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Recent developments in radio frequency drying of food and agricultural products: A review

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ABSTRACT
Radio frequency (RF) drying is an effective and practical dielectric drying method for food and agricultural products due to rapid and volumetric heating, deep penetration and moisture self-balance effects. However, non-uniform heating and sometimes runaway heating are still major problems with implementation of RF drying. RF-related combination drying takes advantages of both conventional drying methods and RF heating, leading to improved drying uniformity, better product quality and higher energy efficiency. This paper provides a brief introduction on the basic principle of RF drying, analyzes the RF heating and drying characteristics and examines recent literature on RF drying applications and possible methods for improving RF heating and drying uniformity. Recommendations for future research have been proposed to achieve practical and effective RF drying requirements and bridge the gap between academia and industry.

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Introduction

Fresh food is easily perishable due to its high moisture contents at harvest, which would result in poor quality stability and short shelf-life of agricultural products, especially for fruits and vegetables.[1] For instance, commercial production of fresh vegetables was approximately 77,403 Mt in China in 2016, but annual loss of vegetables caused by spoilage is about 8,000 Mt and economic loss is about US$ 10 billion every year.[2] Drying (or dehydration) offers a means of preserving food in a stable and safe condition as it reduces water activity and extends shelf-life much longer than that of fresh food.[3] In addition to preservation, the reduction in the bulk volume and weight of dehydrated food reduces handling, packaging and transportation costs.[4] Moreover, drying is a complex multi-physics process, creating food products with particular desirable features, such as flavor, crispiness, and chewiness.[5] The market for dehydrated vegetables and fruits has gained importance in most countries worldwide. For instance, the world raisin production was about 1.5 Mt and valued at more than US$ 110 million in 2013.[6] Particularly, the growth in popularity of convenient food in many Asian countries has stimulated increasing demand for high-quality dehydrated vegetables and fruits.[1] However, drying is an energy-intensive process since a large amount of thermal energy is needed to evaporate water within food. The energy consumption of drying has been reported to account for 12–20% of the energy used by food processing industry every year.[7,8] Therefore, drying technology applied for food dehydration should not only be effective and energy-saving but also provide desirable product quality attributes, such as color, nutrients, flavor, texture and rehydration capacity.

Conventional drying methods include sun drying, hot air drying, osmotic dehydration, vacuum drying, freeze drying, heat pump assisted drying and spray drying.[3,4] However, the major issues of the conventional drying methods are long drying time, low energy efficiency, high energy consumption and poor quality.[9–13] Hot air drying and sun drying are the most commonly used methods for drying food and agricultural products. But long drying times with high temperatures during the hot air drying always result in sensory and nutritional loss of final products.[14] Although sun drying is an energy-saving and environment friendly drying method, it takes lots of times for fresh food, varying from several days to over three weeks and depends on the external weather conditions.[15] In addition, the sun-dried food products may be contaminated by insects or pathogens after exposed to the external environment. Osmotic dehydration alone is not adequate to reduce moisture contents of food to

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a desirable level inhibiting biochemical reactions of degradation.[16] Vacuum drying and freeze drying are often characterized by high energy consumption and operating cost due to the need to maintain vacuum over the entire drying process.[1,17,18] Applications of heat pump assisted drying and spray drying are limited owing to their special demands for the shape and form of materials.[3,19] Recently, microwave (MW) and radio frequency (RF) energy has been widely studied to overcome the low thermal conductivity of conventional drying and improve product quality due to fast and volumetric heating.[20] MW and RF drying methods, also known as dielectric heating, generate heat within materials due to molecular friction as a result of dipolar relaxation and ionic conduction, thus providing opportunities to shorten drying times and prevent product quality degradation.[7] Up to now, MW drying and MW-related combination drying methods have been widely studied for drying various food and agricultural products, such as mango,[9] blueberry,[10] banana,[21–23] carrot,[24] green soybean,[25] potato,[26,27] apple,[28–30] garlic,[31] and aquatic products.[5] But this technology is still difficult to scale up for practical industrial implementations due to small penetration depth and non-uniform heating.[32,33]

Generally, RF heating is endowed with such advantages over MW heating as better heating uniformity, greater penetration depth and more stable product temperature control.[34,35] Moreover, RF heating shows superiority over MW heating on heating bulk food because of its longer wavelength and being more cost effective at a higher power level.[36] Nowadays, RF heating system has demonstrated practical applications in baking and roasting,[37] cooking,[38] disinfesting,[39–44] pasteurization,[45,46] sterilization,[47,48] thawing,[49,50] and many more. Only in recent years, RF heating has been explored as a novel drying method for agricultural commodities. However, non-uniform heating and sometimes runaway heating are still the most important challenges with implementation of RF energy.[50–53] Many methods have been suggested to improve RF heating uniformity, including rotation,[54,55] mixing,[39,40] sample moving,[32,43] forced air,[34,35,52,56] and modifying the composition of surrounding media.[57–59] Furthermore, conventional drying methods could be used in combination with RF heating to improve drying uniformity and energy efficiency, such as hot air-assisted RF drying.[17,34,56] In our recent studies, RF heating and drying uniformity has also been improved by use of vacuum in RF systems, called RF-vacuum drying.

The purposes of this review are to (1) introduce the basic mechanism and characteristics of RF drying, (2) to review the literature on RF drying and RF-related combination drying methods for food and agricultural products, and (3) to highlight further research to enhance applications of RF heating for postharvest drying in food and agricultural products and propose possible industrial applications.

Properties of RF drying

Principle of RF drying

Like MW, RF waves are part of the electromagnetic spectrum (Fig. 1). The major difference between MW and RF is the frequency range. RF treatment involves heating with electromagnetic waves (10 to 300 MHz) and only three frequencies, 13.56 MHz $\pm$ 6.68 kHz, 27.12 MHz $\pm$ 160.00 kHz, and 40.68 MHz $\pm$ 20.00 kHz, are allocated by the US Federal Communications Commission (FCC) to avoid interference with other communication systems.[60] Conventional drying methods depend on the conduction and convection to deliver thermal energy from heating sources to materials, while RF drying is a volumetric heating method where electromagnetic waves directly couple with food to generate heat. When the dielectric material with polarized molecules and charged ions is subjected to an alternating electrical field, one phenomenon that occurs is that positive ions within the material move towards negative regions of the electromagnetic field and negative ions move towards positive regions of the filed, which is often referred to as “ionic migration.”[61] In addition to the migration of charged ions, dipolar molecules, such as water molecules, tend to align themselves appropriately with the changing polarity of the alternating field, which is known as “dipole rotation.” Both migrations of charged ions and rotational responses of polarized molecules can cause friction between molecules, resulting in heat generation. In general, ionic conduction has dominant influences on the dielectric loss mechanism within RF range, whereas both ionic conduction and dipole relaxation can be dominant heating mechanism within frequencies associated with MW heating. In other words, charged ions are more important factors influencing heat generation than water molecules in RF range.

Many factors influence RF drying of food and agricultural products, such as dielectric properties (DPs), thermal and other physical properties as well as distributions of electromagnetic field.[52] Knowledge of DPs is essential and fundamental to understand the interaction between electromagnetic field and agricultural products.

