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Radio frequency disinfestation treatments for dried fruit: Dielectric properties

Bandar Alfaifi [a], Shaojin Wang [a], Juming Tang [a,*], Barbara Rasco [b], Shyam Sablani [a], Yang Jiao [a]

[a] Department of Biological Systems Engineering, Washington State University, 213 L.J. Smith Hall, Pullman, WA 99164-6120, USA
[b] School of Food Science, Washington State University, 106 FSHN Bldg, Pullman, WA 99164-6376, USA

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ABSTRACT

Phytosanitary/quarantine regulations for many countries require that certain dried fruit be disinfected prior to export; however, current technologies involve the use of toxic chemicals and conventional thermal methods are either undesirable or cause loss of volatile components, browning and texture change. Newer physical methods including dielectric heating have been considered, but information on dielectric properties of dried fruits is lacking. Because the loss factor of insect pests, Indian meal moth (*Plodia interpunctella*) and navel orangeworm (*Amyelois transitella*), is several times (26–36) greater than that of dried fruits, RF treatment in particular has great potential for insect disinfection. In this study, the dielectric properties of raisins, dates, apricots, figs, and prunes with water contents of 15–30.2 g/100 g, were determined between 10 and 1800 MHz over a range of 20–60 °C. The dielectric constant and loss factor of all samples decreased with increasing frequency, but increased with increasing temperature at each frequency. The loss factor of all samples increased with increasing water contents/water activity (0.5–0.7). The penetration depths (dps) of RF energy in all samples decreased with increasing frequency and temperature. The deep dp (28.4–103.7 cm) at 27 MHz indicates the potential for developing continuous and large-scale RF treatments for postharvest insect control in dried fruits.
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1. Introduction

Dried fruits are important ingredients in several food formulations, such as breakfast cereals, snack bars, bakery and dairy products. They can be good sources of dietary fiber, various vitamins including pantothenic acid, and minerals (USDA, 2011). The greatest volume of dried fruit in the United States is in the Central Valley of California with more than 460,000 metric tons of raisins (*Vitus vinifera*), dates (*Phoenix dactylifer*), apricots (*Prunus armeniaca*), figs (*Ficus carica*), and dried plums (*Prunos domestica*) being produced yearly with a value of more than $600 million (USDA-NASS, 2009). In 2008, the United States, Turkey, and China were the top three producers of raisins constituting about 73% of the world's production. The United States, Chile, France, and Argentina were the top four producers of prunes, with about 83% of the world's production. Turkey produced the majority of the world's production of dried apricots (more than 80%), much of this imported and resold as Product of Turkey. Dates and dried figs were produced mainly in Middle Eastern and Mediterranean countries with, more than 6,860,000 and 819,000 metric tons, respectively, in 2008, accounting for about 96% and 76% of the world production (FAO, 2008).

One of the main problems in production, storage, marketing and exporting of dried fruits is the loss caused by insect infestation. The Indian meal moth (*Plodia interpunctella*) and navel orangeworm (*Amyelois transitella*) are two of the most serious postharvest pests of dried fruits (Johnson, Yahia, & Brandl, 2009; Simmons & Nelson, 1975). Fumigation using methyl bromide (MeBr) has been a common practice for insect control in the past (Barreveld, 1993), but its use is being phased out globally under the Montreal Protocol (USEPA, 2001) and alternative, preferably non-chemical, treatments for postharvest disinfestation of dried fruits are needed.

Radio frequency (RF) and microwave (MW) heating (also referred to as dielectric heating) have been investigated for insect control in foods (Fu, 2004). In contrast to chemical treatment methods, dielectric heating leaves no chemical residues on products, provides acceptable product quality and has minimal adverse effects on the environment (Wang, Tang, Johnson, et al., 2003). Compared to conventional heating, dielectric heating has a more rapid come-up time to the target temperature due to the phenomenon of volumetric heating (Wang, Birla, Tang, & Hansen, 2006). RF refers to electromagnetic waves from 3 kHz to 300 MHz, and MW between 300 MHz and 300 GHz (Ramaswamy & Tang, 2008). The U.S. Federal Communications Commission (FCC) has allocated specific frequencies for industrial, medical, and scientific applications, including

* Corresponding author. Tel.: +1 509 335 2140; fax: +1 509 335 2722.
E-mail addresses: jtang@wsu.edu, jtang@mail.wsu.edu (J. Tang).

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13.56, 27.12, and 40.68 MHz for RF and 915 and 2450 MHz for MW (Wang & Tang, 2001). Major factors affecting dielectric properties of agricultural and biological materials include frequency, temperature, salt content, water content, the state of water (frozen, free or bound), and food composition (e.g. fat content). In general, the higher the water content, the higher the values of dielectric properties of a material (Nelson, 1978; Ryynanen, 1995; Tang, 2005).

Dielectric properties of a material consist of dielectric constant (ε') and dielectric loss factor (ε'') which can be described by the complex relative permittivity ε^* (Metaxas & Meredith, 1993):

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \tag{1}$$

where $j = (-1)^{0.5}$; ε', the real component, is a measure of the ability of the material to store electromagnetic energy; and ε'', the imaginary component, is a measure of the ability to dissipate electrical energy into heat.

For rapid dielectric heating when heat transfer is negligible, temperature rise due to the interaction between the dielectric material and the electrical field can be calculated using the following equation (Nelson, 1996):

$$\rho C_p \frac{\Delta T}{\Delta t} = 5.563 \times 10^{-11} f E^2 \varepsilon'' \tag{2}$$

where ρ is the density of the material in kg/m^3; C_p is the specific heat of the material in J/kg °C; ΔT is the temperature rise in the material in °C; Δt is the time duration in s, f is the frequency in Hz, and E is the electric field intensity in V/m.

Knowledge of dielectric properties is essential in gaining a better understanding of the heating behavior of the treated materials when subjected to RF or MW fields and for the design and development of continuous systems. Dielectric property data for several agricultural commodities have been reported, including fresh fruits (Sosa-Morales et al., 2009; Venkatesh & Raghavan, 2004; Wang et al., 2005); vegetables (Sıpahıoğlu & Barringer, 2003; Venkatesh & Raghavan, 2004); and dry foods (Berbert et al., 2001; Guo, Wang, Tiwari, Johnson, & Tang, 2010; Sacilik, Tarimci, & Colak, 2006). Dielectric property data are also available for several important insect pests, including rice weevils (*Sitophilus oryzae*) (Nelson & Charity, 1972), potato beetles (*Leptinotarsa decemlineata*) (Colpitts, Pelletier, & Cogswell, 1992), woodworms (Andreuccetti, Bini, Ignesti, Gambetta, & Olmi, 1994), codling moths (*Cydia pomonella*) (Ikediala, Hansen, Tang, Drake, & Wang, 2002; Tang, Ikediala, Wang, Hansen, & Cavalieri, 2000; Wang, Tang, Johnson, et al., 2003), Indian meal moths (*P. interpunctella*), navel orangeworms (*A. transitella*), Mexican fruit flies (*Anastrepha ludens*) (Wang, Tang, Johnson, et al., 2003), Mediterranean fruit flies (*Ceratitis capitata*) (Wang et al., 2005), and, recently, cowpea weevils (*Callosobruchus maculatus*) (Jiao, Johnson, Tang, Tiwari, & Wang, 2011) and chestnut weevils (*Curculio elephas*) (Guo, Wu, Zhu, & Wang, 2011).

