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Dielectric properties of kiwifruit associated with a combined radio frequency vacuum and osmotic drying

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ABSTRACT

To develop a novel combination drying method combining radio frequency (RF) with vacuum and osmotic dehydration (OD), information on dielectric properties is essential so as to understand the interaction between the electromagnetic field and the matrix undergoing drying. In this paper, the dielectric properties of kiwifruit samples were determined across the frequency range of 10 and 3000 MHz using an open-ended coaxial-line probe and impedance analyzer at moisture contents ranging from 19.8% to 79.6% on a wet basis (w.b.) and temperatures between 20 and 80 °C. The effect of pre-treatments including OD and hot air drying (AD) on the dielectric properties, physicochemical properties and RF-vacuum drying characteristics of kiwifruit were also studied. The results showed that both the dielectric constant and loss factor decreased with decreasing moisture content and increasing frequency. At high moisture contents (above 65% w.b.), the dielectric constant decreased slightly with increasing temperature, whereas at lower moisture contents (below 50% w.b.), the dielectric constant increased sharply with increasing temperature. In addition, the OD resulted in less kiwifruit quality deterioration than AD in terms of titratable acidity, ascorbic acid, soluble solids and color. Although dielectric permittivities of OD treated kiwifruits were slightly lower than those of AD treated samples, the effect of the OD treatment on RF energy coupling was negligible compared to the AD. Therefore, OD may provide an alternative way for AD as a pre-treatment before RF drying for kiwifruits with high-quality characteristics.

1. Introduction

Recently, kiwifruit (*Actinidia deliciosa*) has received considerable attentions as a source of phytochemicals, such as phenolics, flavonoids and chlorophyll, increased consumption of which can have substantial health benefits for consumers (Hwang et al., 2017). The global production of kiwifruit was around 4.27 million metric tons (Mt) in 2016, with the majority of this production originating in China (2.39 Mt), Italy (0.52 Mt), New Zealand (0.43 Mt) and Chile (0.23 Mt) (FAOSTAT, 2018). However, fresh kiwifruit is susceptible to microbial spoilage and softening due to its high moisture content (i.e. over 80% on a wet basis (w.b.)) and deteriorates quickly over a very short period of time if improperly handled (Concha-Meyer et al., 2016). In addition, a seasonal availability often limits the consumption of fresh kiwifruits at certain times of year. Therefore, proper postharvest handling and shelf life extension to overcome the seasonal variation in supply is important to maximize the yield of high-quality kiwifruit products.

Drying is a unit operation that can be used to stabilize and preserve fresh fruits under ambient storage conditions by reducing their water activity (Zhang et al., 2017). In addition to its role in preservation, the associated reduction in bulk volume and weight of the resultant products lowers handling, packaging and transportation costs (Mujumdar and Law, 2010). Conventional drying methods, including AD (Maskan, 2001a; b), vacuum drying (VD) (Orikasa et al., 2014), OD (Castro-Giraldez et al., 2011) and freeze drying (FD) (Hwang et al., 2017) used for fruit drying often take a considerable amount of time, varying from several hours to over three weeks. Kiwifruit drying at an industrial scale is most commonly performed by AD, but this is characterized by low energy efficiency and long drying times (Maskan, 2001a). Water diffusivity may be accelerated when higher temperatures are applied during AD, but longer treatment times still remain under elevated temperatures, leading to a greater level of undesirable deterioration of product quality attributes including taste, color and nutritional value (Zhang et al., 2006). Currently, increasing demands for high-quality dehydrated fruits and vegetables have prompted research into dielectric heating based on microwave (MW) and radio frequency (RF) energy (Zhang et al., 2017; Zhou and Wang, 2018). MW and RF drying methods, often referred to as fourth generation drying technologies

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(Vega-Mercado et al., 2001; Wang et al., 2013), which may provide opportunities to reduce drying times and improve product quality and thus hold potential for practical postharvest applications for kiwifruit drying.

RF drying has attracted increasing attention due to its many advantages over MW heating including greater heating uniformity, deeper penetration depths and more stable product temperature control (Wang et al., 2014; Zhou et al., 2018). Pilot-scale RF systems have demonstrated practical applications in pest control (Gao et al., 2010; Wang et al., 2007a; b), pasteurization/sterilization (Li et al., 2017a; Kou et al., 2018) and dehydration (Wang et al., 2014; Zhou et al., 2018; Zhou and Wang, 2018). However, dielectric drying based on RF energy alone has several disadvantages, such as high energy consumption and uneven heating (Zhou et al., 2018; Zhou and Wang, 2018). A combination of drying technologies is often applied to develop fast and energy-saving processes for effectively combining advantages and possible synergies among drying methods and minimize the limitations of individual drying technologies applied alone (Calin-Sanchez et al., 2014; Huang et al., 2012). RF drying can be combined with conventional drying methods, such as VD, OD and AD (Zhou et al., 2018). However, information on dielectric properties of the food matrix undergoing dehydration is critically important in order to develop effective postharvest dehydration methods based on RF combined with conventional drying.

The interaction between dielectric materials and RF energy is governed by the relative complex permittivity ε^* ($\varepsilon^* = \varepsilon'-j\varepsilon''$). The real part of the relative complex permittivity (ε', dielectric constant) describes the ability of a material to store energy. The imaginary part (ε'', loss factor) is associated with energy dissipation or the ability to transform from dielectric to thermal energy. Dielectric properties have been reported for various agricultural products and foods over different frequencies, temperatures and moisture contents for disinfesting (Sosa-Morales et al., 2009; Wang et al., 2003, 2005), pasteurization (Li et al., 2017b; Zhu et al., 2012) and drying (Guo and Zhu, 2014; Zhang et al., 2016). In addition, several studies are available on the dielectric properties of fruits across MW frequencies at different moisture contents and temperatures (Feng et al., 2002; Sipahioglu and Barringer, 2003; Wang et al., 2011). Furthermore, OD involving the immersion of food into hypertonic solutions is often used as a pre-treatment before RF and MW drying, resulting in water removal and simultaneous solute diffusion (Castro-Giraldez et al., 2011). The effects of OD on dielectric properties of fruits and vegetables, such as potato (De los Reyes et al., 2007), carrot or strawberries (Changrue et al., 2008), and mangosteen (Therdthai and Visalrakkij, 2012), were also determined in the literature over the last decade. These studies focused on improving dielectric properties of materials with additional OD treatments. Up to now, however, the effects of frequency, temperature, moisture content and different pre-treatments including AD and OD on the dielectric properties of kiwifruits have not been reported.

The objectives of this research were to fill these gaps in knowledge by: (1) measuring the dielectric properties of kiwifruits across a frequency range of 10–3000 MHz at four temperatures (20, 40, 60 and 80 °C) and five moisture content levels (20%, 35%, 50%, 65% and 80% w.b.) relevant to their dehydration, (2) determining the regression equations for describing the influence of moisture content, temperature and frequency (27, 40, 915 and 2450 MHz) (i.e. the most commonly used for dielectric drying applications), (3) studying the effect of pre-treatments (i.e. AD and OD), on the dielectric and physicochemical properties of kiwifruit, and (4) determining the effect of AD and OD on the RF-vacuum drying characteristics of kiwifruit slices.

