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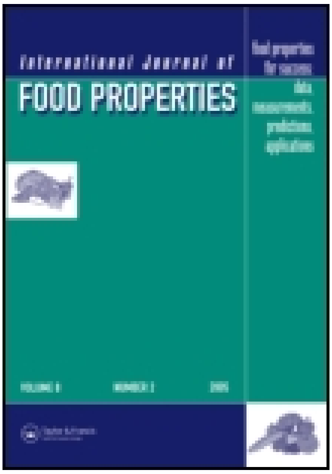

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Dielectric properties of apple, apricot, peach, and pear nectars were studied in the frequency range from 15 kHz to 30 MHz and the temperature range from 25 to 60°C. Both the relative dielectric constants and the dielectric loss factors decreased by increasing frequency and increased linearly with increasing temperature with values in the order 10^4–10^2 and 10^5–10^2, respectively. The power dissipation densities and the power penetration depths were found to increase linearly with temperature. Power dissipation densities remained essentially constant for all the samples while power penetration depths decreased significantly on increasing frequency. The dependence of each of the two dielectric properties on frequency and temperature has been described by two simple equations that proved to be adequate to describe the trend of the relative dielectric constant and dielectric loss factor for all the frequencies temperatures considered. It has been established that the dominant mechanism for the dielectric loss is ionic conductivity.

Keywords: Fruit juice, Fruit nectar, Permittivity, Dielectric constant, Dielectric loss factor, Low frequency, RF heating.

INTRODUCTION

Fruits and vegetables juices are among the top selling beverages worldwide and represent a convenient way to improve consumption of fruits and vegetables with beneficial effects on consumers' health, as recommended by international organizations.[1] Food processing that involves inactivation of pathogenic microorganisms is used to prevent food poisoning during the consumption of raw products. In fact, fruit juices have been the source of several outbreaks, mostly involving Salmonella and *E. coli* O157.[2]

Today, the vast majority of fruit juices is pasteurized by heating the juice to a high temperature, typically between 92 and 105°C for a time sufficient to remove all microbiological hazards. Although thermal treatment has proven to be very effective at inactivating pathogenic organisms, it also alters

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other properties of juices such color, texture or taste, as well as their nutritional value.[3] Therefore, there is a great interest in developing alternative inactivation methods that are able to guarantee the same effectiveness in reducing health hazards while avoiding the previously mentioned disadvantages.[4] Among these, high hydrostatic pressure (HHP) and electro-heating are options.

HHP treatments result in a better final product from the organoleptic point of view and have been increasingly used worldwide. Nevertheless, HHP does not seem to be sufficiently effective in the removal of some pathogens and a residual surviving population is sometimes observed after HHP inactivation.[2] Electroheating seems to be a very promising way to address the problem of inactivation, due to the very high heating rate and uniformity.[5–7] In electroheating methods, an electrical current can be applied directly to the food as in ohmic heating (OH) or can be previously converted to electromagnetic radiation that, in turn, interacts with the sample. Depending on the frequency range used, it is called radio frequency (RF) or microwave (MW) heating. In particular, RF heating has attracted a considerable interest in recent years due to the fact that, in contrast with OH, it can be applied directly to packed food and that RF radiation penetrates much deeper in the sample than MW, thereby generating less hot or cold spots or surface overheating.[5]

RF conventionally occupies the portion of the electromagnetic spectrum between 3 kHz and 300 MHz[8] with most industrial applications using frequencies that lie in the range of 10–50 MHz (6.78, 13.56, 27.12, and 40.68 MHz are reserved for industrial, scientific, and medical applications).[5,9] When RF radiation interacts with a sample the oscillation of the polarity of the electric field makes the ions oscillate forward and backward—ionic polarization—dissipating part of the kinetic energy by friction as heat. In principle, also continuous reorientation of dipolar molecules—dipole rotation—may lead to the production of heat by friction. But this latter phenomenon usually has a significant effect in the case of MW heating (300 MHz–300 GHz).[5,10,11]

In addition to thermal methods that rely on the previously mentioned mechanism, also non-thermal sterilization methods using RF radiation have been recently proposed by Geveke and Brunkhorst.[12–15] In this method high electric fields are applied to liquids for a very short time (<1 ms) at moderately low temperature (<50°C) and the microorganisms are inactivated by electroporation that consist in the rupture of cell membrane due to the induced voltage formed across the membrane because of its capacitance.[14,16] The frequencies used for this application are quite lower than in thermal methods usually ranging from 15 to 70 kHz.

Dielectric properties are the most important attribute needed to understand and characterize the interaction between food samples and the electric field produced at the operating RF. Hence, knowledge of the dielectric properties of materials is important to the development of RF treatment protocol and subsequent scale up to industrial production.[17,18] The dielectric properties of interest for most applications are the relative dielectric constant, ε_r' and the dielectric loss factor, ε_r'', that constitute the real and imaginary part, respectively, of the complex relative permittivity, $\varepsilon_r^* = \varepsilon_r' - j\varepsilon_r''$. The relative dielectric constant is associated with the ability of a sample to store energy in the electric field while the dielectric loss factor is related with the dissipation of electrical energy in the material as heat.