Knowing the dielectric properties of insects and their host materials are important for evaluating the potential of RF or MW differential heating. Insects have much higher water content than dry fruit, thus it is possible that the insects will absorb more RF or MW energy than the host materials and reach a higher temperature than for the surrounding food providing a means of killing them with minimal damage to food quality (Wang, Tang, Cavalieri, & Davies, 2003). Differential heating has been evaluated for control of different insects for various agricultural products as an alternative to chemical fumigation (Jiao et al., 2011; Tang et al., 2000; Wang, Tang, Cavalieri, et al., 2003). The most promising frequency for selective heating of insects in a dried food appears to be between 10 MHz and 100 MHz. Nelson and Charity (1972) investigated the dielectric properties of hard red winter wheat (*Triticum aestivum*) and rice weevils (*S. oryzae*) and suggested the possibility of differential heating at a low frequency region. Nelson and Stetson (1974) achieved complete mortality of rice weevil (*S. oryzae*) infested wheat with much lower energy at 39 MHz than at 2.45 GHz. In recent years, Wang, Tang, Cavalieri, and Davies (2003) provided a theoretical basis and experimental model for destruction of codling moth (*C. pomonella*) larvae by preferential heating in dry nuts at 27 MHz. Guo, Wu, Zhu, and Wang (2011) concluded that dielectric heating below 100 MHz has potential for control of the chestnut weevil (*C. elephas*) in chestnut (*Castanea mollissima*).

Information on the dielectric properties of dried fruits such as raisins, dates, apricots, figs, and prunes over a temperature between 20 and 60 °C is not available in the literature and would be very helpful for developing postharvest insect control treatments using RF and MW energy. The objectives of this study were: (1) to determine the dielectric properties of five important dried fruits (raisins, dates, apricots, figs and prunes) at their storage water content and then compare them with published dielectric properties of two common insect pests in dried fruits; (2) to determine the effects of frequency (10–1800 MHz), temperature (20–60 °C), and water content, on these properties; and (3) to calculate the penetration depth of electromagnetic energy into these five fruits at 27, 40, 915 and 1800 MHz as a function of temperature.

2. Material and methods

2.1. Materials and sample preparation

The following foods were evaluated: Thompson seedless raisins (*V. vinifera*) (Caruthers Raisin Packing, Caruthers, CA), Deglet Nour dates (*P. dactylifera*) (Sundate, Coachella, CA), Turkish apricots (*P. armeniaca*) (Specialty Commodities, Los Angeles, CA), Black Mission figs (*F. carica*) (Valley Fig, Fresno, CA), and d'Agen prunes (*P. domestica*) (Stapleton Spence Packing, San Jose, CA). These materials were selected to represent a water content range of 15.0–30.2 g/100 g, which covers the range of specifications in the applicable United States Standards for Grades of Dried Fruits (U.S. Standards) (USDA, 2004). Samples were stored under refrigeration (5 °C) until tested. An electric blender was used to grind the fruit flesh into a paste. Dried fruits were held at room temperature to reach equilibrium before testing. Values for the dielectric properties of the fifth-instar larvae of Indian meal moths (*P. interpunctella*) and navel orangeworms (*A. transitella*) (10–1800 MHz; 20–60 °C) were obtained from Wang, Tang, Johnson, et al. (2003).

In another experiment, the water contents of raisins, dates, apricots, and figs samples were raised to 30.2% by adding appropriate amounts of de-ionized water to match that of prunes to evaluate the effect of total sugar content on dielectric properties. Samples were kept in covered desiccators at room temperature for 3–5 days for moisture to equilibrate. After two more days, each sample was mixed, sealed in plastic bags and allowed to equilibrate at room temperature. The samples were removed and water content was obtained to ensure that all samples had reached the targeted level of 30.2%.

2.2. Measurements of chemical components, water content, water activity, and particle density

Fruit chemical components, including ash, total sugars, fat, protein, and vitamin C, were analyzed by Columbia Food Laboratories, Inc., Corbett, OR, USA using the standard methods. The initial water content of the dried fruits was determined using the vacuum oven method by drying a known weight of sample in a vacuum oven (ADP-31, Yamato Scientific America, Inc., USA) at 70 ± 1 °C under a pressure of about 100 mm Hg for 6 h (AOAC 934.06, 2000).

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An AquaLab water activity meter (Series 3, Decagon Devices, Inc., Pullman, WA, USA) with an accuracy of ± 0.003 a_w was used to measure the water activity of the tested dried fruits at room temperature. The meter was calibrated using 0.5 M KCl (a_w 0.98 at 25 °C) (Decagon, 2009). The particle density of samples was determined at room temperature using the liquid displacement method with toluene (C_7H_8). Toluene was used due to its low tendency to immerse into the sample, stable specific gravity and viscosity, and ability to flow smoothly over the sample surface (Moshenin, 1986). Sample density was calculated by dividing the weight of randomly selected 25 g by the volume occupied by those samples in 100 ml pycnometers. Three replicates were used for the calculation of the means and standard divisions. Table 1 lists the chemical components of the tested dried fruits along with their initial water contents, water activities, and particle density. Water content, water activity, and particle density ranged from 15.0 to 30.2 g/100 g, 0.5 to 0.7, and 1227.1 to 1422, respectively. Raisins had the lowest water content (15 g/100 g w.b.), water activity (0.5), and particle density (1227.1 kg/m^3) with prunes having the largest water content (30.2 g/100 g w.b.), water activity (0.7), and particle density (1422.0 kg/m^3). Total sugars, obtained by chromatographic method, were 71.6, 66.9, 41.8, 51.6, and 35.1 g/100 g for raisins, dates, apricots, figs, and prunes, respectively. Comparable data can be found for these materials at USDA (2011).

2.3. Dielectric properties measurement system

Dielectric properties of raisins, dates, apricots, figs and prunes were measured at 20, 30, 40, 50, and 60 °C, which covers the range relevant to thermal treatments for controlling insects in agricultural commodities, over a frequency range from 10 to 1800 MHz using the open-ended coaxial probe technique (Fig. 1). A coaxial probe was connected to an impedance analyzer (Model 4291B, Innovative Measurement Solutions Inc., Santa Clara, CA, USA). About 25 g of the sample was filled in a stainless steel test cell (20 mm inner diameter and 94 mm height) to keep the sample at the given water content and temperature during the measurements. A water bath (Model 1157, VWR Scientific Products, Niles, IL, USA) containing a 10% water and 90% ethylene glycol solution was used to control the sample temperature by circulating the solution (15 l/min) into the jacket of the test cell. A type T thermocouple (0.8 mm diameter and 0.8 s response time) was used to monitor the sample center temperature.