2. Material and methods

2.1. Material and sample preparation

Fresh kiwifruits (*Actinidia deliciosa* cultivar “Hayward”) with similar ripeness and size were purchased from a local supermarket in Yangling, Shaanxi, China. The kiwifruits were then stored in a refrigerator (BD/BC-297KMQ, Midea Refrigeration Division, Hefei, China) at 4 °C until required for analysis. Before conducting dielectric property measurements, kiwifruits were removed from the refrigerator and placed in an incubator (GD/JS4010, Haixiang Instrument & Equipment Co., Ltd., Shanghai, China) at 20 ± 0.5 °C and 30% relative humidity (RH) for 12 h to reach an equilibrium temperature. The samples were then hand peeled and cut into slices 10.02 ± 0.26 mm thick with diameters of 45.05 ± 3.10 mm. Moisture content of kiwifruit slice samples was determined following the AOAC Official Method 925.40 (AOAC, 2005). About 10–15 g of the kiwifruit samples were placed in a aluminum dish and dried at 105 °C under pressure ≤13.3 kPa in a vacuum oven until a constant weight was achieved. The calculated moisture content of fresh kiwifruit slices was 84.4 ± 2.1% (w.b.).

To prepare kiwifruit slice samples with five moisture contents (20, 35, 50, 65 and 80% w.b.) for dielectric property measurements, twenty-five fresh kiwifruit slices were randomly divided into 5 groups and spread uniformly on a wire mesh tray mounted at the middle of a temperature-adjustable hot air dryer (DG100D, Zhongkong Lab equipment Inc, Zhejiang, China). The temperature and RH of the hot air were set to 65 °C and 20%, respectively, with an air velocity of 2.0 m s^{-1} measured by a rotating vane anemometer (LCA 6000, AIRFLOW Instrumentation, Buckingham-215 Shire, UK). These parameters were selected as representative of kiwifruit AD recommended by Maskan (2001b) and Orikasa et al. (2014). Every 20 min, the samples were taken out of the tray dryer and their weight was immediately measured using an electronic balance (PTX-FA210, Huazhi Scientific Instrument, Co., Ltd., Fuzhou, China) with a precision of 0.01 g. The moisture content of kiwifruit samples was calculated based on the initial moisture content and the loss of weight during the drying process. Once the calculated moisture content decreased to the desired value, the kiwifruit samples in each group were taken out of the convective drying chamber and then used for DPs determination. The final moisture contents of the samples were 79.6 ± 0.5%, 65.0 ± 1.1%, 50.1 ± 2.5%, 34.9 ± 3.1 and 19.8 ± 3.2% w.b., respectively, which were verified by the vacuum oven method (AOAC, 2005).

To determine effects of OD on the dielectric properties of kiwifruits, a sucrose solution (65 °Brix) prepared with a food grade sugar and deionized water was used as an osmotic solution. The ratio of kiwifruits to solution was 1:20 (w/w) to avoid changes in the osmotic solution during the treatment. The kiwifruit slice samples were placed in a beaker containing the sucrose solution with continuous stirring at 30 °C. The OD times required to reduce the moisture content of kiwifruit from 84.4% to 80.0, 70.0 and 60.0% w.b. were about 20, 60 and 300 min, respectively, which is based on our preliminary experiments and the study reported by Castro-Giraldez et al. (2011) under identical test conditions. The sample with moisture content below 60.0% w.b. was not studied because it took more than 6 h for OD and long osmotic treatment might result in severe product quality degradation and the growth of microorganisms (Cao et al., 2006). The moisture contents of the osmotically dehydrated kiwifruit samples were 80.3 ± 1.5, 70.2 ± 2.4 and 60.5 ± 2.6%, respectively, which was verified by a vacuum oven method (AOAC, 2005) after the osmotic treatments. To compare effects of OD and AD on the dielectric properties of kiwifruits, three sub-lots of kiwifruit slices were dried at 65 °C and 20% RH by the hot-air tray dryer as described above until their moisture content reached the same levels, namely, 80.1 ± 1.2%, 70.0 ± 1.5% and 59.5 ± 1.2% w.b.

2.2. Kiwifruit analysis

For soluble solids determination, 5.0 g samples were blended using a blender (JYL-D022, Joyoung, Jinan, China) to obtain pulp and measured with a hand held refractometer (Model PAL-1, ATAGO Co. Ltd., Atago, Japan). Titratable acidity expressed as percentage of citric acid was measured by the titrimetric method (AOAC, 2005). Ascorbic acid was determined by the 2,6-dichloroindophenol titration method (Huang and Zhang, 2016) and expressed as micrograms per gram solids. The pH value was measured by immersing an electrode into the kiwifruit pulp using a pH meter (PHS-25, Precision & Scientific Instrument Co. Ltd., Shanghai, China), which was initially calibrated with buffers of pH 4.00, 6.86 and 9.18, respectively. The color (L^*, a^* and b^*) of kiwifruit samples was determined by a computer vision system. The details about the computer vision system and procedure used can be found in Hou et al. (2014).

2.3. Dielectric properties measurement

The dielectric properties of kiwifruits over a frequency range from 10 to 3000 MHz were measured by an open-ended coaxial probe system consisting of an impedance analyzer (E4991B-300, Keysight Technologies Co. LTD., Palo Alto, California, USA) with a calibration kit (E4991B-010), a high-temperature coaxial cable, the coaxial probe with dielectric probe kit (85070E-020), a custom-built sample test cell, an oil circulated bath (SST-20, Guanya Constant Temperature Cooling Technology Co. LTD., Wuxi, China) and an auxiliary computer. The dielectric properties were measured at 501 discrete frequencies on a linear scale. Detailed information about the open-ended coaxial probe system can be found in Li et al. (2017b).

Before measurements, the impedance analyzer and the computer were started up and remained steady for at least 20 min. Using a standard E4991B-010 calibration kit, the impedance analyzer was calibrated with open, short and 50 Ω resistance in order. The coaxial probe was then calibrated with air, short and 25 °C distilled water. After the calibration, the kiwifruit slices were gently cut with a sharp blade into samples with 20.50 ± 0.50 mm diameters to ensure a close contact with inner wall of the custom-built sample test cell (21 mm in diameter). The size of the kiwifruit samples was sufficient for dielectric property measurements (Feng et al., 2002). Then samples were then put into the test cell and confined with a pressure spring to eliminate air gaps and contacted closely with the coaxial probe. During measurements, changes of sample moisture content were neglected since the sample cell was air tight.

The sample temperature in the test cell was monitored using a thermocouple (HH-25TC, Type-T, OMEGA Engineering Inc., Stamford, Connecticut, USA) and precisely controlled by circulating oil from an oil bath into the jacket of the test cell, which was held at 20, 40, 60 and 80 °C during measurements. About 4–6 min was required to elevate the sample temperature from one level to the next. The above temperature range covered a representative range of temperatures encountered during the drying of fruits and vegetables. Prior to each measurement, the probe and the sample test cell were rinsed with distilled water and wiped dry.

2.4. Penetration depth

Penetration depth (d_p, m) of MW and RF power is defined as a depth to which the intensity of the electromagnetic power falls to 1/e (e = 2.718) of the original value of power entering material surface. This parameter is useful to select an appropriate thickness of samples to ensure uniform RF and MW heating, which was calculated by the following equation (von Hippel, 1954):

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

Where c is the speed of light in free space ($3 \times 10^8\ \mathrm{m\,s^{-1}}$) and f is the frequency (Hz).

