Dedicated to the 80th Anniversary of Prof. Radoš Řezníček

Dielectric properties of agricultural products and some applications

S.O. Nelson

U.S. Department of Agriculture, Agricultural Research Service, Richard B. Russell Agricultural Research Center, Athens, Georgia, USA

Abstract: The use of dielectric properties of agricultural products for sensing moisture in grain and seed and their application in radio-frequency and microwave dielectric heating is discussed briefly. Values for the dielectric properties of a number of products, including grain and seed, fruits and vegetables, and poultry products, are presented graphically to show the dependence of these properties on frequency, moisture content, and temperature. The potential for using the dielectric properties to sense quality factors other than moisture content is also considered.

Keywords: permittivity; radio frequency; microwave; dielectric constant; loss factor; frequency dependence; moisture content; grain; seed; fruits; vegetables; poultry products

Dielectric properties (electrical characteristics) of agricultural products have been of interest for many years (Nelson 2006). One of the earliest applications of such electrical properties was the study of dc electrical resistance of grain for rapidly determining its moisture content. In later work with radio-frequency (RF) measurements, changes in the capacitance of sample-holding capacitors, when grain samples were introduced between the capacitor plates, were correlated with grain moisture content and used for grain moisture measurement. The subsequent development of electrical grain moisture meters has been described in earlier reviews (Nelson 2006).

Use of dielectric properties of grain for moisture measurement has been the most prominent agricultural application for such data. In the early work, no quantitative data on the dielectric properties of the grain were reported. Interest generally focused on the influence of a grain sample on the response of an electrical circuit, and the instrument readings were calibrated with values measured by standard procedures for moisture determination. The need for quantitative values of the dielectric properties arose from research on the application of RF dielectric heating to agricultural problems. The first quantitative data on the dielectric properties of grain were reported for barley along with a method for reliable measurement of those properties in the 1- to 50-MHz frequency range (Nelson *et al.* 1953). Quantitative dielectric properties data, obtained for similar reasons, were soon reported in Russia for wheat and other grain and crop seeds (Knipper 1959). Extensive measurements on grain and crop seed in the 1- to 50-MHz range, taken over a decade of research on RF dielectric heating applications, were summarized and made available for use in electric moisture meter design and other applications (Nelson 1965).

The other principle application for dielectric properties of agricultural materials has been for use in research on potential dielectric heating applications. One of these was the possible selective dielectric heating for control of insects that infest stored grain (Nelson & Whitney 1960; Nelson 1996).

The dielectric properties, or permittivity, of a material determine the interaction of that material with electric fields. Dielectric properties have been previously defined and discussed in detail from an electrical circuit viewpoint (Nelson 1965) and in terms of electromagnetic field concepts (Nelson 1973). For practical use, the dielectric properties of usual interest are the dielectric constant and the dielectric loss factor, the real and imaginary parts, respectively, of the relative complex permittivity, $\varepsilon = \varepsilon' - j\varepsilon'' = |\varepsilon|e^{-j\delta}$ where δ is the loss angle of the dielectric. In this article, "permittivity" is understood to represent the relative complex permittivity, i.e., the permittivity relative to free space, or the absolute permittivity divided by the permittivity of free space, $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m. Often, the loss tangent, $\tan \delta = \varepsilon''/\varepsilon'$, or dissipation factor, is also used as a descriptive dielectric parameter, and sometimes the power factor ($\tan \delta / \sqrt{1 + \tan^2 \delta}$) is used. The ac conductivity of the dielectric in S/m is $\sigma = \omega\varepsilon_0\varepsilon''$, where $\omega = 2\pi f$ is the angular frequency, with frequency f in Hz. The dielectric constant of a material is associated with the energy storage capability in the electric field in the material and the loss factor is associated with the energy dissipation, conversion of electric energy to heat energy in the material. In this article, ε" is interpreted to include the energy losses in the dielectric due to all operating dielectric relaxation mechanisms and ionic conduction.