Many studies have been conducted on the dielectric properties of solid or semisolid foods such as fruit, vegetables, bread, eggs, meat, and seafood[17] and fluids such as milk, vinegar, fruit juices, and honey.[17,19] However, most of these studies have explored only the higher portion of the frequency spectrum focusing mostly on the MW region or the RF spectrum above 20 MHz. Moreover, many of the published studies were conducted at room temperature only. Therefore, a parallel-plate probe was used to study the dielectric properties of several commercial fruit nectars at frequencies from 15 kHz to 30 MHz (typically used in low frequency RF inactivation processes) within the temperature range of 25–60°C. The results obtained were used to estimate the power dissipation density and power penetration depth for the fruit nectars.

MATERIALS AND METHODS

Materials

The four fruit nectars (from apple, apricot, peach, and pear) were commercially available long-life products (Zuegg S.p.A., Verona, Italy) that were stored in tetra brick® (Tetra Pak, Sweden) aseptic package and were purchased from a local store in Palermo (Italy). The samples were used without any further treatment. Three of them contained citric acid as acidifier and all of them contained L-Ascorbic acid as antioxidant.

Dielectric Properties Measurements

The dielectric properties were measured with the parallel plate method[17] using a precision impedance analyzer Agilent model 4293A equipped with a 16452A liquid test fixture connected with a 16452-61601 cable.[20] The parallel plate method consists of sandwiching a thin sheet of the sample between two electrodes to form a capacitor. The measured capacitance is then used to calculate permittivity.

For each measurement, 800 points were acquired on a logarithmic scale from 15 kHz to 30 MHz. The range includes some of the frequency allocated for industrial, scientific and medical (ISM) applications: 6.78, 13.56, and 27.12 MHz.[9] Before measuring the dielectric properties, the impedance analyzer was allowed to warm up for at least 1 h. The instrument was calibrated at the beginning of every measurement session using the procedure suggested in the operating manual.[20]

The following procedure was used for dielectric measurement: fixture was heated at the maximum experimental temperature—namely 60°C—and capacitance of the void test fixture, C_0, was measured and assumed equal to that of air at the same temperature, as indicated in operating manual and other supporting documentation.[20] After air capacitance was measured, 3.4 mL sample was poured into the test fixture and the temperature was monitored with a K-type thermocouple temperature sensor. Permittivity measurement were conducted pre-heating the measurement cell above 60°C in an oven. Once the sample was introduced in the cell, it thermally equilibrated with the cell very quickly due to its small mass with respect to that of the cell. The measurements at different temperatures were performed at 5°C intervals as the sample cooled from 60 to 25°C: When the temperature reached each targeted value, the thermocouple was removed and the measurement was performed. Temperature remained constant during the measurement that was virtually instantaneous. After finishing the measurements for each replicate, the nectar was drained out from the test fixture, which was disassembled, cleaned with water and acetone, and, finally, dried at room temperature. Relative dielectric constant and dielectric loss factor of the nectar samples were calculated using the following equations:

$$\varepsilon_r' = \alpha \frac{C_P}{C_0} \tag{1}$$

$$\varepsilon_r'' = \alpha \frac{1}{C_0 R_P 2\pi f} \tag{2}$$

where, ε_r', is the relative dielectric constant; ε_r'' is the dielectric loss factor; C_P is the equivalent parallel capacitance of the sample and C_0 is that of the air; R_P is the equivalent parallel resistance and f is the frequency; α is a correction function, depending on C_P, R_P, and f calculated following the procedure indicated in the operating manual.[20] All measurements were repeated three times with a seven days interval, following the procedure above described. For each of the 800 frequencies the mean value of the three replicates and the standard deviation were calculated.

For clarity reasons, all the figures show only the average values of the three measurements as the trends of the three replicates overlapped.

RESULTS AND DISCUSSION

Effect of Frequency on Dielectric Properties

Dielectric constant, ε_r', and dielectric loss factor, ε_r'', for the four fruit nectars are shown in Figs. 1 and 2, respectively, as a function of the frequency (15 kHz to 30 MHz) and temperature of 25°C; the same values, together with standard deviations, are listed for selected frequencies and temperatures in Tables 1a–1d. Overall, the maximum relative error, defined as ratio between the standard deviation and the mean value, was of 15 % for the relative dielectric constant and of 5

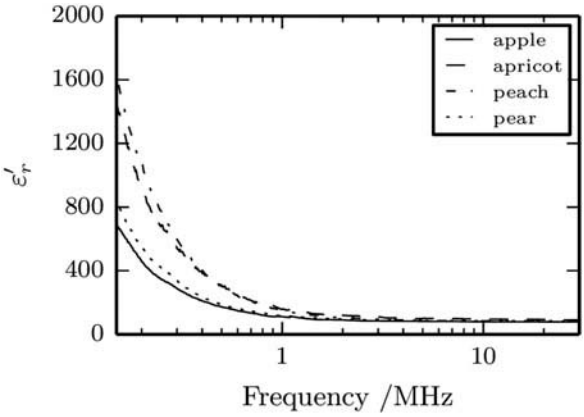

FIGURE 1 Plot of ε_r' as a function of frequency for four fruit nectars at t = 25°C.