2.4. Measurement procedure

The impedance analyzer was first calibrated with open air, a short (a metal block to provide a short to the coaxial tip), a 50 Ω load, and a low-loss capacitor following prescribed standard procedure (Wang, Tang, Cavalieri, et al., 2003). The coaxial probe was further calibrated with a standard air-short-triple de-ionized water calibration procedure. Prior to and after each measurement, the probe and the test cell were cleaned with de-ionized water and dried with dry air. The sample confined within the test cell was compressed with spring at the base to ensure a close contact between the tip of the coaxial probe and the sample during measurements. Dielectric properties of each sample were measured at 200 discrete frequencies between 10 and 1800 MHz at 20, 30, 40, 50 and 60 °C. Mean values and standard deviations of dielectric property data were calculated from two replicates.

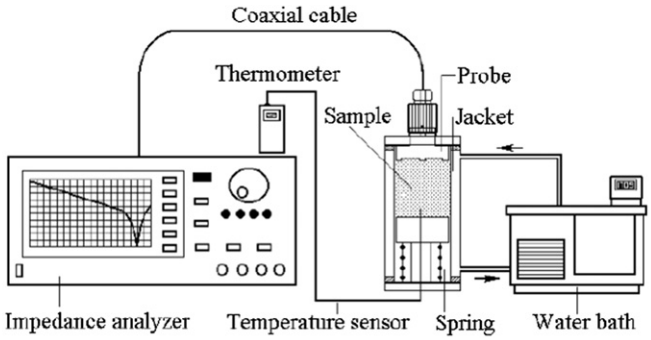

Fig. 1. Schematic view of the dielectric property measurement system (for additional detail, refer to Wang, Tang, Johnson, et al., 2003).

2.5. Penetration depth

Penetration depth (dp) is used to quantitatively describe how MW and RF power 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. It can be calculated by the following equation (Von Hippel, 1954):

$$d_p = \frac{c}{2\pi f\sqrt{2\varepsilon'\left[\sqrt{1+\left(\varepsilon''/\varepsilon'\right)^2}-1\right]}} \quad (3)$$

where c is the speed of light in free space (3×10^8 m/s). This parameter is important in the selection of the appropriate thickness of a material bed to ensure uniform heating and complete disinfestation of insects during RF or MW processes. Mean values and

Table 1
Chemical components, water content, water activity, and particle density of the tested dried fruits.

	Raisins	Dates	Apricots	Figs	Prunes	Methods
Ash (g/100 g)	2.1	1.8	4.8	2.0	3.9	AOAC 941.12
Fructose	36.7	19.4	13.3	25.2	12.1	
Glucose	34.9	20.2	17.9	26.5	22.0	
Lactose	0.0	0.0	0.0	0.0	0.0	
Maltose	0.0	0.0	0.0	0.0	0.0	
Sucrose	0.0	27.4	10.7	0.0	0.99	
Total sugars (g/100 g)	71.6	66.9	41.8	51.6	35.1	Gas chromatographic
Fat (g/100 g)	0.26	0.11	0.20	0.21	0.15	AOAC 996.06
Protein (g/100 g)	2.5	2.5	2.5	2.8	2.9	AOAC 992.15
Vitamin C (mg/100 g)	1.1	0.2	7.1	0.0	0.0	AOAC 967.22
Water content (g/100 g w.b.)[a]	15.0 ± 0.15	19.7 ± 0.14	24.6 ± 0.25	27.3 ± 0.35	30.2 ± 0.45	AOAC 934.06
Water activity[a]	0.5 ± 0.02	0.6 ± 0.03	0.6 ± 0.01	0.7 ± 0.01	0.7 ± 0.00	AquaLab
Particle density (kg/m^3)[a]	1422.0 ± 20.9	1363.7 ± 14.3	1290.4 ± 14.5	1257.9 ± 7.91	1227.1 ± 15.1	Liquid displacement

[a] All chemical components were analyzed by Columbia Food Laboratories, Inc., Corbett, OR, USA while water content, water activity, and particle density were determined in our lab.

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Table 2
Dielectric properties (mean ± SD of two replicates) of five dried fruits at five temperatures and four frequencies.

