CHAPTER-2

Review of Literature

The present research is aimed on investigating the dielectric properties of fruits and vegetables. As such, in this chapter we present a brief review of the important works reported in literature on the dielectric properties of food materials in general and fruits and vegetables, in particular.

As discussed in the last chapter, the dielectric properties of materials reserve as a measure of interaction of electromagnetic radiation with materials and the effect of physical conditions like temperature, density, moisture and frequency of electromagnetic radiation become more apparent in the range of microwave frequencies. Also the internal constitution and molecular structure of the material under test is better revealed by microwaves as compared to the radio-waves of other frequencies. These properties find important applications in different fields, such as, agriculture, food industry, rubber industry, soil and remote sensing, aquametry, life sciences, medical and health etc.

Icier and Baysal (2004); Nelson (1965); Ryynanen (1995) and Venkatesh and Raghavan (2004) have reported that the dielectric properties of food materials are greatly influenced by factors like, the frequency of interacting electromagnetic fields, and temperature, bulk density and moisture level of the sample under test. Venkatesh and Raghavan (2004); Guan et al. (2004); Sipahioglu et al. (2003); Nelson and Bartley (2002); Feng et al. (2002); Nelson (1991, 1992); Nelson et al. (1994); Ohlsson et al. (1974 a); and Engelder and Buffler (1991) have reported that the permittivity of foods is also influenced by the presence of components in ionic form, its concentration and composition of constituents of food materials.

Nelson (1965) studied the effect of frequency and temperature variation on permittivity of different types of seeds and grains and other agricultural products. Guan et al. (2004), Wang et al. (2003) Feng et al. (2002), Ikediala et al. (2000), Nelson et al. (1994) and Nelson (1983) have carried out similar work on different types of fruits and vegetables. Kim et al. (1998) and Zuercher et al. (1990)
investigated dielectric behaviour of the baked foods and flours. Green (1997) and Herve et al. (1998) further extended their work for the dairy products. Investigations have also been reported on the non-destructive testing of materials for prediction of some of the physical characteristics of agri-food products, like fruits, eggs etc. (Dev et al. 2008; Nelson et al. 1995).

Water is the major contributor to the dielectric properties of foods at microwave frequencies. The dielectric properties are closely related to the availability of free water in a sample of food (Mudgett et al. 1977; de Loor, 1968). The dielectric properties of foods, such as, the relative permittivity ($\epsilon'$) and the relative loss factor ($\epsilon''$) are found to strongly depend on the percentage of water present in them, therefore these properties ($\epsilon'$ and $\epsilon''$) have very low values for lower moisture contents, and as such these two quantities are fairly insensitive to temperature changes at moisture levels of about (0.05-0.25 kg/kg) or 5-25% on wet basis. This fact has been verified by Mudgett et al. (1980), who observed that for low moisture contents, small variations in temperature have little effect on the dielectric behavior of fruits and vegetables. They explained this behaviour of food materials in terms of binding of water and ions of salts present in the food at low concentrations of water, where the water is bound in hydration mono and multi layers.

2.1 Dielectric behavior of food and its products

Hlavacova (2003) observed that the knowledge of permittivity of food and its products is useful in understanding the interaction of electromagnetic fields with them during microwave cooking or in any other process involving radio-frequency or microwave dielectric heating. Plenty of data and literature on the dielectric properties of fruits, vegetables, and other agri-products is now available, which can help us to understand their dielectric behavior (Jha et al., 2011). Also reports on the influence of important physical variables on the dielectric properties of agri-food materials are now available, which can be used to understand their molecular behavior (Nelson, 1991; Mudgett, 1985).
2.1.1 Food grains

One of the most prominent application of the dielectric properties of food grain is estimation of their moisture level, which helps in deciding appropriate conditions for safe storage and thus saving the food grains from being spoiled by insects, fungus, illi etc. due to store in wet condition (Kim et al. 2003; Nelson, 2006). Trabelsi and Nelson (2003) have suggested that the electrical behavior of cereal grains and oilseeds can be understood in terms of their dielectric properties. These properties can be used as a non-destructive method for obtaining basic information about their physical properties. Nelson et al. (1953) measured the permittivity of barley for the first time at frequencies 1MHz to 50 MHz. He observed that the parameters like, temperature, moisture content, bulk density and frequency of electromagnetic radiation greatly affect the dielectric properties of food grains. Nelson et al. (2006) reported the results of dielectric spectroscopy measurements carried out by them on winter ground hard red wheat crop in the frequency range from 10 MHz to 1,800 MHz and at temperatures from 25°C to 95°C.

