Turkish Journal of Agriculture - Food Science and Technology, 7(11): 1805-1816, 2019
DOI: https://doi.org/10.24925/turjaf.v7i11.1805-1816.2650

Turkish Journal of Agriculture - Food Science and Technology

Available online, ISSN: 2148-127X | www.agrifoodscience.com | Turkish Science and Technology

Dielectric Properties of Foods

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A R T I C L E I N F O

Review Article

Received : 06/05/2019
Accepted : 08/11/2019

Keywords:
Dielectric properties
Microwave
Radio waves
Food material
Penetration depth

A B S T R A C T

Dielectric properties of materials are used for evaluating their interactions with electromagnetic energy. Dielectric properties of food materials are required for various applications in food industry such as microwave (at 915 or 2450 MHz), radio wave (at 13.56, 27.12 or 40.68 MHz) and magnetic field processing. In order to understand the response of food materials to electromagnetic energy, dielectric parameters must be determined as a function of frequency, temperature, composition and moisture content. In this review, the dielectric properties of different food groups were listed depending on temperature and frequency ranges. In addition to the literature data of dielectric properties, the penetration depths of microwave or radio wave through food groups were calculated. The effects of temperature and composition (mostly moisture content) on dielectric properties depend on the type of the food and sometimes on frequency. However, the effect of frequency is constant; increased frequency decreased dielectric constant, loss factor and penetration depth. The lowest calculated penetration depth belonged to the fish surimi gel as 3.39 mm at microwave frequency whereas they were high generally for fats, oily seeds and flours (max was 372602 mm for corn flour). It appears that dielectric properties of foods should be investigated further depending on the interactions between frequency, temperature and composition. And then, dielectric heating based on the aim of the process can be applied accordingly. Besides, it appears that the moisture content and especially the dipole rotation and the conductivity movements of the molecules in free water content of the food are some of the most critical factors influencing the dielectric properties of food materials.

Türk Tarım – Gıda Bilim ve Teknoloji Dergisi 7(11): 1805-1816, 2019

Gıdaların Dielektrik Özellikleri

M A K A L E B İ L G İ S İ

Derleme Makale

Geliş : 06/05/2019
Kabul : 08/11/2019

Anahtar Kelimeler:
Dielektrik özellikler
Mikrodalga
Radyo dalgası
Gıda maddeleri
Nüfuz derinliği

Ö Z

Maddelerin dielektrik özellikleri elektromanyetik enerji ile olan etkileşimlerini değerlendirmek için kullanılmaktadır. Gıda endüstrisinde mikrodalga (915 veya 2450 MHz), radyo dalgaları (13,56; 27,12 veya 40,68 MHz) ve manyetik alan işlemlerinin uygulanmasında gıda maddelerinin dielektrik özelliklerinin bilinmesi gereklidir. Gıda maddelerinin elektromanyetik enerjiye verdiği cevabın anlaşılması için dielektrik parametreler frekans, sıcaklık, bileşim ve su içeriğinin fonksiyonu olarak belirlenmelidir. Bu derleme çalışmasında farklı gıda gruplarının dielektrik özellikleri sıcaklık ve frekansa göre sınıflandırılmıştır. Buna ilaveten, literatürdeki dielektrik verileri kullanılarak nüfuz derinlikleri hesaplanmıştır. Sıcaklık ve bileşimin (çoğunlukla su içeriğinin) dielektrik özelliklere etkisi gıdaya bağlı olarak bazen de frekansa bağlı olarak değişmektedir. Ancak frekansın etkisi sabittir, frekans arttıkça dielektrik sabiti, kayıp faktörü ve nüfuz derinliği azalmaktadır. Hesaplanan en düşük nüfuz derinliği 3,39 mm ile mikrodalga frekansında ölçülen surimi balık jeline aitken, en yüksek değerler katı yağlar, yağlı tohumlar ve bazı unlarınki (hesaplanan en yüksek nüfuz derinliği mısır unu için 373602 mm'dir) için hesaplanmıştır. Frekansın, sıcaklığın ve bileşimin birbiriyle etkileşimlerinin dielektrik özelliklere etkileri daha detaylı olarak incelenmelidir. Ancak ondan sonra prosesteki amacına göre dielektrik ısıtma işlemi uygulanabilir. Ayrıca nem içeriği ve özellikle dipol rotasyonu ile gıdanın içeriğindeki serbest suda bulunan moleküllerin iletkenlik hareketleri, gıda maddelerinin dielektrik özelliklerini etkileyen en önemli faktörlerden bazıları olduğu görülmektedir.

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Introduction

Dielectric properties are important characteristics determining interactions of materials with electromagnetic energy. When materials are exposed to the intense radio frequency (at 13.56, 27.12 and 40.68 MHz) or microwave electric fields (at 915 or 2450 MHz for industrial heating applications and 2450 MHz for domestic ovens; 5800 or 24225 MHz for laboratory and research projects), the dielectric properties indicate the rate of dielectric heating (DH) (Tang et al., 2002; Venkatesh and Raghavan, 2004; Guo et al., 2008; Guo et al., 2010a). The interactions between dielectric energy and food products at any given frequency range gives useful information related with the microwave or radio frequency processing (Tang et al., 2002; Ahmed et al., 2011). Furthermore, the knowledge about dielectric properties is important for developing successful and uniform pasteurization treatments to select the optimal frequency ranges by radio frequency and microwave heating energy (Wang et al., 2003).

The most important properties of DH are selective and volumetric heating, efficient heat energy and more improved product quality compared to conventional heating. In a conventional heating, heat is transferred from the surface of the material to the centre, whereas heat is generated volumetrically in DH in which is not involved with heat conduction. During DH, molecular rotation takes place because of polar molecules that produce an electrical dipole moment. These polar molecules align themselves with the electromagnetic field in DH due to dipole moment. Under electromagnetic field, these molecules rotate uninterruptedly. This is called as "dipole rotation or dipolar polarization", which causes molecules collide with each other. This is the reason for the "heat" produced in DH (Al Faruq et al., 2019).

