocouples; 14 load cell; 15; vacuum break-up valve; 16 PID controller; 17 PC with data acquisition card; 18 electric heater.

applied in carton including medicine and food labeling (Köse and Erentürk, 2010). Köse and Erentürk (2010) investigated the thin-layer drying behavior of mistletoe (*Viscum album* L.) leaves in UV combined convective dryers.

EHD-related combined drying

Combined electrohydrodynamic and vacuum freeze drying (EHDVFD). EHD drying requires a simpler system and lower energy consumption when compared to convective or freeze drying. However, the product quality dried by EHD is not as good as that obtained by FD. This combined drying technology merges the advantages of two drying methods (high quality of products similar to FD products and low cost) and minimizes the limitations of a single drying method (Bai et al., 2012b).

EHD spray drying. Lastow et al. (2007) studied a novel EHD spray drying setup based on a low-voltage nozzle (Figure 5), which has been characterized in terms of particle size, particle morphology, process output, and the generated particles' yield and size distribution is very narrow. The low-voltage nozzle imparts moderate charge to droplets, making discharging unnecessary. The charged particles can be controlled and collected by using an external EHD field (Lastow et al., 2007).

Tandem combined drying

Tandem combination or hybrid drying refers to drying technologies which employ different drying methods at different stages of drying cycle. Using multi-stage drying can result in better thermal performance but also, more importantly, desirable quality changes (Xu et al., 2004). Such technologies include such combinations as hot air drying followed by microwave or freeze drying, osmotic dehydration followed by hot air drying etc. (Figure 6).

Hot air is relatively efficient at removing free water at or near the surface, whereas the unique pumping action of vacuum microwave energy provides an efficient way of removing internal

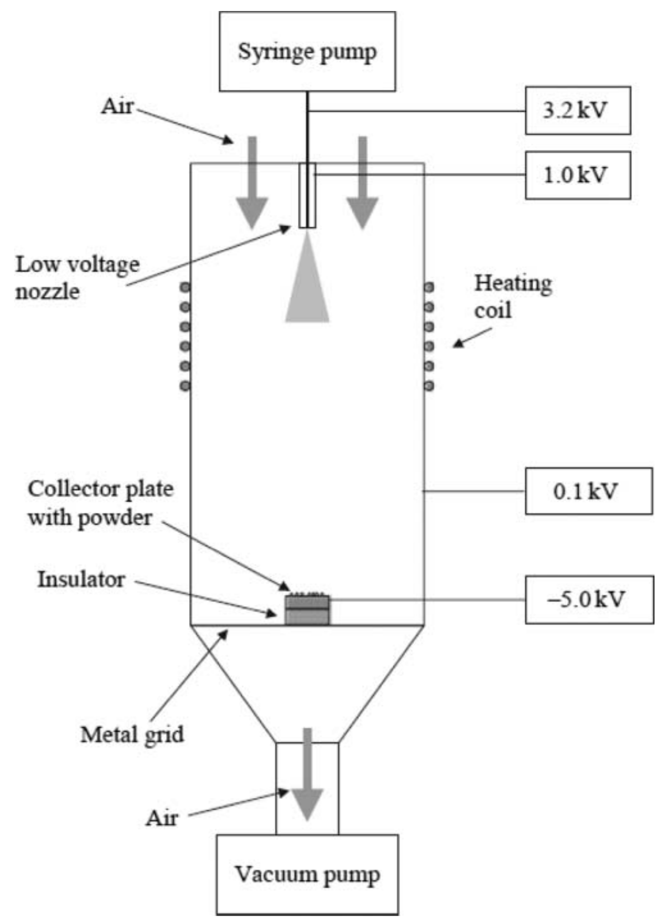


Figure 5. A schematic diagram of EHD spray-drying system (Lastow et al., 2007).