Materials	Temp., °C	Dielectric constant (ε′)				Loss factor (ε″)			
		Frequency, MHz							
		27	40	915	1800	27	40	915	1800
Raisins	20	21.9 ± 0.1	20.2 ± 0.2	7.8 ± 0.2	4.6 ± 0.1	8.1 ± 0.1	7.4 ± 0.1	3.8 ± 0.1	3.1 ± 0.1
	30	24.8 ± 0.4	23.1 ± 0.4	9.4 ± 0.2	6.2 ± 0.1	8.9 ± 0.1	8.2 ± 0.1	4.3 ± 0.1	3.6 ± 0.1
	40	28.0 ± 0.4	26.1 ± 0.3	10.9 ± 0.1	7.6 ± 0.1	9.8 ± 0.2	9.0 ± 0.1	5.2 ± 0.1	4.5 ± 0.1
	50	31.2 ± 0.3	29.3 ± 0.3	13.0 ± 0.2	9.8 ± 0.2	10.6 ± 0.1	9.9 ± 0.0	6.1 ± 0.1	5.3 ± 0.2
	60	33.8 ± 0.3	31.9 ± 0.3	15.2 ± 0.3	11.5 ± 0.3	11.4 ± 0.1	10.6 ± 0.1	7.2 ± 0.1	6.5 ± 0.1
Dates	20	27.2 ± 0.2	25.5 ± 0.2	12.0 ± 0.1	9.8 ± 0.2	10.1 ± 0.1	9.0 ± 0.1	5.7 ± 0.1	5.1 ± 0.2
	30	29.3 ± 0.2	27.3 ± 0.2	13.4 ± 0.2	10.9 ± 0.2	11.9 ± 0.3	10.2 ± 0.2	6.3 ± 0.1	5.6 ± 0.1
	40	31.0 ± 0.2	28.9 ± 0.1	15.0 ± 0.2	12.2 ± 0.2	15.0 ± 0.4	12.2 ± 0.3	6.8 ± 0.1	6.3 ± 0.1
	50	33.0 ± 0.1	30.7 ± 0.1	16.9 ± 0.2	13.8 ± 0.2	20.6 ± 0.6	15.8 ± 0.4	7.3 ± 0.1	7.0 ± 0.1
	60	35.0 ± 0.1	32.9 ± 0.1	18.3 ± 0.1	15.1 ± 0.1	26.9 ± 1.0	20.0 ± 0.7	7.5 ± 0.1	7.1 ± 0.1
Apricots	20	33.9 ± 0.7	32.3 ± 0.6	19.7 ± 0.3	17.6 ± 0.4	11.8 ± 0.2	10.6 ± 0.2	7.1 ± 0.1	6.3 ± 0.1
	30	35.9 ± 0.2	34.2 ± 0.4	21.5 ± 0.5	19.2 ± 0.4	14.8 ± 0.3	12.8 ± 0.3	8.3 ± 0.1	7.7 ± 0.1
	40	37.4 ± 0.2	35.7 ± 0.3	22.9 ± 0.2	20.4 ± 0.2	19.9 ± 0.6	16.2 ± 0.4	9.5 ± 0.1	9.0 ± 0.1
	50	39.1 ± 0.1	37.3 ± 0.2	24.4 ± 0.2	21.5 ± 0.2	28.7 ± 0.4	22.6 ± 0.0	10.3 ± 0.2	10.1 ± 0.2
	60	40.8 ± 0.1	38.9 ± 0.1	26.2 ± 0.1	23.2 ± 0.2	37.4 ± 0.5	28.9 ± 0.1	10.2 ± 0.0	10.0 ± 0.1
Figs	20	37.7 ± 0.1	35.7 ± 0.1	21.3 ± 0.1	19.1 ± 0.2	14.4 ± 0.2	13.1 ± 0.2	8.9 ± 0.2	8.0 ± 0.3
	30	39.6 ± 0.3	37.5 ± 0.2	22.0 ± 0.1	20.4 ± 0.2	17.6 ± 0.2	15.2 ± 0.3	10.3 ± 0.1	9.8 ± 0.2
	40	42.3 ± 0.2	40.1 ± 0.2	24.8 ± 0.1	22.5 ± 0.2	23.8 ± 0.4	19.2 ± 0.5	10.6 ± 0.1	10.3 ± 0.1
	50	44.8 ± 0.2	42.6 ± 0.2	27.4 ± 0.1	25.0 ± 0.2	32.7 ± 0.2	25.3 ± 0.3	10.5 ± 0.1	10.6 ± 0.1
	60	46.5 ± 0.5	44.2 ± 0.5	29.1 ± 0.2	25.7 ± 0.2	42.2 ± 0.3	32.7 ± 0.7	10.8 ± 0.2	11.1 ± 0.2
Prunes	20	40.6 ± 0.2	38.7 ± 0.2	24.2 ± 0.3	22.0 ± 0.5	17.2 ± 0.1	15.7 ± 0.1	10.8 ± 0.2	10.0 ± 0.3
	30	42.8 ± 0.4	40.9 ± 0.3	26.8 ± 0.3	24.5 ± 0.2	20.5 ± 0.2	17.8 ± 0.2	11.9 ± 0.1	11.2 ± 0.1
	40	44.4 ± 0.3	42.7 ± 0.3	29.1 ± 0.1	26.9 ± 0.1	25.4 ± 0.2	20.6 ± 0.2	11.8 ± 0.1	11.5 ± 0.1
	50	46.6 ± 0.2	44.9 ± 0.2	31.8 ± 0.3	29.5 ± 0.5	34.4 ± 0.4	26.6 ± 0.4	11.6 ± 0.1	11.7 ± 0.1
	60	48.9 ± 0.2	47.2 ± 0.2	34.2 ± 0.5	31.8 ± 0.6	47.8 ± 0.1	38.4 ± 0.2	11.3 ± 0.1	11.7 ± 0.2

standard deviations of penetration depths were calculated from two replicates of the measured dielectric properties of samples.

3. Results and analyses

3.1. Frequency-dependent dielectric property

A summary of dielectric properties for the dried fruits is provided in Table 2 and a graphic depiction of dielectric constants and the loss factors at 20 °C is shown in Fig. 2. The dielectric properties for these five dried fruits demonstrated a similar trend: they decreased with increasing frequency. However, differences in the values of dielectric properties of the tested samples at specific frequencies and temperatures were observed. Prunes had the highest dielectric constant and loss factor values among the five fruits, followed by figs, apricots, dates and raisins, respectively; this would be expected since prunes had the highest moisture content. When frequency increased from 27 to 1800 MHz, the dielectric constant of raisins, dates, apricots, figs, and prunes at 20 °C decreased linearly from 21.9 to 4.6, 27.2 to 9.8, 33.9 to 17.6, 37.7 to 19.1, and 40.6 to 22; the loss factor decreased from 8.1 to 3.1, 9.0 to 5.1, 14.4 to 8, 11.8 to 6.3, and 17.2 to 10, respectively.

In the RF and MW frequency regions, ionic conduction and dipole rotation are the main mechanisms that cause heating in food materials. Thus, the frequency dependence of the dielectric properties arises from the frequency dependence of these two mechanisms. Furthermore, the dielectric properties of materials are dominated by free and bound water dispersions and ionic conduction within a broad frequency range (Feng, Tang, & Cavalieri, 2002). The dielectric loss factors of dates, apricots, figs, and prunes which have water contents higher than that of raisins, had negative linear relationship with $\log f$ when plotted in a semi-log plot (Fig. 3), especially at high temperatures in the low frequency range (<100 MHz). This negative linear relationship is caused by the dominant ionic contribution and is common in intermediate ($a_w = 0.6–0.9$) and high water content foods ($a_w = 0.95–0.99$) (Sosa-Morales et al., 2009; Venkatesh & Raghavan, 2004). However, in raisins, which have a low water content of 15 g/100 g, this trend became less evident due to the poor availability of water molecules to interact with the applied electromagnetic field. Similar observations have been reported for various dry products

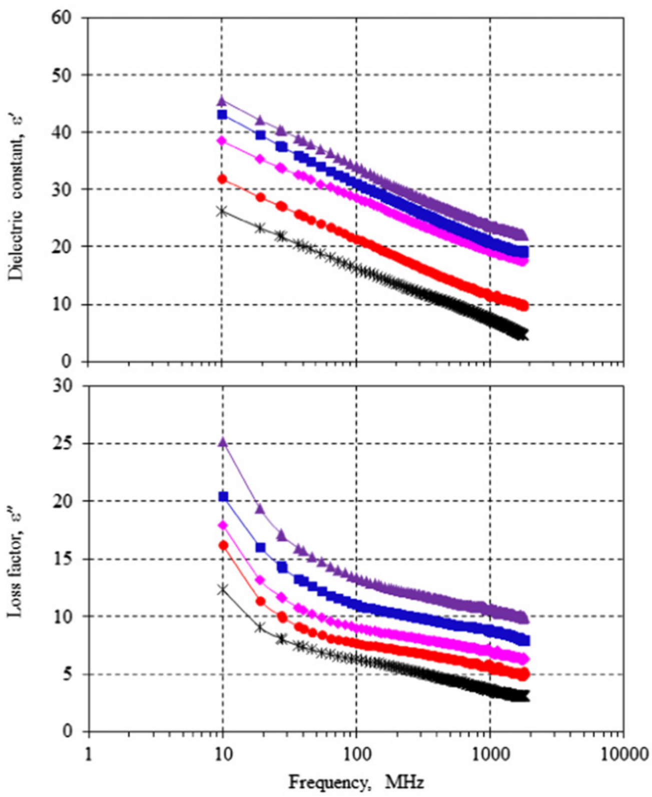

Fig. 2. Dielectric constant (ε′) and loss factor (ε″) of raisins, 15 g/100 g w.b. (–✱–), dates, 19.7 g/100 g w.b. (–●–), apricots, 24.6 g/100 g w.b. (–◆–), figs, 27.3 g/100 g w.b. (–■–), and prunes, 30.2 g/100 g w.b. (–▲–) as a function of frequency at 20 °C.

