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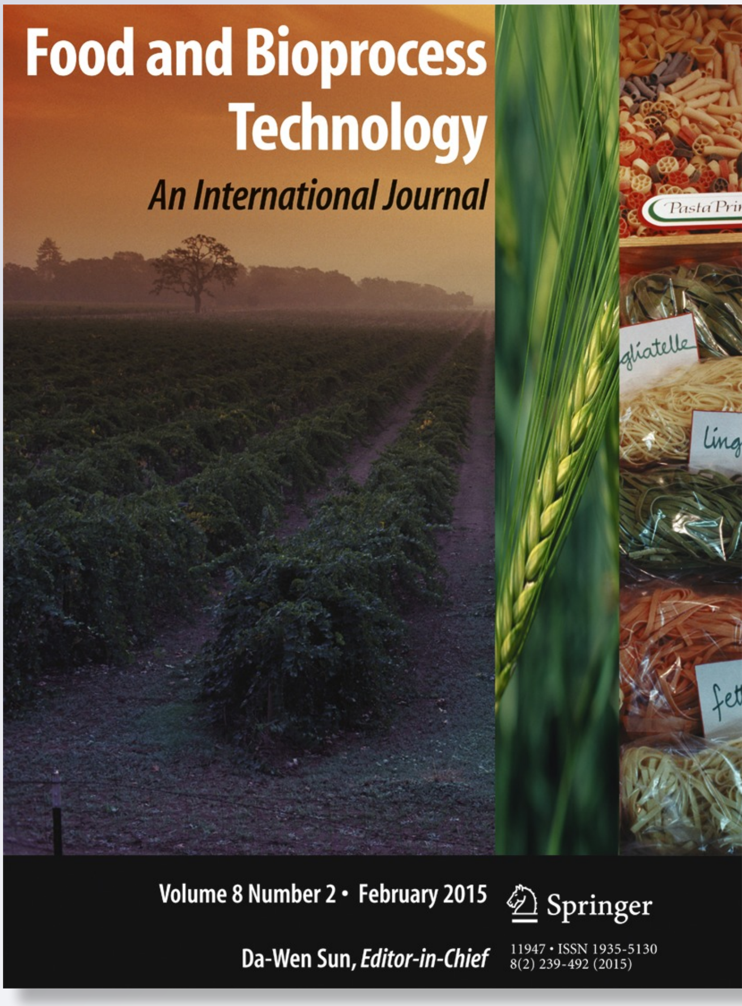

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ORIGINAL PAPER

Dielectric Properties of Pistachio Kernels as Influenced by Frequency, Temperature, Moisture and Salt Content

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Abstract Conventional hot air drying for pistachio nuts results in high energy consumption and low product quality. To develop advanced drying methods based on microwave (MW) and radio frequency (RF) energy, dielectric properties of pistachio kernel samples at different frequencies (10–4500 MHz), temperatures (25–85 °C), moisture contents (3–27 % w.b.), and three salty levels (moisture content 15 % w.b.) were measured by an open-ended coaxial-line probe and network analyzer. The results showed that the permittivities of non-salted pistachio kernel samples were dependent on moisture content, temperature of samples, and frequency of the applied electric field. Both dielectric constant and loss factor increased with increasing temperature and moisture content. The rate of increase was greater at higher temperature and moisture levels than at lower levels, especially in low frequencies. Dielectric loss factor increased with increasing salty levels of pistachio kernel samples, but dielectric constants were not significantly affected. Quadratic polynomial equations were developed to relate dielectric properties of the non-salted samples to temperature and moisture at four specific frequencies with R^2>0.978. Penetration depth decreased with increasing frequency, moisture content, temperature, and salty levels. It is likely that low frequencies, such as RF, may provide potential large-scale industrial drying applications for pistachio nuts with acceptable uniformity and throughputs.

Keywords Dielectric properties · Pistachio kernels · Radio frequency · Microwave · Drying

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Introduction

Pistachio (*Pistacia vera* L.), a member of the *Anacardiaceae* family, is mostly cultivated in hot, arid, and saline zones of Middle East, United States, and Mediterranean countries. The world production of pistachio was around 1 million metric tons in 2012, and the export prices of raw and dried nuts in 2010 reached 6800, 5000, and 7400 dollars per ton in Iran, USA, and Turkey, respectively (FAOSTAT 2012). Pistachio nut has gained increasing attentions due to high contents of several nutrients and health promoting compounds, such as about 50 % of lipids, 20 % of proteins, and some vitamins and antioxidant substances (Arcan and Yemenicioğlu 2009; Arena et al. 2007; Kornsteiner et al. 2006; Venkatachalam and Sathe 2006). Due to its high nutritional value and split shell, pistachio is an increasingly important nut crop consumed as raw, salted, or roasted nuts (Bilim and Polat 2008). Proper postharvest handling is a basic part to achieve maximum yield of good quality nuts that determine marketability and industry profit (Aktas and Polat 2007).

Drying is an important processing technology in pistachio industry. After harvesting, the pistachio nuts should be dried from a moisture content of about 35 % to safe storage moisture of less than 7 % wet basis (w.b.) (Kashaninejad et al. 2006). Pistachio products are commonly dried either with a fossil fuel-based drying system or on paved ground under the sun for a long time (Mujumdar 2006). For various direct or indirect fossil fuel-based dryers, the energy consumption is large with reaching about 10 million liters of diesel fuel and nature gas each year in Iran and energy efficiency was about 70 % for conventional flat plate continuous pistachio dryer (Kouchakzadeh and Tavakoli 2011; Kouchakzadeh 2013). Since the product temperatures are not precisely controlled, this conventional drying also diminishes the quality of the dried nuts, such as discolored, burned, or off-flavor (Ghazanfari et al. 2003). For sun drying, the slow drying rate is dependent on the solar intensity and ambient relative humidity, in which the product quality could not be maintained when it is occasionally under raining (Ferguson et al. 2005). Therefore, it is important to explore an alternative drying method for achieving the high efficiency and maintaining the good pistachio quality.