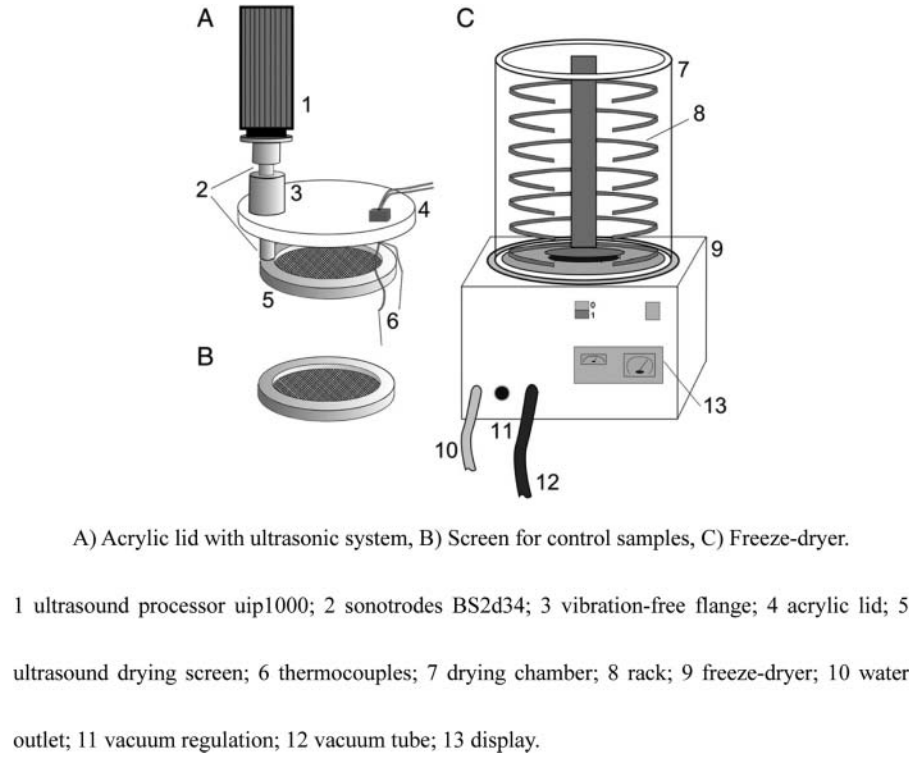


Figure 6. A schematic diagram of laboratory scale contact ultrasound assisted freeze-drying (Schössler et al., 2012). (A) Acrylic lid with ultrasonic system, (B) Screen for control samples, (C) Freeze-dryer. 1 ultrasound processor uip1000; 2 sonotrodes BS2d34; 3 vibration-free flange; 4 acrylic lid; 5 ultrasound drying screen; 6 thermocouples; 7 drying chamber; 8 rack; 9 freezedryer; 10 water outlet; 11 vacuum regulation; 12 vacuum tube; 13 display.

unbound water. So in combining of vacuum microwave and convective air drying process (AD + VMD), vacuum microwave may be advantageous in last stage of air drying because the least efficient portion of a conventional drying system is near the end, when two-thirds of drying time may be spent removing the last one-third of the moisture content (Hu et al., 2006a).

Other recent developments of drying technologies suitable for vegetables, fruits, and aquatics

Pretreatment of vegetables, fruits, and aquatics before drying process

Drying can be combined with pretreatments to have some beneficially physical or chemical changes as well as application of various energy fields that enhance mass transport and product quality (Djendoubi Mrad et al., 2012). The potential of osmotic dehydration as a pretreatment has been proven useful in a number of studies, providing not only water removal but also in many cases a taste improvement (Changrue et al., 2008). In addition, applications of microwaves, pulsed electric fields, ultrasound, and high hydrostatic pressure have resulted in enhanced osmotic dehydration rates. There are also other physical and chemical treatments used to improve the drying rate, which include freezing, thawing, pinning, extrusion, abrasion, or drilling holes on food surface, steam/hot water blanching, SO_2 treatment, and use of high electric fields (Jangam, 2011).

Osmotic treatment is commonly applied in drying of fruits and vegetables to improve quality of dried products, especially color maintenance. There are two examples for novel osmotic dehydration pretreatments. (1) Pulsed vacuum osmotic dehydration (PVOD) is a variation of vacuum in osmotic dehydration (VOD). This dehydration process leads to an exchange of internal gas/liquid by external solution through hydrodynamic mechanism enhanced by vacuum pulse mode, which improves mass transfer rates, increases homogeneous concentration profiles and reduces energy cost (Fante et al., 2011) in the dehydration of fruits (Corrêa et al., 2010), vegetables (Rastogi et al., 1999), and fishes (Corzo et al., 2007) as a technological innovation of traditional osmotic process (Deng and Zhao, 2008). (2) The use of ultrasound has also been known to improve mass transfer for various products and processes in liquid–solid systems, such as osmotic dehydration. Duan et al. (2008b) examined a new pretreatment method involving use of ultrasound prior to microwave freeze drying of sea cucumber and founded that it can reduce by about 2 hours needed for microwave freeze drying and improve the quality of dried sea cucumber.