Dielectric properties of a material are described by the relative complex permittivity (ε^*, relative to that of free space). Permittivity indicates the dielectric properties that lead immersion and emission of the electromagnetic currents at phases including the attenuation of waves within the materials. The absolute permittivity of a vacuum, ε_o, the speed of light (c^2) and the magnetic constant (μ_o) can be combined by the Equation 1 (Al Faruq et al., 2019):

$$c^2\mu_o\varepsilon_o=1 \quad \text{Eq.1}$$

The value of ε_o is 8.854×10^{-12} F/m. The absolute permittivity, ε_{abs}, of an element can be found from the Equation 2 (Al Faruq et al., 2019):

$$\varepsilon_{abs}=\varepsilon_r\varepsilon_o \quad \text{Eq.2}$$

where ε_r is the relative permittivity. The relative complex permittivity, ε^*, is given by the Equation 3:

$$\varepsilon^*=\varepsilon'-j\varepsilon'' \quad \text{Eq.3}$$

where ε' and ε'' are dielectric constant and loss factor, respectively. $j=\sqrt{-1}$. The dielectric constant (ε') is a measure of the ability of the material to store electromagnetic energy. The relative permittivity, which is also called dielectric constant, is the ratio of the amount of stored electrical energy of the material to store in a vacuum. Absolute permittivity is often simply called as permittivity and it defines the measure of the resistance, which is produced by resulting of treatment of an electric field in a medium (Tang et al., 2002).

The dielectric loss factor (ε'') is the imaginary component of permittivity. It is connected to various absorption mechanisms of energy dissipation and is always positive and usually much smaller than ε'. It is approximately proportional to the attenuation of a propagating wave. In another words, loss factor is the energy loss during the wave passing through the food material. This energy loss is also the amount of energy that can be converted into heat. Thus, the more the loss factor of the food, the quicker the heating of the food (Giese, 1992; Cemeroglu, 2005; Cao et al., 2019). The ratio of ε'' to ε' is called the dielectric loss tangent (tan δ). The loss tangent expresses the ability and capacity of the material in order to penetrating by an electrical field and spreading electrical energy as heat (Tang et al., 2002). Higher the value of the dielectric loss tangent means higher the ability of electrical field penetration to material for easier DH.

The appropriate frequency ranges are critical for obtaining rapid and uniform heating processes such as pasteurization. The more the frequency means the less the penetration to the food material. Thus, it is crucial to select an appropriate frequency range depending on the size of the food (Schiffmann, 1986). The penetration depth (d_p) is critical concept in these steps for relatively uniform applying and improving of electromagnetic heating design. The term defines the depth at which the power density has decreased to 37% of its initial value at the surface. It can also be expressed as the depth where the incident power is reduced to 1/e (e = 2.7183) of its value at the surface of the material (Tang et al., 2002). The penetration depth for radio-frequency and microwave energy for food materials can be calculated from the following equation:

$$d_p=\frac{c}{2\pi f\sqrt{2\varepsilon'.\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right]}} \quad \text{Eq.4}$$

where *c* is the speed of the light (3×10^8 m/s) and *f* is the frequency of the wave (Hz). The unit of d_p is meter (m) (Metaxas and Meredith, 1983). In spite of being very small of penetration depths of microwave at high moisture content, microwave provides heating in all the way over the material and can be effective for the foods that are 2-3 times higher than the penetration depth of the foods (Cao et al., 2019).

Dielectric Properties of Food Materials

Dielectric properties have big importance and applications for foods, which are related to novel microwave or radio frequency heating treatments. These are the main parameters that provide information and during heating by microwaves or high frequency electromagnetic radiations, the heating performance of foods is affected by many variables (Bhargava et al. 2013). In order to determine the absorption of microwave energy, heating attitude of foods during microwave heating, and analyse the outcome, the dielectric properties are used to associate with electromagnetic fields (Chen et al., 2013). The microwave heating of foods in domestic microwave ovens is a practical, rapid and proper application, which has been widely used. In this process, the main problem is that non-uniform heating within foods during microwave heating due to different responses of each component in the food to the electromagnetic energy (Ryynanen et al., 2004; Gunasekaran and Yang, 2007; Rakesh et al., 2009).

Commercial food processing applications of microwave contain cooking, thawing, tempering, drying, freeze-drying, pasteurization, sterilization, baking, heating and re-heating and many others. For recognition the performance of a microwave and heat transfer model, suitable foods and accurate information on their properties are essential. Microwaves reduce the processing time for the thermal treatment of food samples, operate easily by comparison with conventional heating systems and provide considerable energy efficiency (Vadivambal and Jayas, 2010; Puligundla et al., 2013; Curet et al., 2014). In this review, the dielectric properties of different food groups were given and evaluated based on the applied frequency ranges and temperatures. The penetration depth of the waves through foods were calculated by using the literature data on dielectric properties. Moisture contents of foods were also presented, so the penetration depths were discussed accordingly. The comments and calculations of this review may be helpful to design DH (radio and microwave applications) systems for foods depending on the applied frequency and temperature.

Meats, Fishes and Seafoods

Microwave applications are used for tempering, thawing, pre-cooking and cooking process of meat products. In addition, microwave-vacuum drying can be used for meat extracts. Due to fact that the required amount of energy is low during microwave applications, the shrinkage of meat products can be kept under control. Besides, the quality, texture, colour and taste of the products can be improved (Konak et al., 2009; Shanen et al., 2012). Meat products are stored at low temperature as frozen in thick and big pieces until ready to use. For applying next stages such as cooking or drying, tempering is necessary for obtaining sliced, small pieces and also applying uniform heating. Microwave tempering is completed successfully in a short span of time. Therefore, the contamination by psychotropic bacteria, which is the outcome of long waiting time and drip loss, is prevented (Tang et al., 2002).