Dielectric properties

The interaction between dielectric materials and RF energy is governed by the relative complex permittivity

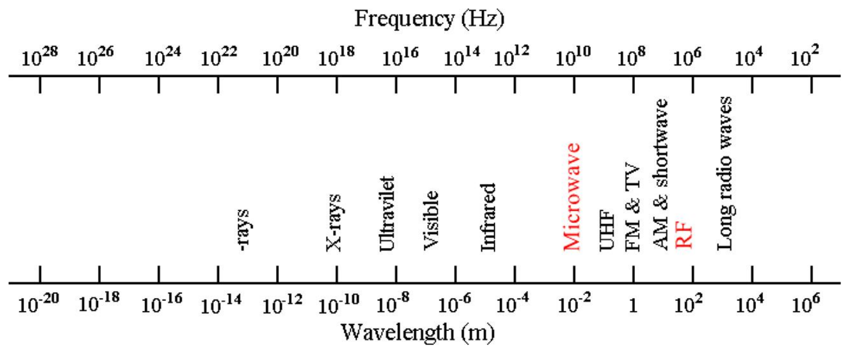

Figure 1. MW and RF in the electromagnetic spectrum.[60] *Note*: MW, microwave; RF, radio frequency.

$\varepsilon^*(\varepsilon^* = \varepsilon' - j\varepsilon'')$. The real part of the relative complex permittivity (ε', dielectric constant) describes the ability of materials to store energy. The imaginary part (ε'', loss factor) is associated with energy dissipation or the transformation ability from dielectric energy to thermal one.

The DPs of food and agricultural products are affected by various factors, such as frequency, moisture content, temperature, density, and composition of food.[62,63] Dielectric properties have been measured using an open-ended coaxial probe method for many agricultural products over different frequency, temperature and moisture content for disinfesting,[64–66] pasteurization,[45,67] and drying.[68–70] In general, the DPs of most food products increased with increasing temperatures (Table 1). However, the increasing trend of loss factor with temperatures may result in accelerating heating during MW and RF heating. As a result, the portion of food with higher temperatures would absorb more electromagnetic energy, giving rise to larger temperature differences within materials, which is called "thermal runaway" effect.[71] On the other hand, both the dielectric constant and loss factor of food decreased with decreasing moisture content, especially for high-moisture materials, such as apples[71] and potato.[72] Fig. 2 shows the dielectric loss factor of a typical fruit (kiwifruit) as a function of moisture contents at 27, 40, 915, and 2,450 MHz. The moisture content dependent-dielectric loss factor suggested that during the RF drying, samples or portions of sample with higher moisture contents may absorb more RF energy and therefore be heated preferentially as compared to those with lower moisture contents. This phenomenon commonly referred to as "moisture leveling" effects,[73] contributing to the uniform drying during RF heating. In other words, RF drying has high potential for providing more even moisture distribution and drying uniformity if the electric field in RF units is uniform. Furthermore, the dielectric constant plays an important role in RF heating characteristics, because the RF electric field distribution within materials is mostly determined by the dielectric constant of the samples.[33,52,58]

Power density

The electromagnetic field energy is transformed into thermal one through interactions with dielectric materials and the power dissipated in a unit volume (P_v, W/m^3) can be expressed as follows:

$$P_V = 2\pi \cdot f \cdot \varepsilon_0 \cdot \varepsilon'' E^2 \tag{1}$$

where f is the frequency of electromagnetic field (Hz), ε_0 represents the dielectric constant in vacuum (8.854×10^{-12} F/m), and E is the electric field strength in food load (V/m). Several factors influence the electric filed strength in RF heating system, such as RF operational parameters, dielectric properties and geometry of materials.[51,57,58]

According to Eq. (1), the power absorbed in dielectric materials is proportional to the frequency, the dielectric constant, loss factor and the square of the electric field strength. For most fresh fruits and vegetables, their high dielectric loss factors (>100) often result in uncontrolled heating rate, small penetration depth and skin heating. Therefore, it is necessary to combine conventional drying methods with RF heating to control temperatures and improve heating uniformity.

Figs. 3 and 4 show the typical temperature-time history and drying curve of macadamia nuts when subjected to hot air-assisted RF drying. Sample temperatures at seven representative locations in a plastic container were measured using an eight-channel fiber optic sensor system. Fiber optic sensor probes were inserted into macadamia nut kernels through predrilled holes to record the temperature of the RF treated samples at 2 min intervals during the entire hot air-assisted RF drying process. Detailed description of the plastic container with macadamia nut samples and fiber optic probe positions for temperature measurements can be found in Wang et al.[34] In general, a complete temperature-time history during RF drying consists of three stages: (1) warming-up period during which RF energy is transformed into thermal one and most of thermal

Table 1. Dielectric properties of typical agricultural products at 27.12 MHz (RF) and 915 MHz (MW) over three temperatures.

Material	Moisture (% w.b.)	Temperature (°C)	Dielectric constant		Loss factor		Penetration depth (cm)		Source
			27.12 MHz	915 MHz	27.12 MHz	915 MHz	27.12 MHz	915 MHz	
Walnut, *Juglans regia* L.	3	20	4.9	2.2	0.6	2.9	654	3	Wang et al.[98]
		40	5.1	3.0	0.4	2.3	995	4	
		60	5.3	3.8	0.4	1.8	1015	6	
Pistachio, *Pistacia vera L.*	15	25	11.9	7.3	6.0	1.8	104	8	Ling et al.[64]
		45	12.7	7.6	7.4	1.9	88	8	
		65	13.7	8.0	10.2	2.1	68	7	
Chestnut, *Castanea mollissima*	45	20	31.2	14.6	45.9	5.2	25	4	Guo et al.[99]
		40	38.8	16.5	77.9	6.3	18	3	
		60	57.7	20.1	158.1	9.5	12	3	
Almond, *Nonpareil*	20	20	20.6	11.0	20.2	3.6	40	5	Li et al.[45]
		60	25.2	11.7	45.5	4.7	22	4	
		90	29.9	12.2	100.3	6.8	13	3	
Macadamia nut, *Macadamia tetraphylla*	3	25	4.3	5.2	0.3	0.8	1121	15	Wang et al.[100]
		40	4.3	5.1	0.4	0.9	1016	14	
		60	4.5	5.2	0.4	1.0	916	12	
Peanut, *Arachis hypogea L.*	20	25	11.3	5.3	8.3	2.0	9	3	Zhang et al.[68]
		45	14.3	8.4	12.0	2.2	8	3	
		65	17.8	9.5	27.5	3.1	7	2	
Nectarine, *Prunus persica* var. *nectarine*	88	20	68.9	64.0	195.8	11.6	11	4	Ling et al.[64]
		40	69.5	63.2	292.5	12.9	8	3	
		60	69.0	61.6	412.1	15.4	7	3	
Peach, *Prunus persica*	88	20	69.2	64.6	198.2	13.2	11	3	Ling et al.[64]
		40	72.9	66.1	292.4	15.3	8	3	
		60	73.1	64.4	411.4	17.7	7	2	
Persimmon, *Diospyros kaki*	75–85	20	79.8	68.4	207.5	21.1	11	2	Wang et al.[101]
		40	77.6	70.8	295.6	15.9	8	3	
		60	75.4	66.0	401.3	16.9	7	3	
Red delicious apple	87	20	74.6	77.0	92.0	10.0	18.9	4.6	Wang et al.[101]
		40	70.6	71.5	130.7	10.0	14.0	4.4	
		60	66.8	67.1	178.6	8.9	11.2	4.8	
Golden delicious apple	86	20	72.5	74.3	120.4	8.5	15.2	5.3	Wang et al.[98]
		40	69.7	70.0	171.8	8.2	11.6	5.3	
		60	66.5	65.6	234.1	8.7	9.4	4.8	
Plum, *Prunus domestica*	85	20	70.9	63.4	174.2	11.0	12	4	Ling et al.[64]
		40	66.3	57.9	228.3	10.8	10	4	
		60	62.7	52.8	285.9	11.5	8	3	
Potato, *Solanum tuberosum L.*	82	−20	–	3.71	–	0.29	–	12.9	Wang et al.[72]
		20	–	60.8	–	17.4	–	0.8	
		65	–	58.3	–	16.1	–	0.9	
Raisins, *Vitus vinifera*	15	20	21.9	7.8	8.1	3.8	104	4	Alfaifi et al.[102]
		40	28.0	10.9	9.8	5.2	97	3	
		60	33.8	15.2	11.4	7.2	91	3	
Black-eyed peas, *Vigna unguiculata*	8	20	3.4	2.8	0.24	0.24	1340	38	Jiao et al.[103]
		40	3.5	2.9	0.28	0.34	1233	30	
		60	3.8	3.1	0.31	0.42	1109	26	
Mung bean*Vigna radiata*	10	20	3.2	2.6	0.23	0.34	1375	25	Jiao et al.[103]
		40	3.5	2.8	0.26	0.36	1263	25	
		60	4.1	3.1	0.37	0.46	976	20	