Combination with other new technologies

Some new technologies like dielectric constant control technology and microencapsulation technology, can improve some properties of foods to benefit to drying process. What's more novel nonthermal technologies such as ultrasounds, nanotechnology among others, have shown promise for inactivating microorganisms at near-ambient temperatures and reducing thermal degradation of food components, therefore consequently preserving the sensory and nutritional quality of food products (Pereira and Vicente, 2010).

Dielectric constant control technology

Knowledge on dielectric properties of foods is critical to develop effective dielectric drying with RF or MW energy (Zhu et al., 2012). Dielectric constant (ε′, ε″) commonly results in heat generation. Dielectric constant (ε′) presents the ability of material to store energy when it is subjected to an electric field, influencing the electric field distribution and the phase of waves traveling through the material (Jiang et al., 2013). Therefore, dielectric properties and specially the loss factor, influence both energy absorption and attenuation and describe the ability to dissipate energy in response to an applied electric field (Sisquella et al., 2014). Major factors affecting dielectric properties of food materials include frequency, temperature, food compositions (e.g. fat content, salt content, and water content), and water state (e.g. frozen, free, or bound) (Alfaifi et al., 2013). For example, water molecules have the largest dielectric constant and can absorb MW energy and generate evident heat effect (Hu et al., 2006b). The higher the water contents, the higher the values of dielectric properties of materials.

Thus, the temperature distribution inside a food sample heated by MW or RF is determined by both dielectric properties of food and distribution of the absorbed energy (Alfaifi et al., 2013). There were few studies published about measurement of the temperature distribution during MFD drying and relationship between the dielectric properties and temperature distribution (Jiang et al., 2012). However, there are still some problems in full-scale application of MFD, because the dielectric constant and dielectric loss factor of frozen water sharply decrease (Venkatesh and Raghavan, 2004). Hence, when ordinary MFD is applied for dehydration of high moisture-content materials, the drying rate cannot be distinctly enhanced (Wang et al., 2010b). More studies based on improving dielectric properties of materials will still need to be implemented.

Ultrasound technology

Ultrasound applications can be mainly classified into two fields: high-frequency (low-energy diagnostic ultrasound in the MHz range, used as an analytical technique), and low-frequency (high-energy power ultrasound, relatively new application in food industry) (Zheng and Sun, 2006). For instance, ultrasound pretreatment of fruits before drying has shown promise in greatly reducing the overall drying time and enhancing the retention of quality aspects of dried fruits (Mothibe et al., 2011). Because ultrasound wave can produce minute vapor-filled bubbles that collapse rapidly and generate a series of alternative compressions and expansions (sponge effect) while traveling through a solid medium, resulting in complete and accelerated degassing of immersed solid (Stojanovic and Silva, 2006). Also, the oscillatory motion of a sound wave causes acoustic streaming and thus enhancing mass transfer (Fernandes et al., 2008). In addition, the higher than surface tension force caused by this mechanism maintains the moisture inside the capillaries of material creating microscopic channels which may promote moisture removal (Cárcel et al., 2007).

A contact ultrasound system for integration into freeze drying processes was developed by Schössler et al. (2012). They used red bell pepper cubes as food model and investigated ultrasound induced heating effects and relevant process parameters compared with freeze drying. Results showed that ultrasound combines the positive effects of heating due to attenuation and adsorption with mechanical effects of pressure waves to improve drying rates and can thus be used to shorten drying times and has shown promise in reducing related costs (Schössler et al., 2012). A schematic diagram of laboratory scale contact ultrasound assisted freeze-drying is showed in Fig.6.