Dielectric heating, which includes radio frequency (RF) and microwave (MW) treatment, has been studied as a potential novel drying technology for various agricultural products (Albanese et al. 2013; Balakrishnan et al. 2004; Jumah 2005; Wang et al. 2005b, 2014; Zielinska et al. 2013). As generated volumetrically within the materials, dielectric heating offers several distinct advantages over conventional convection, conduction, and radiation heating, such as short heating times, uniform heating throughout the material, consistent product quality, and efficient energy conversion (Marra et al. 2009; Pereira and Vicente 2010). Knowledge of dielectric properties of pistachio kernels is essential to the design, optimization, and control of the drying process with RF or MW energy (Sosa-Morales et al. 2010).

In the past 10 years, dielectric properties have been studied over different frequency, temperature, and moisture ranges of food and agricultural product for drying, disinfestations, thawing, pasteurization, and sterilization (Farag et al. 2008; Guo et al. 2008, 2010; Liu et al. 2011 ; Hu and Mallikarjunan 2005; Wang et al. 2003b, 2005a; Zhu et al. 2012, 2014a). Several studies have been reported on dielectric properties of nuts using the open-ended coaxial probe method. For example, Wang et al. (2003a) reported that the dielectric properties of almond kernels with low moisture content (3 % w.b.) had a similar trend to those of walnuts at low density level. Zhu et al. (2014b) developed polynomial equations for temperature, moisture contents, and frequencies of ground hazelnuts based on dielectric property data measured from 10 to 4500 MHz at 20 to 60 °C. Wang et al. (2013) reported that the dielectric properties of ground macadamia nut kernels decreased with increasing frequency and increased with increasing moisture content. Boldor et al. (2004) also found the similar trends in ground shelled peanuts as influenced by frequency, temperature, and moisture content. Up to now, dielectric properties of pistachio kernels as influenced by temperature, moisture, and salt contents are still not available for dielectric drying in the literature.

The objectives of this study were (1) to determine the permittivity data for pistachio kernels over the frequency range from 10 to 4500 MHz at temperatures between 25 to 85 °C with five moisture contents, (2) to provide the empirical equations describing pistachio kernel's dielectric properties as a function of moisture content and temperatures at interested frequencies (27, 40, 915, and 2450 MHz), (3) to evaluate the influence of salty processing on the dielectric properties of pistachio kernels, and (4) to determine the penetration depth of electromagnetic energy into pistachio kernels at four interested frequencies.

Materials and Methods

Materials

Dried pistachio nuts of the Kerman variety were obtained from Paramount Farming Company (Lost Hills, CA, USA). After removing shells and pellicle, they were sorted to remove any damaged kernels and then sealed into polyethylene bags at 5 °C until testing. The chemical compositions of the nut samples were determined with standard methods (AOAC 2005) and are summarized in Table 1.

Sample Preparation

The open-ended coaxial probe technique is widely used to measure the dielectric properties of many materials due to its broadband measurements and easy to operate, but this method is best suited for homogeneous liquids and soft semi-solids (Hewlett-Packard 2005; Sheen and Woodhead 1999). Irregularly shaped nut kernels do not make close contact with the flat tip of the probe for accurate measurements. This measurement problem has been solved by using a ground sample of the nuts and matching the true kernel density of the nuts (Guo et al. 2008). This measurement method has been applied for determining the dielectric properties of dry products, such as almonds, chestnuts, hazelnuts, and macadamia nuts (Gao et al. 2012; Wang et al. 2013; Zhu et al. 2012, 2014b). Therefore, compressed cylindrical samples made of homogenous nut kernel flour with flat surface were prepared using the method in this study.

Five-hundred grams of pistachio kernels with the original moisture content of 3.2 % w.b. were equally divided into five sublots and then placed in plastic bottles (500 mL). A calculated quantity of distilled water was intermittently sprayed on the kernel surface so as to adjust the moisture content to higher levels of 9, 15, 21, and 27 % w.b.. After thorough mixing, the bottles were tightly capped and kept in a refrigerator at 5 °C. An equilibrium period of 1 week was provided to achieve the desired moisture level and uniformity. During this period, they were thoroughly mixed three times per day.

Table 1 Chemical compositions (g/100 g, Ave±SD over three replicates) of studied pistachio kernels

Compositions	Content	Methods
Protein[a]	20.15±0.51	AOAC950.48
Fat	47.25±0.41	AOAC948.22
Moisture	3.20±0.11	AOAC925.40
Ash	3.11±0.22	AOAC950.49
Carbohydrate	22.34±0.21	Estimated by difference[b]

[a] Protein was calculated based on nitrogen conversion factor of 5.4.
[b] Carbohydrate content=100 % (% moisture+% protein+% fat+% ash)

To quantitatively determine the influences of salt contents on the dielectric properties of pistachio kernels, salted samples were prepared according to an Iranian traditional method (Hojjati et al. 2013). One hundred grams of non-salted kernels (moisture content 3.2 % w.b.) were soaked in 500 mL brine solutions (NaCl 5, 10, and 20 % *w/v*) for 30 min with a continuous stirring to closely match the commercial samples marketed as light, medium, and strong salted nuts. The salted nuts were dried at 60 °C for 1 h to achieve a final moisture content of 15 %. All salted samples were collected immediately after drying and stored under vacuum in individual polyethylene bags at 5 °C until further use.

Since permittivities are density-dependent (Berbert et al. 2002), nut kernels were ground into flour in a blender (JYL-D022, Shandong Joyoung Co., Ltd., Jinan, China), and then known weights of flour calculated from true density of nut kernels were placed in a metal cylindrical mould (∅ 22 mm× H 100 mm). The flour samples were compressed on a hydraulic press (QYL-32, Shandong Qiyang Company, Linyi, China) to make cylindrical samples (H ~30 mm) whose density matched with true density of nut kernel at the same moisture content.