energy is used for heating materials. Thus, the temperatures of agricultural products increase rapidly during this period (Fig. 3). (2) After the average temperature of agricultural products reach its highest value, the drying process enters into rapid drying period. The temperature of samples remains at a fairly constant level since the heat converted from RF energy is mostly used for water evaporation (Fig. 3). (3) Falling drying temperature period during which the temperatures of RF dried samples later decrease as moisture content decreases to a certain level (Fig. 4). This may be due to the reduced absorption of RF energy as a result of decreased dielectric loss factor of relatively dried samples. In addition, the thermal energy used for breaking away bound water was higher than that used for free water. As a result, the drying rate gradually decreased at the final RF drying stage. These trends are also observed in RF drying for almonds[42] and in-shell walnuts.[17,56] It can be concluded that RF heating combined with hot air may provide an effective drying process with desirable heating rate and stable product temperature control.

Penetration depth

When electromagnetic radiation is incident on the surface of an object, it may be partly reflected and the remaining part transmits into the material and gradually decays. Penetration depth (d_p, m) of RF power is theoretically defined as a depth where the intensity of electromagnetic power falls to $1/e$ ($e = 2.718$) of the

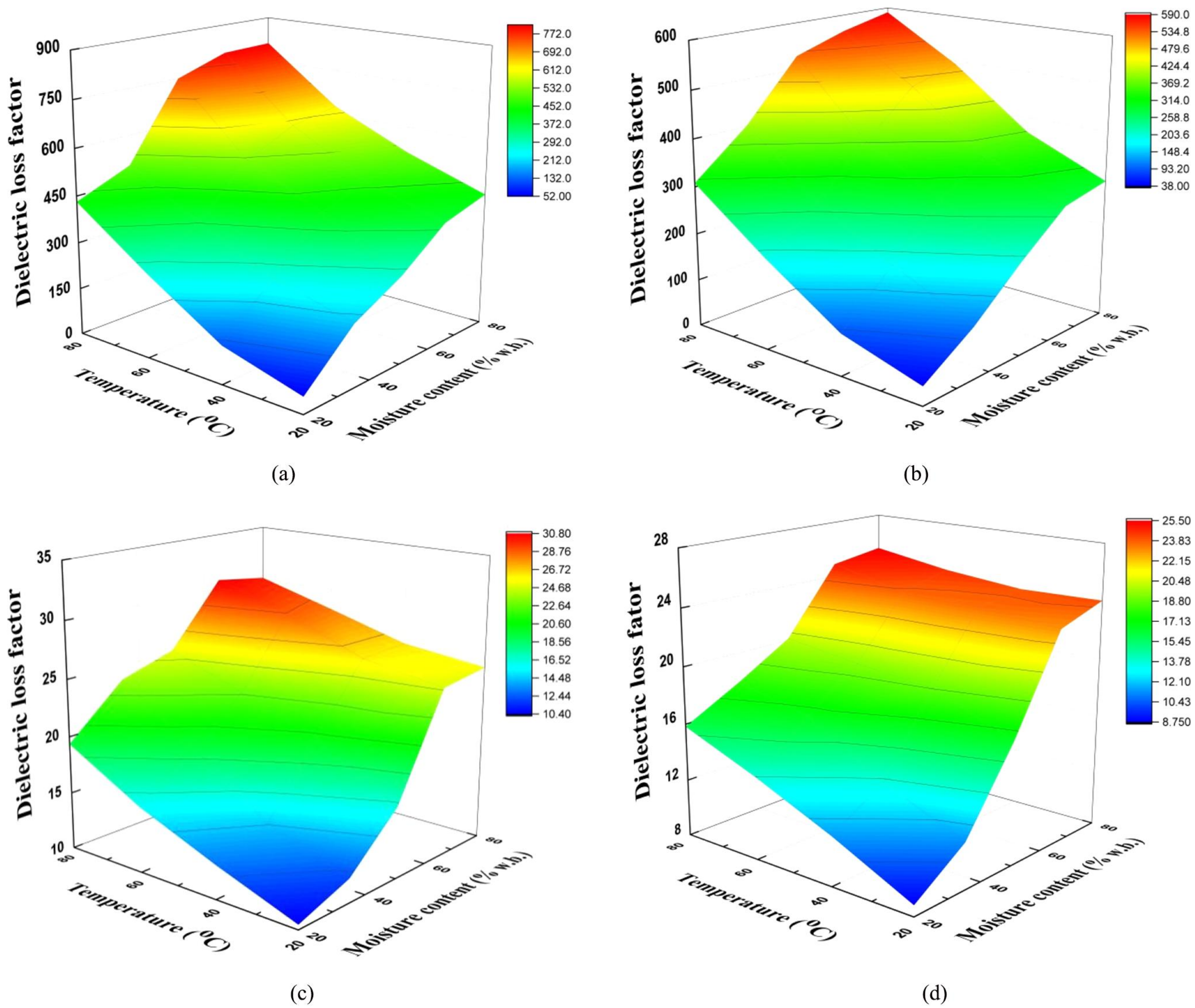

Figure 2. Moisture and temperature-dependent dielectric loss factor of a typical fruit (kiwifruits) at 27 (a), 40 (b), 915 (c), and 2450 MHz (d).

original value of power entering material surface. This parameter is useful to select an appropriate thickness of samples to ensure uniform RF heating, which can be calculated by the following equation[74]:

$$d_p = \frac{c}{2\pi f \sqrt{2\varepsilon' \left[\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'} \right)^2} - 1 \right]}} \tag{2}$$

where c is the speed of light in free space (3×10^8 m/s).

