Dielectric characterization of raw and packed soy milks from 0.5 to 20 GHz at temperatures from 20 to 70 °C

Tejinder Kaur Kataria¹ · Alonso Corona-Chávez^{1,2} · José Luis Olvera-Cervantes² · Roberto Rojas-Laguna¹ · María Elena Sosa-Morales³

Revised: 2 April 2018 / Accepted: 21 May 2018 / Published online: 1 June 2018
© Association of Food Scientists & Technologists (India) 2018

Abstract For microwave heating pasteurization processes, knowledge of the dielectric characteristics of foods are very important. In this paper, we present the dielectric properties of raw soy milk and commercial packed soy milk of four different flavors (light, natural, chocolate and pecan) from 500 MHz to 20 GHz, covering most of the assigned frequencies by the Federal Communications Commission for heating purposes. Experiments were performed using an open-ended-coaxial probe and a vector network analyzer. This characterization was carried out for temperatures ranging from 20 to 70 °C in steps of 10 °C. The dielectric constant of soy milks decreased with increasing frequency, while increasing temperature resulted in decreasing of the values. The dielectric loss factor presents a U shape behavior, where the loss started decreasing from 500 MHz to about 3 GHz and then, it increased again up to 20 GHz. In addition, higher temperatures decreased the dielectric loss. Applying the higher order Debye's equation, two relaxation times were calculated for the soymilks, with good agreement with the measured properties. Deeper penetration of microwaves were obtained for raw soy milk at 915 MHz, making it suitable for microwave pasteurization.

Keywords Dielectric properties · Soy milk · Penetration depth · Open ended coaxial probe · Debye's equation

Introduction

In daily use, soy beverages are used as a supplement of proteins and as a good choice for lactose-intolerant people. Soy milk is produced by soaking dried and ground soybeans in water. Packed soy-milk is also added with vitamins and minerals, iodized salt, natural colors and sucralose. It contains at least 3% protein and less than 1% fat. Its protein content is similar to cow's milk, it has little saturated fat, and it is naturally cholesterol free. As soy milk contains indigestible calcium, which is bound to the bean's pulp, manufacturers add calcium carbonate to their products. Soy based milk can be used as an infant formula for the children with galactosemia as it does not contain galactose (Muraro et al. 2002).

Ultra High Temperature (UHT) treatment is one of the most popular methods for milk pasteurization. However, cow's milk under UHT treatment develops over-cooked and other undesirable flavors (Oupadissakoon et al. 2009). In the case of soy milk, the use of intense heat for the extraction from the beans destroys the trypsin inhibitor, but also, denatures proteins, resulting in amino acid degradation and other deteriorative reactions (Murugkar 2014). Recently, microwave heating is being considered as an alternative for pasteurization processes in several fluid foods (Salazar-González et al. 2012). Huge potential of microwave for green coconut water has been reported (Franco et al. 2015). Also, certain advantages of microwave pasteurization at 915 MHz over indirect UHT for skim milk were detected, such as less darkness and absence of astringency (Clare et al. 2005).

✉ María Elena Sosa-Morales
msosa@ugto.mx

¹ Departamento de Electrónica, Universidad de Guanajuato, Salamanca, Guanajuato, Mexico

² Instituto Nacional de Astrofísica, Óptica y Electrónica, Tonanzintla, Puebla, Mexico

³ Departamento de Alimentos, Universidad de Guanajuato, Irapuato, Guanajuato, Mexico

Early studies explored the microwave pasteurization of milk at 2450 MHz in batches, by Jaynes (1975). However, in order to develop effective pasteurization processes, the dielectric properties of foods must be well known (Sosa-Morales et al. 2010). Dielectric properties, which include the dielectric constant and dielectric loss factor have important effects on the interaction between electromagnetic energy and the material to be heated, and are important to control further processes (Torrealba-Meléndez et al. 2015; Alifakı and Şakıyan 2017).

Dielectric properties of certain milks have been reported, such as cow's milk from 1 to 20 GHz (Nunes et al. 2006), milk and soy beverages at 915 MHz (Coronel et al. 2008) and diluted cow's milk as a new technique for quality milk evaluation (Guo et al. 2010). In addition, dielectric properties of raw cow's milk and goat's milk were reported by Zhu et al. (2014) at temperatures from 25 to 75 °C, over the frequency range of 10–4500 MHz.