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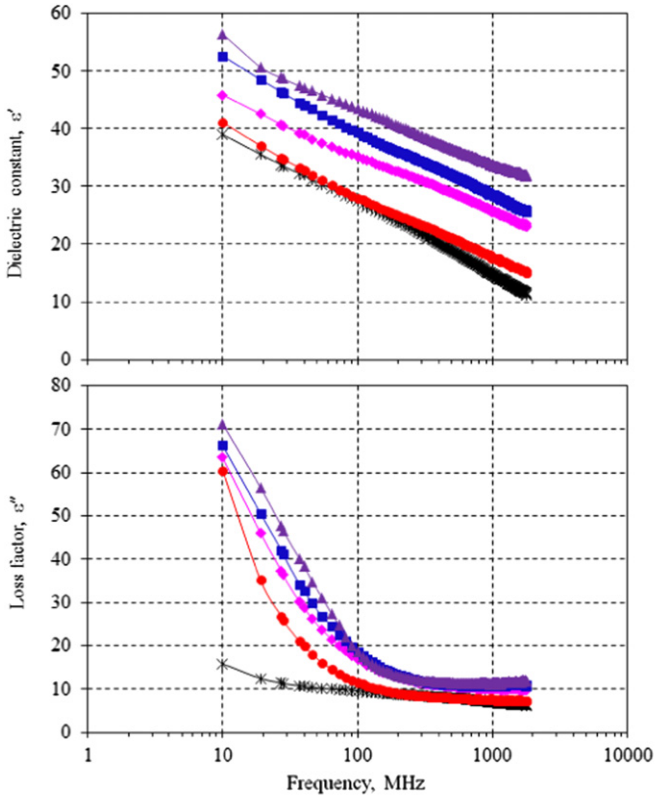

Fig. 3. Dielectric constant (ε′) and loss factor (ε″) of raisins, 15 g/100 g w.b. (—✱—), dates, 19.7 g/100 g w.b. (—●—), apricots, 24.6 g/100 g w.b. (—◆—), figs, 27.3 g/100 g w.b. (—■—), and prunes, 30.2 g/100 g w.b. (—▲—) as a function of frequency at 60 °C.

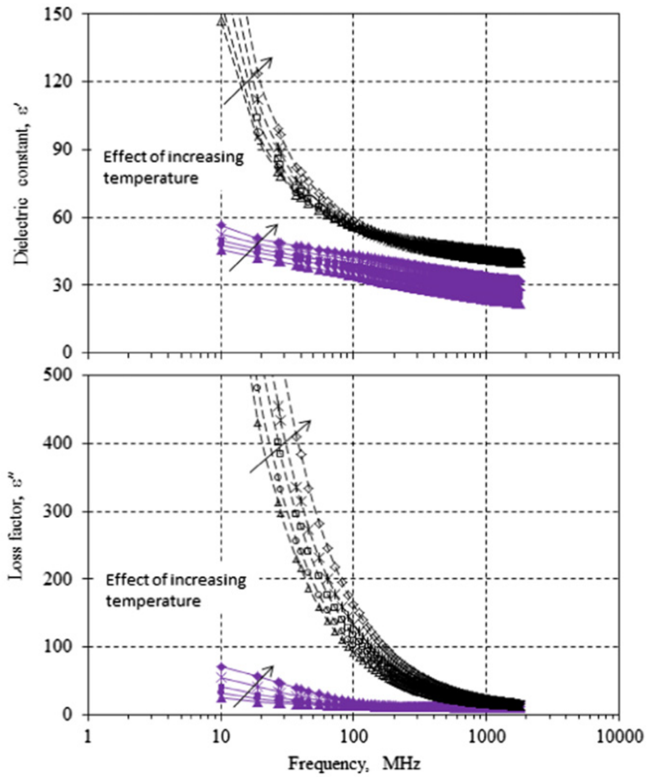

Fig. 4. Dielectric constant (ε′) and loss factor (ε″) of prunes (——), compared to the data of navel orangeworms (– – – –) from Wang, Tang, Johnson, et al. (2003), as a function of frequency and temperature (△ 20 °C, ○ 30 °C, □ 40 °C, ✱ 50 °C, ◇ 60 °C).

such as grains (Nelson, 1987), sunflower seeds (Sacilik et al., 2006), and legume flour (Guo et al., 2010).

3.2. Temperature-dependent dielectric properties

Mean values of the dielectric constant and the loss factor of all tested dried fruits as a function of temperature at 27, 40, 915, and 1800 MHz are shown in Table 2. The dielectric properties of all the tested dried fruits increased with increasing temperature from 20 to 60 °C at each frequency tested. Raisins had the smallest values of dielectric constants (4.6–11.5) and the loss factors (3.1–6.5) at 1800 MHz among the measured samples when increasing temperature from 20 to 60 °C. These values are comparable to the dielectric constants (6–13) and the loss factors (2–6) of grapes at 2450 MHz and at the same range of temperature and water content as obtained by Tulasidas, Raghavan, van de Voort, and Girard (1995). Prunes had the highest values of dielectric constant (40.6–48.9) and loss factor (17.2–47.8) between 20 and 60 °C and at 27 MHz. In food with low water content, most of the water in the food system is chemically associated with other molecules, reducing its response to alternating electromagnetic fields compared to solvent water. When sample temperature was raised to 60 °C, the viscosity was reduced and the mobility of water molecules increased, and this resulted in an increase in loss factor (Tang, 2005).