According to Eq. (2), the d_p is reversely proportional to the frequency (f). Since RF frequency is much lower than MW frequency, RF power can penetrate much deeper into materials without surface over-heating and charring or uneven temperature distributions, which are more likely to take place during MW drying. For instance, the d_p for macaroni and cheese decreased from 68 to 16 mm at 20°C when the frequency increased from 27 to 2,450 MHz.[48] The d_p for peach decreased from 67 to 24 mm at 60°C when the frequency increased from 27 to 915 MHz.[64] Therefore, RF energy has advantages of more uniform heating for bulk food samples due to deeper penetration compared to MW energy.

RF heating and drying characteristics

RF heating characteristics

Conventional heating relies mainly on two heat transfer mechanisms, i.e., convection at the surface and conduction within the food, which alternately have dominated effects at different stages during heating process. It is necessary to heat materials for much longer times to ensure the interior of products be heated to an appropriate temperature, which in turn may bring

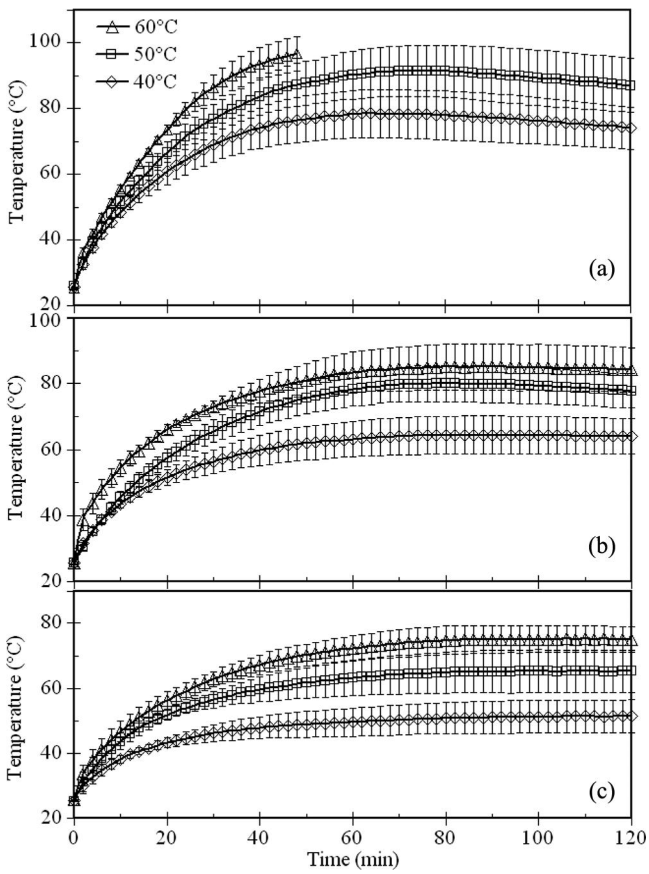

Figure 3. A typical temperature-time history of in-shell macadamia nuts when subjected to hot air assisted RF drying with RF electrode gap of 14.5 cm (a), 15.5 cm (b), and 16.5 cm (c) with three hot air temperatures (40, 50, and 60°C).[34]

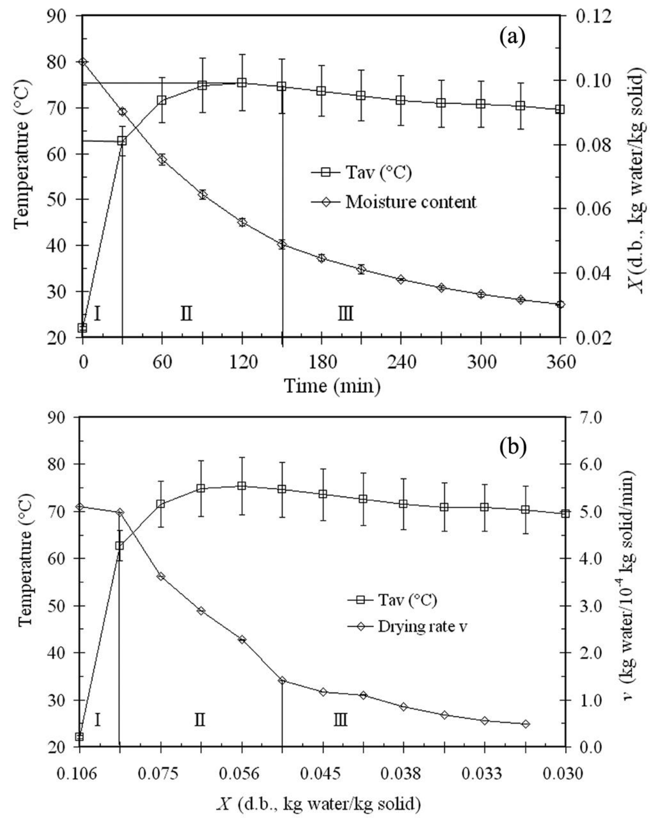

Figure 4. A typical drying curve (a) and drying rate (b) of in-shell macadamia nuts at three stages (I, II, III) with average surface temperature (T_{av}) during hot air (50°C) assisted RF drying (15.5 cm).[34]

about overheating on the surface of products. In contrast, during RF heating process heat is generated volumetrically within the products. Many studies have shown the obvious heating rate difference between RF treatment and conventional hot water or hot air heating for agricultural products, such as milled rice,[39] legumes,[75] coffee beans,[76] almonds,[42] and chestnuts.[40] For instance, from typical temperature-time histories of milled rice for disinfestation when treated by hot air at 50°C and RF heating with electrode gap of 11 cm, respectively, it took 480 min for hot air heating to raise the center temperature of milled rice to reach 48°C while only 4.3 min were needed for RF heated rice to reach 50°C, suggesting that RF treatments have high potential for achieving fast and volumetric heating in food and agricultural products.[39]

However, uneven heating uniformity still exists and limits successful practical applications of RF energy. The heating non-uniformity has been studied in lots of food and agricultural products, such as dry nuts,[43,77] fresh fruits and vegetables,[55] grains,[78] and meats.[49] With numerical technologies, computational modeling has been used in simulation of RF heating to predict RF power and temperature distributions in materials. A 3D finite element model of heat transfer during RF treatments was established using the commercial software, COMSOL, by Huang et al.[78]. Experiments were conducted using dry soybeans as a test material packed in a rectangular plastic container ($300 \times 220 \times 60\ mm^3$) and the simulation model was validated using a 6 kW, 27.12 MHz RF heating system. Detailed information about the governing equations, boundary conditions and solution procedure for numerical models can be found elsewhere.[78] Both simulated and experimental results showed that the average temperatures were highest in the middle layer (55–65°C) whereas they were lower in the both top (50–60°C) and bottom layers (55–60°C) (Fig. 5). Moreover, higher temperatures (60–65°C) were observed at the edges and corners on the each layer, with lower temperatures (50–55°C) observed in the central areas. Hot spots at the edge and corners may be due to the refraction and reflection of RF electromagnetic field at interfaces, resulting in a higher volumetric power density on these areas.[79] Similar temperature distribution patterns were also found by Tiwari et al.,[58] Alfaifi et al.,[52] and

Hou et al.[40]. Non-uniform heating during RF treatments may result in many problems, such as poor drying uniformity, degradation of final product quality, insect survivals and microbial safety concern. It is, therefore, critical to explore methods to improve heating uniformity. Developing RF-related combination drying methods (which are discussed in the following section) provides great potential to improve heating and drying uniformity.