Nevertheless, dielectric properties of soy milk covering a wide frequency range relevant to develop microwave heating protocols for pasteurization have not been published. The ISM frequencies (frequency allocations for Industrial, Scientific and Medical applications) by the Federal Communications Commission for heating are 915, 2450, 5800 and 24,125 MHz (USDA 2000).

The dielectric properties of a material determine the interaction between the material and the applied electromagnetic field. These include the dielectric constant (ϵ') and the loss factor (ϵ''), the real and imaginary parts of the permittivity, respectively, where $\epsilon = \epsilon' - j\epsilon''$ and $j = \sqrt{-1}$.

The dielectric constant is related to the energy stored in the material and directly affects the intensity of the electric field inside it. The dielectric loss factor is related to the converted electromagnetic energy into heat in the material. Therefore, a material with higher value of loss factor is capable of converting more energy into heat than a material with lower loss factor. The ratio of the dielectric loss factor over the dielectric constant is called loss tangent:

$$\tan \delta = \epsilon''/\epsilon' \quad (1)$$

The mathematical expression to describe the permittivity for pure polar materials was developed by Debye in 1929. The real and the imaginary parts can be expressed as (Metaxas and Meredith 1993):

$$\epsilon' = \epsilon_{\infty} + \frac{\epsilon_s - \epsilon_{\infty}}{1 + (2\pi f)^2 \tau^2} \quad (2)$$

$$\epsilon'' = \frac{(\epsilon_s - \epsilon_{\infty})2\pi f \tau}{1 + (2\pi f)^2 \tau^2} \quad (3)$$

where ϵ'_s is the static dielectric constant, ϵ'_{∞} is dielectric constant at high frequencies, f is frequency in Hz, and τ is the relaxation time in seconds. This time is defined as the

period in which dipoles revert to random orientation when the electric field is suppressed (Nelson and Trabelsi 2012). Any change in dielectric properties will change the absorption of microwaves and hence, the heating rate and uniformity of the temperature distribution of the product. However, foods and milks are not pure materials, they are heterogeneous mixtures with more than one relaxation time. Therefore, higher order equations may be needed, for which, Debye equation may be rewritten as (Duhamel et al. 1997):

$$\epsilon = \epsilon_{\infty} + \sum_{i=1}^n \frac{\Delta\epsilon_i}{1 + j\omega\tau_i} \quad (4)$$

where τ_i 's are the relaxation times, and $\Delta\epsilon_i$'s are the changes in dielectric permittivity due to dispersion related to τ_i .

The Cole–Cole diagram is the graphical representation of Debye equations, represented by plotting ϵ'' versus ϵ' . For pure materials, a semicircle shape is obtained in the complex plain, where the summit represents the relaxation time (Nelson and Trabelsi 2012). But, for a material with more than one component, more than one relation time may be involved.

The objective of this work was to determine and analyze the dielectric properties of raw soy milk and different ultra-pasteurized soy milk formulations (natural, light, chocolate and pecan) over a wide microwave range from 0.5 to 20 GHz and different temperatures.

Materials and methods

Materials

Raw soy milk was prepared in the lab. Yellow soybeans ((100g) were soaked in purified water overnight (16 h at room temperature). Soaked beans were ground with 1500 mL of hot water (70 °C) in a soy milk maker machine. Soy milk was cooled in iced-water until room temperature.

Ultra-pasteurized packed *AdesTM* soy milks from four different formulations were bought at a Mexican supermarket. From the nutrimental information declared by manufacturers, chocolate flavor soy milk has highest contents of energy (132 kcal), proteins (6.6 g), sugar (14.5 g), carbohydrates (16.1 g), dietary fibers (3.1 g), and sodium (205 mg). Light soy milk contains the least amount of energy (83 kcal), proteins (6.2 g, similar in natural and pecan flavors), sugar (0.2 g), carbohydrates (4.6 g), dietary fibers (2.9 g), and sodium (199 mg). Total fats are higher in pecan flavored milk (4.8 g) compared to natural (4.7 g), chocolate (4.6 g), and light (4.4 g) formulations.

Physicochemical analysis

pH and total soluble solids were determined in the soy milk samples. pH was measured for 50 mL of soy milk by using a pH meter (model pH120, Conductronic, Mexico), previously calibrated with buffers 4 and 7. Total soluble solids (°Brix) were determined with a digital refractometer (model 96801, Hanna Instruments, Romania), previously calibrated with distilled water. Both analyses were carried out in triplicate at room temperature (20 °C).