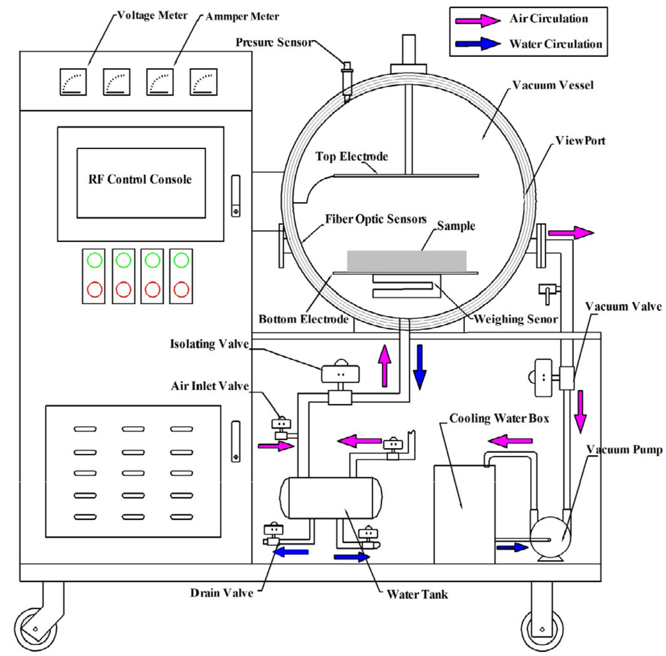

Fig. 1. Schematic view of the lab-scale 3 kW, 27.12 MHz RF-vacuum system showing the plate electrodes, control system, and vacuum system.

2.5. RF-vacuum drying systems and characteristics

A multifunctional and programmable RF-vacuum drying system, with a maximum nominal power of 3.0 kW and an operation frequency of 27.12 MHz, was used for kiwifruit drying. This dehydrator was designed and manufactured by Hebei Huashijiyuan Industrial High Frequency Equipment, Ltd. (Langfang, Hebei, China). It consisted of two parallel plate RF electrodes (600 mm × 400 mm), a vacuum vessel (800 mm in diameter and 800 mm long), a view port (200 mm × 200 mm), a vacuum pump (2BV-2071, Aoli Pump Instrument & Equipment Co., Ltd., Zibo, China), a water collector and monitoring system for continuously measuring the vacuum pressure, sample temperatures and weights (Fig. 1). Moreover, the electrode gaps between the two parallel plates can be adjusted from 20 mm to 300 mm to deliver the desired RF energy for a specific load. The maximum vacuum level achieved was −0.10 MPa, which can be reached within 20 s using the vacuum pump. In addition, the sample temperature and the pressure of vacuum vessel were continuously measured by four fiber optic sensors (HQ-FTS-D120, Heqi Technologies Inc., Xian, China) and a pressure sensor (APC500, Sensor Way Technologies Inc., Beijing, China) included in the RF cavity. A weighting sensor (AT8106, Pengheng Electronic Inc., Shanghai, China) with a precision of 0.1 g underneath the bottom electrode was used to measure the weight changes of samples during the entire drying process without the need to remove samples from the cavity. All data were recorded at a time interval of 5 s and stored in an embedded system (TPC1061Ti, Kunluntongtai Electronic Inc., Shenzhen, China).

To determine effects of different pre-treatments (i.e. AD and OD) on the RF-vacuum drying characteristics of kiwifruits, 1.0 kg kiwifruit slices were previously dried by AD and OD, respectively, until their moisture content reached 60% w.b., and then dried in the RF-vacuum system to the final moisture content (20% w.b.). An electrode gap of 60 mm and vacuum level of −0.075 MPa were selected for RF-vacuum drying following the performance of preliminary experiments to identify rapid heating rates and desirable drying temperatures. A plastic container (350 mm × 250 mm × 20 mm) with perforated screens (5 mm in diameter) on the side and bottom walls containing kiwifruit samples was placed on the center of the bottom electrode. Four fiber temperature sensors were inserted into kiwifruit samples at four locations in the geometric center of the plastic container to record sample temperatures. The moisture content of kiwifruit samples was determined based on the initial moisture content and weight loss during the drying process. The change of moisture content was expressed as moisture ratio (*MR*) defined as

$$MR = \frac{M_i - M_e}{M_0 - M_e} \quad (2)$$

Where M_i is the moisture content (%, on a dry basis (d.b.)) at any drying time *i*, M_0 is the initial moisture content (%, d.b.) and M_e is the equilibrium moisture content (%, d.b.). The range of RH in this drying environment was 8–20%, so the estimated M_e *of* the product could attain in the oven under these conditions ranged from 5 to 8% (d.b.) with an average value of 6.5% (d.b.) based on sorption isotherms for kiwifruits (ASAE, 1996; Kaya et al., 2010).

2.6. Statistical analysis

The results are expressed as mean ± standard deviations over three replicates. Analysis of variance (ANOVA) was performed using a statistical analysis software (Design Expert, version 10, Stat-Ease Inc., Minneapolis, USA). Significant differences test was performed using the Microsoft Excel variance procedure (Microsoft Office Excel, 2010) to determine difference between the means ($P < 0.05$).

3. Results and discussion

3.1. Frequency-dependent dielectric properties

Figs. 2 and 3 show the frequency-dependent dielectric constant (ε') and loss factor (ε'') respectively of kiwifruits having moisture contents of either 19.8% or 79.6% w.b. at four temperatures. In samples with a high moisture content (79.6% w.b.), the dielectric constant decreased with increasing frequency with a more pronounced decrease at lower frequencies (Fig. 2b), whereas the loss factor decreased to a minimum level and subsequently increased slightly with frequency (Fig. 3b, d). The gradual reduction of the dielectric constant of samples at high moisture contents can mainly be attributed to the dispersion of water molecules (Jiao et al., 2014). Moreover, the slightly U-shape relationship between loss factor and frequency at the high moisture contents was likely to have been caused by the superposition of ionic conduction and the dispersion of free water. This result is in agreement with studies of Ling et al. (2015) and Sosa-Morales et al. (2009). On the other hand, at the low moisture content (19.8% w.b.), the dielectric constant also decreased with increasing frequency (Fig. 2a). However, the slightly U-shape for the dielectric loss factor was not present (Fig. 3a, d). The most likely explanation for this phenomenon is because the free water relaxation peak was depressed due to the decreased amount of free water (Feng et al., 2002). In addition, bound water is most likely to dominate the dielectric dispersion at this water level (Feng et al., 2002). To clearly investigate the frequency-dependent of loss factor, results for kiwifruit samples at two moisture contents were plotted against frequency in logarithmic scale (Fig. 3c and d). It was observed that the log of dielectric loss factor and log of frequency had a negative linear relationship at lower frequencies (below 100 MHz), suggesting that ionic conduction has the dominant influence on the dielectric loss mechanism within RF range (Sosa-Morales et al., 2009; Wang et al., 2003; Zhang et al., 2016; Zhu et al., 2012). Moreover, the reduction of the loss factor with increasing frequency was more rapid at lower frequencies (below 100 MHz) than at higher frequencies.

3.2. Moisture and temperature-dependent dielectric properties

Figs. 4 and 5 show the dielectric properties of kiwifruit samples as a function of moisture contents and temperatures at 27, 40, 915 and 2450 MHz. It was observed that at a certain frequency, both the dielectric constant and the loss factor decreased with decreasing moisture contents. In general, as the drying progressed, water dipoles became less mobile, resulting in a decrease in loss factor. In addition, the decreasing moisture content reduced ionic conductivity since less free water is available as a solvent. Moreover, air voids induced in the kiwifruit samples during drying would have also contributed to the reduction in the dielectric properties. The moisture-dependent dielectric properties observed in this study are similar to results observed with apples (Feng et al., 2002), potato (Wang et al., 2011), grape marc (Solyom et al., 2013) and pineapple (Barba and Lamberti, 2013). Furthermore, the thermal energy transformed from RF or MW energy is either used for sample temperature increase or moisture evaporation. Therefore, the moisture content dependent-dielectric loss factor indicated that during RF or MW drying, samples or locations within samples which had higher moisture contents may absorb more RF or MW energy and be heated preferentially as compared to those with lower moisture contents. This phenomenon commonly referred to as "moisture leveling", contributing to uniform heating during the dielectric drying (Metaxas and Meredith, 1988).