The principles governing the interaction between materials and RF and microwave electric fields, as influenced by the dielectric properties, have been detailed in a recent review article (Nelson 2006). The same article included a review of principles and techniques for dielectric properties measurements at frequencies ranging from audio frequencies through radio frequencies well into the microwave region. The purpose of this paper is to present dielectric properties data for a number of agricultural products and to discuss some of the related applications.

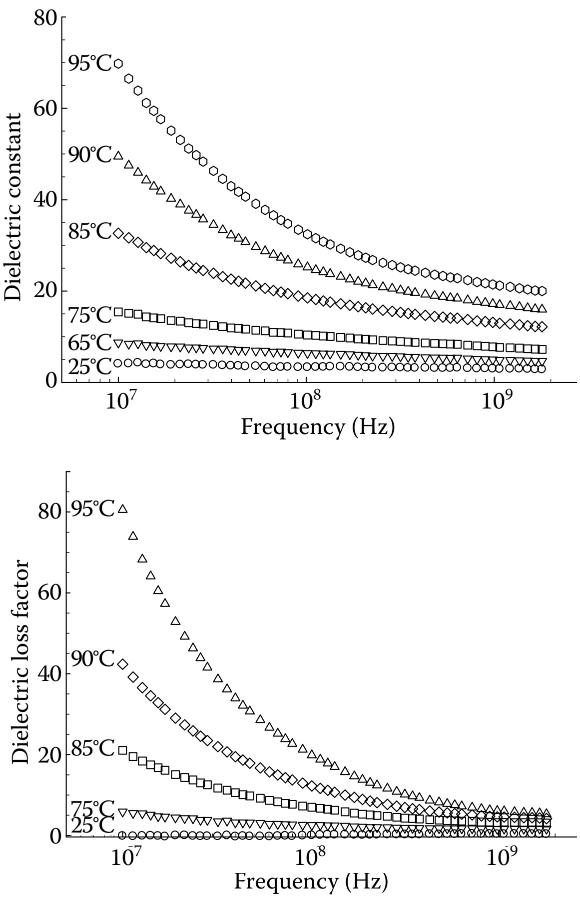

Figure 1. Frequency dependence of the dielectric properties of ground hard red winter wheat of 11.2% moisture content at 0.8 g/cm^3 density and indicated temperatures over the frequency range from 10 MHz to 1.8 GHz (Nelson & Trabelsi 2006)

Cereal grains and oilseeds

Dielectric properties of grain and seed over wide ranges of frequency and moisture content have been summarized previously, and graphical and tabular data are available for reference (ASAE 2000). Models for calculating dielectric constants of many cereal grains and soybeans as functions of frequency, moisture content, and bulk density have been reported (Nelson 1987; Kraszewski & Nelson 1989; ASAE 2000). Some recent dielectric spectroscopy measurements (Nelson & Trabelsi 2006) on ground hard red winter wheat at frequencies from 10 to 1800 MHz over the temperature range from 25 to 95°C are shown in Figure 1. The earlier reported data were useful to those developing improved grain and seed moisture meters. The recent measurements (Figure 1) were part of a study to improve understanding of the temperature dependence of grain permittivity.

Although grain moisture meters, which sense the moisture content through correlations between the RF dielectric properties of the grain and its moisture content, have been in common use for more than 50 years, recent advances have been reported in use of higher frequencies in the microwave range for grain and seed moisture sensing. The basis for one such application is illustrated in Figure 2. Here, the dielectric constant and loss factor of hard red winter