Microencapsulation technology

Microencapsulation (ME) has become an attractive approach to converting liquid food flavorings into a dry and free-flowing powder form that is easy to handle and to incorporate into a dry system (Christelle and Elisabeth, 2013). ME is a technology of packaging solid, liquid, and gaseous materials in small capsules that can release their contents at controlled rates over prolonged period (Champagne and Fustier, 2007), particularly in the food industry to protect substances that are sensitive to temperature, light, oxygen, and humidity (e.g. functional compounds, additives, dyes, flavors) (Rocha et al., 2012). The applications of microencapsulation increased in an exponential form over the last two decades (Champagne and Fustier, 2007), as well as the publications concerning spray drying techniques (Estevinho et al., 2013).

Nanotechnology

Nanotechnology can be defined as control of matters at dimensions of roughly 1–100 nm, where unique phenomena enables novel applications. As the size of particles gets reduced to nanoscale range, there is an immense increase in the surface to volume ratio which increases reactivity and changes mechanical, electrical, and optical properties of particles (Neethirajan and Jayas, 2010). During the last decade, several review articles have articulated basic aspects of nanoscience, nanomaterials, and nanotechnology when applied to food industries (Kalpana Sastry et al., 2012).

Some nanoscale inorganic materials have high dielectric constant and loss factor, which is helpful to improve dielectric drying rates. Gong et al. (2009) developed a suitable method based on vacuum impregnation to inject calcium into fruits or vegetables (strawberries, blueberries, carrots, and corn) and further applied it to develop snack foods rich in vitamins, minerals, and dietary fiber. Duan et al. (2010a) found that vacuum impregnation with nanoscale calcium carbonate combined with microwave freeze drying was an efficient drying method for sea cucumber. Li et al. (2011) reported that nanosilver coating treatment of sea cucumber was effective in lowering microorganism count with no significant negative effect on efficiency of microwave freeze drying. If the dose of nanoaddition could be controlled in a safe range, nanoscale materials could make up for some disadvantages of dielectric drying (Duan et al., 2008a).

Models and simulations

The increasing demand for high-quality and shelf-stable dried products requires design, simulation, and further optimization for drying process in order to obtain not only efficiency of the process but also high quality of the final dried product (Scala and Crapiste, 2008). Kinetic parameters, such as reaction order, rate constant, and activation energy are helpful in predicting changes of quality parameters during drying process (Saxena et al., 2010). The knowledge of drying kinetics also contributes to analyzing effects of the most relevant process variables on capability of the drying condition itself in terms of process

Table 3. Applications of advanced detection technologies related with drying technology.

Detection technologies	Advantages	Examples
Online Volatiles Monitoring	Online volatiles monitoring and control with fuzzy logic and linear control strategies; Less time and energy.	A zNoseTM microwave drying system with the ability of online volatiles monitoring and control by Li et al. (2010).
Near-Infrared Reflectance Spectroscopy	Nondestructive technique applied in detection of food product quality Quickness, good reproducibility No sample preparation	Determination of moisture and fat content in potato chips (Shiroma and Rodriguez-Saona, 2009)
Laser Light Backscattering	Nondestructive technique applied in predicting internal quality properties Less cost than near-infrared reflectance spectroscopy	Determination of color changes and moisture content during banana drying (Romano et al., 2010) Continuously monitoring moisture content, soluble solid content, and hardness of apple tissue during drying (Romano et al., 2011).
Low-Field Pulsed Nuclear Magnetic Resonance	Noninvasive tool to investigate the content, state, migration, and distribution of water in polymer systems	Investigating the water state of squid fillets dried in a heat pump dryer, alone or assisted with far-infrared radiation (Deng et al., 2011b). Studying distribution and migration of unfrozen water in stem lettuce cubes during the microwave freeze drying (Wang et al., 2012c).
X-Ray Microtomography	Nondestructive technique, scanning an entire sample to obtain such information as total pore volume and pore size distribution	Investigating the effect of far-infrared radiation assisted drying on microstructure of banana (Léonard et al., 2008).

efficiency, energy yield, and products quality, etc. (Vega-Gálvez et al., 2011).