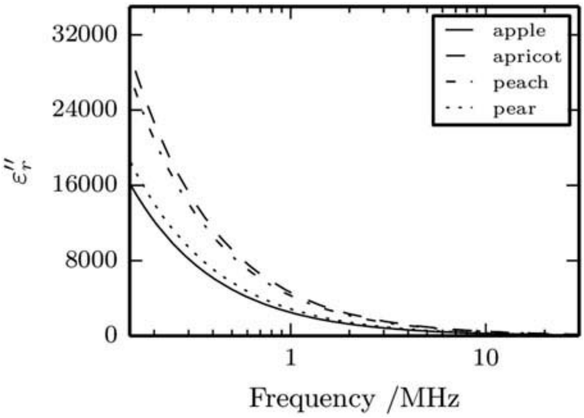

FIGURE 2 Plot of ε_r'' as a function of frequency for four fruit nectars at t = 25°C.

TABLE 1A

Relative dielectric constant and dielectric loss factor at different temperatures and selected frequencies for the apple nectar (mean ± standard deviation for three replicates)

		Apple							
Freq [Hz]	*T [°C]*	*60*	*55*	*50*	*45*	*40*	*35*	*30*	*25*
1.2E+05	ε_r'	1060 ± 50	1060 ± 30	1060 ± 20	1030 ± 15	1000 ± 12	970 ± 13	940 ± 19	880 ± 12
	ε_r''	33,500 ± 800	31,500 ± 900	30,000 ± 1000	27,300 ± 800	25,000 ± 700	23,000 ± 600	21,800 ± 1000	19,400 ± 500
2.5E+05	ε_r'	400 ± 13	404 ± 8	410 ± 11	410 ± 12	391 ± 8	380 ± 10	380 ± 13	350 ± 11
	ε_r''	16,900 ± 400	15,900 ± 400	14,900 ± 500	13,800 ± 400	12,600 ± 300	11,600 ± 300	11,000 ± 500	9800 ± 300
5.0E+05	ε_r'	200 ± 20	210 ± 20	210 ± 20	200 ± 18	200 ± 18	190 ± 16	190 ± 17	170 ± 14
	ε_r''	8500 ± 200	8000 ± 200	7500 ± 300	7000 ± 200	6400 ± 180	5900 ± 170	5600 ± 300	4900 ± 150
1.0E+06	ε_r'	120 ± 18	120 ± 17	130 ± 17	120 ± 15	120 ± 14	120 ± 12	120 ± 12	110 ± 10
	ε_r''	4300 ± 110	4000 ± 110	3800 ± 130	3500 ± 110	3200 ± 90	2940 ± 80	2800 ± 130	2480 ± 80
2.0E+06	ε_r'	90 ± 14	90 ± 11	90 ± 11	90 ± 10	90 ± 11	91 ± 8	90 ± 7	91 ± 7
	ε_r''	2130 ± 50	2010 ± 60	1890 ± 70	1750 ± 60	1610 ± 50	1480 ± 40	1400 ± 60	1240 ± 40
4.0E+06	ε_r'	75 ± 9	76 ± 7	78 ± 7	79 ± 7	80 ± 7	81 ± 6	81 ± 5	83 ± 5
	ε_r''	1070 ± 30	1000 ± 30	940 ± 30	880 ± 30	800 ± 20	740 ± 20	700 ± 30	620 ± 20
6.7E+06	ε_r'	74 ± 9	75 ± 9	77 ± 8	78 ± 7	78 ± 7	79 ± 6	80 ± 6	81 ± 5
	ε_r''	630 ± 18	600 ± 18	560 ± 20	520 ± 17	480 ± 14	440 ± 13	410 ± 19	370 ± 12
1.4E+07	ε_r'	74 ± 9	74 ± 8	76 ± 8	77 ± 8	78 ± 7	78 ± 6	80 ± 6	80 ± 5
	ε_r''	314 ± 8	295 ± 8	277 ± 10	256 ± 8	235 ± 6	216 ± 6	204 ± 8	181 ± 5
2.7E+07	ε_r'	71 ± 8	72 ± 7	74 ± 7	75 ± 7	76 ± 6	76 ± 5	78 ± 5	78 ± 4
	ε_r''	150 ± 1.5	141 ± 1.5	132 ± 2	121 ± 1.2	110.6 ± 0.6	101 ± 0.4	95 ± 1.9	83.5 ± 0.3