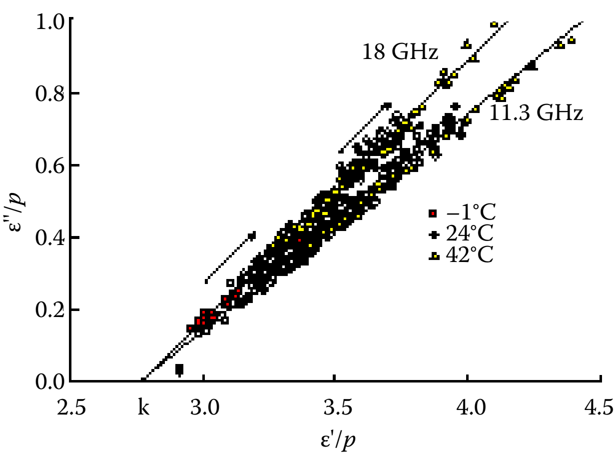

Figure 2. Complex-plane plot of the dielectric constant, ε', and loss factor, ε", divided by bulk density, ρ, for hard red winter wheat of various moisture contents and bulk densities at indicated temperatures for two frequencies, 11.3 and 18.0 GHz (Trabelsi *et al.* 1998)

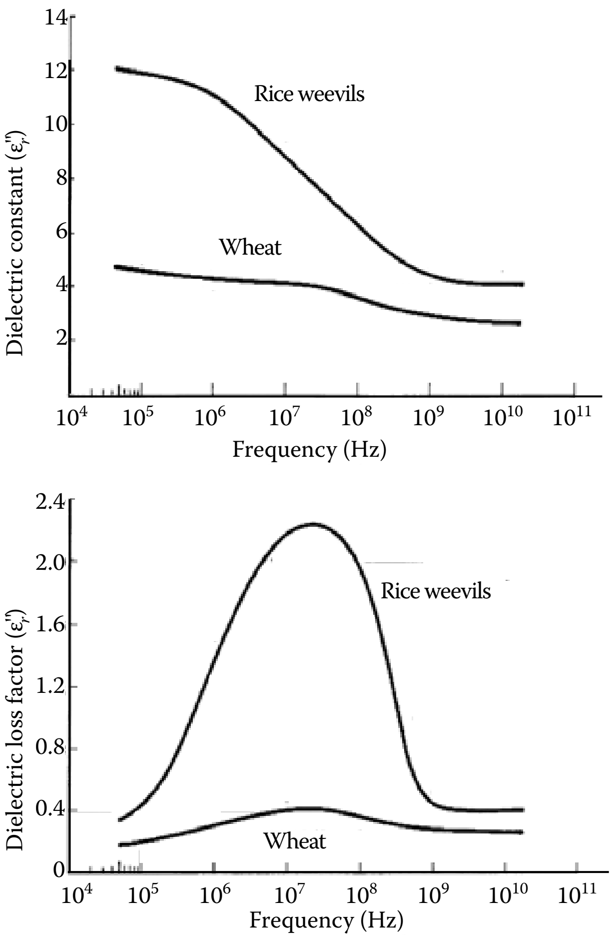

Figure 3. Variation with frequency of the dielectric properties of bulk samples of adult rice weevils and wheat at 24°C from 50 kHz to 12 Ghz (Nelson 1996)

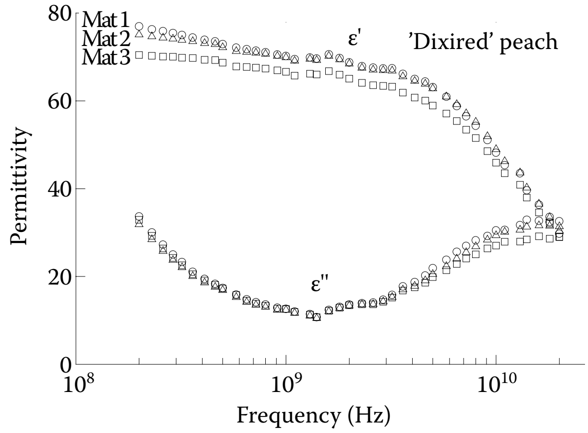

Figure 4. Frequency dependence of the dielectric properties at 23°C of 'Dixired' peaches at first, second and third stages of tree-ripe maturity (Nelson *et al.* 1995)

wheat, each divided by bulk density ρ of the grain, are plotted in the complex plane. Note that, at a given frequency, all of the points, regardless of frequency and temperature, lie along a straight line. The slope of the line increases with frequency and pivots about a point on the $\varepsilon''/\rho = 0$ axis that represents the ε'/ρ value for completely dry grain. The equation of the straight line provides a means for determining the bulk density of the grain independent of moisture content and temperature and also provides a basis for sensing moisture content independent of density and temperature from the measured permittivity at a single frequency (Trabelsi *et al.* 1998). This microwave sensing technique should be useful for monitoring moisture content in moving grain and other particulate materials, since it offers a density-independent method for sensing moisture content in granular and particulate materials.