Fig. 4 shows an example of the dielectric constants and loss factors of navel orangeworm larvae and prunes as a function of temperature over the measured frequency range between 10 and 1800 MHz. In general, the dielectric properties of navel orangeworm larvae were much larger than that of prunes, especially at the low frequencies (<100 MHz). This may be due to the main ionic dispersion at low frequencies, as stated previously. The dielectric constants of navel orangeworm larvae and prunes increased from about 80.2 to 99.4 and from 40.6 to 48.9 at 27 MHz when temperature increased from 20 to 60 °C, respectively. The dielectric loss factors of navel orangeworm larvae and prunes increased from 307.8 to 562.7 and from 17.2 to 47.8 at 27 MHz when temperature increased from 20 to 60 °C, respectively. In the MW region (*e.g.* 915 MHz), the dielectric loss factor of navel orangeworm larvae and prunes increased slightly from 16.1 to 24.0 and from 10.8 to 11.3 when the temperature increased from 20 to 60 °C, respectively. The large difference of dielectric loss factors between insects and the tested dried fruits at RF frequencies (<100 MHz) should lead to a high degree of preferential heating of insects compared to MW frequencies, although it may be possible to develop MW treatments for preferential heating if these can be tightly controlled to avoid quality loss to the fruit from overheating.

3.3. Water content-dependent dielectric properties for dried fruits

The water content of dried fruits is relatively low; however, the effect of a small change in water content has a significant impact on the dielectric properties of these foods. Fig. 5 illustrates the effect of water content (among different fruits) on the dielectric properties of dried fruits from 20 to 60 °C and 27 MHz. Both dielectric constants and dielectric loss factors increased linearly with increasing water contact, from 15 g/100 g (raisins) to 30.2 g/100 g (prunes) at all tested temperature and frequencies. At temperature 20 °C and frequency 27 MHz, the dielectric constants and loss factors increased from 21.9 to 40.6 and from 8.1 to 17.2 when water content increased from 15 g/100 g to 30.2 g/100 g, respectively. Similar trends were observed at other tested frequencies (data not shown). The higher the water content, the larger was the dielectric

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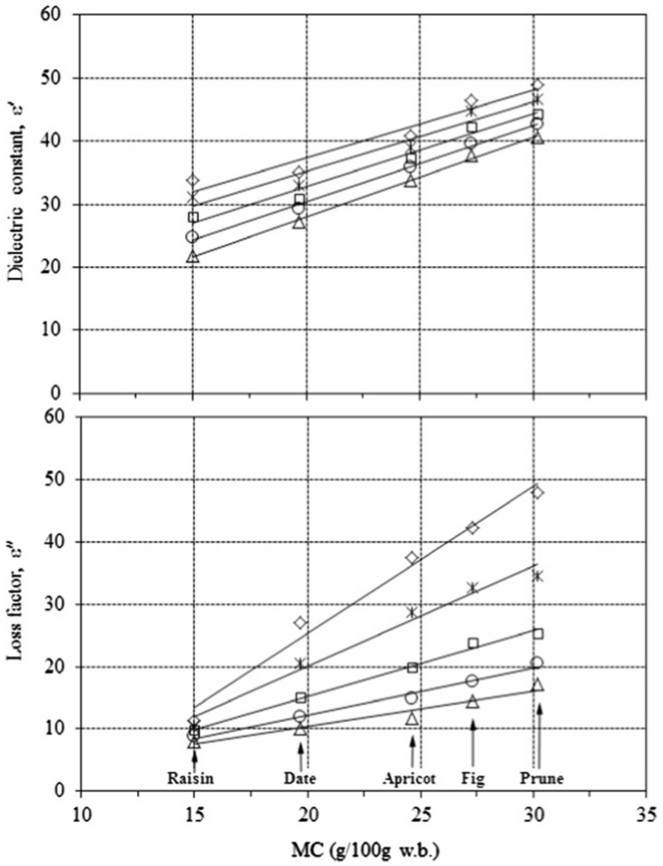

Fig. 5. Comparison of the dielectric constants (ε') and loss factors (ε'') of samples as a function of water contents (fruit type) and temperatures (△ 20 °C, ○ 30 °C, □ 40 °C, ⚹ 50 °C, ◇ 60 °C) at 27 MHz.

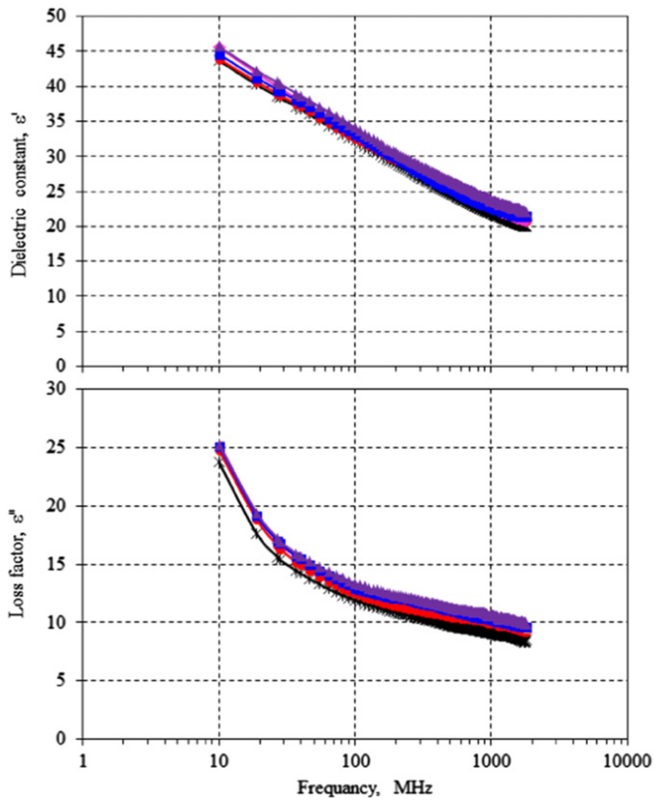

Fig. 6. Dielectric constant (ε') and loss factor (ε'') of raisins (—⚹—), dates (—●—), apricots (—◆—), figs (—■—), and prunes (—▲—) as a function of frequency and at water content of 30.2 g/100 g and temperature of 20 °C.

constant and loss factor. Table 3 shows predictive equations for the dielectric constant and the loss factor as a function of water content at 27 MHz. R^2 values ranged from 0.94 to 0.99. Earlier studies on high ($a_w = 0.95–0.99$) or low ($a_w = 0.40–0.60$) water content foods have found a similar effect of water content on the dielectric properties of food products including corn (Nelson, 1978); grapes (Tulasidas et al., 1995); apples (Feng et al., 2002); and legume flour (Guo et al., 2010), but there is little reported data for intermediate ($a_w = 0.60–0.90$) or low ($a_w = 0.40–0.60$)water content foods having a high sugar content. Sugar and starch have different water binding properties (Datta, Sumnu, & Raghavan, 2005), so it would be expected that sugar containing foods would exhibit greater changes in dielectric properties with temperature or frequency than high starch foods such as legume flour from earlier studies.