Guo et al. (2008) used an open-ended coaxial-line probe and impedance analyzer to measure the permittivity of chickpea, green pea, lentil and soybean flour samples in the frequency range 10 MHz to 1,800 MHz, over the temperature range 20°C to 90°C and the range of moisture contents 8 to 21 g/100 g. Sacilik et al. (2006) studied the dielectric properties of flax seeds in the range of moisture content 5.92 % to 22.18 % on dry basis (d.b.), at bulk densities 586.7–722.9 kilograms/m$^3$ and in the frequency range of 50 KHz–10 MHz by the help of a sample holder in the form of a parallel-plate capacitor. Ahmed et al. (2007) reported that the dielectric constant of Indian Basmati rice samples usually does not vary with frequency in the frequency range 500 MHz to 2500 MHz while the loss factor shows an increasing trend with frequency as obtained by them on using an open ended coaxial probe as sensor with an impedance analyzer, over this frequency range.

Guo et al. (2010 a) have reported their results of permittivity measurements for the compressed chickpea flour samples at frequencies from 10 MHz to 1800 MHz, moisture contents from 7.9% to 20.9% w.b., and over the temperatures from 20°C to 90°C. They observed that as the frequency is increased, the dielectric
constant and loss factor of chickpea samples show a decreasing trend at all the temperatures and moisture levels. However, both of these parameters were found to increase as the temperature and moisture content were increased, the rate of increase being comparatively higher at higher temperatures and moisture levels.

Dielectric constant ($\varepsilon'$), loss factor ($\varepsilon''$), loss tangent ($\tan \delta$), and conductivity ($\sigma$) have been measured at 10.0 GHz by Jain and Shukla (2001) for five varieties of oilseeds, namely groundnut, sesame, linseed, rapeseed (yellow sarson) and Indian rape (toria) at various levels of moisture content and temperatures ranging from $15^\circ$C to $45^\circ$C. Both the parameters ($\varepsilon'$ and $\varepsilon''$) were observed to increase with moisture content for all the oilseeds under investigation. Positive temperature coefficients were observed for $\varepsilon'$, while both positive and negative temperature coefficients were recorded for $\varepsilon''$, depending on moisture content and temperature range. Conductivity also exhibited similar trend, while loss tangent did not show any specific trend.

Bansal et al. (2001) reported values of dielectric parameters ($\varepsilon'$ and $\varepsilon''$) for five varieties of rapeseed-mustard seeds, having different percentages of erucic acid at frequencies 100 KHz, 8.93 GHz and optical frequencies of sodium light. They observed that the dielectric constant at optical frequencies ($\varepsilon_o$) is almost the same for all the five samples, while the dielectric constant at 100 KHz ($\varepsilon_0$), the dielectric constant at 8.93 GHz ($\varepsilon'$) and loss factor ($\varepsilon''$) show dependence on erucic acid content, but no systematic variation with the contents of erucic acid was found by them.

2.1.2 Fruits and vegetables

In order to understand interaction of electromagnetic waves with the fruits and vegetables, their dielectric properties have been analyzed by many researchers (Garcia et al. 2001; Kato, 1997; Nelson et al. 1994; Nelson, 2003; Sosa-Morales et al. 2009; Tran et al. 1984). Nelson (1980) observed that the role of electrical permittivity of fruits and vegetables is very important in non-destructive testing of their quality factors, such as, maturity of peaches and chilling injury in sweet potatoes etc. Early measurements for dielectric properties of carrots were reported by Dunlap and Makower, (1945) in the frequency range 18 KHz to 5 MHz. They
noticed that the dielectric constant and conductivity of carrots are greatly influenced by factors like, moisture content, frequency of electric fields, temperature, density and particle size. They also observed that the dielectric constant remains almost uniform for moisture contents up to 6-8% and thereafter it increases rapidly with moisture contents for higher values of moisture. Similar behavior was also observed for variation of conductivity with moisture.