Measurements of Moisture Content and True Density

The moisture content of nut kernels was determined according to the AOAC Official Method 925.40. An accurately weighed sample (4~5 g) was placed in an aluminum disk, and the sample was dried in a preheated vacuum oven (DZX-6020B, Shanghai Nanrong Instrument Co., Ltd., Shanghai, China) to a constant weight at 95–100 °C and ≤0.1 kPa.

The true density of nut kernels was determined at room temperature using the liquid displacement method within 2 min. Toluene (C_7H_8) was used as the displaced liquid to avoid absorption by nut kernels. Toluene also fills shallow dips in a kernel due to its low surface tension (Razavi et al. 2007). The results showed that when the moisture content of pistachio kernels was between 3 to 27 % w.b., the kernels density was within 1.0356 to 1.1014 g/cm^3, which are in agreement with the trend of Ohadi pistachio kernels in the moisture range 4 to 38 % w.b. reported by Kashaninejad et al. (2006). The slight increase in true density may be attributed to the possible higher weight increase of kernels in comparison to its volume expansion on moisture gain. Because the changes in the kernel density with moisture content were negligible, the density effect of the pistachio kernels was not considered in this study.

Dielectric Properties Measurement

Dielectric properties of the cylindrical samples were obtained with an open-ended coaxial probe system (Fig. 1). The main parts of the system consisted of an Agilent E5071C vector network analyzer, a 85070B open-ended coaxial probe, a 85070 dielectric probe kit software (Agilent technologies, Penang, Malaysia), a computer, and a constant temperature water bath (DK-98-1, Tianjin Taisite Instrument Co., Ltd., Tianjin, China). To obtain repeatable readings, the network analyzer was turned on and kept in a standby condition for at least 1 h, and then calibrated following the standard procedure described by Wang et al. (2003a) and Zhu et al. (2014a).

Once the system was calibrated, the cylindrical samples were placed into a custom-built stainless steel cylindrical holder (∅ 23 mm×H 25 mm) welded onto a stainless steel plate that can be submerged in a water bath to allow conditioning of the samples to the selected temperatures before each measurement. The water bath was lifted by the hydraulic platform to ensure the cylindrical samples contact well with the coaxial probe. The sample moisture content was maintained during the measurements because the test holder was water and air tight. The sample temperature was controlled by circulating water in the water bath and raised incrementally to four different levels (25, 45, 65, and 85 °C). The selection of this temperature range was based on drying conditions in nut industry (Aktas and Polat 2007; Ferguson et al., 2005; Tarigan et al. 2007). Preliminarily experiments via a precalibrated type-T thermocouple (TMQSS- 020U-6, Omega Engineering, Inc., Stamford, CT, USA) inserted into the center of the cylindrical sample showed that about 20 min needed for the sample temperatures to reach the next temperature level. After the sample temperature reached the set value, measurements of the dielectric properties were conducted in three replicates at 51 discrete frequencies on a logarithmic scale from 10 to 4500 MHz. Prior to and after each measurements, the probe and the sample holder were cleaned with deionized water and wiped dry. Mean values and standard deviations were calculated from the three replicates.

Power Penetration Depth

Penetration depth (d_p) is used to quantitatively describe how MW and RF powers interact with the food, and is defined as the distance in meters where the power is decreased to 1/*e* (*e*= 2.718) of the power passing the surface. This parameter is important in the selection of the appropriate thickness of a material bed to ensure uniform heating during RF or MW processes. It can be calculated according to the following equation (von Hippel 1954):

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

where c is the speed of light in free space (3×10^8 m/s), f is the frequency (Hz), ε' is the dielectric constant, and ε'' is the dielectric loss factor.

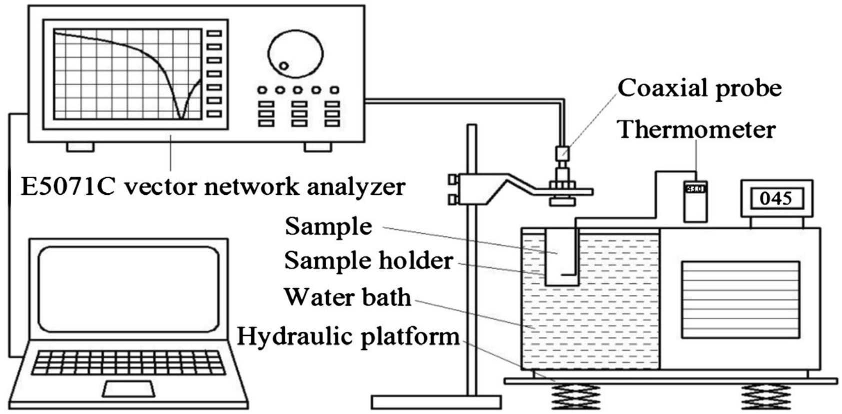

Fig. 1 Schematic diagram of the dielectric property measurement system

Results and Discussions

Dielectric Constant

Frequency-Dependent Dielectric Constant

The semi-log plot of the dielectric constant at different frequencies is presented for pistachio kernel samples with moisture contents of 9 % w.b. (Fig. 2a) and 27 % w.b. (Fig. 2b) over temperatures of 25 to 85 °C. The dielectric constants of both 9 and 27 % w.b. pistachio kernel samples at any temperature decreased with increasing frequency. Lower frequencies (i.e., 100 MHz) led to more pronounced depression of dielectric constant with increasing frequency from 10 to 4500 MHz, especially for higher moisture content. The dielectric properties of food materials depend on the free and bound water contents in the material (Calay et al. 1994). The dielectric polarization attributable to bound water is much less than that of free water. As the moisture content increased, the dielectric polarization increased. Figure 2 also shows that dielectric constant increased with increasing temperature at a given frequency. The increased temperature improved ionic mobility, which resulted in increased dielectric constant (Feng et al. 2002).