Fig. 6 shows the dielectric properties of dried fruits at a constant water content of 30.2 g/100 g and 20 °C as a function of frequency. When increasing water content of raisins, dates, apricots, and figs from their initial values to 30.2 g/100 g, the dielectric properties had comparable values as that of prunes. The standard divisions of the ε' and ε'' for all tested sample were ±0.79, 0.74, 0.70, 0.75 and ±0.64, 0.58, 0.60, 0.50 at 27, 40, 915, 1800 MHz, respectively. This indicates that although the total sugars content vary on these dried fruits, 62.2, 60.5, 39.6, 50.2, and 35.1 g/100 g for raisins, dates, apricots, figs, prunes, respectively, at the same water content, their dielectric properties did not differ significantly. Sugar molecules are relatively large, uncharged, and thus do not interact well with the electromagnetic energy in the tested frequency range. Several earlier studies on fruits such as honeydew melons (Guo, Nelson, Trabelsi, & Kays, 2007) and honey (Guo, Liu, Zhu, & Wang, 2011) showed that sugar reduced the value of the dielectric properties. Higher ash content also reduces the value of dielectric constant but raised the value of loss factor. The reduction in dielectric constant with higher ash content is due to binding of water in the system which reduces the availability of water for polarization. On the other hand, higher ash content may lead to high ionic conductivity because of larger amount of changed metal ions in the tested samples (Datta et al., 2005). Ahmed, Prabhu, Raghavan, and Ngadi (2007) measured the dielectric properties of seven Indian honey samples and showed that when samples have similar water content and different ash contents (even though small difference), their dielectric properties exhibit significantly difference. Raisins, dates, and figs have lower ash content (1.4–1.9 g/100 g) and higher total sugars content (62.2–50.2 g/100 g), while apricots and prunes have higher ash content (4.6 and 3.9 g/100 g, respectively) and lower total sugars content (39.6 and 35.1 g/100 g, respectively). These different combinations in compositions might balance the effect of the total sugars content on the dielectric properties. Thus, water content

Table 3
Predictive equations for dielectric constant and loss factor of samples as a function of water content (fruit type) at 27 MHz and five temperatures.

Temp., °C		R^2		R^2
20	$\varepsilon' = 1.07\ M + 15.98$	0.94	$\varepsilon'' = 2.35\ M - 21.77$	0.98
30	$\varepsilon' = 1.10\ M + 13.20$	0.95	$\varepsilon'' = 1.60\ M - 12.02$	0.98
40	$\varepsilon' = 1.15\ M + 9.76$	0.98	$\varepsilon'' = 1.06\ M - 5.89$	0.99
50	$\varepsilon' = 1.21\ M + 6.10$	0.99	$\varepsilon'' = 0.75\ M - 2.72$	0.98
60	$\varepsilon' = 1.26\ M + 2.79$	0.99	$\varepsilon'' = 0.57\ M - 1.07$	0.95

*Based on the measured dielectric properties of the tested dried fruit.

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plays the dominant role in determining the dielectric properties of the dried fruits more than other components.

3.4. Comparing the dielectric properties of dried fruits and insects

The dielectric constant and loss factor for Indian meal moths were clearly greater than those of raisins, particularly in the RF range (<100 MHz) (Fig. 7). The dielectric constants of Indian meal moths and raisins at 20 °C ranged from about 81.3 to 69.1 and from 21.9 to 20.2, respectively, when frequency increased from 27 to 40 MHz. The loss factors for Indian meal moths and raisins at 20 °C ranged from about 210.9 to 149 and from 8.1 to 7.4, respectively, when frequency increased from 27 to 40 MHz. On the other hand, the dielectric constants and loss factors of Indian meal moths and raisins were close at the MW range (>100 MHz), which would likely minimize the possibility for using differential heating to kill insects above 100 MHz. Increasing frequency from 915 to 1800 MHz resulted in further reduction of the dielectric constants of Indian meal moths and raisins at 20 °C from 39.9 to 37.5 and from 7.8 to 4.6, respectively. The loss factors of Indian meal moths and raisins from 915 to 1800 MHz at 20 °C changed from 13.4 to 10.6 and from 3.8 to 3.1, respectively.

A similar trend as observed in Fig. 7, for Indian meal moths and raisins is also shown in Fig. 8 for the dielectric properties of Navel orangeworm and prunes. The dielectric constant (80.2–68.6) and loss factor (307.8–12.6) of navel orangeworm larvae were almost double those of prunes (40.6–38.7 for dielectric constant and 17.2–15.7 for loss factor) in the RF range (27–40 MHz) at 20 °C. Navel orangeworm is a highly heat tolerant insect (Johnson, Valero, Wang, & Tang, 2004), and prunes had the highest dielectric properties among the dried fruits considered in this study.

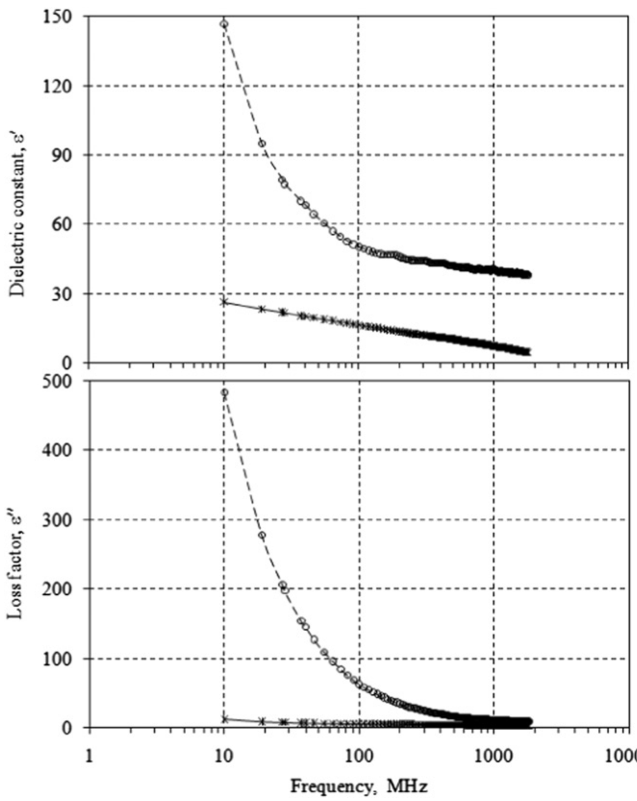

Fig. 7. Dielectric constant (ε') and loss factor (ε'') of raisins (—×—), compared to the data of Indian-meal moths (IMM) (– – ○ – –) from Wang, Tang, Johnson, et al. (2003), as a function of frequency at 20 °C.