Fig. 4 also shows that the effect of temperatures on the dielectric constant depends on the moisture content of kiwifruit samples. At high moisture contents (above 65% w.b.), the dielectric constant decreased slightly or remained almost constant with increasing temperature, but at low moisture contents (below 50% w.b.) it increased sharply with increasing temperature. These phenomena were also found in RF treatments, with RF heating rate increasing with increasing moisture content but once a threshold value is exceeded, the heating rate decreased with increasing moisture content (Huang et al., 2015; Zhang et al., 2016). The most likely explanation for this observation might be because free water dispersion accounted for the dielectric behavior at high moisture content (> 70%), ionic conduction played a major role at medium moisture (~23%) and bound water accounted for the major

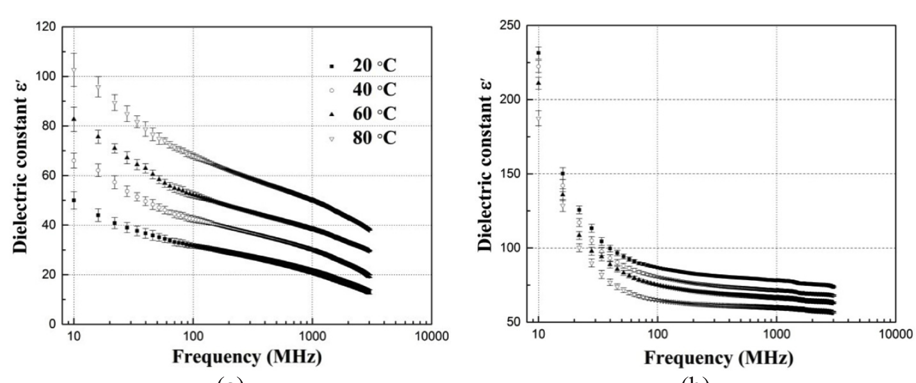

Fig. 2. Frequency-dependent dielectric constant (ε') of kiwifruit samples with moisture content of 19.8% (a), and 79.6% w.b. (b) at four temperatures.

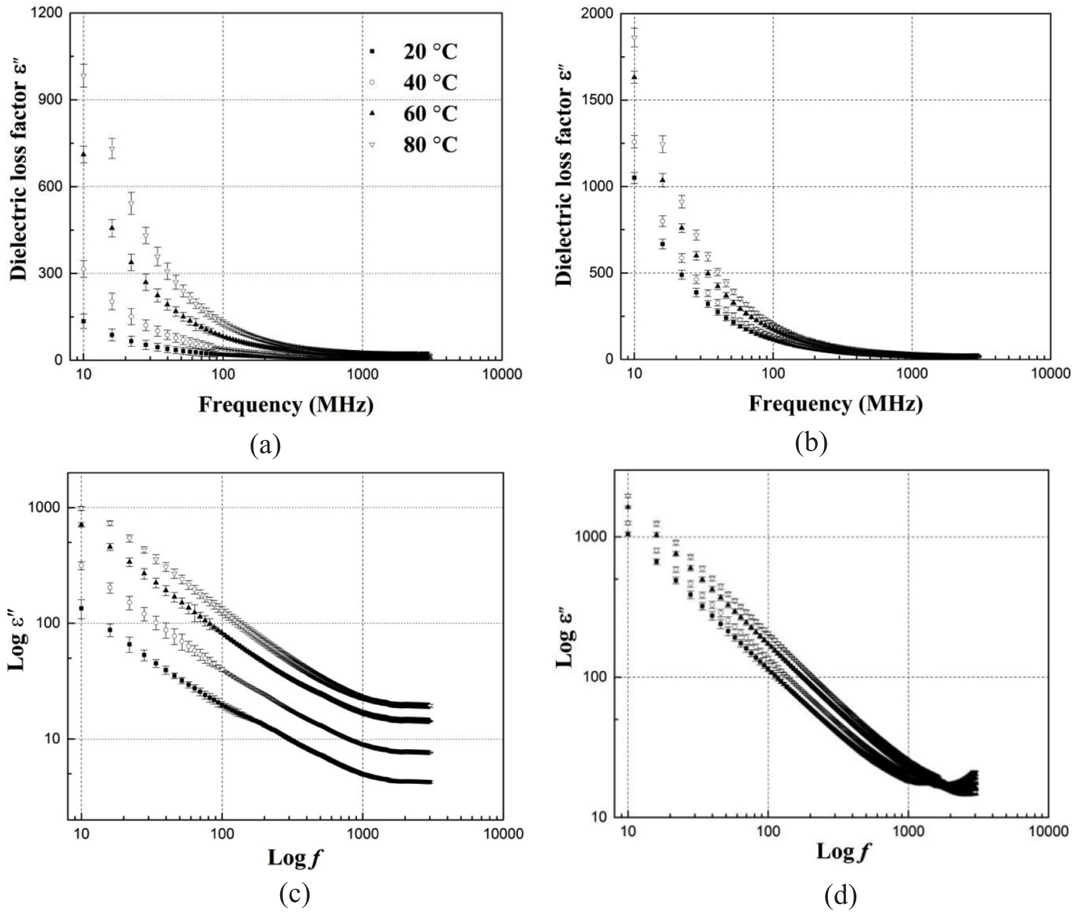

Fig. 3. Frequency-dependent dielectric loss factor (ε'') of kiwifruit samples with moisture contents of 19.8% (a), and 79.6% w.b. (b) together with the log-log plot at 19.8% (c), and 79.6% w.b. (d) at four temperatures.