RF drying characteristics

As compared to conventional drying, RF heating significantly reduces drying times and improves product quality for its rapid and volumetric heating. Recently, comparative analyzes were performed to study the effect of three drying methods, including RF drying, vacuum drying and hot air drying, on drying characteristics and oil quality of in-shell walnuts.[17] Fig. 6 shows the changes in moisture ratio, average sample temperatures and drying rate of in-shell walnut samples during the drying process. The result shows that the total drying time required for in-shell walnuts using RF energy was the shortest (138 min), followed by vacuum drying (185 min) and hot air drying (300 min). Three drying rate stages, including increasing rate stage, constant rate stage and falling rate stage, were observed during the RF drying. Compared to hot air drying, RF drying mostly occurred at the constant rate stage. Therefore, RF drying has great superiority on drying rates than vacuum and hot air drying (Fig. 6). Wang et al.[34,35] developed a hot air-assisted RF drying treatment for in-shell macadamia nuts. Their results reveal that the drying rate increased significantly when RF power and hot air temperature increased. The drying time decreased by about 70% when using RF energy as compared to hot air drying. Moreover, the suitability of six commonly used drying kinetic models was evaluated for hot air and RF drying of macadamia nuts, indicating that the Page models with R^2 of 0.9997 showed the best fit to describe hot air drying while the logarithmic model with R^2 of 0.9976 provided best fit for RF drying (Fig. 7). Similar results were also reported for in-shell walnuts.[56]

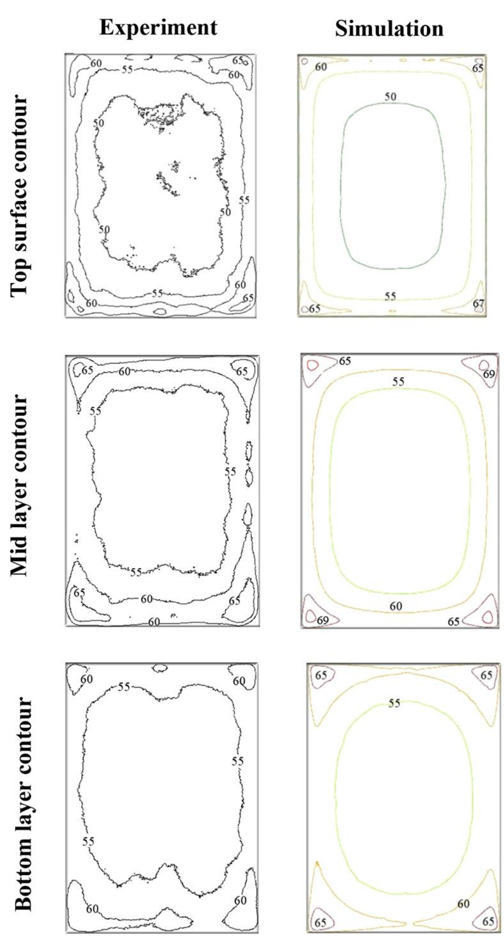

Figure 5. Experimental and simulated temperature distributions (°C) of dried soybeans in top, middle, and bottom layers (20, 40, and 60 mm from the bottom of sample) placed in a polypropylene container ($300 \times 220 \times 60\ mm^3$) on the bottom electrode, after 6 min RF heating with an initial temperature of 25°C and a fixed electrode gap of 120 mm.[78]

Applications and development of RF-conventional combined drying

Many different combination drying methods, such as MW-, RF- and IR-assisted conventional drying, have been studied to overcome disadvantages of single drying method, such as lengthy drying time, low energy efficiency, and poor product quality.[1,3] Combined drying methods include parallel and tandem drying. Parallel drying refers to a drying technology using two or more drying methods, which are implemented simultaneously, such as hot air-assisted RF drying[34] and RF-assisted fluidized bed drying.[80] Tandem drying uses one drying method followed by one or more other drying methods, such as RF post-baking drying.[81] The recent typical applications and developments of RF-related combined drying methods for food and agricultural products are listed in Table 2 and discussed in the following sections.

Parallel combined RF drying

Combined RF heating with conventional drying methods together, such as vacuum, hot air and fluidized bed drying, could avoid the limitation of low heat transfer in convective and conductive drying.

Early work with RF assisted vacuum drying dates back to the 1990s. Extensive studies have focused on

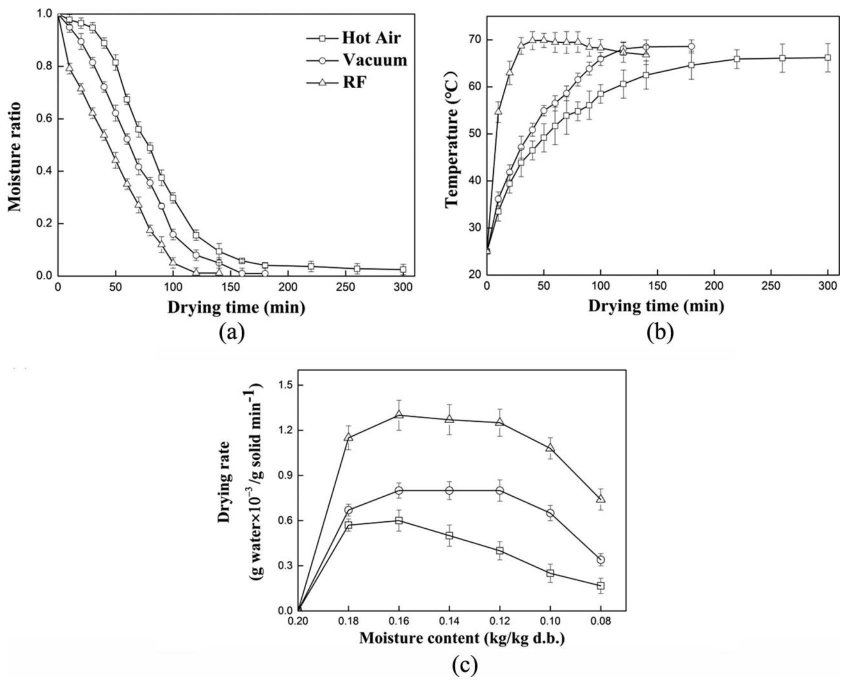

Figure 6. Changes in moisture ratio (a), temperature (b), and drying rate (c) of in-shell walnuts during the hot air drying (70°C), vacuum drying (70°C with 0.03 MPa) and hot air assisted RF drying (electrode gap of 18.0 cm with hot air of 50°C).[17]