Dielectric properties of meat products at selected temperature and frequency range including calculated penetration depths according to the Eq.4 were given in Table 1. Previous studies indicated that increasing protein content increased dielectric loss factor while an increase in fat content reduced loss factor (Lyng et al., 2005). Increasing frequency leads to a decrease in dielectric constant, loss factor and penetration depth of meat products based on the calculations. In general, dielectric constant decrease with increasing temperature and/or moisture content. Besides, dielectric loss factor increases with temperature (Cao et al., 2019; Wang et al., 2019).

Table 1 Dielectric properties of meats, fishes and seafoods

Food	Moisture(%db)	ε'	ε''	T(°C)	f (MHz)	d_p*(mm)	Ref.
Codfish (raw)	-	7.5	3.8	2	100	354.3	Kent, 1987
Cooked codfish	-	46.5	11.9	20	2800	9.8	Kent, 1987
Sprat	-	79.0	122.0	2	100	41.4	Kent, 1987
Fish	-	2.1	0.5	90	10000	13.9	Kent, 1987
Fish	-	2.1	0.5	50	10000	13.9	Kent, 1987
Tuna	70.9	103.2	300.0	5	27.12	85.1	Llave et al., 2014
Sea cucumber	88.0	52.3	11.0	60	915	36.1	Cong et al., 2012
Frozen Beef	-	4.9	0.47	-20	2450±50	91.9	Luan and Wang, 2015
Frozen Beef	-	6.1	1.12	-10	2450±50	43.1	Luan and Wang, 2015
Frozen Beef	-	12.3	4.21	-5	2450±50	16.5	Luan and Wang, 2015
Frozen Beef	-	30.0	12.02	-2.2	2450±50	9	Luan and Wang, 2015
Frozen Beef	-	49.2	17.93	-1.0	2450±50	7.7	Luan and Wang, 2015
Frozen Beef	-	48.9	17.02	10	2450±50	8.1	Luan and Wang, 2015
Frozen Beef	-	48.2	16.12	20	2450±50	8.5	Luan and Wang, 2015
Fish surimi gel	78	56.43	29.61	20	2450	5.10	Cao et al., 2019
Fish surimi gel	78	52.19	35.13	50	2450	4.21	Cao et al., 2019
Fish surimi gel	78	50.76	39.81	70	2450	3.72	Cao et al., 2019
Fish surimi gel	78	46.34	42.50	90	2450	3.39	Cao et al., 2019
Chicken breast	75.1	59.0	18.3	20	915	23.2	Basaran et al., 2010
Chicken breast	75.1	56.7	21.4	40	915	19.5	Basaran et al., 2010
Chicken breast	73.6	49.0	16.1	-	2450	8.6	Lyng et al., 2005
Turkey (breast)	74.5	73.5	458.4	-	27.12	63.0	Lyng et al., 2005
Turkey (breast)	74.5	56.3	18.0	-	2450	8.2	Lyng et al., 2005
Lamb (leg)	73.0	49.4	15.0	72.6	2450	9.2	Lyng et al., 2005
Pork (back)	19.0	7.9	0.8	90.1	2450	68.5	Lyng et al., 2005
Pork (shoulder)	73.9	51.3	15.1	90.1	2450	9.3	Lyng et al., 2005
Beef	71.5	43.7	13.7	-	2450	9.5	Lyng et al., 2005
Beef	71.5	70.5	418.7	-	27.12	66.1	Lyng et al., 2005
Raw beef	-	5.0	0.8	-15	1000	133.9	Kent, 1987

*****Calculated by using the penetration depth equation (Equation 4)

Table 2 Dielectric properties of eggs and egg products

Food	Moisture(%wb)	ε′	ε″	T(°C)	f(MHz)	d_p*(mm)	Ref.
Precooked egg white	-	92.5	762.1	60	27	48.1	Wang et al., 2009
Precooked egg white	-	99.5	937.1	80	27	43.1	Wang et al., 2009
Precooked egg white	-	55.7	28.1	60	915	14.3	Wang et al., 2009
Precooked egg white	-	53.0	34.6	80	915	11.5	Wang et al., 2009
Liquid egg white	85.0	81.3	646.4	60	27	52.4	Wang et al., 2009
Liquid egg white	85.0	98.3	866.5	80	27	45.0	Wang et al., 2009
Liquid egg white	85.0	51.5	25.3	60	915	15.9	Wang et al., 2009
Liquid egg white	85.0	50.5	33.3	80	915	12.2	Wang et al., 2009
Egg (white) albumen	87-89	67.2	22.3	20	2450	7.3	Dev et al., 2008
Egg (white) albumen	87-89	60.7	20.3	40	2450	7.6	Dev et al., 2008
Egg white powder	8.3	2.27	0.02	20	27.12	132604	Chen et al., 2019
Egg white powder	8.3	2.89	0.34	50	27.12	8816	Chen et al., 2019
Egg white powder	8.3	3.25	0.60	70	27.12	5311	Chen et al., 2019
Egg white powder	8.3	3.68	1.07	100	27.12	3188	Chen et al., 2019
Egg yolk	47.0	41.4	12.1	20	2450	10.5	Dev et al., 2008
Egg yolk	47.0	37.1	10.0	40	2450	12.0	Dev et al., 2008

*Calculated by using the penetration depth equation (Equation 4)