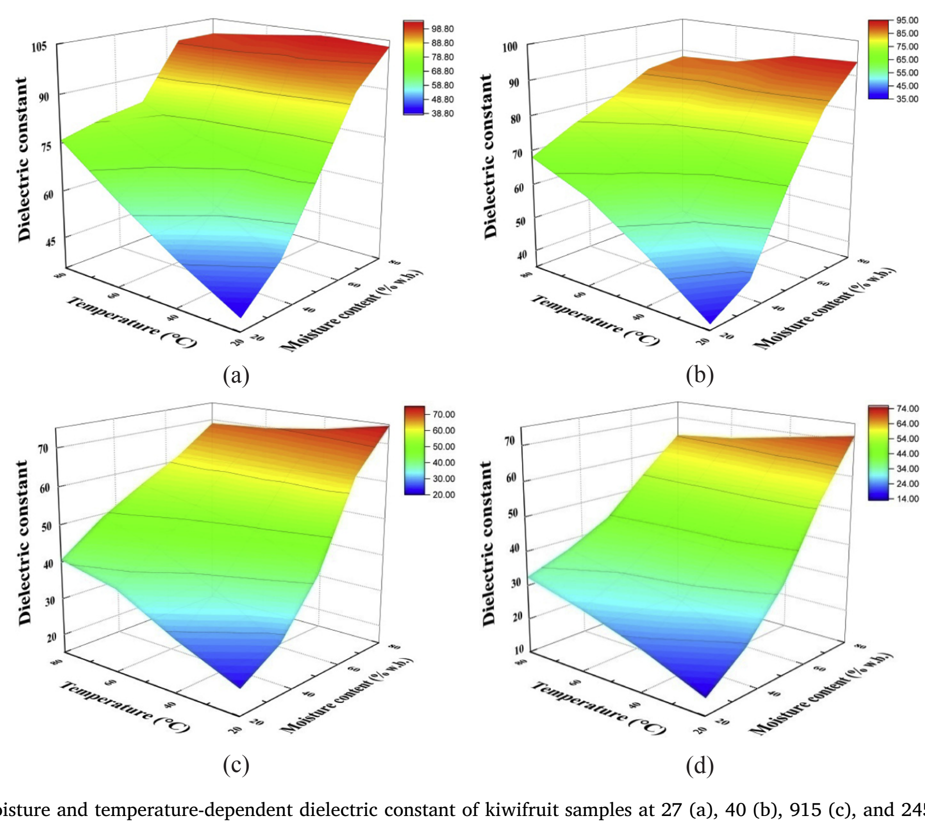

Fig. 4. Moisture and temperature-dependent dielectric constant of kiwifruit samples at 27 (a), 40 (b), 915 (c), and 2450 MHz (d).

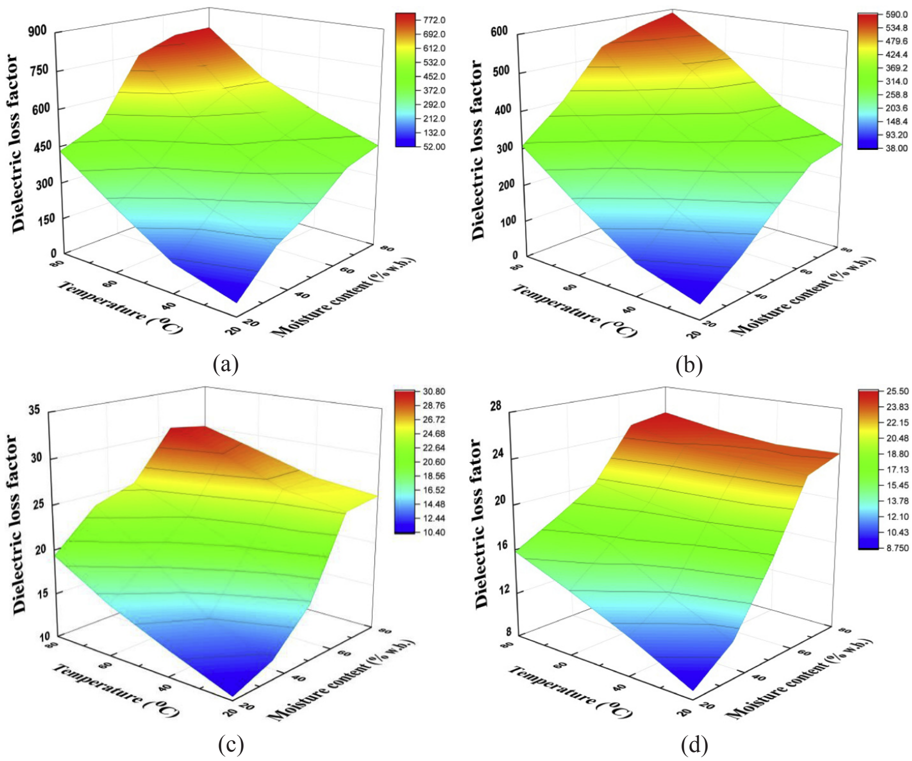

Fig. 5. Moisture and temperature-dependent dielectric loss factor of kiwifruit samples at 27 (a), 40 (b), 915 (c), and 2450 MHz (d).

dispersion mechanism at low moisture contents (~4%) (Jiao et al., 2014). The temperature had little effect on free water dispersion and thus the dielectric constant remained within a small range at high moisture contents. On the other hand, the dielectric loss factor increased with increasing temperature over the entire moisture content range, especially at RF frequencies. It was assumed that the increased dielectric loss factor with increasing temperature at a given frequency was due to the reduced viscosity, resulting in increased ionic conductivity (Feng et al., 2002). Similar results are also found in Wang et al. (2005), Nelson and Trabelsi (2006), Guo et al. (2008) and Ling et al. (2015).

3.3. Regression models for dielectric properties

The regression equations (3)–(10) for moisture and temperature-dependent dielectric properties of kiwifruit samples at four frequencies (27, 40, 915 and 2450 MHz) are listed in Tables 1 and 2. For the dielectric constant of kiwifruits, the cubic polynomial equations showed the best fit for 27, 40 and 2450 MHz, whereas the quadratic polynomial equation was best fit for 915 MHz. For the dielectric loss factor of kiwifruits, the cubic polynomial equation was determined to be the best model for 40, 915 and 2450 MHz, whereas the quadratic polynomial one was found to be the best to describe loss factor of kiwifruit at 27 MHz.

Analysis of variance (ANOVA) shown in Tables 3 and 4 was used to determine whether moisture content and temperature had significant influences on the models as listed in Tables 1 and 2. The linear, quadratic and cubic term of M had strong influences on these models ($p < 0.001$). Each equation provided a good fit to dielectric property values with a significance level of 0.0001 and the coefficients of determination were greater than 0.9770, suggesting that these equations were very suitable for predicting the dielectric properties of kiwifruits at any given moisture contents and temperatures within ranges encountered during drying at frequencies of 27, 40, 915 or 2450 MHz, respectively, and thus are adequate to describe moisture and temperature-dependent dielectric properties used in future computer simulations.

3.4. Effects of pre-treatments on dielectric and physicochemical properties

The OD method had a simultaneous influence of reducing moisture contents and raising sucrose contents of the sample, whereas by contrast, only moisture content decreased during the AD process. The comparative analyses for dielectric properties of samples pretreated with OD and AD were carried out to determine effects of the pre-drying methods on dielectric and physicochemical properties of kiwifruits (Table 5). The result shows that the dielectric properties, especially the loss factor, of hot air dried samples were slightly larger than those of osmotically dehydrated samples at same moisture contents (i.e. 70% and 60% w.b.). That may be because the sucrose gained through the OD reduced the dielectric properties of osmotically dehydrated kiwifruits. In addition, native ionic compounds in the kiwifruits were lost during the OD and the sucrose was bound with polar molecules, resulting in the decreased free water content and dielectric properties (Castro-

Table 1
Regression equations for the dielectric constant of kiwifruit samples as a function of temperature (T, 20–80 °C) and moisture content (M, 19.8%–79.6% w.b.).

Frequency (MHz)	Dielectric constant (ε′)
27	$\varepsilon' = 38.08 + 0.83T - 171.83M - 0.98TM - 1.71 \times 10^{-3}T^2 + 668.96M^2 - 0.65 \times 10^{-3}T^2M + 0.49TM^2 + 3.37 \times 10^{-5} - 448.91M^3$ (3)
40	$\varepsilon' = 19.40 + 1.28T - 94.32M - 1.11TM - 7.20 \times 10^{-3}T^2 + 472.69M^2 + 7.23 \times 10^{-3}T^2M - 0.78TM^2 + 1.35T^3 - 289.75M^3$ (4)
915	$\varepsilon' = -10.04 + 0.68T + 93.63M - 0.82TM - 1.19 \times 10^{-3}T^2 + 14.72M^2$ (5)
2450	$\varepsilon' = -5.43 + 1.19T - 23.30M - 0.95TM - 0.01T + 242.00M^2 + 4.62 \times 10^{-3}T^2M - 0.24TM + 6.24 \times 10^{-5}T^3 - 120.53M^3$ (6)

Table 2
Regression equations for the dielectric loss factor of kiwifruit samples as a function of temperature (T, 20–80 °C) and moisture content (M, 19.8%–79.6% w.b.).