Moisture and Temperature-Dependent Dielectric Constant

To better understand the relationship between dielectric constant, moisture content, and temperature, the dielectric constant values of pistachio kernel samples at 27 MHz (Fig. 3a), 40 MHz (Fig. 3b), 915 MHz (Fig. 3c), and 2450 MHz (Fig. 3d) are plotted as functions of moisture content and temperature over a moisture range from 3 to 27 % w.b. and a temperature range from 25 to 85 °C in Fig. 3. It was observed that at a given frequency, the dielectric constants increased with increasing temperature and moisture content. For example, at 27 MHz, when temperature increased from 25 to 85 °C, the dielectric constant increased from 2.5 to 4.0, from 11.9 to 17.7, and from 28.9 to 37.0 at moisture contents of 3, 15, and 27 % w.b., respectively (Fig. 3a). At 2450 MHz, when the moisture content increased from 3 to 27 % w.b., the dielectric constant increased from 2.6 to 13.5 at 25 °C, from 2.7 to 15.0 at 45 °C, and from 3.2 to 17.0 at 85 °C (Fig. 3d). The similar trends at a given frequency were also reported in other agricultural products, such as macadamia nut kernels (Wang et al. 2013), wheat (Nelson and Trabelsi 2006), and some legumes (Jiao et al. 2011) in the frequency range of 10–1800 MHz.

The regression equations for the dielectric properties of pistachio kernel samples as affected by temperature and moisture are shown in Table 2 at four specific frequencies (27, 40, 915, and 2450 MHz). All the equations were quadratic polynomials.

Table 3 shows analysis of variance (ANOVA) results for Eqs. (2)–(5). The linear terms and interaction term of M and T had strong influence on these models ($p<0.005$). The quadratic term of M also had obvious influence on the models. Each model provided a good fit to the experimental data at the significance level of 0.0001 and with a coefficient of determination of greater than 0.986. Accordingly, it can be stated that Eqs. (2)–(5) were acceptable enough for predicting the dielectric constants of pistachio kernel at any given moisture content and temperature over the observed range of each variable at 27, 40, 915 and 2450 MHz, respectively. These specific data could be used as temperature and moisture-dependent dielectric properties in computer simulation.

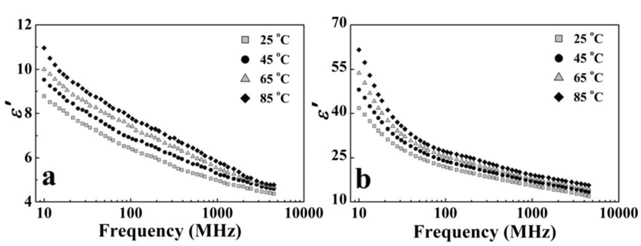

Fig. 2 Frequency-dependent dielectric constant of non-salted pistachio kernel samples at moisture contents of 9 % (**a**) and 27 % w.b. (**b**) and four temperatures

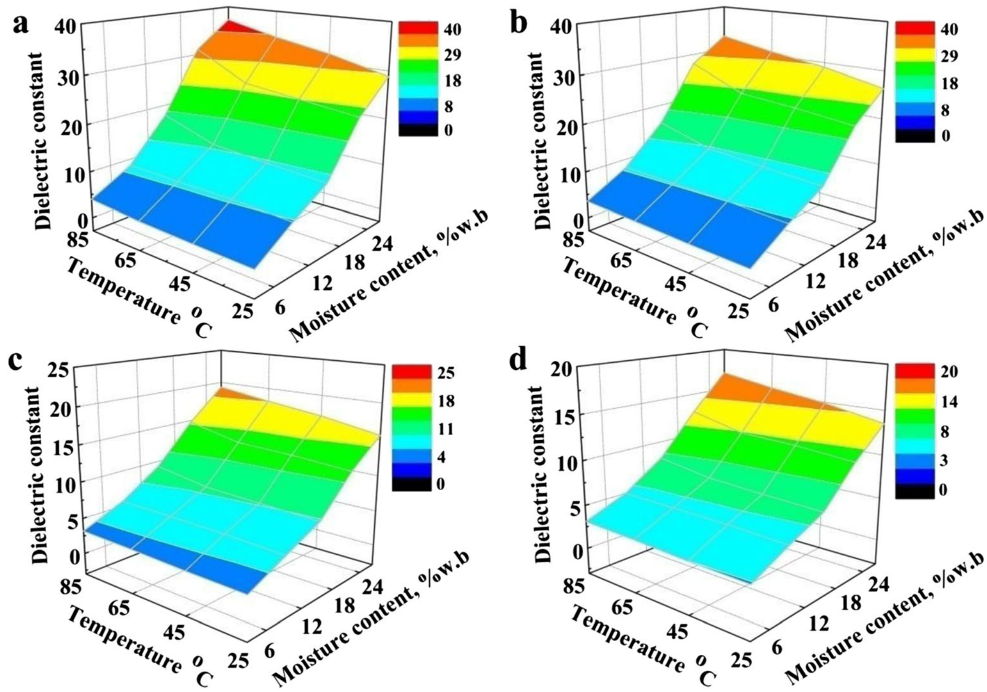

Fig. 3 Dielectric constants of pistachio kernel samples as function of moisture content and temperature at 27 (**a**), 40 (**b**), 915 (**c**), and 2450 MHz (**d**) over a moisture content range from 3 to 27 % w.b. and temperature range from 25 to 85 °C

Dielectric Loss Factor

Frequency-Dependent Dielectric Loss Factor

The dielectric loss factors of pistachio kernel samples with two selected moisture contents at four temperatures from 10 to 4500 MHz are shown in Fig. 4a and b. Like the dielectric constant, the dielectric loss factor of pistachio kernel samples also increased with increasing temperature and moisture content, while it decreased with increasing frequency, especially at the higher moisture (27 % w.b.) and low frequencies (i.e., 100 MHz). For example, when the frequency increased from 10 to 100 MHz, the loss factors of pistachio kernel samples with the moisture content of 9 and 27 % w.b. decreased from 2.2 and 146.1 to 1.0 and 19.4, and then decreased from 1.0 and 19.4 to 0.8 and 5.1 when the frequency increased from 100 to 4500 MHz at 25 °C, respectively.