Vegetables show quite high values of relative permittivity because of the presence of high water content in them. Bengtsson and Risman (1971), on the basis of experiments performed at 2.8 GHz, reported that the value of dielectric constant for cooked peas and mashed potato mixture varies from about 54 to 65 and for cooked carrots; it varies from about 61 to 76, when temperature is varied from 3 to 6°C. For dried vegetables, dielectric constant is found to be low, as the water content in them is low. The single frequency measurements, however, could not reveal quality factors like, maturity of peaches and chilling injury in sweet potatoes (Nelson, 1980) and therefore need for measurements over a broad band of microwave frequencies was realized.

Shaw and Galvin (1949) investigated the electrical permittivity of potato, carrot, apple and peach tissues over the frequency range from 1 MHz to 40 MHz. They identified a band of frequencies from 100 KHz to 20 MHz, which may be considered as the general region of dielectric dispersion for fruits and vegetables under consideration. They also provided some useful data on the temperature dependence of conductivity in the above mentioned fruits and vegetables.

Dielectric constant of raw potato was found to drop appreciably with increasing frequency in the frequency range from 300 MHz to 3000 MHz (Pace et al., 1968). It was also found that the absorption of energy was higher at 1.0 GHz and 3.0 GHz as compared to other frequencies and it was observed to further increase for higher values of moisture contents and temperatures.

Nelson et al. (1994) reported the permittivity measurements taken on 23 varieties of fruits and vegetables by using an open ended coaxial probe with a vector
network analyzer. They observed that as the frequency is increased, the dielectric constant decreases, the rate of decrease being more rapid at about 5 GHz. The loss factor was also found to decrease as the frequency was increased above 200 MHz. shows broad minima in the frequency range 1 GHz to 3 GHz and thereafter it increases steadily with frequency up to 20 GHz, the maximum frequency of observation.

Calay et al. (1995) investigated the dielectric properties of foods for changes taking place with variation in applied microwave frequency, moisture content, composition of food and temperature. Sun et al. (1995) developed predictive equations for some fruits and vegetables and observed good correlation for the relative permittivity, but the correlation obtained for the relative loss factor at different values of moisture content and temperature was found to be not so good (Favreau et al., 1997). This is of even greater importance during the preparation of maple syrup products from the maple syrup, because of their reduced water contents.

Sipahioglu and Barringer (2003) measured the complex permittivity of 15 fruits and vegetables at 2.45 GHz at temperatures 5°C to 130°C by using an open-ended coaxial probe method. Dielectric constant of these samples was found to decrease with rise in temperature. They also observed the dielectric constant to increase with the increasing moisture content. It was also noticed that for most of the fruits and vegetables, the dielectric loss factor does not show definite trends for its variation with frequency, temperature or moisture content.

Sosa-Morales et al. (2009) studied the dielectric properties of mangoes ripening at 21°C for 16 days storage at frequencies 1 MHz to 1,800 MHz and in the temperature range of 20°C to 60°C by using an open-ended coaxial-line probe method. They reported that both $\varepsilon'$ and $\varepsilon''$ of mangoes decrease with increasing frequency, but the rate of reduction with frequency was larger for $\varepsilon''$ as compared to $\varepsilon'$. They also observed that the state of optimal ripening of mangoes in storage can be easily decided through measurements of parameters of $\varepsilon'$ and $\varepsilon''$ for them. This state is considered to be suitable for giving post harvest pest control treatment by
dielectric heating. Penetration depth is found to decrease with increasing frequency; therefore for disinfestation treatment of mangoes, radio frequency radiation is more suited because it penetrates deeper in mangoes as compared to microwaves (Sosa-Morales et al. 2009).