Table 3 Dielectric properties of dairy products

Food	Moisture(%db)	ε′	ε″	T(°C)	f(MHz)	d_p*(mm)	Ref.
Premixed yogurt	-	71.0	21.0	22	915	22.1	Konak et al., 2009
Premixed yogurt	-	68.0	17.5	22	2450	9.3	Konak et al., 2009
Milk powder	-	1.9	0.5	20	20	6636	Kent, 1987
Skim milk	86.1	60.0	13.2	30	3000	9.4	Kent, 1987
Skim milk	86.1	55.0	12.1	50	3000	9.8	Kent, 1987
Butter (unsalted)	23.6	22.5	4.6	50	915	56.6	Guo et al., 2010b
Milk	75.0	70.4	12.4	22	915	37.1	Guo et al., 2010b
Milk	75.0	68.5	12.6	22	2450	12.9	Guo et al., 2010b
Milk	86.0	69.9	11.3	35	2450	14.5	Ghanem, 2010
Milk	88.0	79.4	15.0	35	2450	11.6	Ghanem, 2010
Human milk		58.87	15.32	5	2450	9.8	Leite et al.,2019
Human milk		51.37	8.68	30	2450	16.1	Leite et al.,2019
Human milk		43.77	7.24	50	2450	17.9	Leite et al.,2019
Human milk		37.62	5.67	70	2450	21.1	Leite et al.,2019
Whole cow milk		69.78	19.11	5	2450	8.6	Leite et al.,2019
Whole cow milk		65.66	13.35	30	2450	11.9	Leite et al.,2019
Whole cow milk		60.01	12.19	50	2450	12.4	Leite et al.,2019
Whole cow milk		54.09	10.59	70	2450	13.6	Leite et al.,2019
Low fat cow milk		72.48	19.47	5	2450	8.6	Leite et al.,2019
Low fat cow milk		68.62	13.36	30	2450	12.1	Leite et al.,2019
Low fat cow milk		64.23	12.0	50	2450	13.1	Leite et al.,2019
Low fat cow milk		59.36	11.91	70	2450	12.7	Leite et al.,2019

*Calculated by using the penetration depth equation (Equation 4)

On the other hand, it was indicated for the temperatures below zero (-10 to 0°C), the increasing temperature causes a very sharp increase in dielectric constant and dielectric loss factor which was thought to be a result of the phase change of ice to water (Luan and Wang, 2015; Yang et al., 2017; Zhang et al., 2019).

Eggs and Egg Components

The main purposes of the microwave treatment of eggs are preserving shelf-stable products and improvement of microwave pasteurization. In addition, microwave can be used in drying stages of eggs (Uslu and Certel, 2006).

It is indicated in the previous studies that the dielectric properties of egg whites depend on protein contents whose denaturation temperatures change from 58 to 84°C (Wang et al., 2009). The dielectric constants and loss factors of egg whites increased with increasing temperatures at 27 MHz (Chen et al., 2019). While the dielectric constants decreased with increasing temperatures at 915 MHz, loss factors increased which means egg whites can be cooked more quickly at 915 MHz (Wang et al., 2009). It is also indicated that, the dielectric behaviors of egg white, yolk and albumen were revealed as similar to each other for higher frequencies and dielectric constants and loss factors of egg white, yolk, albumen decreased with increasing temperature at 2450 MHz (Dev et al., 2008; Lau and Subbiah, 2018). The effects of moisture on penetration depth are not clear but generally that d_p values decrease with increasing frequency and temperature (Table 2). By using these informations, more appropriate process conditions can be applied and improve the efficiency of microwave pasteurization of eggs (Dev et al., 2008; Wang et al., 2009).

Dairy Products

Microwave applications of dairy products are used for reducing surface spoilage of microorganisms and extending the shelf-life of the products. For these purpose, microwave can be used for heating in a sealed package. Thus, the potential risk of contamination is prevented and also the heating time is reduced by using microwave pasteurization (Herve et al., 1998). Microwave sterilization is also used for some dairy products. According to a research on cheese samples, results indicated that sterilization of the cheese by microwaves saves the original structure while the canned one became "lumpy and gooey" (Tang et al., 2002).

Dielectric properties of dairy products at selected temperature and frequency range were given in Table 3 along with the calculated penetration depths. The effects of moisture on dielectric properties depend on the type of the products. Increasing moisture leaded to high dielectric constant and loss factor with decreased penetration depth values for milk (Ghanem, 2010). It might be attributed to the free water of food that makes dipole rotation results in hydrogen bond distruption and rapid heating (Pandey et al., 2018; Leite et al., 2019). The d_p values also decreased with the increasing frequency and temperature (Konak et al., 2009; Guo et al., 2010b; Munoz et al., 2018; Dag et al., 2019; Leite et al.,2019). Dielectric constant and loss factor generally decreased with increasing frequency (Konak et al., 2009; Munoz et al., 2018; Dag et al., 2019; Leite et al., 2019). The moisture content of milk was also inversely proportional to the penetration depth value and proportional to the dielectric constant value (Ghanem, 2010; Guo et al., 2010b). Temperature generally decreased the dielectric constant and loss factor (Kent, 1998; Leite et al., 2019).

Table 4 Dielectric properties of honey

Honey type	Moisture (%wb)	ε′	ε″	T (°C)	f (MHz)	d_p*(mm)
Yellow locust	18.0	12.9	6.3	25	915	30.6
Yellow locust	22.1	17.2	9.1	25	915	24.5
Rape	18.0	11.0	4.7	25	915	37.6
Rape	22.1	17.6	9.2	25	915	24.5
Jujube	17.6	12.3	5.4	30	915	34.7
Jujube	17.6	9.5	3.8	30	2450	16.1

*Calculated by using the penetration depth equation (Equation 4) Adapted from Guo et al. (2011a).