The dielectric properties of materials are governed by free water dispersion, bound water dispersion, and ionic conduction within a broad frequency range (Feng et al. 2002). When the loss factors of pistachio kernel samples at two moisture contents were plotted against frequency in a log-log plot (Fig. 4c, d), log of dielectric loss factor had a negative linear relationship with log of frequency below 100 MHz, especially at the higher moisture (27 % w.b.). On the other hand, in low moisture samples (9 %), most water molecules are bound to proteins or starch in the nut kernels and the solvent effect for charged ions becomes less available, resulting in low loss factor in the RF range (Singh et al. 2006). The negatively liner relationship in the log-log plot is a clear indication of the dominant ionic contribution to the dielectric loss mechanisms in biomaterials (Liu et al. 2009). Similar relationships are reported for other biomaterials, especially for high moisture materials, such as moist foods, meat products, fresh fruits, and insects (Guan et al. 2004; Guo et al. 2007; Wang et al. 2003a, 2008).

Moisture and Temperature-Dependent Dielectric Loss Factor

Figure 5 shows the dielectric loss factors of pistachio kernel samples as a function of moisture content and temperature at 27 (a), 40 (b), 915 (c), and 2450 MHz (d). The dielectric loss factors increased with increases in either moisture content or temperature, especially for moisture content. Most foods and agricultural products can store and dissipate electromagnetic

Table 2 Regression equations for the dielectric constant of non-salted pistachio kernel as a function of moisture content (3%≤M≤27% w.b.) and temperature (25 °C≤T≤85 °C)

Frequency (MHz)	Dielectric constant (ε')
27	$\varepsilon' = 3.246 + 0.357M - 0.108T + 5.67 \times 10^{-3}MT + 0.021M^2 + 9.48 \times 10^{-4}T^2$ (2)
40	$\varepsilon' = 2.805 + 0.373M - 0.081T + 4.74 \times 10^{-3}MT + 0.017M^2 + 6.86 \times 10^{-4}T^2$ (3)
915	$\varepsilon'=2.825 + 0.115M - 0.025T + 2.23 \times 10^{-3}MT + 0.013M^2 + 1.96 \times 10^{-4}T^2$ (4)
2450	$\varepsilon' = 3.032 + 0.032M - 0.024T + 2.18 \times 10^{-3}MT + 0.012M^2 + 1.70 \times 10^{-4}T^2$ (5)

Table 3 Significance of probability (p) of regressed models of Eqs. (2)–(5) for non-salted pistachio kernel samples at four frequencies of interest

Variance and R^2	27 MHz (Eq. 2)	40 MHz (Eq. 3)	915 MHz (Eq. 4)	2450 MHz (Eq. 5)
M	<0.0001	<0.0001	<0.0001	<0.0001
T	0.0001	0.0003	<0.0001	<0.0001
MT	0.0083	0.0106	0.0010	0.0002
M^2	0.0033	0.0043	<0.0001	<0.0001
T^2	0.2982	0.3841	0.4547	0.4219
Model	<0.0001	<0.0001	<0.0001	<0.0001
R^2	0.9865	0.9871	0.9949	0.9955

energy when subjected to alternating electric field, and the loss factor measures the energy dissipated in the material from the applied electric fields, resulting in temperature increases in the material (Nelson 1996). Therefore, the higher the dielectric loss factor, the more the electromagnetic power is absorbed by the material, and the higher the rate of temperature increases.

The dielectric loss factor of pistachio kernel samples in higher moisture content was significantly larger than that in lower moisture level. This behavior may lead to the potentially advantageous phenomenon, generally referred to as "moisture leveling effect" (Feng et al. 2002; Metaxas and Meredith 1983). During RF or MW drying, the portion with lower moisture content may absorb less energy, resulting in lower temperature, which would be beneficial to product quality after drying. On the other hand, the pistachio kernel in higher temperature had larger loss factor, leading to a phenomenon referred to as "thermal run away" during drying with dielectric heating (Houben et al. 1991; Zhao et al. 2000). That is, the portion of the nut with high moisture content could be heated preferentially, resulting in high temperature, thus high loss factor. For MW and RF drying, this thermal run away phenomenon could be effectively reduced by water evaporation and moisture leveling effect (Wang et al. 2014). During dielectric drying, since the vapor pressure gradient could be develop from the kernel center to the surface, surface air drying in combination with internal MW and RF heating might be an appropriate way to improve drying uniformity (Wang et al. 2014).

The polynomial regression models describing the relationship between loss factor, moisture content, and temperature at 27, 40, 915, and 2450 MHz are listed in Table 4. Quadratic polynomial relationships were the best fit to correlate the dielectric loss factor with moisture content and temperature.

ANOVA analysis was carried out to determine whether moisture content and temperature had significant influences on these models in Table 5. The linear, quadratic, and interaction terms of M and T had strong influence on these models at a 0.005 significance level ($p<0.005$). The significant probability of each model was less than 0.0001 and R^2 was above 0.978. It suggests that these models can be used to precisely estimate the dielectric loss factor value of pistachio kernel from known moisture content and temperature at selected frequencies.