Dielectric properties

The open-ended-coaxial probe is a common instrument to study dielectric properties of liquid and semi liquid materials (Coronel et al. 2008; Sosa-Morales et al. 2010; Salazar-González et al. 2012; Zhu et al. 2014). The equipments employed for the measurements were a Keysight Technologies N9918A FieldFox vector network analyzer (VNA) and an 85070E open-ended-coaxial probe kit. The VNA was turned on for approximately 1.5 h for stabilization. Then, the standard open-short-load calibration was performed with 101 discrete frequencies. Subsequently, the open-ended-coaxial probe was connected to the VNA and air, short, and deionized water calibrations were conducted at room temperature (25 °C). The height of the probe was optimized based on a 500 mL of liquid sample. The probe end was kept at 36 cm from ground level, the liquid sample was kept in a glass flask of 13.5 cm height having diameter of 5, and 2 cm of the probe tip was dipped inside the sample. With this setup, a distance of about $\lambda/8$ from the tip of the probe to the bottom of the sample at the lowest frequency was assured (considering water).

Initially, 500 mL of light soy milk were poured in a glass vessel at a temperature of 20 °C. Air bubbles were manually removed to prevent measurement errors. The soy milk temperature was changed to the required value using a hot water bath. The sample was manually stirred to get uniform heating. Once the desired temperature of the milk was obtained, the permittivity measurements were conducted in less than 1 min over the whole frequency range from 500 MHz to 20 GHz. Ten readings were taken at each temperature and the mean values were calculated. After 10 measurements, the temperature of the water bath was adjusted to the next required temperature. In total, the temperatures were changed from 20 to 70 °C and measurements were taken every 10 °C.

Penetration depth calculation

Penetration depth (D_p) determines the penetration of electromagnetic energy inside the material. Theoretically, D_p is the level beneath the surface of the material where the

intensity of the radiation falls to $1/e$ ($e = 2.718$) of its original value; one expression to calculate D_p is given in Eq. (5) (Sosa-Morales et al. 2010). In microwave heating this parameter is important to determine the heat penetration to maintain uniform heating inside the food.

$$D_p = \frac{\lambda}{2\pi \sqrt{2\epsilon' \left[\sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} - 1 \right]}} \quad (5)$$

Relaxation times for soymilks

To complete the dielectric characterization of soy milks, a dielectric relaxation model was applied. Since soy milk is a multi-component and heterogeneous fluid, a second order Debye's equation was employed and parameters were calculated for the different formulations from Eq. (4).

Statistical analysis

Results were analyzed by ANOVA and differences between means were established at the 0.05 probability level (Tukey's pairwise comparison), using the software Minitab Release 16® (Palo Alto, CA, USA).

Results and discussion

Physicochemical properties of natural and flavored soy milks

Table 1 shows the physicochemical parameters determined in the soybean milk samples. Both pH and total soluble solids values were significantly affected by the soy milk type ($p < 0.05$). Higher pH value (7.3) was determined in the light soy milk formulation, while the lowest pH (6.7) was observed in the raw soy milk. No differences in pH value were observed for natural and pecan flavored soy milk samples ($p > 0.05$). Based on the obtained pH values, all soy milk samples can be classified as neutral beverages.

Table 1 Physicochemical parameters of soy milk samples at 20 °C

Soy milk formulation	PH value	Total soluble solids (°Bx)
Raw soy milk	6.72 ± 0.04 ^d	5.96 ± 0.4
Light soy milk	7.29 ± 0.01 ^a	8.3 ± 0.6 ^b
Natural soy milk	7.11 ± 0.03 ^b	9.9 ± 0.1 ^a
Chocolate soy milk	6.83 ± 0.01 ^c	14.8 ± 0.7 ^c
Pecan soy milk	7.11 ± 0.01 ^b	10.6 ± 0.4 ^a

Means within a column followed by a common letter are not significantly different ($p > 0.05$)

Fig. 1 Dielectric constant of soy milk from 500 MHz to 20 GHz at temperature range from 20 to 70 °C, for **a** raw, **b** light, **c** natural, **d** chocolate, and **e** pecan formulations

Respect to total soluble solids, the soy milk with lowest soluble solids content was the raw soy milk, (almost 6°Bx). Among the packed beverages, light soy milk had the lower content of solids, with 8.3 °Bx. On the other hand, the formulation with highest soluble solid content was the chocolate flavored soy milk (14.8°Bx), in accordance with the ingredients list. Differences of pH and solids between raw soy milk and packed natural soy milk are due to water employed for soaking and the formulation, because packed

milks include sugars (sucralose and other no specified), hydrocolloids, and vitamins.