Table 5 Dielectric properties of fresh fruits and vegetables

Food	Moisture (%wb)	ε′	ε″	T (°C)	f (MHz)	d_p*(mm)	Ref.
Asparagus	-	73.6	20.6	21	915	21.9	Tang et al., 2002
Asparagus	-	71.3	16.0	21	2450	10.4	Tang et al., 2002
Bean	7.3	2.8	0.8	19	9000	11.2	Torrealba-Meléndez et al.,2014
Mung bean	10.2	2.6	0.3	20	915	280.9	Jiao et al., 2011
Black eyed pea	8.8	2.8	0.2	20	915	457.2	Jiao et al., 2011
Broccoli	40.8	15.7	8.3	21.5	915	26.9	Kristiawan et al., 2011
Avocado	71.0	47.0	16.0	23	915	23.7	Venkatesh and Raghavan, 2004
Apple	88.0	57.0	8.0	23	915	51.7	Venkatesh and Raghavan, 2004
Cantaloupe	92.0	68.0	14.0	23	915	32.3	Venkatesh and Raghavan, 2004
Carrot	87.0	59.0	18.0	23	915	23.6	Venkatesh and Raghavan, 2004
Cucumber	97.0	71.0	11.0	23	915	42.0	Venkatesh and Raghavan, 2004
Grape	82.0	69.0	15.0	23	915	30.4	Venkatesh and Raghavan, 2004
Grapefruit	91.0	75.0	14.0	23	915	33.9	Venkatesh and Raghavan, 2004
Honeydew	89.0	72.0	18.0	23	915	25.9	Venkatesh and Raghavan, 2004
Kiwifruit	87.0	70.0	18.0	23	915	25.6	Venkatesh and Raghavan, 2004
Lemon	91.0	73.0	15.0	23	915	31.3	Venkatesh and Raghavan, 2004
Lime	90.0	72.0	18.0	23	915	25.9	Venkatesh and Raghavan, 2004
Mango	86.0	64.0	13.0	23	915	33.8	Venkatesh and Raghavan, 2004
Onion	92.0	61.0	12.0	23	915	33.0	Venkatesh and Raghavan, 2004
Orange	87.0	73.0	14.0	23	915	33.5	Venkatesh and Raghavan, 2004
Papaya	88.0	69.0	10.0	23	915	45.5	Venkatesh and Raghavan, 2004
Peach	90.0	70.0	12.0	23	915	38.2	Venkatesh and Raghavan, 2004
Potato	79.0	62.0	22.0	23	915	19.8	Venkatesh and Raghavan, 2004
Radish	96.0	68.0	20.0	23	915	22.8	Venkatesh and Raghavan, 2004
Squash	95.0	63.0	15.0	23	915	29.1	Venkatesh and Raghavan, 2004
Sweet potato	80.0	55.0	16.0	23	915	25.6	Venkatesh and Raghavan, 2004
Turnip	92.0	63.0	13.0	23	915	33.5	Venkatesh and Raghavan, 2004
Honeydew melon	90.0	72.0	14.0	24	1000	29.1	Nelson and Trabelsi, 2009
Apple	86.0	24.5	3.2	24	2450	30.2	Guo et al., 2011c
Pineapple	84.0	3.6	0	25	915	2565.0	Barba and Lamberti, 2013

*Calculated by using the penetration depth equation (Equation 4).

Honey

DH, by using RF and or MW, provides rapid and volumetric heating for pathogen control in honey due to the direct transfer of electromagnetic energy into bulk materials (Wang et al., 2007). In addition, dielectric properties are used for detecting sucrose-adulterated honey or sense sucrose content in honey, as sucrose syrup is widely used as an adulteration material. DH are significant for obtaining proper, simple, cheaper and rapid sucrose adulterated honey detector (Guo et al., 2011a).

As seen in Table 4, dielectric parameters of honey increase with increasing moisture content generally. This might be attributed to the dipole rotation of free water content of honey (Pandey et al., 2018; Leite et al., 2019). Frequency also played an important role and it was inversely proportional to the dielectric properties of honey (Guo et al., 2011a; Pentos and Luczycka, 2018). The dielectric constants and loss factors decreased with increasing frequency over 10 to 4500 MHz range at room temperature (Guo et al., 2011a; Pentos and Luczycka, 2018). In addition, increasing sucrose content cause the biggest fall in the loss factor (Guo et al., 2011a, Guo et al., 2011b).

Microwave applications are quite convenient in drying, tempering, blanching of fruits and vegetables and for preventing microbial growth as well. Especially, blanching is significant stage of fruits and vegetables in food industry. However, conventional blanching methods cause low quality products due to the loss of vitamin and mineral contents and also considerable energy cost. In microwave blanching, heat transfer accomplish with little amount of water or without. Furthermore, time of process decreases, taste and flavor of fruits and vegetables are protected at the same time. The other application is microwave-drying which protects the texture of fruits and vegetables from hardening. In addition, frozen fruits and vegetables can be tempered properly by using microwave (Konak et al., 2009).