TABLE 1B

Relative dielectric constant and dielectric loss factor at different temperatures and selected frequencies for the apricot nectar (mean ± standard deviation for three replicates)

		Apricot							
Freq [Hz]	*T [°C]*	*60*	*55*	*50*	*45*	*40*	*35*	*30*	*25*
1.2E+05	ε_r'	3120 ± 50	2970 ± 30	2880 ± 30	2620 ± 15	2500 ± 15	2340 ± 15	2140 ± 19	1950 ± 13
	ε_r''	64,900 ± 800	60,600 ± 900	56,000 ± 1000	51,800 ± 800	47,800 ± 700	43,700 ± 600	39,800 ± 1000	35,900 ± 600
2.5E+05	ε_r'	1014 ± 5	971 ± 6	970 ± 11	899 ± 9	860 ± 11	800 ± 9	730 ± 15	680 ± 12
	ε_r''	32,900 ± 400	30,700 ± 400	28,500 ± 500	26,300 ± 400	24,200 ± 400	22,200 ± 300	20,200 ± 500	18,200 ± 300
5.0E+05	ε_r'	450 ± 20	470 ± 20	430 ± 18	420 ± 19	380 ± 15	360 ± 15	340 ± 18	310 ± 14
	ε_r''	16,500 ± 200	15,400 ± 200	14,300 ± 300	13,200 ± 200	12,200 ± 180	11,200 ± 170	10,200 ± 300	9200 ± 150
1.0E+06	ε_r'	220 ± 19	220 ± 16	200 ± 16	190 ± 14	180 ± 13	170 ± 12	170 ± 11	160 ± 10
	ε_r''	8300 ± 110	7700 ± 120	7200 ± 140	6600 ± 110	6120 ± 90	5600 ± 90	5100 ± 130	4600 ± 80
2.0E+06	ε_r'	160 ± 15	160 ± 13	140 ± 12	140 ± 10	132 ± 9	128 ± 8	124 ± 9	120 ± 7
	ε_r''	4190 ± 60	3900 ± 60	3630 ± 70	3350 ± 60	3090 ± 50	2830 ± 50	2570 ± 70	2320 ± 40
4.0E+06	ε_r'	125 ± 8	121 ± 8	117 ± 7	113 ± 7	110 ± 7	105 ± 6	105 ± 6	102 ± 5
	ε_r''	2080 ± 30	1950 ± 30	1810 ± 40	1670 ± 30	1540 ± 20	1410 ± 30	1280 ± 30	1160 ± 20
6.7E+06	ε_r'	133 ± 9	129 ± 8	124 ± 8	120 ± 8	117 ± 7	113 ± 6	109 ± 6	108 ± 5
	ε_r''	1240 ± 19	1160 ± 19	1070 ± 20	990 ± 18	910 ± 15	840 ± 18	760 ± 20	690 ± 12
1.4E+07	ε_r'	126 ± 9	122 ± 8	117 ± 8	114 ± 8	110 ± 7	108 ± 6	106 ± 6	104 ± 5
	ε_r''	618 ± 9	576 ± 9	540 ± 10	492 ± 8	453 ± 7	415 ± 7	377 ± 9	340 ± 5
2.7E+07	ε_r'	118 ± 8	114 ± 7	110 ± 7	108 ± 7	105 ± 6	103 ± 5	101 ± 5	100 ± 4
	ε_r''	294 ± 2	274 ± 1.9	254 ± 3	233 ± 1.4	214 ± 1.1	195.7 ± 0.6	177 ± 2	159 ± 0.5

TABLE 1C

Relative dielectric constant and dielectric loss factor at different temperatures and selected frequencies for the peach nectar (mean ± standard deviation for three replicates)