Dielectric constant of soybean milks

Figure 1 presents the experimental results of the dielectric constant of raw milk and the four samples of packed soy milks. For raw soy milk (Fig. 1a), ϵ' decreased with increasing both frequency and temperature from 500 MHz

Table 2 ϵ' , ϵ'' , and Dp for soy milk formulations at ISM frequencies and temperatures from 20 to 70 °C

T (°C)	ISM freq (MHz)	Raw soy milk			Light soy milk			Natural soy milk			Chocolate soy milk			Pecan soy milk		
		915	2450	5800	915	2450	5800	915	2450	5800	915	2450	5800	915	2450	5800
20	ϵ'	76.1	73.0	64.0	73.1	71.25	66.87	66	63.45	59.76	70.4	67.37	62.74	68.33	65.79	61.89
	ϵ''	14.0	18.1	26.8	21.3	15.56	20.16	21.3	13.48	16.52	20.7	15.27	19.41	23.5	14.05	14.68
	Dp (cm)	3.06	0.92	0.24	1.98	1.06	0.33	1.79	1.15	0.38	2.02	1.05	0.33	1.61	1.01	0.39
30	ϵ'	70.9	68.9	62.7	68.09	66.23	62.91	61.75	59.99	57.01	65.3	62.73	58.16	64.54	62.28	58.44
	ϵ''	11.1	14.45	22.3	21.5	14.5	18.2	21.17	13.07	15.1	22.68	14.59	16.6	24.9	14	13.22
	Dp (cm)	3.7	1.12	0.29	1.89	1.09	0.35	1.83	1.16	0.41	1.76	1.06	0.38	1.54	1.06	0.43
40	ϵ'	69.5	68.0	64.8	66.19	64.42	60.5	58.95	57.31	54.6	58.37	55.92	52.08	58.03	56.01	53.89
	ϵ''	10.7	12.3	18.4	19.4	14.03	18.07	20.45	12.17	13.91	22.62	13.6	14.23	22.57	12.73	12.15
	Dp (cm)	3.8	1.3	0.35	1.88	1.12	0.37	1.85	1.22	0.43	1.67	1.07	0.41	1.67	1.15	0.51
50	ϵ'	66.0	64.9	62.3	60.72	58.74	55.92	54.58	52.74	50.5	53.59	50.78	47.63	52.69	50.9	49.58
	ϵ''	9.4	10.0	14.8	21.19	13.94	15.8	22.61	12.49	12.5	16.4	10.98	11.98	20.88	11.6	11.03
	Dp (cm)	4.23	1.56	0.4	1.82	1.07	0.38	1.62	1.14	0.46	2.18	1.4	0.51	1.82	1.31	0.58
60	ϵ'	63.1	62.0	60.2	56.68	55.19	52.77	51.68	49.62	47.44	47.81	45.98	43.77	49.02	47.51	46.39
	ϵ''	9.07	9.2	13.2	19.77	12.17	14.2	21.9	13.1	11.77	16.2	8.89	9.71	18.7	10.4	9.87
	Dp (cm)	4.3	1.67	0.46	1.89	1.2	0.42	1.63	1.05	0.48	2.23	1.59	0.59	1.85	1.42	0.68
70	ϵ'	61.2	60.3	58.26	52.52	51.07	48.26	48.3	46.9	45.43	42.84	41.11	39.34	45.64	44.22	43.24
	ϵ''	7.8	8.0	12.1	20.34	13.85	13.82	20.16	11.41	9.72	17.7	9.09	8	17.21	9.4	9.01
	Dp (cm)	4.9	1.9	0.5	2.07	1.04	0.41	1.71	1.17	0.56	1.83	1.38	0.64	2.23	1.78	0.83