Another application for dielectric properties of grain was involved in the study of high-frequency dielectric heating for the selective heating of stored-grain insects (Nelson 1996). In this instance, the dielectric properties of hard red winter wheat and a common stored-grain insect, the rice weevil, *Sitophyluls oryzae* L., were measured over a broad range of frequencies and compared to determine the frequencies for optimally heating the insects. Results of that study are summarized in Figure 3. Because the loss factor is the dominant characteristic determining the energy absorption and heating, the frequency range between about 10 and 100 MHz provides the best opportunity for selective heating of the insects.

Fruits and vegetables

Because of the need for rapid nondestructive quality measurements for fresh fruits and vegetables, the dielectric properties of a few products were measured at microwave frequencies (Nelson 1980, 1983, 1992). Although these studies provided background data on dielectric properties of several fruits and vegetables, the measurements did not show any promise for detecting peach maturity or hardcore condition in sweet potatoes by measurements at single frequencies (Nelson 1980). Therefore, broadband permittivity measurements were initiated to study the dielectric properties of several fruits and vegetables over the frequency range from 200 MHz to 20 GHz (Nelson *et al.* 1994). Measurements over the same frequency range were obtained for tree-ripened peaches, *Prunus persica* (L.) Batsch., of different maturities (Nelson *et al.* 1995). Differences in the dielectric properties for different stages of maturity were noted at particular frequencies as shown in Figure 4. Permittivity-based maturity indices, which combined the dielectric constant values at 200 MHz and the loss factor values at 10 GHz, were

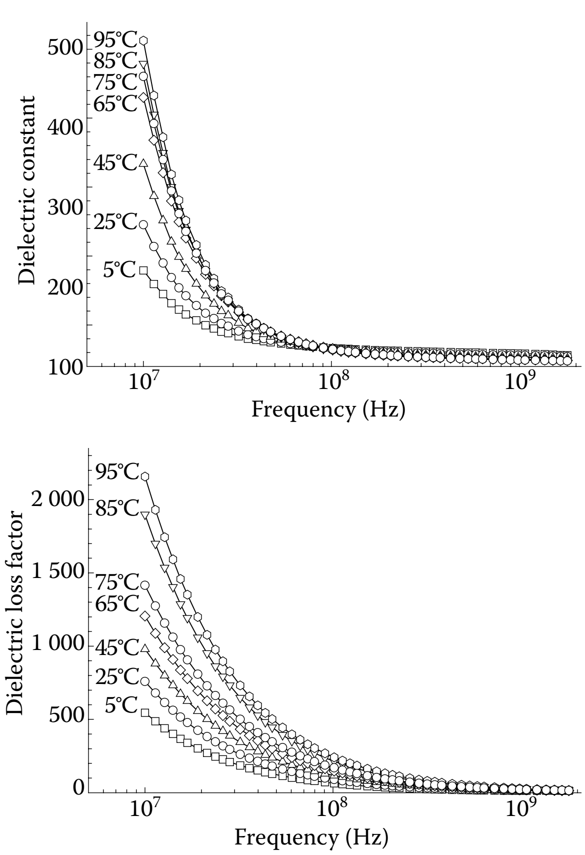

Figure 5. Frequency and temperature dependence of the permittivity of avocado, *Persea americana* Miller var. Americana, at indicated temperatures (Nelson 2003)