Table 6 Dielectric properties of dried fruits and agricultural products

Dried fruits	Moisture (%wb)	ε′	ε″	T (°C)	f (MHz)	d_p* (mm)	Ref.
Raisin	15.0	7.8	3.8	20	915	39.4	Alfaifi et al., 2013
Raisin	15.0	9.4	4.3	30	915	38.1	Alfaifi et al., 2013
Dates	19.7	12.0	5.7	20	915	32.5	Alfaifi et al., 2013
Apricots	24.6	19.7	7.1	20	915	33.1	Alfaifi et al., 2013
Apricots	24.6	17.6	6.3	20	1800	17.9	Alfaifi et al., 2013
Figs	27.3	19.1	8.9	20	915	26.3	Alfaifi et al., 2013
Prunes	30.2	24.2	10.8	20	915	24.3	Alfaifi et al., 2013
Prunes	30.2	26.8	11.9	30	915	23.2	Alfaifi et al., 2013
Agricultural products	Moisture (%db)	ε′	ε’’	T (°C)	f (MHz)	d_p* (mm)	Ref.
Barley	7.5	2.5	0.9	21	1000	85.2	Kent, 1987
Susame seed	8.6	2.3	0.3	20	1000	241.8	Kent, 1987
Coffee beans	15.2	3.4	0.4	21	10	22043.9	Kent, 1987
Coffee beans	20.0	4.7	0.7	21	10	14825.4	Kent, 1987
Pecans	4.4	1.9	0.1	22	1000	658.2	Kent, 1987
Pecans	3.6	1.7	0.1	22	1000	622.7	Kent, 1987
Oat	10.7	2.1	0.2	24	1000	346.3	Kent, 1987
African nutmeg seed	20.0	1.9	8.1	22	-	-	Burubai and Meindinyo, 2013
African nutmeg seed	30.0	20.8	12.0	22	-	-	Burubai and Meindinyo, 2013
Corn seed	16.3	3.7	0.4	23	1	229897.2	Sacilik and Colak, 2010
Corn seed	16.3	3.4	0.2	23	5	88061.9	Sacilik and Colak, 2010
Walnut	-	3.0	2.3	40	915	41.8	Sosa-Morales et al., 2010
Walnut	-	5.8	0.6	40	27.12	7074.8	Sosa-Morales et al., 2010
Almond	-	3.3	6.0	40	915	19.6	Sosa-Morales et al., 2010
Almond	-	3.1	6.4	60	915	18.4	Sosa-Morales et al., 2010
Brazil nut kernel		2.87	0.18	20	2450	183.5	Da Silva et al., 2016
Brazil nut kernel		3.11	0.21	50	2450	163.7	Da Silva et al., 2016
Brazil nut seed shell		2.76	0.32	30	2450	101.3	Da Silva et al., 2016
Brazil nut seed shell		2.09	0.10	80	2450	281.8	Da Silva et al., 2016
Soybean powder	-	2.8	0.14	20	27	21139	Huang et al., 2018
Soybean powder	-	3.61	0.33	50	27	10190.4	Huang et al., 2018
Soybean powder	-	6.0	0.41	70	27	10569.2	Huang et al., 2018
Soybean powder	-	12.48	7.54	90	27	862.5	Huang et al., 2018
Soybean (bulk)	-	1.80	0.02	20	27	118607	Huang et al., 2018
Soybean (bulk)	-	2.10	0.05	50	27	51246	Huang et al., 2018
Soybean (bulk)	-	2.91	0.20	70	27	15089.3	Huang et al., 2018
Soybean (bulk)	-	4.84	1.03	90	27	3797.5	Huang et al., 2018

*Calculated by using the penetration depth equation (Equation 4)

Table 7 Dielectric properties of liquid foods

Food	ε′	ε″	T (°C)	f (MHz)	dp*(mm)	Ref.
Water	80.3	2.8	20	600	254.7	Nelson and Trabelsi, 2012
Water	79.2	7.9	20	1700	31.7	Nelson and Trabelsi, 2012
Rose wine	49.6	33.1	22-24	915	11.6	Bohigas and Tejada, 2010
Beer (4.6% alcohol)	56.1	29.2	22-24	915	13.8	Bohigas and Tejada, 2010
Beer (7.2% alcohol)	48.8	32.4	22-24	915	11.8	Bohigas and Tejada, 2010
Tomato juice	81.3	33.6	35	2450	5.3	Ghanem, 2010
Strawberry juice	92.6	23.6	35	2450	8	Ghanem, 2010
Apple juice	72.7	10.9	35	2450	15.3	Zhu et al., 2012a
Pear juice	70.2	11.6	35	2450	14.1	Zhu et al., 2012a
Orange juice	72.3	13.0	35	2450	12.8	Zhu et al., 2012a
Grape juice	70.4	13.5	35	2450	12.2	Zhu et al., 2012a
Pineapple juice	70.9	13.4	35	2450	12.3	Zhu et al., 2012a
Fresh potato juice	42.6	35.8	35	2450	3.8	Vijay et al., 2013
Coconut water	63.4	24.0	80	915	17.6	Franco et al., 2013
Tamarind beverage	79.36	11.32	10	915	4110	Gonzalez-Monroy et al., 2018
Tamarind beverage	73.67	18.58	10	2450	900	Gonzalez-Monroy et al., 2018
Tamarind beverage	59.68	29.94	10	5800	210	Gonzalez-Monroy et al., 2018
Tamarind beverage	75.02	10.17	30	915	4450	Gonzalez-Monroy et al., 2018
Tamarind beverage	72.10	12.53	30	2450	1320	Gonzalez-Monroy et al., 2018
Tamarind beverage	64.67	21.62	30	5800	310	Gonzalez-Monroy et al., 2018
Tamarind beverage	68.90	10.59	50	915	4090	Gonzalez-Monroy et al., 2018
Tamarind beverage	67.12	9.17	50	2450	1740	Gonzalez-Monroy et al., 2018
Tamarind beverage	63.05	14.82	50	5800	440	Gonzalez-Monroy et al., 2018
Tamarind beverage	65.07	11.74	70	915	3590	Gonzalez-Monroy et al., 2018
Tamarind beverage	63.66	7.91	70	2450	1960	Gonzalez-Monroy et al., 2018
Tamarind beverage	60.88	11.86	70	5800	540	Gonzalez-Monroy et al., 2018

*Calculated by using the penetration depth equation (Equation 4)

Fruits and Vegetables

Dielectric constant and loss factor of fruits and vegetables decrease with increasing frequency (Table 5). Moisture content is also critical for these food groups. In general, dielectric constant increase with increasing moisture content while loss factor decrease for some fruits and vegetables, so the tendency varies with types of vegetables or fruits. Some fruits undergo change during the storage period. According to a study, the dielectric constant and loss factor remain mostly same throughout storage at refrigerator (Sosa-Morales et al., 2009). For instance, the dielectric constant and loss factor values of mangoes reduce with storage time due to primarily decreasing moisture content and the increased pH, which is observed during that period (Sosa-Morales et al., 2009). Similarly, dielectric constant values remain the same for potato starch, tapioca flour, broccoli powder and onion powder with increasing frequency, while loss factors of them were decreasing with increasing frequency. Besides loss factor values were very low because of the very low water content of the samples (Ozturk et al., 2016). For berry samples (blackberry, raspberry, and strawberry), the permittivity increased with increasing temperature and decreased with increasing frequency; the imaginary permittivity decreased with temperature and increased with frequency. The penetration depth into strawberry (3.5 cm) is deeper than other berry samples' depth values (2.5 cm) which were decreased with increasing frequency from 915 to 5800 MHz (Sosa-Morales et al., 2017). In addition, the salt and sugar contents are affected on the dielectric properties of the samples. Especially, sucrose addition indicates the dielectric properties of the thawing samples (Wang et al., 2011; Leite et al., 2019; Wang et al., 2019).