until 9 GHz. Around 9 GHz there is an inflection point, which causes increasing in ϵ' with increasing temperature from 20 to 50 °C ($p < 0.05$). Temperature between 50 and 70 °C had no effect on ϵ' for raw soy milk ($p > 0.05$). For packed soy milks, and from Fig. 1b, the dielectric constant (ϵ') for light soy milk at $T = 20$ °C was 75.4 at the lowest frequency (500 MHz) and it decreased to 40.9 at the highest frequency (20 GHz). At 70 °C and 500 MHz the value was 56.48, decreasing to 34.03 at 20 GHz. From Fig. 1c, we can see that at 20 °C the dielectric constant (ϵ') of natural milk was 69.02 at 500 MHz and it decreased at higher frequencies ($\epsilon' = 40$ at 20 GHz). For 70 °C, the value was 50.32 at 500 MHz and at 20 GHz, ϵ' value decayed to 36.5. For chocolate soy milk (Fig. 1d), at 20 °C and 500 MHz the dielectric constant value was 71.86 and decreased to 39.3 at 20 GHz. At 70 °C, ϵ' was 43.7 at 500 MHz and at 20 GHz it was 30.96. Same behaviour was observed for pecan soy milk, which is shown in Fig. 1e: the dielectric constant at 20 °C and 500 MHz was 70.05 and at 20 GHz, it decreased to 41.4. At 70 °C and 500 MHz, ϵ' was 46.4, and at 20 GHz the value was 36.

The dielectric constant of raw milk had a completely different behaviour in comparison with packed soy milks. These differences may be due to difference in pasteurization process and formulations.

The dielectric constant of the packed soy milk samples decreased with increasing frequency and temperature, in

accordance with other types of milk reported in the literature (Nunes et al. 2006; Coronel et al. 2008; Guo et al. 2010). The reason behind this behaviour can be found in Eq. (2). At a given temperature, ϵ'_s , ϵ'_∞ and τ are almost constant, ϵ' has a negative relationship with the square of frequency. In terms of temperature, the ϵ' values decrease with increasing temperature.

The dielectric constant for packed soy milk samples at 20 °C were in the range from 66 to 73.1 at 915 MHz (Table 2). These values were in agreement with those reported by Coronel et al. (2008) for soy beverages, with ϵ' from 61 to 73 as temperature increased from 10 to 90 °C. The values are also similar to the reported at room temperature and 915 MHz for commercial milk ϵ' (67.98) by Kudra et al. (1992), and UHT whole milk (70) by Nunes et al. (2006). In contrast, raw cow milk $\epsilon' = 57.7$, and goat's milk $\epsilon' = 62.9$ (Zhu et al. 2014) had lower ϵ' values for packed soy milks at same temperature and frequency. As expected, the dielectric constant in raw soy milk was higher than pasteurized and packed soy milks, due to the higher content of water and lower content of fats, sugar, carbohydrates and sodium. Whereas natural, and pecan flavored soy milk have very close dielectric constants. Dielectric constant curves for packed soy milks are similar to those reported for cow's milk, where at lower temperature, higher dielectric constant was achieved (Zhu et al. 2014).

Fig. 2 Dielectric loss factor measurement of soy milks at temperature ranges from 20 to 70 °C, for **a** raw, **b** light, **c** natural, **d** chocolate, and **e** pecan formulations

Dielectric loss factor of soy milks

Figure 2 shows the dielectric loss factor of the different soy milk flavors versus frequency. Generally, the graphs exhibit a U shape behavior, where the loss starts decreasing from 500 MHz to about 3 GHz, and then it started increasing again up to 20 GHz. The decrease in dielectric loss factor at low frequencies is due to ionic conduction, which is present in most dielectric materials (Komarov et al. 2005). The minimum dielectric loss factor values of

raw milk (Fig. 2a) were obtained at lower frequencies than the pasteurized packed samples (Fig. 2b–e). These differences were related to the composition of the samples, as raw milk did not have added ingredients.

Additionally, ionic conduction is the main loss mechanism and it is directly related to the temperature. As a result, dielectric loss factor increases with temperature at higher frequencies (Ryynänen 1995). This behavior is consistent with the reported for goat's milk (Zhu et al. 2014) and soy bean beverages (Ahmed et al. 2008). The

Table 3 Parameters from higher order Debye's equation for soy milk formulations

Soy milk formulation	$\Delta\epsilon_1$	τ_1 (ps)	$\Delta\epsilon_2$	τ_2 (ns)	ϵ_∞
Raw	68	11.19	15,700	237	7.7
Light	67	6.89	16,700	132	3.75
Pecan	47.1	7.34	24,100	192	17.4
Chocolate	58.7	7.52	10,300	77	8.5
Natural	60.3	6.32	5050	47	3

loss factor of raw soy milk was the highest, followed by light, chocolate, natural and pecan formulations (Fig. 2).