Funebo and Ohlsson (1998) attempted to make available dielectric data for several fruits and vegetables at temperatures higher than 20ºC and moisture contents lower than their fresh counterparts. They measured the dielectric properties, $\varepsilon'$ and $\varepsilon''$ for five fruits and vegetables, viz., apple, chervil, mushroom, parsley and strawberry. They found that the peak value for the loss factor occurs at intermediate moisture content, whereas a continuous increase in the relative permittivity is observed with increasing % moisture content. The measurements were performed by them by using a cylindrical resonant cavity excited in TM$_{012}$ mode, as described by Risman and Bengtsson (1971). The data obtained by them was found to be quite useful for understanding microwave drying and also for subsequent modeling of microwave and hot air drying.

Castro-Giraldez et al. (2010) reported the results of dielectric measurements taken on apple (Granny smith) during its maturity at 30ºC and in the frequency range from 500 MHz to 20 GHz by using an Agilent 85070 E open-ended coaxial probe connected to an Agilent E 8362B vector network analyzer. They also attempted to find out relationship of dielectric properties with apple’s physiological compounds, such as, sugar content, malic acid etc. This work was found to be very useful for the prediction of maturity in climacteric fruits by non-destructive methods.

Feng et al. (2002) performed measurements on dielectric parameters for several samples of apple with different moisture levels. They studied with the help of the open-ended coaxial probe technique the dielectric properties of fresh apple samples (87.5% moisture content), sliced apples (23.8% to 80.7% moisture content), and diced apples (3.8% to 22.4% moisture content), obtained from fresh apples and drying them by controlled heating. They found that both $\varepsilon'$ and $\varepsilon''$ of apple decrease with decreasing moisture content.
Zhu et al. (2012) measured the dielectric properties of apple, pear, orange, grapes and pineapple juice in the frequency range 20 to 4500 MHz at 15°C to 95°C. They reported that the parameter $\varepsilon'$ of fruit juices decreases with increasing frequency. The loss factor of fruit juices was also found to decrease with increasing frequency, reaching a minimum value in between 1000 MHz and 3000 MHz, and then it increases as the frequency is increased beyond the minima position of $\varepsilon''$. The frequency of minima (obtained between 1000 MHz and 3000 MHz) depends on temperature of the sample. Below 1000 MHz the temperature has +ve influence on $\varepsilon''$, whereas above 3000 MHz, its influence is found to be –ve.

Guo et al. (2007) measured electrical properties of apples at 24°C in the frequency range from 10 MHz to 1800 MHz for sensing quality of stored apples, which were stored for about 70 days at 4°C. It was concluded that permittivity of the apples does not show any appreciable change during the 10-weeks period of refrigerated storage.

Fresh apples have been the choice of a number of Agro Physicists for investigation of their dielectric characteristics. Such studies include realistic measurements in the frequency range 300 MHz to 900 MHz on immature and matured apples by Thompson and Zachariu (1971) and from 100 MHz to 12 GHz by Trans et al. (1984).

Measurements on three cultivars of fresh apples (namely: Red Rome, Pink Lady and Fuji) both for external surface and exposed flesh were made in the frequency range 150 MHz to 6.4 GHz by Seaman and Seals (1991) and similar measurements on internal tissues of the same three cultivars were also made by Nelson et al. (1994), at frequencies from 200 MHz to 20 GHz.

Martin – Esparza et al. (2006) measured the electrical characteristics of vacuum impregnated (VI) and non-vacuum impregnated (NVI) apple, var. Granny Smith, at the frequency 2.45 GHz and temperature 25°C, by using the open-ended coaxial probe method. They examined the effect of moisture content, water activity and porosity on the dielectric properties of two types apple samples (VI and NVI).
They concluded that the dielectric loss mechanism in apple is related to the availability of free water in it.