Effect of Salty Levels on Dielectric Properties

The changes of dielectric properties with respect to temperature and frequency were similar for both salt-enriched and non-salted pistachio kernel samples. Added salt did not significantly influence dielectric constant, especially at MW frequencies (Table 6). The results in this study agreed with the trend reported by Lyng et al. (2014). They indicated that dielectric constants of reconstituted potato flakes increased slightly from a salt concentration of 4.5 to 5.8 %. Bengtsson

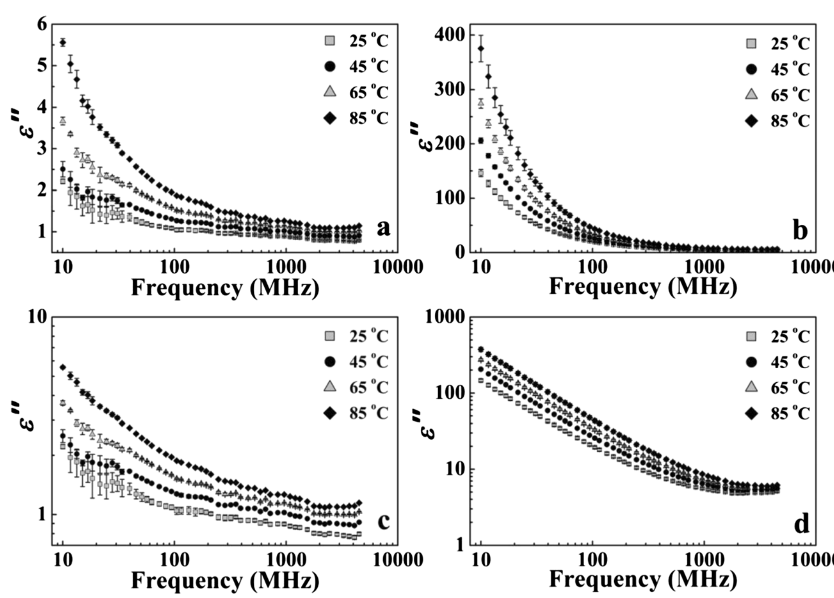

Fig. 4 Frequency-dependent dielectric loss factor of the non-salted pistachio kernel samples at four temperatures and moisture contents of 9 % (**a**) and 27 % w.b. (**b**) together with the log-log plot at 9 % (**c**) and 27 % w.b. (**d**)

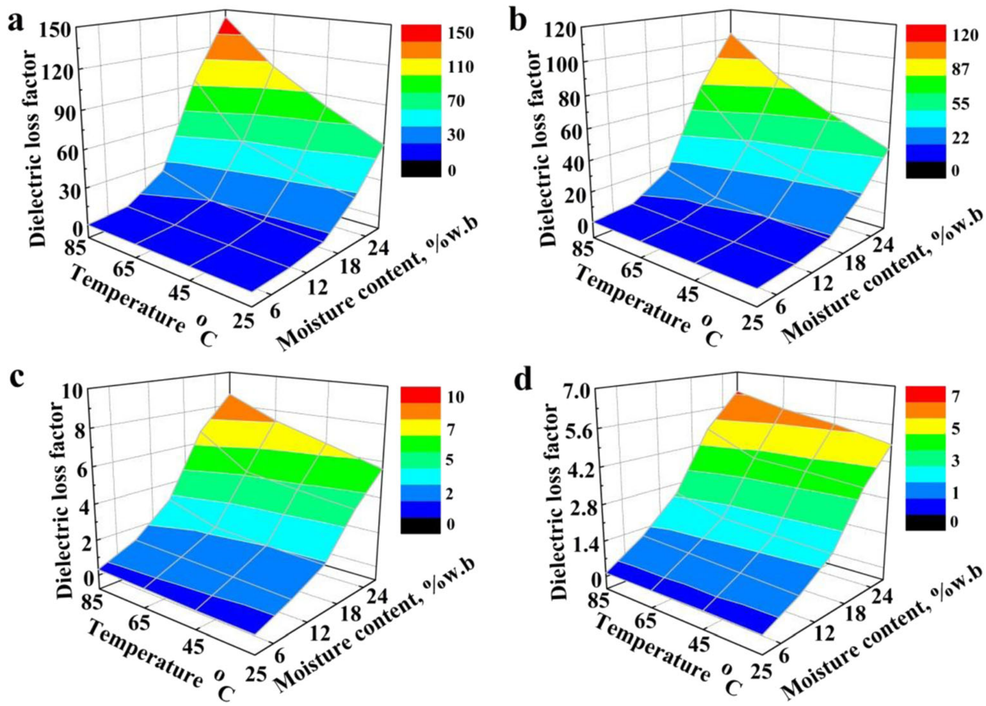

Fig. 5 Dielectric loss factor of non-salted pistachio kernel samples as function of moisture content and temperature at 27 (**a**), 40 (**b**), 915 (**c**), and 2450 MHz (**d**) over a moisture content range from 3 to 27 % w.b. and temperature range from 25 to 85 °C

and Risman (1971) also reported that a salt increase from 3.7 to 6.1 % resulted in small increases in the dielectric constant of pork. The salty level had a highly significant positive effect on dielectric loss factors; both the absolute increase and the relative increase were larger at 27 and 40 MHz than at 915 and 2450 MHz. For example, at 27 MHz, the absolute increase of dielectric loss factor between strong salty pistachio kernel and non-salted samples was 38.83 at 25 °C, representing a relative increase of 648 %; the absolute increase was 110.1 at 85 °C, representing a relative increase of 476 %. At the frequency of 915 MHz, the absolute and relative increases were 2.38 and 134 % at 20 °C and the corresponding values were 3.02 and 169 % at 85 °C. The influence of salts is directly related to the nuclear charge effect and depends on the size and charge of the dissolved ions (Bircan and Barringer 1998). Salts or dissolved ions reduce polarization of water and the overall dielectric constant by binding water. As observed in this study, the presence of an electrolyte (NaCl) did not seem to influence dielectric constant greatly, but it did have a marked effect on the dielectric loss factor. The increased dielectric loss factor could be caused by the enhanced electrophoretic migration of the increased salt in the materials (Mudgett 1985). It needs to develop RF heating and drying protocols separately for non-salted and salted pistachio nuts.