Penetration depth in soy milks

The penetration depth (D_p) values obtained from dielectric constants and loss factors for frequencies of 915, 2450 and 5800 MHz are shown in Table 2. Raw soymilk, showed penetration depth between 3 and 4.9 cm for 915 MHz depending on temperature. Penetration depth decreased with increasing frequency and temperature. Raw milk at

frequency of 5800 MHz showed, the penetration depth in the range of 0.24 and 0.5 cm. For uniform heating during pasteurization, the thickness of the material to be treated should not be more than 2–3 times the penetration depth (Schiffman 1995). Then, for future continuous microwave systems for raw soy milk pasteurization, pipes could have big diameters bigger than 2 inches under treatments at 915 MHz, which is a common frequency for industrial applications.

Overall, low depth of waves is achieved in packed soy milk samples. At 915 MHz and 20 °C, D_p of soy milk was 0.22 cm; at 70 °C, same frequency of 915 MHz, D_p was 0.27 cm for light soy milk, 0.26 cm for natural soy milk, 0.29 cm for chocolate soy milk and 0.3 cm for pecan soy milk. In general, chocolate flavor soy milk exhibited lower D_p their other soy milk samples.

The pasteurization process and formulation (composition and flavor) effected the penetration depth of microwaves in the soy milk samples. Higher penetration was calculated for the raw soy milk than that for packed samples. Thus, raw soy milk is suitable for microwave pasteurization, especially at frequency of 915 MHz.

Fig. 3 Dielectric constant—experimental, and fitted from modified higher order Debye's equation—for soymilk **a** natural and chocolate formulations, and **b** light and pecan formulation; and dielectric loss

factor—experimental, and fitted from modified higher order Debye's equation—for soymilk **c** natural and chocolate formulations, and **d** light and pecan formulation

Relaxation times for soy milks

By conventional curve fitting, the respective τ_i 's and $\Delta\epsilon_i$'s for soymilk beverages were obtained from a second order equation [Eq. (4), using $n = 2$]. The results at 20 °C are shown in Table 3, and the plotted results are shown in Fig. 3. Good agreement between the experimental (measured) data and the fitting equation was obtained. Soy milk, being complexed system showed two relaxation times, of ps ($6.32\text{--}7.52 \times 10^{-12}$ s) and the other one in the order of ns ($47\text{--}192 \times 10^{-9}$ s). These relaxation times are similar to those reported for other organic fluids with complex composition, such as beef blood with values of 8.38 ps and 132.63 ns at 37 °C (Duhamel et al. 1997). The relaxation times, besides the fitting from Debye's equation for soy milks, contribute with information to describe the distinctive nature and features of this fluid food when is subjected to microwaves. Additionally, this information aids to describe the frequency-dependent behaviour of the materials, as they are influenced by multiple factors (Nelson and Trabelsi 2012).

Conclusion

Dielectric constant (ϵ') of the soy milk samples decreased with increasing of frequency and temperature. The behaviour of ϵ' for raw milk was different from packed samples, due to mainly to the composition and the pasteurization process which the packed samples were subjected. Dielectric loss factor of the soy milk exhibited U shape behavior, where the loss decreased from 500 MHz to about 3 GHz, and then it increased again up to 20 GHz. The dielectric loss factor of light soy milk was higher than other packed soy milk flavors, due to its higher water content, which is an advantage for further microwave pasteurization processes. Penetration of microwaves was deeper in raw soy milk at 915 MHz among all the studied soy milks. These results contribute valuable data for further applications, such as microwave continuous pasteurization processes for soy milks.

Acknowledgements Authors would like to thank CONACYT (Consejo Nacional de Ciencia y Tecnología, México) for financial support through the Project 180061, and PRODEP-NPTC UGTO 543/2016.