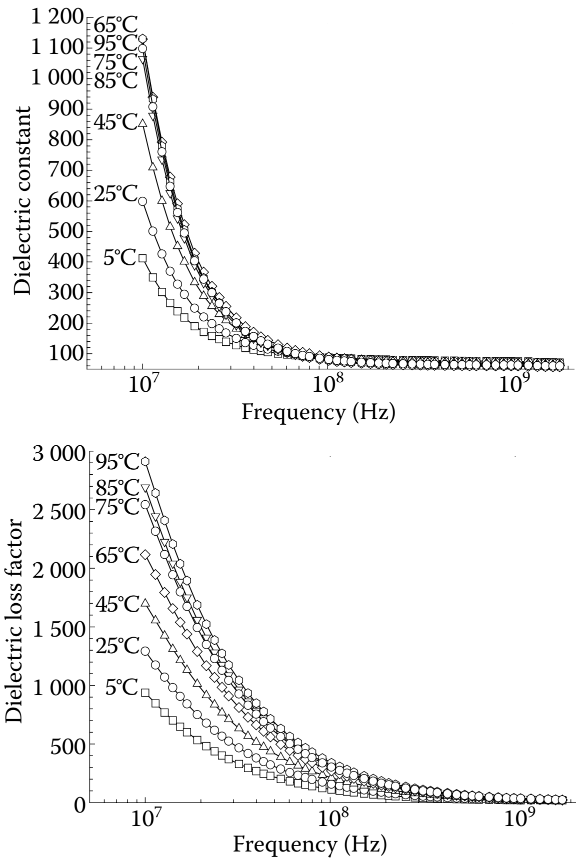

Figure 6. Frequency and temperature dependence of the permittivity of carrot, *Daucus carota* subsp. sativus (Hoffm.) Arcang, at indicated temperatures (Nelson 2003)

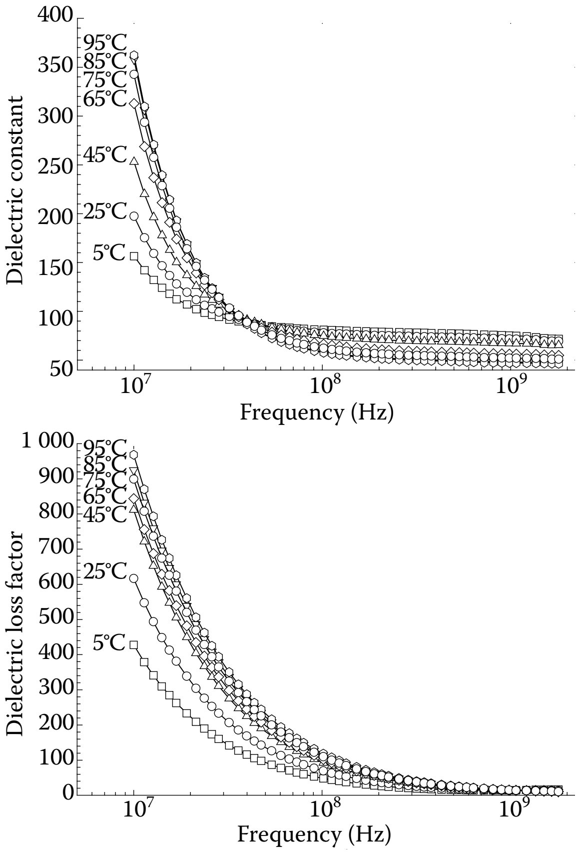

Figure 7. Frequency and temperature dependence of the permittivity of navel orange, *Citrus aurantium* subsp. *bergamia*, at indicated temperatures (Nelson 2003)

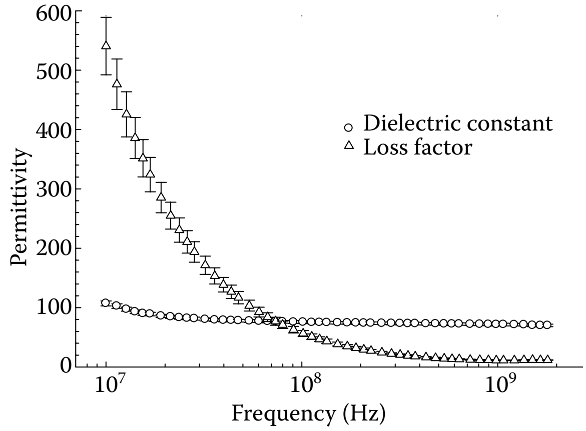

Figure 8. Frequency dependence of the dielectric properties of a honeydew melon (Nelson *et al.* 2007)

suggested, but it was noted that much more work was needed to establish their practicality.