Penetration Depth

Tables 7 and 8 list calculated power penetration depths of electromagnetic energy in pistachio kernel samples at four specific frequencies, four moisture levels (non-salted), and four salty levels (moisture content 15 % w.b.). Generally, the penetration depth decreased with increasing frequency, moisture content, and temperature in non-salted pistachio kernels. For example, for non-salted pistachio kernels at 65 °C with the moisture content of 15 %, the penetration depth decreased from 67.8 cm at 27 MHz to 2.7 cm at 2450 MHz. When moisture content of pistachio kernel increased from 3 to 27 % w.b., the penetration depth decreased from 819 to 16.8 cm at 45 °C and 27 MHz. When the temperature increased from 25 to 85 °C, the penetration depth at 40 MHz was reduced from 34.8 to 15.1 cm for samples with moisture content of 21 % w.b. Similar effects of frequency, temperature, and moisture content on the penetration depth were listed in Table 8. The penetration depth decreased with increasing salty level.

Table 4 Regression equations for the dielectric loss factor of non-salted pistachio kernel as a function of moisture content (3 %≤M≤27 % w.b.) and temperature (25 °C≤T≤85 °C)

Frequency (MHz)	Dielectric loss factor (ε'')
27	$\varepsilon''=50.18 - 6.537M - 1.279T + 0.064MT + 0.236M^2 + 7.96 \times 10^{-3}T^2$ (6)
40	$\varepsilon''=35.110 - 4.503M - 0.911T + 0.045MT + 0.165M^2 + 5.70 \times 10^{-3}T^2$ (7)
915	$\varepsilon''=1.310 - 0.076M - 0.045T + 2.20 \times 10^{-3}MT + 8.18 \times 10^{-3}M^2 + 3.33 \times 10^{-4}T^2$ (8)
2450	$\varepsilon''=0.386 + 0.031M - 0.020T + 9.78 \times 10^{-4}MT + 4.81 \times 10^{-3}M^2 + 1.53 \times 10^{-4}T^2$ (9)

Table 5 Significance of probability (p) of regressed models of Eqs. (6)–(9) for non-salted pistachio kernels samples at four frequencies of interest

Variance and R^2	27 MHz (Eq.6)	40 MHz (Eq.7)	915 MHz (Eq.8)	2450 MHz (Eq.9)
M	<0.0001	<0.0001	<0.0001	<0.0001
T	<0.0001	<0.0001	<0.0001	0.0003
MT	<0.0001	<0.0001	0.0001	0.0037
M^2	<0.0001	<0.0001	<0.0001	<0.0001
T^2	0.0714	0.0686	0.1206	0.2725
Model	<0.0001	<0.0001	<0.0001	<0.0001
R^2	0.9786	0.9792	0.9869	0.9900

It is evident that the penetration depths at RF frequencies were much larger than those at MW frequencies for pistachio kernels with the same moisture contents and temperatures both in non-salted and salted pistachio nuts. Penetration depth at 27 MHz ranged from 1093 to 12 cm and 104 to 12 cm for non-salted and salted kernels, respectively. In contrast, the penetration depth at 2450 MHz for the non-salted kernels was from 8.9 to 1.3 cm and much lower than that at 27 MHz (Table 7). The smaller penetration depth at MW frequencies results in more surface drying. For uniform and effective drying of pistachio kernels with dielectric heating, the thickness of kernel samples should be not more than two or three times the penetration depth (Schiffmann 1995). Considering the influence of temperature and moisture content, the drying

Table 6 Dielectric properties (Ave±SD) of pistachio kernels (moisture content 15 % w.b.) with different salty levels

Sample	T(°C)	Dielectric Properties	Frequency (MHz)			
			27.12	40.68	915	2450
Non-salted	25	ε'±SD	11.85±0.12	11.18±0.04	7.30±0.00	6.38±0.00
		ε''±SD	5.99±0.11	5.02±0.04	1.77±0.00	1.68±0.00
	45	ε'±SD	12.69±0.03	11.88±0.00	7.64±0.02	6.69±0.01
		ε''±SD	7.42±0.04	6.12±0.04	1.91±0.01	1.77±0.01
	65	ε'±SD	13.74±0.03	12.78±0.02	8.00±0.00	6.99±0.00
		ε''±SD	10.21±0.10	8.22±0.04	2.11±0.00	1.90±0.00
	85	ε'±SD	17.74±0.05	15.94±0.03	9.23±0.01	8.01±0.01
		ε''±SD	23.09±0.22	17.75±0.15	3.02±0.01	2.43±0.01
Light	25	ε'±SD	15.73±0.18	14.12±0.15	7.37±0.04	6.37±0.03
		ε''±SD	15.65±0.63	12.22±0.44	2.36±0.03	1.87±0.03
	45	ε'±SD	17.22±0.11	15.27±0.10	7.66±0.03	6.54±0.03
		ε''±SD	23.04±0.50	17.60±0.36	2.82±0.03	2.12±0.02
	65	ε'±SD	19.02±0.08	16.62±0.06	8.02±0.02	6.77±0.02
		ε''±SD	36.91±0.68	27.72±0.48	3.55±0.03	2.50±0.02
	85	ε'±SD	24.65±0.08	20.93±0.06	9.12±0.01	7.62±0.01
		ε''±SD	63.36±0.16	46.94±0.13	4.92±0.01	3.20±0.00
Medium	25	ε'±SD	21.41±0.19	18.76±0.18	8.26±0.06	7.10±0.04
		ε''±SD	24.92±0.94	19.38±0.68	3.20±0.06	2.31±0.04
	45	ε'±SD	24.83±0.20	21.48±0.16	8.98±0.05	7.62±0.04
		ε''±SD	38.49±0.96	29.35±0.72	4.02±0.05	2.76±0.03
	65	ε'±SD	28.05±0.13	23.86±0.08	9.49±0.02	7.95±0.01
		ε''±SD	55.05±1.03	41.51±0.76	4.93±0.05	3.23±0.03
	85	ε'±SD	32.55±0.23	27.19±0.18	10.09±0.06	8.33±0.06
		ε''±SD	82.66±1.36	61.45±0.98	6.27±0.06	3.90±0.03
Strong	25	ε'±SD	22.15±0.05	19.45±0.04	8.39±0.02	7.07±0.02
		ε''±SD	44.82±0.30	33.64±0.21	4.15±0.02	2.78±0.01
	45	ε'±SD	25.26±0.05	21.97±0.04	9.17±0.02	7.58±0.01
		ε''±SD	68.72±0.78	50.74±0.56	5.36±0.04	3.43±0.02
	65	ε'±SD	28.32±0.15	24.36±0.08	9.78±0.04	7.96±0.03
		ε''±SD	97.03±0.83	70.91±0.50	6.64±0.03	4.07±0.02
	85	ε'±SD	31.42±0.31	26.50±0.32	10.26±0.11	8.24±0.11
		ε''±SD	133.21±0.44	96.62±0.32	8.12±0.01	4.79±0.00