		Peach							
Freq [Hz]	*T [°C]*	*60*	*55*	*50*	*45*	*40*	*35*	*30*	*25*
1.2E+05	ε_r'	3080 ± 60	2770 ± 40	2730 ± 20	2590 ± 20	2540 ± 13	2421 ± 9	2260 ± 14	2120 ± 13
	ε_r''	53,000 ± 800	55,500 ± 900	51,000 ± 1000	47,200 ± 800	43,400 ± 700	39,600 ± 600	36,000 ± 1000	33,100 ± 500
2.5E+05	ε_r'	1040 ± 15	1030 ± 12	1030 ± 12	1000 ± 12	950 ± 12	910 ± 12	840 ± 15	774 ± 9
	ε_r''	26,900 ± 400	28,000 ± 400	26,000 ± 500	23,900 ± 400	22,000 ± 300	20,100 ± 300	18,300 ± 500	16,800 ± 300
5.0E+05	ε_r'	370 ± 20	410 ± 20	400 ± 20	370 ± 20	370 ± 18	350 ± 18	320 ± 17	300 ± 14
	ε_r''	13,600 ± 200	14,100 ± 200	13,100 ± 300	12,100 ± 200	11,100 ± 180	10,200 ± 160	9300 ± 200	8500 ± 160
1.0E+06	ε_r'	170 ± 18	180 ± 17	180 ± 16	180 ± 15	170 ± 13	160 ± 11	150 ± 10	149 ± 10
	ε_r''	6900 ± 130	7100 ± 140	6600 ± 160	6100 ± 120	5600 ± 100	5120 ± 80	4700 ± 160	4270 ± 80
2.0E+06	ε_r'	100 ± 15	110 ± 10	110 ± 13	110 ± 11	113 ± 9	109 ± 8	108 ± 7	107 ± 7
	ε_r''	3450 ± 60	3560 ± 80	3310 ± 100	3050 ± 50	2810 ± 50	2560 ± 50	2330 ± 70	2140 ± 40
4.0E+06	ε_r'	73 ± 9	88 ± 8	89 ± 8	90 ± 9	90 ± 8	90 ± 7	90 ± 6	92 ± 5
	ε_r''	1730 ± 30	1780 ± 40	1660 ± 40	1530 ± 30	1410 ± 30	1280 ± 20	1170 ± 30	1070 ± 20
6.7E+06	ε_r'	80 ± 9	94 ± 8	95 ± 8	96 ± 8	95 ± 8	95 ± 6	95 ± 6	95 ± 5
	ε_r''	1030 ± 19	1060 ± 18	980 ± 20	910 ± 17	830 ± 15	760 ± 15	690 ± 19	630 ± 14
1.4E+07	ε_r'	77 ± 10	90 ± 9	91 ± 8	91 ± 7	92 ± 7	91 ± 6	92 ± 6	92 ± 5
	ε_r''	514 ± 8	526 ± 9	490 ± 10	450 ± 8	415 ± 7	379 ± 6	345 ± 8	315 ± 5
2.7E+07	ε_r'	76 ± 8	88 ± 8	89 ± 7	90 ± 7	90 ± 6	90 ± 5	91 ± 5	91 ± 4
	ε_r''	254 ± 2	259 ± 1.9	241 ± 1.8	221 ± 1.3	203 ± 0.9	185 ± 0.6	168 ± 1.9	153 ± 0.6

TABLE 1D
Relative dielectric constant and dielectric loss factor at different temperatures and selected frequencies for the pear nectar (mean ± standard deviation for three replicates)

		Pear							
Freq [Hz]	*T [°C]*	*60*	*55*	*50*	*45*	*40*	*35*	*30*	*25*
1.2E+05	ε_r'	1410 ± 60	1420 ± 40	1430 ± 30	1390 ± 20	1290 ± 15	1280 ± 17	1220 ± 20	1100 ± 15
	ε_r''	39,100 ± 900	37,000 ± 1000	34,000 ± 1200	32,000 ± 900	27,800 ± 800	27,300 ± 700	25,000 ± 1100	22,300 ± 600
2.5E+05	ε_r'	530 ± 18	540 ± 11	540 ± 14	520 ± 15	490 ± 10	480 ± 13	460 ± 16	420 ± 14
	ε_r''	19,700 ± 500	18,800 ± 500	17,400 ± 600	16,200 ± 500	14,100 ± 400	13,800 ± 400	12,700 ± 600	11,300 ± 300
5.0E+05	ε_r'	240 ± 30	240 ± 30	230 ± 20	220 ± 20	210 ± 20	210 ± 18	200 ± 18	190 ± 16
	ε_r''	9900 ± 200	9400 ± 300	8800 ± 300	8200 ± 200	7100 ± 200	6900 ± 200	6400 ± 300	5700 ± 170
1.0E+06	ε_r'	130 ± 19	130 ± 19	130 ± 17	130 ± 16	120 ± 14	120 ± 13	120 ± 13	120 ± 10
	ε_r''	5000 ± 120	4700 ± 130	4400 ± 150	4100 ± 130	3540 ± 100	3480 ± 100	3200 ± 140	2850 ± 90
2.0E+06	ε_r'	100 ± 15	100 ± 12	100 ± 12	100 ± 11	100 ± 11	97 ± 9	97 ± 8	96 ± 7
	ε_r''	2490 ± 60	2370 ± 70	2200 ± 80	2050 ± 70	1760 ± 50	1750 ± 50	1600 ± 70	1430 ± 50
4.0E+06	ε_r'	90 ± 11	87 ± 9	87 ± 8	86 ± 8	88 ± 8	87 ± 7	88 ± 6	88 ± 6
	ε_r''	1240 ± 30	1190 ± 40	1100 ± 40	1030 ± 30	890 ± 30	870 ± 30	800 ± 40	710 ± 20
6.7E+06	ε_r'	90 ± 11	90 ± 11	91 ± 10	91 ± 9	92 ± 8	91 ± 7	92 ± 7	92 ± 5
	ε_r''	740 ± 20	710 ± 20	660 ± 20	610 ± 20	520 ± 16	520 ± 15	470 ± 20	420 ± 14
1.4E+07	ε_r'	90 ± 11	90 ± 10	91 ± 10	90 ± 9	90 ± 8	90 ± 7	91 ± 7	91 ± 5
	ε_r''	365 ± 10	350 ± 10	320 ± 11	300 ± 9	262 ± 7	255 ± 7	232 ± 10	207 ± 6
2.7E+07	ε_r'	87 ± 10	87 ± 9	86 ± 8	86 ± 7	87 ± 7	86 ± 5	87 ± 5	88 ± 4
	ε_r''	175 ± 1.9	166 ± 1.8	154 ± 2	143 ± 1.4	130.1 ± 0.8	120.4 ± 0.5	109 ± 2	96.4 ± 0.5