In another study, dielectric contant, loss factor and penetration depth values of apple slices decrease with increasing frequency from 915 to 2450 MHz during frying (Al Faruq et al., 2018). For fresh and stale apple and potato, dielectric constant decrease with increasing frequency, however loss factor increases with increasing frequency (Ates et al., 2017).

Dried Fruits and Agricultural Products

Dielectric properties are used in fruit drying processes if DH is applied. Drying process can be accomplished in a short time and provides more qualified dried products with low energy requirement (Konak et al., 2009). Radio frequency and DH also protect food materials from insects that already present in dried fruits. The dielectric properties and calculated penetration depths of dried fruits and agricultural products at selected temperature and frequencies are given in Table 6. In a study, it was revealed that the dielectric constant and loss factor of all samples decreased with increasing frequency. Increasing temperature results increasing dielectric constant and loss factor for each frequency. The loss factor of all dried fruit samples increased with increasing moisture content (Alfaifi et al., 2013). Dielectric properties are also used in drying processes and insect control of agricultural products. According to the previous studies, dielectric constant of agricultural products mostly decreased with frequency increase. However, increasing of moisture content and temperature lead to increase dielectric constant and loss factor (Kent, 1987; Sacilik and Colak, 2010; Sosa-Morales et al., 2010; Burubai and Meidinyo, 2013; Auksornsri et al., 2018; Huang et al., 2018).

Table 8 Dielectric properties of bakery products

Food	Moisture (%wb)	ε′	ε″	T (°C)	f (MHz)	d_p*(mm)	Ref.
Paddy flour	10.8	2.6	-	20	9000		Ahmed et al., 2011
Paddy flour	11.0	2.4	-	20	9000		Ahmed et al., 2011
Chesnut flour	11.6	2.4	0.3	20	915	269.9	Zhu et al., 2012b
Chesnut flour	30.2	22.4	16.3	20	915	16	Zhu et al., 2012b
Madeira cake	17.0	11.0	4.2	20.4	915	41.9	Al-Muhtaseb et al., 2010
Madeira cake	17.0	8.5	3.5	20.4	2450	16.6	Al-Muhtaseb et al., 2010
White bread	37.1	8.0	2.7	23	915	55.4	Liu et al., 2009
White bread	37.1	7.2	2.7	23	1800	26.8	Liu et al., 2009
White bread	37.1	2.1	0.7	40	915	109.5	Liu et al., 2009
White bread	38.6	2.1	0.7	40	915	109.5	Liu et al., 2009
Soybean flour	8.9	9.4	5.3	60	915	31.3	Guo et al., 2010a
Lentil flour	8.4	22.0	5.5	60	915	44.8	Guo et al., 2010a
Greenpea flour	10.8	29.0	7.8	60	915	36.3	Guo et al., 2010a
Corn flour	10.3	3.86	0.16	20	13.56	43238.3	Ozturk et al., 2017
Corn flour	10.3	9.11	1.11	80	13.56	9590.5	Ozturk et al., 2017
Corn flour	10.3	3.68	0.13	20	27.12	25978.8	Ozturk et al., 2017
Corn flour	10.3	8.43	0.74	80	27.12	6913.1	Ozturk et al., 2017
Corn flour	16.7	4.94	0.21	20	13.56	372602	Ozturk et al., 2017
Corn flour	16.7	21.27	6.14	80	13.56	2671.2	Ozturk et al., 2017
Corn flour	16.7	4.77	1.7	20	27.12	2296	Ozturk et al., 2017
Corn flour	16.7	18.51	4.23	80	27.12	1801.8	Ozturk et al., 2017
Wheat germ	7.05	2.78	0.3	25	13.56	19594.4	Ling et al., 2018
Wheat germ	7.05	5.39	0.68	85	13.56	12043.3	Ling et al., 2018
Wheat germ	7.05	2.64	0.29	25	27.12	9877.1	Ling et al., 2018
Wheat germ	7.05	5.14	0.62	85	27.12	6448.3	Ling et al., 2018
Wheat germ	7.05	2.58	0.27	25	40.68	6990.7	Ling et al., 2018
Wheat germ	7.05	4.98	0.53	85	40.68	4948	Ling et al., 2018
Wheat germ	11.33	3.72	0.40	25	13.56	16999.6	Ling et al., 2018
Wheat germ	11.33	10.2	1.14	85	13.56	9878.1	Ling et al., 2018
Wheat germ	11.33	3.55	0.37	25	27.12	8975.8	Ling et al., 2018
Wheat germ	11.33	9.27	0.90	85	27.12	5961.8	Ling et al., 2018
Wheat germ	11.33	3.48	0.3	25	40.68	7303.8	Ling et al., 2018
Wheat germ	11.33	8.60	0.86	85	40.68	4006.6	Ling et al., 2018
Wheat germ	15.96	4.87	0.75	25	13.56	10389.2	Ling et al., 2018
Wheat germ	15.96	11.0	2.22	85	13.56	5285.9	Ling et al., 2018
Wheat germ	15.96	4.56	0.66	25	27.12	5710	Ling et al., 2018
Wheat germ	15.96	9.75	2.18	85	27.12	2536.8	Ling et al., 2018
Wheat germ	15.96	4.50	0.59	25	40.68	4228.3	Ling et al., 2018
Wheat germ	15.96	9.11	1.94	85	40.68	1835.9	Ling et al., 2018

*Calculated by using the penetration depth equation (Equation 4)