RF-vacuum drying for wood.[82–85] For example, Avramidis and Liu[82] studied the drying characteristics of thick lumber in a lab-scale RF vacuum dryer. Their results suggested that the sample temperature, pressure and moisture content changed as function of dimension of wood squares and drying time during the RF-vacuum drying. The total drying time using RF-vacuum required for western red cedar and western hemlock was 24 and 32 h, respectively, when the moisture content of wood samples decreased from 38 and 35% to the final moisture content (15% w.b.). Moreover, the level of the RF electrode plate voltage had significant effects on RF-vacuum drying rates. But when the RF voltage remained constant throughout the drying cycle, drying rates still decreased with time due to the decreasing dielectric properties of wood caused by moisture content reduction at the final RF drying stage. Subsequently, the internal moisture flow patterns of wood were studied with attempt made to mathematically determine the drying characteristic and vapor pressure during RF-vacuum drying.[83] Koumoutsakos et al.[84,85] also investigated the internal moisture content flow pattern for two softwoods using a laboratory RF-vacuum dryer. A 1D simplified model was developed to predict the moisture content and drying time influenced by different drying conditions, including RF voltage, power density, ambient pressure and initial moisture content. From then on, RF-vacuum technology has gradually scaled up for industrial and commercial applications in wood dehydration. In China, a high-frequency equipment company, Hebei Huashijiyuan Industrial High Frequency Equipment, Ltd. (Shijiazhuang, Hebei, China), was established in 1999 and has made a great achievement in the practical and large-scale wood drying industry. However, the research for RF-vacuum drying was mostly stopped after the 2000s. More recently, our lab cooperated with the Hebei Huashijiyuan Industrial High Frequency Equipment, Ltd. designed and manufactured a multifunctional and programmable RF-vacuum drying system (GJ-3-27-JY, Jiyuan High Frequency Electric, Shijiazhuang, China) with a maximum nominal power of 3.0 kW and an operation frequency of 27.12 MHz (Fig. 8a), which marks the beginning of RF-vacuum research for drying food and agricultural products. The RF-vacuum drying system consists of two parallel plate electrodes ($600 \times 400\ mm^2$) in the applicator for RF heating, a vacuum vessel (800 mm in diameter and 800 mm long), a view port ($200 \times 200\ mm^2$), a vacuum pump (2BV-2071, Aoli Pump Instrument & Equipment Co., Ltd., Zibo, China), a water collector and monitoring systems for continuously measuring the vacuum pressure, sample temperatures and weights. Moreover, the electrode gaps between the two parallel plates can be adjusted from 20 to 300 mm to deliver desired RF energy for a specific load. The maximum vacuum degree was 0.09 MPa, which can be reached within 20 s using the vacuum pump. In addition, the sample

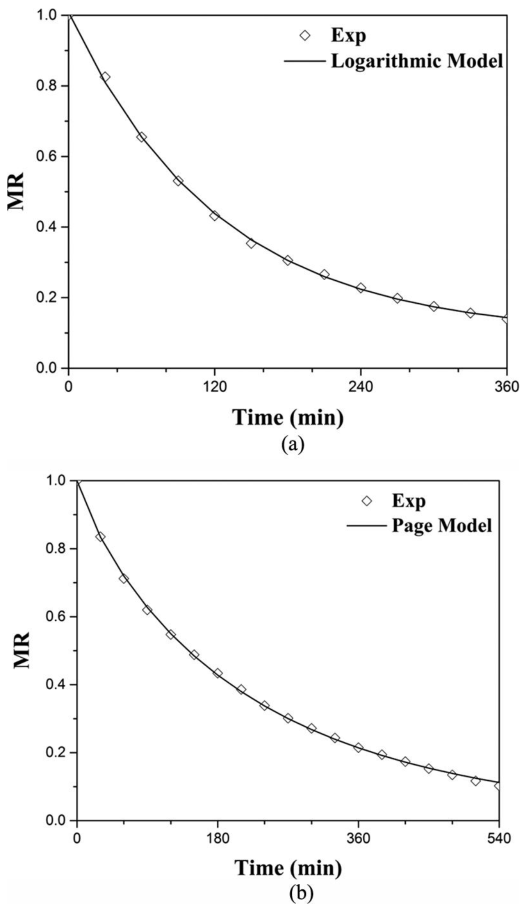

Figure 7. Drying kinetics of macadamia nuts when subjected to hot air (60°C) assisted RF drying (electrode gap of 15.5 cm) (a) and hot air drying (60°C) (b) fitted with the models against experimental values (Exp).[34]

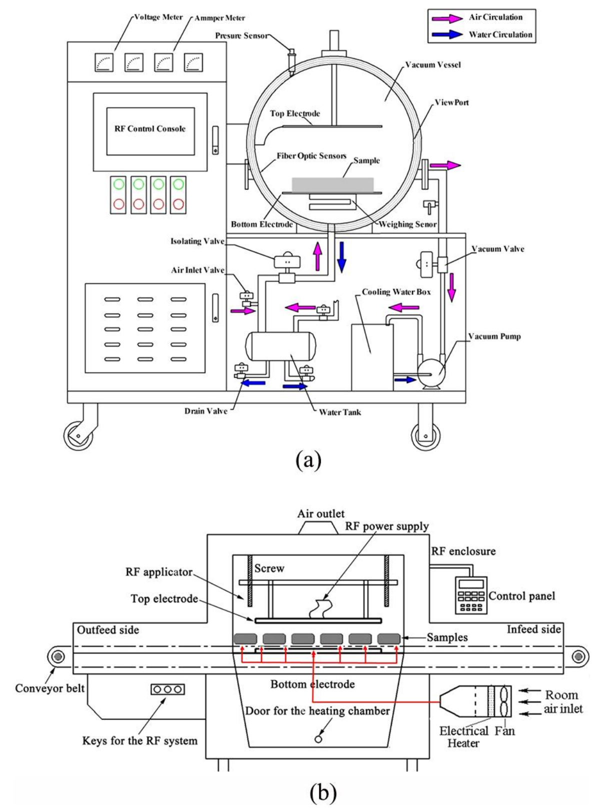

Figure 8. Schematic view of the lab-scale 3 kW, 27.12 MHz RF-vacuum drying system (a) and the free-running oscillator 6 kW, 27.12 MHz RF system combined with hot air drying system (b).[73]

temperature and the pressure of vacuum vessel were continuously measured by a four-channel fiber optic sensor system (HQ-FTS-D120, Heqi Technologies Inc., Xian, China) and a pressure sensor (APC500, Sensor Way Technologies Inc., Beijing, China) included in the RF cavity, respectively. A weighting sensor (AT8106, Pengheng Electronic Inc., Shanghai, China) with a precision of 0.1 g underneath the bottom electrode was used to record weight changes of samples over the entire drying process without taking out the samples. All data were measured and recorded at a time interval of 5 s and stored in an embedded system (TPC1061Ti, Kunluntongtai Electronic Inc., Shenzhen,

Table 2. Applications of radio frequency (RF) drying for food and agricultural products.