Frequency (MHz)	Dielectric loss factor (ε'')
27	$\varepsilon'' = -231.28 + 0.05T + 1405.36M + 1.08TM + 0.06T^2 - 804.01M^2$ (7)
40	$\varepsilon'' = 57.37 - 4.35T - 360.63M + 9.80TM + 0.11T^2 + 1936.92M^2 - 0.05T^2M - 4.50TM^2 - 4.08 \times 10^{-4}T^3 - 1474.55M^3$ (8)
915	$\varepsilon'' = 20.32 - 0.06\mathrm{T} - 105.29M + 0.33TM + 3.31 \times 10^{-3}T^2 + 287.94M^2 - 4.31 \times 10^{-4}T^2M - 0.44TM^2 - 1.77 \times 10^{-5}T^3 - 183.88M^3$ (9)
2450	$\varepsilon'' = 7.35 + 0.31T - 49.66M - 0.47TM - 1.45 \times 10^{-3}T^2 + 202.72M^2 + 2.10 \times 10^{-3}T^2M + 0.08TM^2 + 1.30 \times 10^{-6}T^3 - 142.36M^3$ (10)

Table 3
Analysis of variance of regressed models of Eqs. (3)–(6) for kiwifruit samples at four frequencies relevant to dehydration.

Variance and R^2	27 MHz (Eq. 3)		40 MHz (Eq. 4)		915 MHz (Eq. 5)		2450 MHz (Eq. 6)	
	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value
T	2.3579	0.1557	15.1603	0.0030	44.0089	< 0.0001	2.0490	0.1828
M	84.1882	< 0.0001	177.1840	< 0.0001	786.8955	< 0.0001	529.6573	< 0.0001
TM	40.9442	< 0.0001	181.0509	< 0.0001	58.3299	< 0.0001	224.5101	< 0.0001
T^2	0.0021	0.9644	2.2983	0.1605	0.8765	0.3650	5.6873	0.0383
M^2	0.7951	0.3935	0.0074	0.9332	1.1842	0.2949	66.2956	< 0.0001
T^2M	0.4210	0.5310	2.2043	0.1684	–	–	2.9488	0.1167
TM^2	0.2362	0.6374	2.5263	0.1430	–	–	0.7558	0.4050
T^3	0.0455	0.8354	0.0307	0.8645	–	–	2.1478	0.1735
M^3	9.1820	0.0127	16.13	0.0025	–	–	9.1301	0.0129
Model	157.82	< 0.0001	169.2983	< 0.0001	178.2590	< 0.0001	565.3658	< 0.0001
R^2	0.9978		0.9974		0.9983		0.9978	

Table 4
Analysis of variance of regressed models of Eqs. (7)–(10) for kiwifruit samples at four frequencies relevant to dehydration.

Variance and R^2	27 MHz (Eq. 3)		40 MHz (Eq. 4)		915 MHz (Eq. 5)		2450 MHz (Eq. 6)	
	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value
T	468.8717	< 0.0001	150.1154	< 0.0001	15.6271	0.0027	6.6899	0.0271
M	430.0696	< 0.0001	229.0035	< 0.0001	94.8938	< 0.0001	201.2723	< 0.0001
TM	0.5825	0.4580	1.6964	0.2220	7.9465	0.0182	34.9281	0.0001
T^2	12.4173	0.0034	20.3495	0.0011	0.4791	0.5046	0.3239	0.5818
M^2	20.3947	0.0005	49.5394	< 0.0001	2.0479	0.1829	3.0121	0.1133
T^2M	–	–	2.0923	0.1786	0.0205	0.8891	1.4782	0.2520
TM^2	–	–	2.0099	0.1867	2.0670	0.1811	0.2170	0.6513
T^3	–	–	0.6713	0.4317	0.1375	0.7185	0.0023	0.9630
M^3	–	–	9.9636	0.0102	16.9599	0.0021	30.9258	0.0002
Model	186.4672	< 0.0001	365.7561	< 0.0001	62.7212	< 0.0001	133.2621	< 0.0001
R^2	0.9768		0.9787		0.9920		0.9958	

Giraldez et al., 2011). Wang et al. (2011) also reported that the dielectric permittivity of potato purees decreased with the addition of sucrose at 2450 MHz. Moreover, the changes of dielectric properties with respect to moisture, temperature and frequency were similar both for AD and OD treated kiwifruit samples (Table 5). Generally, the small difference in dielectric properties between OD and AD treated samples indicated that the moisture removal of kiwifruits was the dominant effect influencing the changes of dielectric properties and the effect of moisture removal overcame that of solid gain during the OD process. However, the difference in dielectric properties between OD and AD treated samples became larger when the moisture content decreased. This is probably due to increasing solid and decreasing ionic compounds in samples as the OD progressed. For example, the relative decreases of dielectric constant and loss factor at 27 MHz and 20 °C from AD to OD treated kiwifruit samples were 6.4% and 8.9% at moisture content of 70% w.b., whereas the relative decreases of dielectric constant and loss factor were 10.2% and 12.1% at moisture content of 60% w.b. These results were also found in osmotically dehydrated and hot air dried kiwifruit samples with the moisture content of 80% w.b.

Table 6 shows the effects of AD and OD on physicochemical properties of kiwifruit samples. There was no significant difference ($P > 0.05$) between fresh and OD treated samples in three physicochemical attributes including titratable acidity, ascorbic acid and pH. The mean soluble solids of OD treated kiwifruit sample was significantly higher ($P < 0.05$) than that of both fresh and AD treated samples. In addition, OD resulted in the highest value of L^*, followed by fresh and AD treated samples. The similar effects of drying methods on color changes of kiwifruit were also reported in other researches (Fathi et al., 2011; Maskan, 2001b).

In general, OD treatment maintained the quality attributes of kiwifruit samples as compared to fresh ones and resulted in less quality deterioration than AD. Moreover, the relatively small difference in dielectric properties between osmotically dehydrated and hot air dried samples was acceptable and unlikely to influence the electromagnetic energy coupling. Therefore, OD may provide an alternative way for AD as a pre-drying treatment before RF or MW drying.

3.5. Penetration depth

Tables 7 and 8 show the calculated penetration depths of RF or MW energy in kiwifruit samples influenced by the frequency, moisture content, temperature and pre-treatments (i.e. AD and OD). The penetration depth increased with decreasing frequency and temperature for kiwifruit samples (Table 7). Such change is most likely due to the decreasing dielectric properties. In addition, the moisture content had

Table 5
Dielectric properties (means ± SD over three replicates) of kiwifruit slices pretreated with hot air drying (AD) and osmotic dehydration (OD) at four frequencies relevant to dehydration and over four temperatures and two moisture contents.