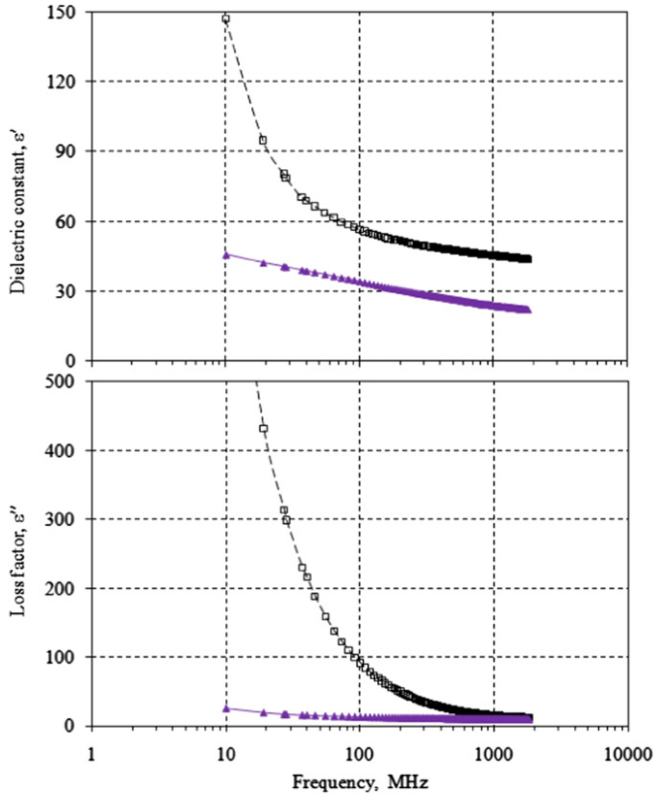

Fig. 8. Dielectric constant (ε') and loss factor (ε'') of prunes (—▲—), compared to the data of navel orangeworms (NOW) (– – □ – –) from Wang, Tang, Johnson, et al. (2003), as a function of frequency at 20 °C.

As shown in Eq. (2), the larger the dielectric loss factor, the larger the generation of thermal energy at a given frequency. Therefore, Indian meal moth larvae and navel orangeworms are likely to absorb more energy than dried fruits at frequencies in the RF range, and this could provide a practical alternative to chemical disinfection.

3.5. Penetration depth

Penetration depths calculated from the measured dielectric properties of five dried fruits are summarized in Table 4 for four frequencies over five temperatures at the initial water contents of those samples. The penetration depths of all tested dried fruits decreased with increasing frequency and temperature. The penetration depth in prunes was the lowest among the five dried fruits; in raisins the penetration depth was the largest under the same conditions. The penetration depth of raisins ranged from 103.7 to 91.3 cm when the temperature increased from 20 to 60 °C at 27 MHz. In contrast, the penetration depth of prunes ranged from 66.9 to 28.4 cm when the temperature increased from 20 to 60 °C at 27 MHz. The penetration depths for the dried fruits at the MW region were smaller than those at the RF region. For apricots, when the frequency increased from 27 MHz to 1800 MHz, the penetration depth decreased from 88.8 to 1.8 cm at 20 °C. These results suggest that dried fruits could be treated in large containers and thick layers of 30 cm or greater in the RF system due to the deeper penetration; however, smaller containers and thinner layers of product would need to be used in MW treatments to achieve uniform heating in dried fruits. Deep penetration depths at 27 MHz hold the potential to develop large-scale industrial RF treatments for postharvest insect control in dried fruits with acceptable heating uniformity.

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Table 4
Penetration depths (cm) (mean ± SD of two replicates) of five dried fruits calculated from measured dielectric properties at five temperatures and four frequencies.

Materials	Temp., °C	Penetration depth, cm			
		Frequency, MHz			
		27	40	915	1800
Raisins	20	103.7 ± 1.13	74.0 ± 0.95	4.0 ± 0.10	1.9 ± 0.03
	30	100.3 ± 0.36	71.5 ± 0.31	3.8 ± 0.06	1.9 ± 0.03
	40	96.9 ± 0.78	68.7 ± 0.63	3.4 ± 0.03	1.7 ± 0.02
	50	94.3 ± 0.14	66.4 ± 0.11	3.1 ± 0.02	1.6 ± 0.04
	60	91.3 ± 0.47	64.4 ± 0.29	2.9 ± 0.02	1.4 ± 0.01
Dates	20	93.0 ± 0.99	68.2 ± 0.47	3.3 ± 0.06	1.7 ± 0.04
	30	81.9 ± 1.45	62.5 ± 0.71	3.1 ± 0.05	1.6 ± 0.02
	40	67.5 ± 1.53	53.9 ± 0.93	3.0 ± 0.04	1.5 ± 0.01
	50	51.6 ± 1.29	43.2 ± 0.95	3.0 ± 0.03	1.4 ± 0.01
	60	41.4 ± 1.38	35.7 ± 1.04	3.0 ± 0.03	1.5 ± 0.01
Apricots	20	88.8 ± 0.82	64.9 ± 0.72	3.3 ± 0.07	1.8 ± 0.03
	30	72.9 ± 1.31	55.3 ± 0.88	3.0 ± 0.07	1.5 ± 0.04
	40	56.3 ± 1.54	45.0 ± 0.81	2.7 ± 0.03	1.4 ± 0.01
	50	40.8 ± 0.44	33.6 ± 0.02	2.6 ± 0.04	1.3 ± 0.02
	60	32.8 ± 0.30	27.4 ± 0.15	2.7 ± 0.01	1.3 ± 0.01
Figs	20	76.7 ± 1.19	55.5 ± 0.57	2.7 ± 0.05	1.5 ± 0.06
	30	64.9 ± 0.58	48.9 ± 0.71	2.4 ± 0.02	1.3 ± 0.01
	40	50.0 ± 0.61	40.5 ± 0.91	2.5 ± 0.01	1.3 ± 0.02
	50	38.3 ± 0.17	32.0 ± 0.31	2.6 ± 0.01	1.3 ± 0.01
	60	31.0 ± 0.33	25.7 ± 0.59	2.6 ± 0.05	1.2 ± 0.02
Prunes	20	66.9 ± 0.35	48.3 ± 0.28	2.4 ± 0.02	1.3 ± 0.02
	30	57.9 ± 0.26	44.0 ± 0.24	2.3 ± 0.00	1.2 ± 0.01
	40	48.1 ± 0.49	38.9 ± 0.54	2.4 ± 0.01	1.2 ± 0.01
	50	37.2 ± 0.47	31.3 ± 0.47	2.6 ± 0.02	1.3 ± 0.02
	60	28.4 ± 0.02	22.9 ± 0.07	2.7 ± 0.00	1.3 ± 0.01

4. Conclusions

Dielectric properties of raisins, dates, apricots, figs, and prunes at different frequencies (10–1800 MHz), temperatures (20–60 °C) were measured by an impedance analyzer. Differential heating for postharvest insect pest control is possible since the dielectric constant and loss factor of the tested dried fruits is lower than for common insect pests, particularly at RF frequencies. The dielectric constants and loss factors of the five dried fruits and insects decreased with increasing frequency and increased with increasing temperature. Lower water content raisins had the lowest values of dielectric properties, while the higher water content prunes had the highest. The penetration depth of all dried fruits decreased with increasing frequency and temperature, but is on the order of tens of centimeters, making the development of industrial treatment systems or disinfection possible, particularly at RF frequencies (*e.g.* 27 MHz).

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