Commodities	Drying methods	Conclusions	Reference
Alfalfa	ARFD*	Increased drying rate with uneven drying uniformity	Murphy et al.[86]
Broad bean	ARFD	A semi-empirical model developed for seed quality	Ptasznik et al.[87]
In-shell macadamia nut	ARFD	Increased drying rate with acceptable heating uniformity and product quality	Wang et al.[34,35]
In-shell walnut	ARFD	More rapid drying rate and better quality than AD and VD	Zhang et al.[56] and Zhou et al.[17]
Stem lettuce	ARFD	More uniform drying with acceptable product quality as compared to AD, ID, and MWD	Roknul et al.[88]
Duck egg	ARFD	DPs increasedwith addition of salt and sucrose, leading to increased RF drying rate	Lin et al.[89]
Corn	RFFD	A diffusion model developed for temperature and moisture simulation under continuous and intermittent patterns	Jumah[80]
Cracker	RF post-baking	40% output increase without need to extend plant	Mermelstein[93]
Kiwifruit slices	AD + RFVD OD + RFVD	No obvious differences in RF drying times between OD and AD pre-treated samples, but OD shows better quality than AD	

*AD, hot air drying; ARFD, hot air-assisted RF drying; ID, infrared drying; OD, osmotic dehydration; RFFD, RF assisted fluidized bed drying; RFVD, RF-vacuum drying.

China). Recent studies carried out in our lab have determined the effect of different pre-treatments on RF-vacuum drying characteristics of kiwifruit slices. About 1.0 kg kiwifruit slices were previously dried by hot air drying (60°C) and osmotic dehydration (65 Brix, 35°C), respectively, until their moisture content reached about 60% w.b., and then dried in the RF-vacuum system to the final moisture content (20% w.b.). Fig. 9 shows the RF-vacuum drying characteristics and average temperature of hot air and osmotic pre-dried kiwifruit slices. At the beginning of RF-vacuum drying, the temperature of both kiwifruit samples increased rapidly with time and continued to increase to a maximum value corresponding to the water boiling point (65°C) under vacuum degree of 0.025 MPa. When the temperature remained steadily, the absorbed RF energy was mostly used for water evaporation and the drying rate reached to a maximum value. As the drying progressed, loss of water in the samples reduced the absorption of RF energy and as a result the drying rate gradually decreased. In general, RF-vacuum drying may not only improve drying rate but also control the drying temperatures within a desirable range even at the final stage of RF drying, which may be very suitable for heat-sensitive agricultural commodities.

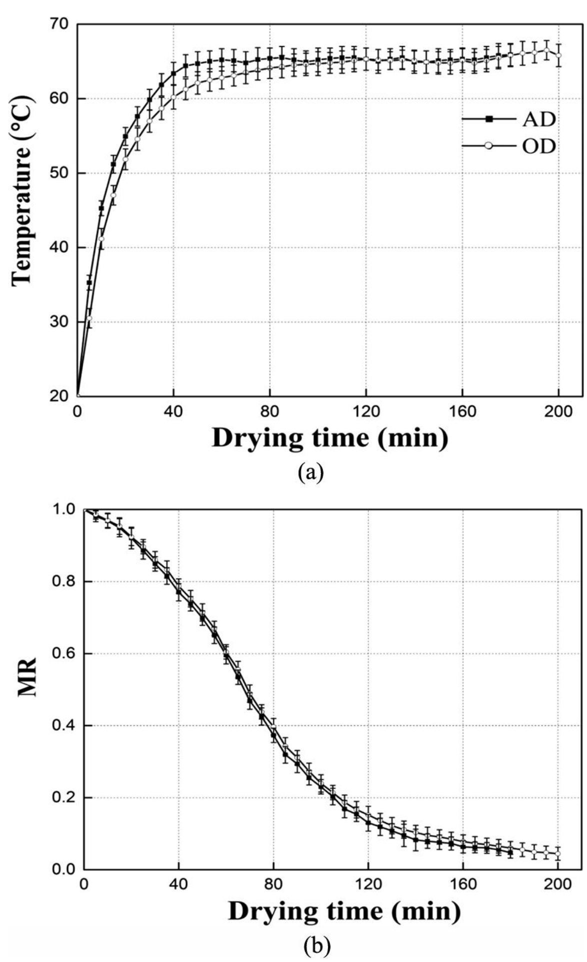

Figure 9. Changes of temperature (a) and moisture ratio (MR) (b) of kiwifruit slices pre-treated with hot air drying (60°C) (AD) and osmotic dehydration (65 °Brix, 35°C) (OD) when subjected to RF heating with electrode gap of 60 mm under 0.025 MPa (60 to 20% w.b., MC).

To improve the low drying rate of convective drying, the first attempt to combine RF heating with hot air was reported in the 1990s. Murphy et al.[86] developed a drying protocol for alfalfa using a combination of RF power at 27 MHz with forced air, which greatly improved the overall drying rate but with non-uniform drying, especially in the stems and leaves. A simulation model for hot air-assisted RF drying was developed to study heat and mass transfer as well as the seed quality of broad bean in 1990.[87] In recent years, a 6 kW, 27.12 MHz pilot-scale free running oscillator RF system (SO6B, Strayfield International, Wokingham, UK) combined with a hot-air system supplied by a 6 kW electric heater (Fig. 8b) was successfully used for drying in-shell nuts.[17,34,35,56] Wang et al.[34] determined the effects of different operational parameters, including RF electrode gap and hot air temperature, on the drying curve and quality attributes of the processed nuts. Two kg of in-shell nut samples were spread uniformly as multi-layers in a plastic container (25.5 cm $L \times$ 15.5 cm $W \times$ 11.0 cm H) with perforated side and bottom walls. The plastic container was placed on the bottom electrode during the RF drying process. Detailed information about the sample plastic container can be found in Wang et al.[34] The results show that an electrode gap of 15.5 cm combined with a hot air temperature of 50°C provided an acceptable heating rate and stable drying temperature during the hot air-assisted RF drying. In general, there were three drying rate stages (I, II, and III) during the hot air-assisted RF drying process (Fig. 4): Stage I (0–30 min) when the sample temperature was below hot air temperatures. The thermal energy absorbed from both RF and hot air heating was mostly used for raising sample temperatures since the energy for water evaporation was still low, resulting in rapid heating rate and increasing drying rate period; Stage II (30–150 min) when the sample temperature exceeded the hot air temperature and reached its maximal value (75°C), the rapid drying rate period occurred. RF energy was the only heat source and hot air (50°C) served as a medium to carry away moisture from the nut surface and lower the sample temperatures, leading to gradually decreasing heating rates; Stage III (150–360 min) when the sample temperature remained at a fairly constant level. The steady drying temperature was due to the fact that the absorbed RF energy was balanced by water evaporation and heat loss by exchanges with convective air. The drying rate decreased gradually at this stage, because the products were in a semi-dry state and thermal energy transfer was sharply reduced by shrunk product surface (Fig. 4b). Generally, approximately 52% of hot air drying time reduction was achieved by using RF energy. In addition, peroxide value and free fatty acid of nuts increased with drying times both for hot air and hot air-assisted RF drying but remained within acceptable range required by the nut industry. Therefore, RF drying could provide a rapid and uniform drying method with acceptable product quality for the nut industry. The same combination drying method was used by Zhang et al.[56] who studied the hot air assisted-RF drying characteristics of in-shell walnuts. Moreover, comparative analyzes were carried out and the results showed that the quality of RF treated samples was better than that of hot air treated ones after drying and during the 20 days accelerated storage in terms of lipid oxidation attributes, fatty acid composition and antioxidant activities.[17] Furthermore, Wang et al.[35] investigated the effect of container locations, moving condition and hot air on the RF heating and drying uniformity of in-shell nuts. The edge or corner overheating was observed during RF alone drying. The drying uniformity was significantly improved by combining hot air heating. However, moving samples reported to improve heating uniformity in many studies, such as for pest or pathogen control,[39,40,49] had little effects on heating uniformity during RF drying. Subsequently, Roknul et al.[88] studied the effect of four drying methods on drying time and quality characteristics of stem lettuce slice. These four drying tests were conducted at fixed air temperature (60°C) and velocity (1 m/s), as well as identical sample load (300 g), bed depth (20 mm), and the same power level for hot air-assisted RF drying, infrared drying, and microwave-assisted hot air drying, which was fixed at 4 W/g. They found that hot air-assisted RF drying provided a more uniform drying while maintaining acceptable product quality as compared to hot air, infrared and microwave-assisted hot air drying. In addition, several studies have investigated the effects of pretreatments on DPs of agricultural products for improving RF drying efficiency.[69,72] With addition of salt and sucrose, the DPs of duck egg white protein increased significantly and thus the RF drying rate was further improved.[89]