Models

Mathematical model. Mathematical model is an important tool used to optimize operating parameters and to predict performance of a drying system (Babalis and Belessiotis, 2004). Numerous mathematical models, empirical, and semi-empirical, have been proposed to estimate drying characteristics of food products. These simple models, also known as thin layer models, are applied to simulate drying curves and predict mass transfer under similar drying conditions (Puente-Díaz et al., 2013). The advantage of these models is easy to use but their applications are restricted and valid only in the range of drying temperature, air velocity, relative humidity and moisture content of product during the experiment (Meziane, 2011). Although most of the models are empirical, they are mainly derived from the diffusion model based on Fick's second law for different geometries (Akpinar, 2006). The most frequently mathematical models used to model the drying of different food products are presented in Table 4.

Artificial neural networks (ANN). Drying is quite complex and uncertain and they can be considered as nonlinear, time-varying properties and many unknown factors, which needs to be modeled with different levels of complexity (Nazghelichi et al., 2011). For example, the spatial evolution of temperature and moisture content in the product during drying can not only be evaluated by modeling heat and mass transfer (Janas et al., 2010). Artificial neural networks (ANN), which are heuristic models, are recognized as good tools for dynamic modeling. Because this method does not require parameters of physical models due to its ability of learning from experimental data, and is capable to handle complex systems with nonlinearities and interactions between decision variables (Lertworasirikul and Tipsuwan, 2008).

Simulations

Mathematical modeling and computer simulation serve as valuable tools for analyzing the complex mechanisms of different drying methods without doing extensive time-consuming experiments. The use of simulative tools opens new ideas without incurring the usual high research costs linked to pilot investigations (Mihoubi et al., 2009).

Table 4. Mathematical models applied to drying curves in recent years.

Model name	Model	Reference
Newton (Lewis)	$MR = \exp(-kt)$	(Ibrahim et al., 2009), (Doymaz, 2008), (Therdthai and Zhou, 2009)
Page	$MR = \exp(-kt^n)$	(Changrue et al., 2008), (Doymaz and İsmail, 2011), (Srinivasakannan et al., 2012), (Deng et al., 2011a), (Santos-Sánchez et al., 2012)
Modified Page	$MR = \exp(-(kt)^n)$	(Phoungchandang et al., 2009), (Köse and Erentürk, 2010), (Arslan and Özcan, 2011), (Naidu et al., 2012)
Henderson and Pabis	$MR = a\exp(-kt)$	(Duan et al., 2005), (Doymaz, 2008), (Song et al., 2009)
Modified Henderson and Pabis	$MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$	(Meziane, 2011)
Logarithmic	$MR = a\exp(-kt) + c$	(Chong et al., 2008), (Lee and Kim, 2009), (Doymaz, 2010), (Vega-Gálvez et al., 2011), (Puente-Díaz et al., 2013), (Doymaz and Kocayigit, 2012)
Two term	$MR = a\exp(-k_0t) + b\exp(-k_1t)$	(Vega-Gálvez et al., 2011), (Zielinska and Markowski, 2010), (Wang et al., 2011a)
Wang and Singh	$MR = 1 + at + bt^2$	(Doymaz, 2008), (Arumuganathan et al., 2009), (Shen et al., 2011), (Miranda et al., 2009)
Midilli et al.	$MR = a\exp(-kt^n) + bt$	(Puente-Díaz et al., 2013), (Shi et al., 2013), (Puente-Díaz et al., 2013), (Arslan and Özcan, 2011)
Weibull model	$MR = \exp(-(t/\beta)^{\alpha})$	(Uribe et al., 2009), (Aghbashlo et al., 2010), (López et al., 2010)

Niamnuy et al. (2008) developed a model to simulate heat conduction and mass diffusion as well as shrinkage changes of shrimp and stress distributions within shrimp during jet spouted bed drying. Good agreement between the theoretical and experimental results was observed and the models had potential to predict deformation and cracking of foods during drying. Alfaifi et al. (2014) developed a computer simulation model using finite element-based commercial software COMSOL to investigate heating uniformity of raisins treated in a 27.12 MHz RF system. This model could be used for future investigations to improve the heating uniformity for insect disinfection of dried fruit and other similar applications.