Table 9 Dielectric properties of fats and oils

Food	ε′	ε″	T (°C)	f (MHz)	d_p*(mm)	Ref.
Pork fat	12.4	124.0	10	10	318.6	Kent, 1987
Pork fat	2.1	0	80	10	-	Kent, 1987
Beef fat	3.4	0.1	40	20	44016.7	Kent, 1987
Beef fat	3.2	0.2	20	20	21359.3	Kent, 1987
Corn oil	2.6	0.2	25	915	420.9	Tang et al., 2002
Corn oil	2.5	0.1	25	2450	308.1	Tang et al., 2002
Soybean salad oil	2.9	0.2	25	100	4067.1	Kent, 1987
Soybean salad oil	2.6	0.2	25	1000	385.2	Kent, 1987
Soybean salad oil	2.9	0.1	49	100	8130.6	Kent, 1987
Cotton oil	2.9	0.1	49	100	8130.6	Kent, 1987
Cotton oil	2.8	0.2	25	100	3996.6	Kent, 1987
Cotton oil	2.6	0.2	25	1000	385.2	Kent, 1987
Susame oil	2.5	0.2	25	2200	171.7	Kent, 1987
Susame oil	2.6	0.2	75	2200	175.1	Kent, 1987
Brazil nut seed oil	2.87	0.18	30	2450	183.5	Da Silva et al., 2016
Brazil nut seed oil	2.96	0.23	60	2450	145.9	Da Silva et al., 2016
Castor oil	4.5	0.3	-	10	33774.3	Kent, 1987

*Calculated by using the penetration depth equation (Equation 4)

Liquid Foods

Dielectric application can be used in pasteurization, sterilization, tempering of concentration of liquid foods such as fruit juices (Konak et al., 2009). For an appropriate and uniform pasteurization process, it is crucial selecting of frequency ranges. In previous studies, it was revealed that dielectric constants of liquid foods decreased as frequency and temperature increased (Nelson and Trabelsi, 2012; Siguemoto and Gut, 2016; Franco et al., 2017; Kubo et al., 2018; Gonzalez-Monroy et al., 2018; Sobreiro et al., 2018; Kumar and Shrivasta, 2019). The effects of applied frequency and temperature on loss factor values, may vary (Table 7). Moreover, the sugar content of liquid foods is another important factor in dielectric properties. It was indicated that as Brix increases, although dielectric constant and penetration depth decrease, loss factor increases (Siguemoto and Gut, 2016; Franco et al., 2017; Kubo et al., 2018; Sobreiro et al., 2018; Kumar and Shrivasta, 2019).

Bakery products

Microwave drying is commonly used in the final drying of bakery products. Microwave cooking in oven, pasteurization and sterilization of fresh pasta products and preventing of microbial growth in bakery products can be accomplished by using dielectric properties and for DH applications. Especially, for pasta production, microwave drying is commonly used in food industry (Konak et al., 2009).

The dielectric properties of some bakery products at selected temperature and frequencies are given in Table 8. The dielectric parameters are affected by the frequency and the composition differently according to the type of products. The dielectric constants and loss factors of bakery products decreased as frequency increased (Song et al., 2015). While increasing moisture content results in no change in loss factor in general except chesnut flour, dielectric constant values changes depending on the composition of products. The chemical compositions have direct effects on the dielectric properties of food materials. Even though the main effect belongs to the moisture content, the content of salt and other minerals which are related to the dielectric properties (Guan et al., 2004, Song et al., 2015; Ling et al., 2018; Pongpichaiudom et al., 2018; Leite et al., 2019; Wang et al., 2019). As the temperature increases, polarization of the molecules and ionic conductivity increase and effects dielectric properties similarly (Ling et al., 2018; Leite et al., 2019). When temperature increases dielectric properties decrease (Table 8)

Fats and Oils

Dielectric properties are used in identification, processing, quality monitoring of fats and oils and improvement during oil processing and storage (Lizhi et al., 2008). The dielectric parameters at selected temperature and frequencies of oils and fats are given in Table 9. According to the studies, dielectric constant decrease and loss factor decrease or remain constant with increasing frequency. The increasing temperature also increased the dielectric constants, but did not affect the loss factors in general (Kent, 1987; Tang et al., 2002; Rubalya Valantine et al., 2017). Dielectric behaviors may differ in frying processes. For instance, a dielectric relaxation was revealed because of the dipole polarization around 10 MHz for soybean oil after dough frying in which, dielectric constant decreased with increasing frequency. However loss factor first decreased until this frequency (10 MHz), then it increased with further frequency increase (Yang et al., 2016).

Conclusion

In this literature review, the microwave and radio frequencies - food interactions and their roles of dielectric properties of foods have been summarized. The influence of temperature, frequency and moisture on the dielectric properties for different food groups have listed from various studies and penetration depths were calculated theoretically.

Dielectric constant, loss factor and penetration depth were greatly influenced by the moisture content, frequency and temperature. The moisture content is one of the most critical factor influencing the dielectric properties of food materials. Besides, dipole rotation and conductivity of molecules in/and free water content of foods are very important factors on dielectric properties, especially for the imaginary permittivity values. Thus, the amount of added salt and sucrose changes the moisture content of foods, and as a matter of course, dielectric properties. Dielectric constant and loss factor of foods generally increased with increasing moisture content. The effect of moisture content on penetration depth is not distinct; it can vary with the composition and type of foods. The increased moisture content of fruits result in increasing penetration depth in fruit samples, while for dried fruits, penetration depth reduce with increasing moisture content.

For many of food groups, the dielectric constant, loss factor and penetration depth decreased with increasing frequency. Temperature is not a predictive factor in dielectric measurement. Changing of temperature may affect differently on dielectric properties depended on the composition, characteristics of food materials and applied frequency.

By considering these parameters and the response of food materials to microwave applications, dielectric properties has provided a good qualitative understanding of the behaviour of the food materials under microwave applications. However, there is still a requirement for further investigation on dielectric properties of food materials. For this purpose, more experimental studies should be conducted. Furthermore, these experimental studies should be extended to industrial scale to produce food products with more natural taste by using less energy and time.

Acknowledgement

Dr. Filiz Altay acknowledges and appreciates the support from the TUBITAK for the project (No: 113O491). This review was done in the light of researches for the above-mentioned project.

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