Table 7 Penetration depths (Ave±SD) for non-salted pistachio kernels at different moisture contents (% w.b.)

Sample moisture content (% w.b.)	T(°C)	Penetration depth (cm)			
		27	40	915	2450
3	25	1093.05±36.31	702.41±53.47	17.66±1.20	8.92±0.62
	45	818.86±63.12	697.78±17.24	16.54±2.16	7.96±1.01
	65	626.87±38.47	589.25±22.31	15.84±2.26	6.67±0.67
	85	481.42±20.73	410.37±4.15	13.94±2.29	5.68±0.30
9	25	334.68±40.83	235.00±17.05	13.20±0.25	5.24±0.10
	45	277.57±13.11	198.75±2.01	11.90±0.03	4.74±0.01
	65	223.40±3.98	157.85±1.95	10.80±0.04	4.31±0.02
	85	163.68±3.44	123.55±0.71	9.88±0.07	3.98±0.03
15	25	104.27±1.34	80.10±0.54	8.01±0.00	2.96±0.00
	45	87.90±0.54	68.15±0.46	7.63±0.03	2.87±0.01
	65	67.79±0.51	53.42±0.17	7.06±0.00	2.74±0.00
	85	36.93±0.30	29.51±0.22	5.32±0.02	2.30±0.01
21	25	34.85±0.12	28.36±005	4.62±0.00	1.76±0.00
	45	28.34±0.32	23.17±0.26	4.34±0.02	1.72±0.00
	65	22.80±0.30	18.61±0.24	4.01±0.02	1.69±0.01
	85	15.09±0.23	12.21±0.18	3.08±0.03	1.48±0.01
27	25	20.65±0.53	16.95±0.43	3.75±0.06	1.50±0.02
	45	16.78±0.23	13.73±0.18	3.38±0.03	1.43±0.01
	65	14.14±0.25	11.51±0.21	3.06±0.04	1.39±0.01
	85	11.80±0.44	9.57±0.36	2.71±0.07	1.32±0.02

thickness of non-salted kernels should be less than 24 and 3 cm at 27 and 2450 MHz, respectively. The uniformity under dielectric heating at RF frequencies could be better than at MW frequencies and RF heating may provide practical large-scale and high throughput treatments for drying of pistachio nuts.

Table 8 Penetration depths (Ave ±SD) for pistachio kernels (moisture content 15 % w.b.) with different salty levels

Sample	T(°C)	Penetration depth (cm)			
		27	40	915	2450
Non-salted	25	104.27±1.34	80.10±0.54	8.01±0.00	2.96±0.00
	45	87.90±0.54	68.15±0.46	7.63±0.03	2.87±0.01
	65	67.79±0.51	53.42±0.17	7.06±0.00	2.74±0.00
	85	36.93±0.30	29.51±0.22	5.32±0.02	2.30±0.01
Light	25	49.06±1.53	38.95±1.10	6.08±0.07	2.66±0.03
	45	36.67±0.57	29.31±0.44	5.21±0.04	2.38±0.01
	65	26.26±0.34	20.96±0.26	4.26±0.03	2.07±0.01
	85	18.92±0.02	15.04±0.02	3.31±0.00	1.72±0.00
Medium	25	36.85±1.24	29.00±0.94	4.78±0.09	2.28±0.04
	45	27.20±0.47	21.53±0.38	3.98±0.04	1.98±0.02
	65	21.45±0.27	16.95±0.22	3.36±0.03	1.73±0.01
	85	16.60±0.17	13.13±0.13	2.76±0.02	1.48±0.01
Strong	25	23.60±0.11	18.85±0.08	3.75±0.01	1.90±0.00
	45	17.99±0.13	14.39±0.11	3.06±0.02	1.60±0.01
	65	14.60±0.07	11.67±0.05	2.58±0.01	1.39±0.00
	85	12.13±0.01	9.67±0.00	2.20±0.01	1.21±0.01

Conclusions

Dielectric constant and loss factor of pistachio kernel samples decreased with increasing frequency or decreasing temperature and moisture content. Salty processing of pistachio kernels resulted in slight increases in dielectric constant but sharp increases in the dielectric loss factor, especially in the RF range. Moisture content and temperature had strong effect on dielectric loss factor in lower frequencies, leading to the phenomenon of "moisture leveling effect" and "thermal run away" during pistachio kernel drying with dielectric heating. At low frequencies with high temperatures and moisture contents, negative relationships between the loss factor and the frequency on a log-log plot suggested that ionic conductance was the dominant heating mechanism. At four specific frequencies used for industrial, scientific, and medical applications, permittivity values as a function of temperature and moisture content could be precisely described by a series of quadratic polynomial models, which could be used in computer simulation. The penetration depth decreased with increasing frequency, temperature, salty levels, and moisture content. Larger penetration depths at low frequencies indicated that RF heating could be used in large-scale treatments and achieve a relatively uniform heating in drying thick layers of pistachio nuts.

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