Fluidized bed and heat pump are other two commonly applied conventional dryers, which provide good heat and mass transfer between products and drying medium. Combining RF heating with these two drying methods could further shorten drying times and improve product quality. Merashalla and Metaxasa[90] studied the heat pump assisted RF drying technology, suggesting that heat pump assisted RF drying raised drying rate and reduced the discoloring of dried products as compared to heat pump drying alone. In addition, cracking caused by great pressure due to serious shrinkage during heat pump assisted conventional drying can be prevented by heat pump assisted RF drying.[3] Jumah[80] developed a numerical model to analyze the change of electric field strength, drying time, temperature and moisture in corn during RF assisted-fluidized bed drying when continuous and intermittent models of RF heating were considered. Simulated results were in a good agreement with the experimental ones, which showed that the drying rate and sample temperatures were proportional to the electric field strength.

Tandem combined RF drying

Tandem combination or hybrid drying method is a drying technology that employs different drying methods at different stages of the drying process, contributing to better thermal performance, higher energy efficiency, more even drying uniformity and desirable product quality.[91] The first commercial application for such technology using RF energy in the food industry was post-baking drying for crackers and cookies, which began in the 1980s. Orfeuil[92] reported that a 300 ft conventional oven in a commercial cracker production line was modified with improvement of cracker productions from 5,250 to 7,350 lbs per hour by adding a 100 kW, 27.12 MHz RF post baking unit to remove 80 kg/h of water in the final drying. It was possible to improve productions and save floor space by applying an RF drying immediately after a conventional baking process.[93] RF energy used in post-baking also shows its advantages in avoiding discoloration and loss of flavor of baked products.[94] But non-uniform drying of final products was still a major problem in bakery industry. Post-baking using RF energy could provide more uniform moisture content distribution in final crackers and cookies, and also reduced the problem of checking.[81] Moreover, many researches have shown that RF post-drying had no adverse effects on hardness and fracturability of cookies and was effective in lowering acrylamide level of processed samples and avoiding surface browning.[95–97]

More recently, researches carried out in our lab have focused on the application of RF energy in the final drying of fruits and vegetables. For instance, the RF-vacuum drying was used and followed by a conventional drying process (hot air drying or osmotic dehydration) to finish the kiwifruits drying (Fig. 9). There were no obvious differences in RF drying temperature and times between osmotically and hot air pre-dried kiwifruits due to the small difference in DPs between hot air and osmotic pre-treated samples. But the osmotic dehydration resulted in less quality deterioration of kiwifruits than hot air drying in terms of titratable acidity, ascorbic acid, soluble solids, and color. Therefore, combined osmotic dehydration and RF-vacuum drying may provide a rapid and practical method for drying kiwifruits with high-quality characteristics.

Conclusion and suggestions for future research

RF drying offers considerable advantages over conventional drying methods, such as rapid and volumetric heating, more stable temperature control and high energy efficiency. RF drying is more suitable for practical and industrial applications due to deeper penetration and better heating uniformity as compared to MW drying. However, the commercial drying applications of RF energy are mainly limited to textile, bakery and wood industry. To speed up applications of RF heating technology to food and agricultural products, future research on RF drying should focus on the following areas:

1. It is possible and necessary to expand RF heating technology developed for disinfestation and pasteurization to drying process based on systematic studies. Integrating disinfestation, pasteurization and drying purposes together is critical if effective and efficient RF postharvest handling technologies are to be developed.
2. Drying uniformity is one of the most important indicators for high-quality drying technology. Combining RF heating with conventional drying method, such as hot air and vacuum drying, has high potential to improve heating and drying uniformity. In addition, RF-related combination drying is more economically viable with high energy efficiency and product quality. Therefore, further studies are desirable to develop different RF-conventional combination drying technologies and optimize these combined drying methods with consideration of drying rate, product quality, energy consumption, and food safety.
3. Computer simulations serve as an emerging technology for rapid, cheap, and flexible analysis for facilitating the design and scale-up, and providing an optimal process to simulate and predict important operational parameters, such as the distributions of RF power, temperature and moisture in target materials. Moreover, mathematical modeling complemented with experimentation may determine effects of different factors and methods on improving heating and drying uniformity and provide a clear and in-depth understanding of electromagnetic interactions with drying materials. Although many simulation models have been successfully developed to predict temperature distributions of samples and improve heating uniformity during RF treatments, more efforts are needed to develop 3D coupled electromagnetics and multi-phases transport models with considering sample shape changes for detailed understanding of RF drying process.
4. Knowledge of DPs is essential for better understanding the heating and drying behaviors of food products and designing treatment beds in industrial applications. Reliable information about DPs is also necessary to improve the computer model prediction precision. However, DPs of many food and agricultural products influenced by temperature, moisture content and frequency are still not available in the literature for RF drying. More studies about DPs of food and agricultural products are required to design adequate RF drying treatments.
5. Pre-treatment of agricultural product and food before drying is necessary, which may provide opportunities to not only regulate the DPs of samples but also reduce quality deterioration of final products. Except for additions of salt or sucrose, other pre-treatments such as osmotic dehydration, blanching, dipping ultrasound and pulsed electric fields are benefit for color, rehydration and nutritional value of final products upon drying. Future extensive research would be required for exploring different pre-treatments to provide desirable physical and chemical changes as well as to improve heat and mass transfer.

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