% for the dielectric loss factor. It can be clearly seen that for all the different nectars both ε_r' and ε_r'' decrease sharply on increasing the frequency.

In particular, for all the samples, the relative dielectric constant assumes very high values in the range 15–150 kHz, decreases on increasing frequency until it approaches values similar to that of water (≈80). This behavior seems to indicate the presence of α and/or β relaxations[21,22] which are quite common in biological samples with complex membrane structures. The α relaxation can be mainly attributed to the lateral movement of the ions forming a counter-ion layer around colloidal particles present in the sample (macromolecules, subcellular structures, etc.). In the presence of an external electric field, the ions move as a whole like a large dipole determining a low-frequency relaxation. Movements of ions through membrane pores may also represent a contribution to the overall effect. The β relaxation is caused by the accumulations of ions at membrane surfaces under an external electric field due to the blocking of ions movements by the membrane. This phenomenon is also known as Maxwell-Wagner effect. It can be noted that the four samples show a qualitatively similar behavior, even though there are small differences for the rate at which ε_r' falls with frequency. Perusal of the experimental data suggested to the authors to perform a non-linear regression of results via the following analytical expression:

$$log\ \varepsilon_r' = \frac{ab + 1.9f}{b + f} \tag{3}$$

where, *log* is the decimal logarithm, *a* is a numeric parameter, equal for all the nectars, function of the temperature (as explained in the section "Effect of Temperature on Dielectric Properties"), *f* is the frequency, 1.9 = *log* 80, namely the relative dielectric constant of water, and *b* is a parameter [Hz] that takes into account the type of nectar considered. Table 2 shows the values of parameter *b*, calculated at 25°C ($a = 5.00$), together with the correlation coefficient *R* and the standard error SE for each fruit nectar; the very good values of *R* and SE demonstrates the good predictive capability of Eq. (3) that makes it adequate for practical applications.

Parameter *b* corresponds to the frequency at which the relative dielectric constant is about 40 times that of water; smaller *b* values entail that ε_r' will fall more rapidly with frequency. However, the nature of the biological structures involved in the dispersion phenomena is quite complex and the physical modeling of *b* is made difficult by the fact that the similarities between biological structures are more in their functions and composition and less in their exact structure.[21]

The dielectric loss factor can be generally expressed as:[17]

$$\varepsilon_r'' = \varepsilon_\sigma'' + \varepsilon_{om}'' \tag{4}$$

where, ε_σ'' represents the ionic conductivity loss contribution and ε_{om}'' takes into account other mechanisms. The ionic contribution is given by the following equation:[17,23]

TABLE 2
Parameter *b* of dielectric constant model, calculated at 25°C (*a* = 5.00), with correlation coefficient *R* and standard error SE for the four nectars

@ 25°C	b *[Hz]*	*R*	*SE*
Apple	5.32E+04	0.994	7.70E-02
Apricot	9.66E+04	0.997	6.95E-02
Peach	1.02E+05	0.998	6.02E-02
Pear	6.52E+04	0.997	5.90E-02

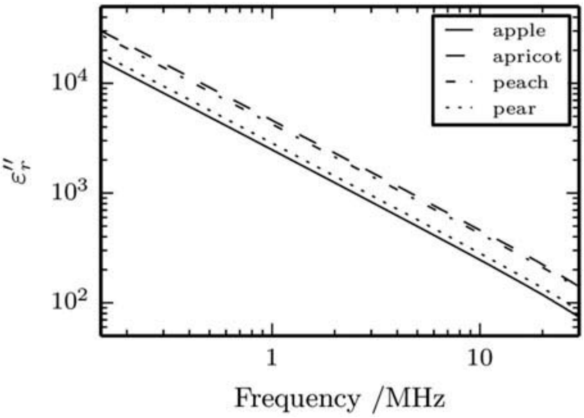

FIGURE 3 Graph of $log\varepsilon_r'' vs. logf$ for four fruit nectars at t = 25°C.

$$\varepsilon_\sigma'' = \frac{\sigma}{2\pi f \varepsilon_0} \tag{5}$$

where, σ is the conductivity in S m^{-1} and ε_0 is the absolute permittivity of vacuum.