Dielectric characteristics of four cultivars of apple (viz., Red Delicious, Golden Delicious, Granny Smith, and Fuji) and third and fifth instars codling moth (Cydia pomonella) were studied by Ikediala et al. (2000) in the frequency range from 30 MHz to 3000 MHz over the temperatures from 5°C to 55°C, by using the open-ended coaxial-line probe technique. It was observed that as the frequency is increased $\varepsilon'$ for apple decreases. Increase in temperature also causes $\varepsilon'$ to slightly decrease. However, the loss parameter $\varepsilon''$ was observed not to show any appreciable effects when the frequency and temperature are changed.

Nelson and Bartley (2002) measured the dielectric characteristics of a commercial apple juice in the frequency range 200 MHz to 20 GHz. They observed that for apple juice the dielectric properties show temperature dependence similar to that obtained for pure liquid water.

To et al. (1974) and Zhang et al. (2007) measured the electrical properties ($\varepsilon'$ and $\varepsilon''$) of carrots. They reported that these parameters are greatly affected by moisture content and also influenced by other factors, like frequency, temperature, density, and particle size. It was observed that although moisture content plays a dominant role but dielectric properties are also affected by carbohydrates, ash and protein content present in carrots.

Solyom et al. (2013) reported dielectric properties of grape marc obtained from the resonant cavity method at three moisture contents and three temperatures viz, 28°C, 39°C and 50°C. They observed that at higher moisture contents, both the $\varepsilon'$ and $\varepsilon''$ show increasing tendency as the moisture is increased, while the temperature does not exhibit a definite trend.

Liu and Liu (2012) investigated the effect of postharvest dehydration on dielectric properties of Red globe grapes during cold storage, at the frequencies 0.1 KHz, 1 KHz, 10 KHz, 100 KHz and 1 MHz by using an LCR electronic measurement instrument. They compared the dielectric property values of Red globe
grapes with the un-dehydrated grapes and observed that the dehydrated grapes have comparatively higher values of impedance, inductance, resistance and lower values of dielectric constant.

Nelson (2005) measured the dielectric properties of nine fresh fruits and vegetables (viz., apple, grapes, orange, avocado, banana, cantaloupe, carrot, cucumber and potato) over the frequencies from 10 MHz to 1.8 GHz and temperatures ranging from 5°C to 65°C for the tissue samples cut from the above mentioned fruits and vegetables. He observed that the dielectric constant in the above mentioned fruits increases with increase in temperature at lower frequencies, whereas at higher frequencies, it decreases with increase in temperature. The loss factor on the other hand was found to increase consistently on increasing the temperature, the frequency being below 1 GHz.

Guan et al. (2004) reported that the temperature has a significant effect on the dielectric properties of food materials. The loss factor was found to increase on increasing the temperature at low frequencies, which was attributed to the ionic conductance by Guan et al. On the other hand, decrease in loss factor on increasing temperature at higher frequencies was attributed to the free water dispersion by Wang et al. (2003 b).

Tulasidas et al. (1995) used open ended coaxial transmission line technique to study the electrical properties of grapes at 2.45 GHz in the moisture range from 80% to 15% (wt. basis) and in temperature range from 25°C to 80°C. They observed that both the dielectric parameters ($\varepsilon'$ and $\varepsilon''$) show a decreasing trend when the moisture content is decreased. These results are useful in estimating the volumetric heating of grapes by microwave energy.

Nelson et al. (2007) measured the dielectric properties of four cultivars of small-sized watermelon, over the frequency range from 10 MHz to 1.8 GHz, by using an open-ended coaxial-line probe and impedance analyzer. They took measurements on the samples containing external surfaces and other samples containing their edible internal tissues. They also measured the moisture content and
soluble solids content (SSC) for internal tissues of melons and treated SSC (sweetness) as the quality factor for establishing a correlation between sweetness and dielectric properties of grapes.