Moisture content (% w.b.)	Treatment	T (°C)	Dielectric properties	Frequency (MHz)			
				27	40	915	2450
70.0	AD	20	ε′ ± SD	97.53 ± 0.56	88.62 ± 0.77	69.26 ± 0.58	63.68 ± 0.58
			ε″ ± SD	407.45 ± 2.68	284.32 ± 1.24	25.11 ± 0.08	23.54 ± 0.09
		40	ε′ ± SD	98.86 ± 1.63	89.33 ± 1.69	67.14 ± 1.61	62.35 ± 1.49
			ε″ ± SD	489.40 ± 3.25	355.50 ± 2.11	26.08 ± 0.18	23.77 ± 0.11
		60	ε′ ± SD	98.38 ± 0.44	87.78 ± 0.52	65.75 ± 0.20	60.42 ± 0.71
			ε″ ± SD	613.35 ± 5.66	478.94 ± 3.49	28.46 ± 0.18	24.13 ± 0.21
		80	ε′ ± SD	96.74 ± 0.85	86.06 ± 0.58	66.08 ± 0.44	59.28 ± 0.37
			ε″ ± SD	808.19 ± 5.96	576.96 ± 2.69	30.46 ± 0.51	25.18 ± 0.44
70.2	OD	20	ε′ ± SD	91.28 ± 0.75	82.48 ± 0.58	66.19 ± 0.34	61.04 ± 0.22
			ε″ ± SD	371.19 ± 3.69	258.78 ± 2.89	23.62 ± 0.26	21.65 ± 0.15
		40	ε′ ± SD	92.94 ± 0.76	83.26 ± 0.54	64.85 ± 0.37	60.58 ± 0.68
			ε″ ± SD	454.58 ± 6.84	321.06 ± 4.03	24.68 ± 0.65	21.84 ± 0.13
		60	ε′ ± SD	92.41 ± 0.81	82.45 ± 0.74	63.32 ± 0.86	58.46 ± 0.59
			ε″ ± SD	574.68 ± 5.23	439.17 ± 4.88	26.30 ± 0.26	22.53 ± 0.16
		80	ε′ ± SD	89.71 ± 0.45	80.76 ± 0.63	63.58 ± 0.54	57.20 ± 0.38
			ε″ ± SD	757.67 ± 10.23	545.84 ± 5.36	27.50 ± 0.51	23.69 ± 0.15
59.5	AD	20	ε′ ± SD	81.49 ± 0.83	74.12 ± 0.98	52.84 ± 0.71	45.96 ± 0.51
			ε″ ± SD	332.14 ± 2.69	235.17 ± 5.32	20.53 ± 0.32	19.79 ± 0.11
		40	ε′ ± SD	84.44 ± 0.88	77.09 ± 0.88	56.04 ± 0.71	47.93 ± 0.52
			ε″ ± SD	437.91 ± 1.68	314.14 ± 5.69	23.12 ± 0.32	21.18 ± 0.51
		60	ε′ ± SD	86.66 ± 0.59	80.05 ± 0.99	57.29 ± 0.82	48.57 ± 0.77
			ε″ ± SD	562.62 ± 2.51	417.68 ± 2.73	25.73 ± 0.05	21.54 ± 0.30
		80	ε′ ± SD	90.68 ± 1.11	82.98 ± 0.98	58.39 ± 0.84	48.83 ± 0.72
			ε″ ± SD	777.66 ± 3.62	546.03 ± 2.63	27.99 ± 0.62	22.51 ± 0.32
60.5	OD	20	ε′ ± SD	73.15 ± 1.54	67.46 ± 1.05	50.35 ± 0.76	43.23 ± 0.64
			ε″ ± SD	291.92 ± 4.83	201.50 ± 7.05	18.22 ± 0.22	18.35 ± 0.31
		40	ε′ ± SD	75.63 ± 1.52	71.96 ± 1.36	53.12 ± 0.84	45.13 ± 0.77
			ε″ ± SD	384.73 ± 2.31	275.68 ± 4.86	20.28 ± 0.26	19.41 ± 0.30
		60	ε′ ± SD	78.25 ± 2.02	73.40 ± 1.59	54.60 ± 0.76	46.01 ± 0.63
			ε″ ± SD	499.89 ± 2.31	366.86 ± 4.15	23.36 ± 0.22	19.95 ± 0.18
		80	ε′ ± SD	82.00 ± 1.32	75.91 ± 0.99	25.90 ± 0.86	46.52 ± 0.67
			ε″ ± SD	703.63 ± 10.31	494.31 ± 7.24	31.03 ± 0.32	20.56 ± 0.22

Table 6
Physicochemical properties (means ± SD over three replicates) of kiwifruit samples pretreated with hot air drying (AD) and osmotic dehydration (OD).

Physicochemical Properties	Treatment		
	Fresh	AD	OD
Moisture content (% w.b.)	84.51 ± 0.15a*	59.52 ± 0.21b	60.55 ± 0.64b
Soluble solids (°Brix)	13.40 ± 0.20b	10.23 ± 0.53c	16.55 ± 0.31a
Titratable acidity (% citric acid)	1.62 ± 0.10a	1.23 ± 0.08b	1.50 ± 0.13a
Ascorbic acid (mg/100 g)	107.43 ± 5.05a	81.14 ± 6.31b	98.22 ± 8.47a
pH	3.51 ± 0.21a	2.92 ± 0.22b	3.48 ± 0.25a
*L**	57.18 ± 2.55b	49.25 ± 3.43c	65.41 ± 2.03a
*a**	−17.25 ± 0.80b	−10.36 ± 1.59a	−16.82 ± 1.02b
*b**	37.50 ± 1.52a	30.86 ± 2.84b	38.88 ± 1.23a

*Means followed by different lowercase letters are significantly different at P ≤ 0.05 among pretreatments.

little effect on the penetration depth until its level was reduced to about 35% w.b. Similar results were also observed on Red Delicious apples (Feng et al., 2002) and grape marc (Solyom et al., 2013).

Table 8 shows similar effects of frequency, temperature and moisture content on the penetration depth for kiwifruit samples pretreated with different pre-drying methods. Generally, the penetration depth for osmotically dehydrated kiwifruit was slightly larger than that for hot air dried samples due to the solid gain through the osmotic treatment (Lin et al., 2014) and the larger values of penetration depth in osmotically dehydrated samples would be preferable for subsequent kiwifruit drying by dielectric means. In addition, the penetration depth for RF energy (27 and 40 MHz) was about 3–10 times the values for MW energy (915 and 2450 MHz). Dielectric drying using RF energy combined with OD can provide better heating uniformity, deeper bed depths and therefore larger practical throughputs for kiwifruits.

3.6. Effects of pre-treatment on RF-vacuum drying characteristics

Fig. 6 shows the temperature changes and RF-vacuum drying characteristics of both AD and OD treated kiwifruit samples. It was noted that the total drying times required to reduce the moisture content of OD and AD pre-treated kiwifruit samples from 60% to 20% (w.b.) were 198 and 185 min, respectively. Only an approximate 7.4% reduction in drying time was achieved for hot air dried samples. At the beginning of RF-vacuum drying, the temperature of kiwifruit samples with high moisture contents increased rapidly with time and continued to increase to a maximum value corresponding to the water boiling point (65 °C) under a vacuum level of −0.075 MPa (Fig. 6a). When the temperature remained steady, the absorbed RF energy was mostly used for water evaporation and thus the drying rate reached 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 (Fig. 6b). Although there were slight differences in drying temperature and times between OD and AD treated kiwifruit samples, the effect of the OD treatment on the RF energy coupling was negligible as compared to the AD, and therefore the OD can be used as a pre-drying method prior to RF-vacuum technology.