Fig. 3 presents $log\ \varepsilon_r''$ vs. $log\ f$ at 25°C for the four nectars. It can be clearly noted that the respective experimental data form straight lines parallel to each other. These findings strongly indicate that the ionic conductivity loss mechanism is dominant in the frequency range considered and it is consistent with previous results at higher frequency range:[19] Indeed, assuming negligible the contribution of the other mechanisms ε_{om}'' in Eq. (4) it follows that:

$$log\ \varepsilon_r'' = log \frac{\sigma}{2\pi\varepsilon_0} - log\ f \tag{6}$$

that represents, in logarithmic terms, a sheaf of parallel straight lines.

Fitting Eq. (6) to the experimental data permitted to estimate the conductivity σ for each sample, reported in Table 3 together with the statistical parameter R and SE. Since σ proved to be constant with frequency in the range evaluated, it follow from Eq. (5) that the ionic contribution decreases with increasing frequency.

TABLE 3
Intercept, correlation coefficient R, standard error SE of the linear regression, and conductivity σ of the four nectars, calculated at 25°C

@ 25°C	$\log\frac{\sigma}{2\pi\varepsilon_0}$	*R*	*SE*	*σ [S m^{-1}]*
Apple	9.38	0.999	1.81E-02	1.35E-01
Apricot	9.65	0.999	1.90E-02	2.51E-01
Peach	9.62	0.999	2.20E-02	2.31E-01
Pear	9.44	0.999	1.89E-02	1.55E-01

Effect of Temperature on Dielectric Properties

Temperature could have a great effect on the dielectric properties of many substances.[24,25] In this study for the four fruit nectars considered an increase in temperature led to an increase in both the relative dielectric constant and the dielectric loss factor, although effects do not occur in the same manner for the two properties.

Mean values with standard deviations of ε'_r and ε''_r in the temperature range of 25–60°C for selected frequencies are listed in Tables 1a–1d.

The increase of dielectric constant on increase temperature is more noticeable in the lower part of the frequency spectrum investigated ($f < 1$ MHz approximately); at higher frequencies the temperature influence becomes less important till the trend of ε'_r, tend to flatten where it becomes negligible. Conversely, the temperature effect on the dielectric loss factor is significant over the whole frequency range with increases up to about 15% going from one temperature to the next.

Equation (3) proved to be adequate to describe the trend of the relative dielectric constant for all the temperature considered, keeping unaltered the parameter b and substituting the parameter a with a linear function of temperature, which is the same for all nectars, i.e.:

$$a = \frac{t}{140} + 4.82 \tag{7}$$

where, t is the temperature in °C. The minimum R value obtained considered the four fruit nectars and the temperature range 25 to 60°C was 0.985 while the maximum SE was $3.1\ 10^{-3}$.

As for the dielectric loss factor, the bi-logarithmic model continues to be an adequate description of experimental data for each nectar and at each temperature considered. Linear regression of Eq. (6) results in correlation factors above 0.999 and SEs smaller than $2.17\ 10^{-2}$.

Fig. 4 shows how conductivity linearly increases with temperature for all the samples, while Table 4 reports the linear fitting parameters together with the correlation coefficients and the standard errors.

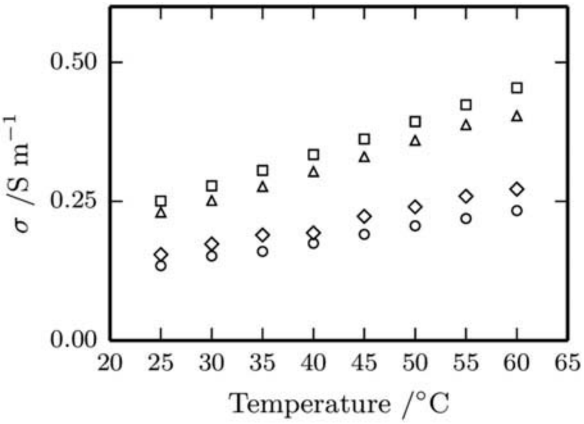

FIGURE 4 Graph of conductivity, σ as a function of temperature for the four fruit nectars (circle apple, square apricot, triangle peach, diamond pear).

TABLE 4
Linear fitting parameters with correlation coefficients *R* and standard errors SE for conductivity σ with temperature of the four nectars

$\sigma = mt + q$	*m*	*q*	*R*	*SE*
Apple	2.82E-03	6.41E-02	0.999	1.97E-03
Apricot	5.82E-03	1.03E-01	0.999	1.86E-03
Peach	5.16E-03	9.86E-02	0.999	3.60E-03
Pear	3.41E-03	6.83E-02	0.994	5.12E-03

Effect of Frequency and Temperature on Power Dissipation Density and Penetration Depth