The sugar content is the most significant factor affecting the maturity of watermelon. Sugar content in 10 matured red seedless watermelons was measured by Ibrahim et al. (2009) to compare sweetness of watermelon juice with sugar solution in water, over the frequency range from 200 MHz to 20 GHz by using the open ended coaxial – line probe technique. In this study, the data obtained suggests that dielectric properties show strong relationship with sugar content of watermelon. Sharma and Prasad (2002) investigated garlic for its electrical properties at a frequency of 2.45 GHz, moisture content (6%–185%, dry basis), and temperature (35–75°C). They observed that both $\varepsilon'$ and $\varepsilon''$ vary linearly with moisture content. On the other hand, at high moisture levels, both $\varepsilon'$ and $\varepsilon''$ decrease with increase in temperature and at lower moisture levels, a reverse trend is observed. The variation of both $\varepsilon'$ and $\varepsilon''$ with temperature was found to be linear. Penetration depth of radio waves in garlic was found to increase with decreasing moisture content whereas the temperature variation did not show any significant effect on it.

The relaxation frequency for fresh golden apple was estimated by Kuang and Nelson (1997) to lie between 10.1 and 15.8 GHz at 23°C. The same researchers estimated the relaxation frequency for fresh strawberry to lie in the frequency range of 11.0 GHz to 13.2 GHz at 23°C. It was observed that a decrease in moisture content causes reduction in the relaxation frequency because of the decrease in the availability of free water.

Guo et al. (2010 a) studied the electrical properties of four Legumes i.e., green pea, chickpea, soybean and lentil in the frequency range from 10 MHz to 1800 MHz and in the temperature limits from 20°C to 90°C, for four different values of moisture content by using an open-ended coaxial probe and impedance analyzer. Both the dielectric parameters ($\varepsilon'$ and $\varepsilon''$) of the legume samples were found to decrease with increasing frequency, but they were observed to increase with increase in temperature and moisture content. Negative linear correlations was
established between the loss factor and frequency on a log-log plot at low frequencies, high temperatures and high values of moisture contents, which is mainly due by the ionic conductance.

Coronel et al. (2008) investigated the dielectric behavior of pumpable food materials at 915 MHz over the temperatures from 10°C to 90°C. Their results showed that $\varepsilon'$ decreases and $\varepsilon''$ increases on increasing the temperature. Polynomial correlations were developed for the temperature dependence of dielectric parameters ($\varepsilon'$ and $\varepsilon''$) for designing of a continuous flow microwave heating system suitable for processing pumpable food materials.

Sacilik et al. (2006) reported that both the dielectric parameters ($\varepsilon'$ and $\varepsilon''$) of flaxseed increase on increasing the moisture content or bulk density or on decreasing the frequency. Kent (1970, 1972) investigated the relationship between the dielectric properties of fish meat and its temperature and moisture content. He found that both $\varepsilon'$ and $\varepsilon''$ vary linearly with increase in temperature, while they show non-linear dependence with increase in moisture content.

To et al. (1974) investigated beef products and observed that both that both $\varepsilon'$ and $\varepsilon''$ of beef decrease on increasing the frequency while keeping the temperature constant. On the other hand if temperature is increased while keeping the frequency constant, $\varepsilon'$ decreases while $\varepsilon''$ is observed to increase.

Nelson (2005 a) measured the dielectric properties of mature-green and full-ripe peaches at 2.45 GHz to check whether these properties depend on the degree of maturity of the peaches. He observed that dielectric measurements at 2.45 GHz do not offer any promise for detecting maturity state of peaches.

Dielectric properties of six fresh/dry fruits (viz., apple, grape-fruit, orange, cherry, almond and walnut) along with four associated insect larvae (viz., indian-meal moth, codling moth, navel orange worm and mexican fruit fly) were measured by Wang et al. (2003 b) in the frequency range from 1 MHz to 1800 MHz by using an open ended coaxial –line probe technique, at temperatures between 20°C and 60°C. They reported that the values of both the dielectric parameters ($\varepsilon'$ and $\varepsilon''$) of
nuts were very low as compared to those of fresh fruits and insects. Dielectric constant and loss factor of the insects were found to be much higher than those of the apples at frequencies lower than 2,450 MHz, which suggests that differential heating can be used for killing insects at frequencies lower than 2,450 MHz. This process may be unpractical at 2,450 MHz or higher frequencies for codling moth larvae in the apple host (Ikediala et al., 2000).