Computer simulation is not only an effective tool for studying influence of various parameters on heating uniformity in drying process, but also providing information on dielectric properties of foods (Wang et al., 2008; Wang et al., 2012b). Wang et al. (2012b) investigated how different dielectric properties of various components in meat lasagna influenced its overall RF heating pattern, via pilot-scale experimentation and computer simulation. Simulation results suggested that in spite of large differences of electric field intensities in different food components, adequate heat transfer reduced differential heating. Tiwari et al. (2011) developed one computer model based on a commercial software-FEMLAB for a 12 kW, 27.12 MHz parallel plate RF system which could be applied to study the effect of some important parameters such as sample size, position, shape, and dielectric properties on RF heating of dried food materials.

Advanced detection technology

Advanced detection technology is applied in assessment of food product quality due to its characteristics such as quickness, requiring no sample preparation, online monitor and control, reproducibility, and accuracy of measurements. Recent applications of advanced detection technologies related with drying technology are presented in Table 3.

Trends and chanllenges in high-quality drying of vegetables, fruits, and aquatic products

Development and application of new drying technologies with the characteristics of both high-quality and high-efficiency

Apart from drying source of field assisted methods (IR, MW, RF, and combined drying, etc.), mode of drying process (like steady or pulse spouted bed mode) can be controlled to improve efficiency and quality. For example, an intermittent drying scheme is one possible method to reduce energy consumption while maintaining the desired product quality (Thomkapanich et al., 2007). Intermittent drying can be applied in batch processing by varying with airflow rate, temperature, humidity, or operating pressure individually or in tandem. This method is to match the drying condition to the instantaneous drying rate so as to obtain high energy efficiency without increasing product temperature beyond its limited level. On the other hand, drying efficiency and product quality can also be improved by varying the mode of heat input, such as convection, conduction, radiation, or microwave/radio frequency heating (Fernandes et al., 2010).

Optimization of new drying process conditions with both high-quality and high-efficiency

Drying optimization is especially important for heat sensitive foodstuffs, like vegetables, fruits, and biological products (Cernîşev, 2010). However, optimization of food dehydration process is a challenging problem that demands evaluation of many interconnected and opposing nonlinear phenomena because of complex drying process involving simultaneous mass and heat transfer in a hygroscopic system with variable properties (Scala and Crapiste, 2008). The increasing demand for high-quality and shelf-stable dried products requires the optimization of drying process conditions with the purpose of accomplishing not only efficiency of the process but also high quality of the final dried product as well as less environmental impact (Banga et al., 2003).

Combination of high-quality drying with other new technologies

Current technologies used for improvement of drying rates (e.g. heated plates, infrared radiation, microwave application) are still limited to heating effects and can easily impair product quality. In order to efficiently fulfill the drying process, applications of shortening operation times and enhancing final products quality, and combining drying methods with different sources of energy are becoming more and more widespread (Zhang et al., 2010; Jangam, 2011). Novel nonthermal technologies such as ultrasounds, high pressure processing, pulsed electric fields among others, are able to inactivate microorganisms at near-ambient temperatures, avoid thermal degradation of food components, and consequently preserve sensory and nutritional quality of food products (Pereira and Vicente, 2010). With the development of science and technology, high-quality drying technology will have new breakthroughs by combining with the latest technologies.

Models and simulations of high-quality complicated index system

Because of the complexity of food quality indicators, control of these variables is a challenging problem that demands evaluation of many interconnected nonlinear mass and heat transport phenomena in a system with variable properties and modifications of quality attributes (Vega-Gálvez et al., 2009). So modeling and computer simulation of complicated drying process combining with temperature field, microwave field, flow field, and pressure field is a challenging task and the design of computer software also need to be studied innovatively.

Conclusion

This review has shown some recent developments in high-quality drying of foods, especially vegetables, fruits, and aquatic products based on flavor, nutrients, color rehydration, uniformity, appearance, and texture. More and more novel and multiage-combined high-quality and high-efficiency drying technologies have been developed, such as MW-enhanced combined drying methods (PSMVD, PSMFD), RF-combined drying methods (RFHAD, RFHPD). The trends and challenges for future can be concluded: development and application of high quality and efficiency new drying technologies, optimization techniques of drying process, combination with other novel technology and advanced detection technology, and model and simulation of complex systems in drying process.

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