During RF heating, the electromagnetic radiation is converted in heat by the interaction of the electromagnetic field with the charges present in the sample. The overall effect depends on the ε_r'' as well as on the intensity and frequency of the electric field applied and other physical properties of the sample.[16,22,25] The amount of energy dissipated per unit of time and volume is the power dissipation density that depends on ε_r'' of the sample as illustrated in the following equation:

$$P_V = 2\pi f \varepsilon_0 \varepsilon_r'' E^2 \tag{8}$$

where, E is the intensity of electric field (in V m^{-1}) of frequency f associated with the electromagnetic radiation. From Eq. (8) it is clear that the dissipated power depends on its dielectric loss factor and also on the frequency and the intensity of the electric field (that is influenced by the dielectric properties of the sample and the geometry of the sample and device). P_V is not significantly affected by the frequency (as can be seen by Eq. (5) and Eq. (8), knowing that σ is virtually constant, in this frequency range) and increases with temperature. As a consequence, the samples will increase their ε_r'' that in turn will lead to an increase in their ability to dissipate electric energy into heat. If convective and conductive effects are neglected, P_V, in turn, determines the heating rate of the sample[17] expressed as:

$$\frac{dT}{dt} = \frac{P_V}{\rho C_P} \tag{9}$$

where, T is the absolute temperature in K; t is time in s; ρ is the density of the material in kg m^{-3} and C_p is its specific heat in JK^{-1}kg^{-1}. The increase of the dielectric loss factor and P_V with temperature may lead to the so called *thermal runaway effect* in which a heated region will continue to increase its temperature, leaving colder regions elsewhere. The resulting non-uniform heating could hinder the inactivation process and should be avoided by stirring the sample during the treatment.

Equation (8) shows how the dielectric loss factor has a direct effect on the energy conversion. Nevertheless, also the effect of the relative dielectric constant should be taken into consideration. Actually, ε_r' determines the intensity of the electric field in the sample which also has a crucial role in determining the amount of energy converted into heat.[26] In order to take into account this effect, it is convenient to use a parameter known as the penetration depth, d_p. It is defined as the depth into a sample where the radiation power has dropped to $1/e$ ($e = 2.718$) corresponding to 36.8% of the value at the surface of the sample. It is an important parameter to evaluate the ability of a radiation to provide uniform heating.[17,18] The penetration depth (in meters) for RF and MW radiations is a function of the relative dielectric constant, ε_r', and the dielectric loss factor, ε_r''. It can be calculated by the following equation:[17]

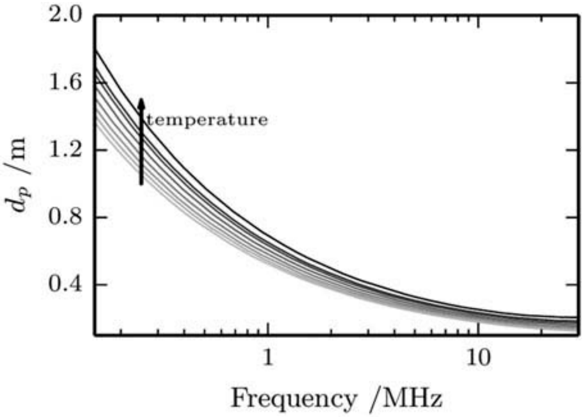

FIGURE 5 Penetration depth, d_p as a function of frequency for apple nectar in the temperature range from 25 to 60°C.

$$d_p = \frac{c}{2\pi f \sqrt{2\varepsilon_r'\left[\sqrt{1+\left(\frac{\varepsilon_r''}{\varepsilon_r'}\right)^2}-1\right]}} \tag{10}$$

where, c is the speed of light in free space in m s^{-1} and f is the frequency of the radiation in Hz. As it can be easily deduced, the penetration depth decreases on increasing frequency and high values for the relative dielectric constant and loss factor lead to a reduction of its value. Fig. 5 shows a representative plot of d_p vs. f. It can be noted that the penetration depth is strongly reduced on increasing frequency, going from nearly 2 m to a little less than 10 cm. Increasing temperature affects also d_p: at 60°C its value is reduced by roughly one third of its value at 25°C.

CONCLUSIONS

The characterization of the dielectric properties of four different fruit nectars in the frequency range from 15 kHz to 30 MHz and in the temperature range from 25 to 60°C demonstrated how the dielectric behavior of this kind of materials is influenced by frequency and temperature in the low region of the RF spectrum. Both the relative dielectric constant and the dielectric loss factor show a decrease on increasing frequency and an increase on increasing temperature. The dependence of each of the two dielectric properties on frequency and temperature has been described by two simple equations with very good results. It has been established that the dominant mechanism for the dielectric loss is ionic conductivity. In addition, power dissipation densities and penetration depths calculated for all the samples were found to increase linearly with temperature. The data obtained and the proposed models provide useful information about the dielectric properties of fruit juices and could be of great value for the development of RF pasteurization processes at low frequencies. The data obtained show that RF inactivation processes could benefit from the use of radiation in the lower portion of the RF spectrum where penetration depths are quite large so that, in principle, it would be possible to treat large volumes both in continuous or batch processes. At the same time, the trends observed for the power dissipation densities with temperature indicate that it will probably be needed to assure a continuous mixing of the samples in order to avoid a possible *thermal runaway effect*.

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