Thus, one of the important uses of microwaves of frequency lower than 2,450 MHz is to kill insects in fruits, dry fruits and vegetables through selective heating. Andreuccetti et al. (1994) reported on the possibility of using 2450 MHz microwaves to kill woodworms by selectively heating the larvae to 52-53°C in less than 3 minutes.

Hallman and Sharp (1994) and Nelson (1996) have submitted a consolidated report on the application of microwave treatment to selectively kill pests in many post-harvest crops.

2.1.3 Dry Fruits

Not much literature is available on the dielectric properties of nuts and dry fruits. Dielectric constant and loss factor of peanuts were measured by Nelson (1973) in the frequency range 1 to 50 MHz, and also studied variation of \( \varepsilon' \) and \( \varepsilon'' \) with frequency and moisture content. Nelson (1991) made a more detailed investigation of dielectric parameters (\( \varepsilon' \) and \( \varepsilon'' \)) of chopped pecans at frequencies from 50 KHz to 12 GHz for the moisture contents from 3% to 9%, wet basis at 22°C. The temperature dependence of the dielectric properties of shelled and separated pecan kernel pieces over temperatures from 0°C to 40°C were also determined by Lawrence et al. (1992, 1998) for frequencies from 100 KHz to 110 MHz over a similar range of moisture contents. It was found that both \( \varepsilon' \) and \( \varepsilon'' \) increase with increasing temperature, increase with increasing moisture content, and decrease with increasing frequency.

Guo et al. (2011) measured the dielectric properties of chestnut and chestnut weevil in the temperature range 20 °C to 60 °C and in the frequency range from 10
MHz to 4500 MHz by using an open-ended coaxial-line probe and network analyzer. The dielectric constant ($\varepsilon'$) of both the materials was found to decrease with increasing frequency. The dielectric loss factor ($\varepsilon''$) of chestnut was observed to decrease with increasing frequency below 3000 MHz, and slightly increase above 3000 MHz. The $\varepsilon''$ of chestnut weevil however, decreases with increasing frequency and acquires a minimum value at about 1000 MHz and increases thereafter. It was also observed that below the turning point, mentioned as above, the value of $\varepsilon''$ increases with increasing temperature, while as it decreases with increasing temperature above that point.

Berbert et al. (2002); and Lawrence et al. (1992, 1998) independently reported dielectric properties for common bean and nuts at frequencies (75 kHz–5 MHz) and moisture content ranging from 13.4% to 15.5% w.b. They found that at any fixed moisture content, the value of relative permittivity decreases at any fixed moisture content decreases regularly with increasing frequency. The frequency dependence of $\varepsilon''$ and loss tangent was found to be less regular as compared to the permittivity. Both the dielectric constant and the loss factor of nuts were found to increase regularly with moisture content at all the frequencies, whereas both of them decrease as the frequency is increased at any constant moisture content.

Alfaifi et al., (2012) reported the dielectric properties of raisins, dates, apricots, figs and prunes with water contents of 15 to 30.2 g/100g, in the frequency range 10-1800 MHz over a range of temperatures 20°C to 60°C. They observed that both the dielectric parameters ($\varepsilon'$ and $\varepsilon''$) of all the samples decrease with increasing frequency, and increase with increasing temperature at each frequency.

Burubai and Meindinyo (2013) reported the dielectric properties of African nutmeg seeds as a function of moisture content and frequency by using the parallel-plate capacitor technique. Both, the dielectric parameters ($\varepsilon'$ and $\varepsilon''$) were found to increase with increasing moisture levels. On the contrary, the loss tangent was found to be negatively affected by moisture variation, as it decreases with increasing moisture.
Dairy Products

There are not many reports on dielectric properties of dairy products available in literature. Nunes et al. (2006) investigated the dielectric properties of milk at room temperatures (17–20°C) over the frequency range from 1 GHz to 20 GHz. They suggested that dielectric properties of milk may be useful to roughly predict the milk’s content in terms of ionic compounds, fats, carbohydrates and proteins. Kudra et al. (1992) also studied the electrical properties of milk and their relationship with its constituents at 2.45 GHz. Guo et al. (2010a, b) determined dielectric properties of pure honey and water-added honey at frequencies 10 to 500 MHz at 25°C temperature and moisture content (18% to 42.6%). They observed that $\varepsilon'$ decreases monotonically with increase in frequency, and increases with increasing water content. Dielectric relaxation also becomes evident from the dielectric loss factor. The relaxation frequency and the peak value of loss factor were found to increase with increasing water content.