4. Conclusions

Moisture content, frequency and temperature have great effects on the dielectric properties of kiwifruits. Both the dielectric constant and loss factor decreased with decreasing moisture content and increasing

Table 7
Penetration depth (means ± SD over three replicates) of electromagnetic waves into samples calculated from the measured dielectric properties of kiwifruit samples at four frequencies relevant to dehydration and over four temperatures and five moisture contents.

Moisture content (% w.b.)	T (°C)	Penetration depth (cm)			
		27 MHz	40 MHz	915 MHz	2450 MHz
19.8	20	23.98 ± 2.33	20.37 ± 2.70	4.40 ± 0.11	1.69 ± 0.05
	40	13.83 ± 0.99	11.81 ± 1.47	4.21 ± 0.13	1.63 ± 0.06
	60	8.51 ± 0.87	7.11 ± 0.60	4.07 ± 0.06	1.57 ± 0.04
	80	6.54 ± 0.31	5.36 ± 0.49	3.76 ± 0.08	1.52 ± 0.03
34.9	20	10.04 ± 1.38	9.89 ± 0.80	2.35 ± 0.12	0.86 ± 0.0.6
	40	8.59 ± 0.62	7.22 ± 0.48	2.23 ± 0.14	0.81 ± 0.05
	60	7.07 ± 0.53	5.76 ± 0.55	1.84 ± 0.08	0.70 ± 0.05
	80	6.01 ± 0.48	4.61 ± 0.41	1.59 ± 0.07	0.68 ± 0.04
50.1	20	8.45 ± 0.84	7.09 ± 0.73	2.12 ± 0.15	0.72 ± 0.02
	40	6.68 ± 0.81	5.63 ± 0.62	1.85 ± 0.12	0.69 ± 0.03
	60	5.82 ± 0.18	4.85 ± 0.25	1.70 ± 0.09	0.67 ± 0.05
	80	4.80 ± 0.14	3.96 ± 0.22	1.58 ± 0.11	0.65 ± 0.03
65.0	20	7.12 ± 0.14	5.92 ± 0.16	1.80 ± 0.05	0.69 ± 0.02
	40	6.42 ± 0.12	5.15 ± 0.11	1.71 ± 0.08	0.68 ± 0.05
	60	5.52 ± 0.40	4.28 ± 0.12	1.57 ± 0.05	0.65 ± 0.0.2
	80	4.67 ± 0.12	3.83 ± 0.15	1.55 ± 0.15	0.62 ± 0.04
79.6	20	6.78 ± 0.22	5.75 ± 0.29	1.71 ± 0.04	0.64 ± 0.02
	40	6.06 ± 0.19	4.99 ± 0.15	1.62 ± 0.06	0.63 ± 0.02
	60	5.39 ± 0.28	4.16 ± 0.13	1.46 ± 0.09	0.62 ± 0.05
	80	4.64 ± 0.13	3.74 ± 0.12	1.45 ± 0.08	0.59 ± 0.02

Table 8
Penetration depths (means ± SD over three replicates) of kiwifruit slices pretreated with hot air drying (AD) and osmotic dehydration (OD) at four frequencies relevant to dehydration and over four temperatures and two moisture contents.

Moisture content (% w.b.)	Treatment	T (°C)	Penetration depth (cm)			
			27	40	915	2450
70.0	AD	20	6.94 ± 0.68	5.83 ± 0.71	1.76 ± 0.09	0.67 ± 0.08
		40	6.22 ± 0.63	5.07 ± 0.69	1.67 ± 0.10	0.66 ± 0.09
		60	5.44 ± 0.44	4.22 ± 0.52	1.52 ± 0.10	0.64 ± 0.04
		80	4.64 ± 0.45	3.78 ± 0.28	1.42 ± 0.14	0.61 ± 0.07
70.2	OD	20	7.30 ± 0.75	6.14 ± 0.58	1.82 ± 0.08	0.72 ± 0.05
		40	6.46 ± 0.26	5.36 ± 0.44	1.72 ± 0.17	0.70 ± 0.08
		60	5.63 ± 0.61	4.42 ± 0.54	1.61 ± 0.16	0.67 ± 0.09
		80	4.80 ± 0.45	3.89 ± 0.33	1.55 ± 0.14	0.63 ± 0.08
59.5	AD	20	7.71 ± 0.53	6.42 ± 0.48	1.88 ± 0.11	0.68 ± 0.05
		40	6.54 ± 0.48	5.37 ± 0.38	1.72 ± 0.11	0.66 ± 0.02
		60	5.67 ± 0.39	4.54 ± 0.29	1.57 ± 0.12	0.64 ± 0.07
		80	4.73 ± 0.21	3.89 ± 0.38	1.46 ± 0.14	0.62 ± 0.02
60.5	OD	20	8.25 ± 0.54	7.01 ± 0.55	2.06 ± 0.16	0.73 ± 0.04
		40	7.00 ± 0.52	5.78 ± 0.36	1.91 ± 0.14	0.69 ± 0.07
		60	6.02 ± 0.21	4.87 ± 0.58	1.69 ± 0.16	0.68 ± 0.03
		80	4.97 ± 0.32	4.10 ± 0.19	0.97 ± 0.15	0.66 ± 0.07

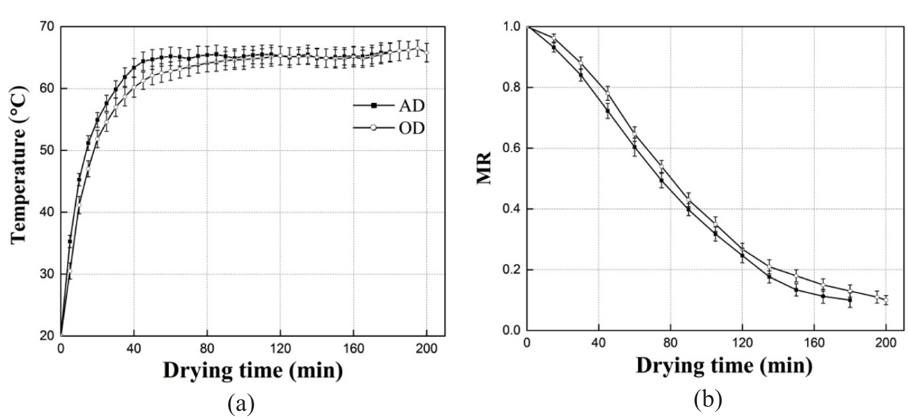

Fig. 6. Changes of temperature (a) and moisture ratio (MR) (b) of kiwifruit slices pre-treated with hot air drying (AD) and osmotic dehydration (OD) when subjected to RF heating with electrode gap of 60 mm under −0.075 MPa.

frequency. The loss factor increased with increasing temperature at any moisture content. However, the effect of temperatures on the dielectric constant depended on the moisture content of kiwifruits. At high moisture contents (over 65% w.b.), the dielectric constant decreased slightly with increasing temperature, whereas at low moisture contents (below 50% w.b.), it increased with increasing temperature. Quadratic and cubic polynomial equations showed the best fit for describing dielectric properties as influenced by moisture content and temperature at the four frequencies of interest. Moreover, the OD resulted in less quality deterioration of kiwifruit samples. The dielectric properties of samples pretreated with AD were slightly larger than those of samples pretreated with OD at the same moisture content. But the effect of the OD treatment on the RF energy coupling was negligible as compared to the AD. Therefore, OD can be considered to be an alternative method as a pre-treatment prior to RF drying to replace AD. A future study is also required to optimize the combination of OD and RF-vacuum drying in terms of assessing the impact on drying kinetics, final product quality and storage stability.

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