References

- Ahmed J, Ramaswamy HS, Raghavan GSV (2008) Dielectric properties of soybean protein isolate dispersions as a function of concentration, temperature and pH. *LWT—Food Sci Technol* 41(1):71–81
- Alifakı YÖ, Şakıyan Ö (2017) Dielectric properties, optimum formulation and microwave baking conditions of chickpea cakes. *J Food Sci Technol* 54(4):944–953
- Clare DA, Bang WS, Cartwright G, Drake MA, Coronel P, Simunovic J (2005) Comparison of sensory, microbiological, and biochemical parameters of microwave versus indirect UHT fluid skim milk during storage. *J Dairy Sci* 88(12):4172–4182
- Coronel P, Simunovic J, Sandeep KP, Kumar P (2008) Dielectric properties of pumpable food at 915 MHz. *Int J Food Prop* 11(3):508–518
- Duhamel F, Huynen I, Vander Vorst A (1997) Measurements of complex permittivity of biological and organic liquids up to 110 GHz. In: *IEEE MTT-S International Microwave Symposium Digest 1997*, vol 1, pp 107–110
- Franco AP, Yamamoto LY, Tadini CC, Gut JAW (2015) Dielectric properties of green coconut water relevant to microwave processing: effect of temperature and field frequency. *J Food Eng* 155:69–78
- Guo W, Zhu X, Liu H, Yue R, Wang S (2010) Effects of milk concentration and freshness on microwave dielectric properties. *J Food Eng* 99(3):344–350
- Jaynes HO (1975) Microwave pasteurization of milk. *J Milk Food Technol* 38(7):386–387
- Komarov V, Wang S, Tang J (2005) Permittivity and measurements. In: Chang K (ed) *Encyclopedia of RF and microwave engineering*. Wiley, New York, pp 3693–3711
- Kudra T, Raghavan V, Akyel C, Bosisio R, Van de Voort F (1992) Electromagnetic properties of milk and its constituents at 2.45 GHz. *J Microw Power Electromagn Energy* 27(4):199–204
- Metaxas AC, Meredith RJ (1993) *Industrial microwave heating*. Peter Peregrinus Ltd, London
- Muraro MA, Giampietro PG, Galli E (2002) Soy formulas and nonbovine milk. *Annals Allergy, Asthma Immunol* 89(6):97–101
- Murugkar DA (2014) Effect of sprouting of soybean on the chemical composition and quality of soymilk and tofu. *J Food Sci Technol* 51(5):915–921
- Nelson SO, Trabelsi S (2012) Factors influencing the dielectric properties of agricultural and food products. *J Microw Power Electromagn Energy* 46(2):93–107
- Nunes AC, Bohigas X, Tejada J (2006) Dielectric study of milk for frequencies between 1 and 20 GHz. *J Food Eng* 76:250–255
- Oupadissakoon G, Chambers DH, Chambers E IV (2009) Comparison of the sensory properties of ultra-high-temperature (UHT) milk from different countries. *J Sensory Stud* 24(3):427–440
- Ryynänen S (1995) The electromagnetic properties of food materials: a raw of basic principles. *J Food Eng* 26:409–429
- Salazar-González C, San Martín-González MF, López-Malo A, Sosa-Morales ME (2012) Recent studies related to microwave processing of fluid foods. *Food Bioproc Technol* 5(1):31–46
- Schiffmann RF (1995) Microwave and dielectric drying. In: Majumdar AS (ed) *Handbook of industrial drying*, 2nd edn. Marcel Dekker, New York, pp 345–372
- Sosa-Morales ME, Valerio-Junco L, García HS, López-Malo A (2010) Dielectric properties of foods: reported data in the 21st century and their potential applications. *LWT- Food Sci Technol* 43:1169–1179
- Torrealba-Meléndez R, Sosa-Morales ME, Olvera-Cervantes JL, Corona-Chávez A (2015) Dielectric properties of cereals at frequencies useful for processes with microwave heating. *J Food Sci Technol* 52(12):8403–8409
- USDA United States Department of Agriculture (2000) Kinetics of microbial inactivation for alternative food processing technologies. Microwave and radio frequency processing. <http://www.fda.gov/Food/FoodScienceResearch/SafePracticesforFoodProcesses/ucm100250.htm>
- Zhu X, Guo W, Jia Y (2014) Temperature-dependent dielectric properties of raw cow's and goat's milk from 10 to 4,500 MHz relevant to Radio-frequency and Microwave Pasteurization. *Food Bioproc Technol* 7(6):1830–1839