Dielectric properties of 16 varieties of processed cheese were investigated in the frequency range 0.3 to 3 GHz by Everard et al. (2006) in the range of temperature 5°C to 85°C at intervals of 10°C. They observed that $\varepsilon'$ gradually decreases with increase in frequency for all varieties of cheese. Dielectric constant was found to be highest at 5°C and then it decreases up to a temperature between 55°C and 75°C. Dielectric loss factor was observed to increase on increasing the temperature for cheeses having high and medium moisture/fat ratio. For low moisture / fat ratio cheeses, the loss factor decreases with increase in temperature between 5°C and 55°C and then increases at higher temperatures. Dielectric measurement techniques have also been used for determination of cheese composition and to sense cheese maturity by Everard et al. (2006); Green (1997) and Herve et al. (1998).

Hlavacova (2003) reported that the dielectric methods can be used for detection of mastitis in milk. Wang et al. (2003) reported that the dielectric constant of macaroni and cheese increases with frequency in the range of 27 MHz to 40 MHz, while as, it decreases with the frequency in the range of 915 MHz to
1,800 MHz. The dielectric properties of macaroni and cheese food products were also determined by Nelson and Bartley (2000). They observed that as the temperature of macaroni or cheese is increased, its $\varepsilon'$ decreases and $\varepsilon''$ increases with temperature.

### 2.1.4 Dielectrics in the form of solutions and Suspensions

Water is the essential component of agriculture and food products. Electrical properties of, sucrose, glucose, potato starch, glycerol and ethanol were measured by Roebuck et al. (1972) at frequencies 1 GHz and 3 GHz and at the temperature 25°C. They observed that gelatinized potato with an intermediate water concentration has higher values of $\varepsilon'$ and $\varepsilon''$ as compared to the granular potato; the granular form having about 10% less permittivity and up to a 20% smaller loss factor as compared to gelatinized potato starch. The dielectric loss for most of the forms of starches generally decreases on heating; though it remains almost constant in the temperature range associated with the thermal transition of starch. Miller et al. (1991) reported that the chemical modification influences the dielectric behaviour of all types of starches very much. Dielectric constant of starches is observed to decrease slightly on increasing the frequency, whereas the loss factor is found to decrease rapidly on increasing the temperature.

The dielectric properties of powder potato starch, locust bean gum and carrageenan have been investigated by Nelson (1991) at 2.45 GHz. He found that in the range of moisture content (0-20 %) wet basis, the dielectric constant and loss factor of the samples under test increase regularly with increasing moisture content. The dielectric parameters ($\varepsilon'$ and $\varepsilon''$) of hydro-colloids were found by Nelson (1991) to increase markedly with increase in temperature at higher values of moisture contents.

Ahmed et al. (2009) determined electrical properties of potato slurry (Potato flour-water dispersions) at frequencies 500 to 2500 MHz; concentrations (10%-25% w.b.) and temperatures (20–75 °C). They observed that $\varepsilon'$ decreases with increase in temperature and frequency while it increases with increasing concentration. $\varepsilon''$ on the other hand, increases with frequency and concentration; however, a mixed effect
is observed for temperature dependence of $\varepsilon''$. Penetration depth for slurry was observed to decrease with increase in frequency but it showed a non-systematic behaviour for variation with temperature. Additions of salts substantially reduce penetration depth in potato slurry.

For materials containing sugars, the free water is influenced by the hydroxyl groups of the sugars, and hydrogen bonds are stabilized, as pointed out by Tulasidas et al. (1995) in their article on dielectric properties of grapes. Thus, foods containing a considerable fraction of sugars should be treated differently from other foods.