Because the dielectric constants of peaches at different maturities diverged at the lower end of the frequency range shown in Figure 4, it appeared worthwhile to explore the dielectric behaviour of some fruits and vegetables at frequencies somewhat below this range (Nelson 2003). Also, because changes in the dielectric properties of materials are important in RF and microwave heating, temperature-dependent data were obtained. Some examples of permittivity data obtained in the frequency range from 10 MHz to 1.8 GHz over the temperature range from 5°C to 95°C are shown in Figures 5 to 7 (Nelson 2006).

In Figures 5 to 7, the temperature dependence of the dielectric constant disappears at some frequency in the range shown. Above that frequency, the temperature coefficient for the dielectric constant is negative, but below that frequency the temperature coefficient is positive. This is most likely the frequency above which dipole relaxation accounts for most of the energy loss and below which ionic conduction is the dominant loss mechanism. That frequency is about 100 MHz for the avocado and carrot, but it is about 40 MHz for the navel orange tissue.

It should also be noted that as temperature increases at the lower frequencies, the dielectric constant of avocado and navel orange tissue increases in regular fashion, whereas that for carrot tissue peaks at 65°C and then decreases slightly as temperature increases to 95°C. The increase in the loss factor with temperature at lower frequencies is regular for all three materials.

Dielectric properties of freshly harvested melons have been studied to determine whether useful correlations exist between their dielectric properties and sweetness, as measured by soluble solids content (Nelson *et al.* 2006, 2007). The measured permittivities for honeydew melons are shown in Figure 8, where error bars indicate plus and minus one standard deviation for 6 measurements on internal tissue of a melon. The same data are shown in Figure 9 in a log-log plot, which reveals a linear relationship for the loss factor between 10 and about 500 MHz and confirms the dominant influence of ionic conduction in that frequency range. Similar permittivity values for internal tissue measurements on watermelon are shown in Figure 10, and measurements on the surface of the watermelons are shown in Figure 11. Measurements on internal tissue and those on the surface are quite different. A broad dielectric relaxation was noted for the surface measurements, which probably can be attributed to the influence of bound water and a complex combination of Maxwell-Wagner and ion-related phenomena. Although interesting correlations were obtained relating dielectric properties and soluble solids in complex-plane plots, correlations for predicting melon sweetness from the dielectric properties have so far not been successful (Nelson *et al.* 2007).

Dielectric properties of apples were recently measured and studied to determine whether they might be useful in sensing quality of stored apples (Guo *et al.* 2007a). The permittivity values of internal tissues obtained for three different cultivars are shown in Figure 12, and those for surface measurements on

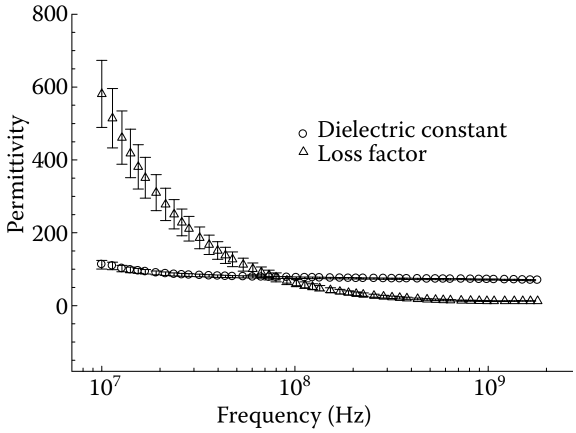

Figure 10. Mean values of dielectric properties from six probe measurements on internal watermelon tissue (Nelson *et al.* 2007)

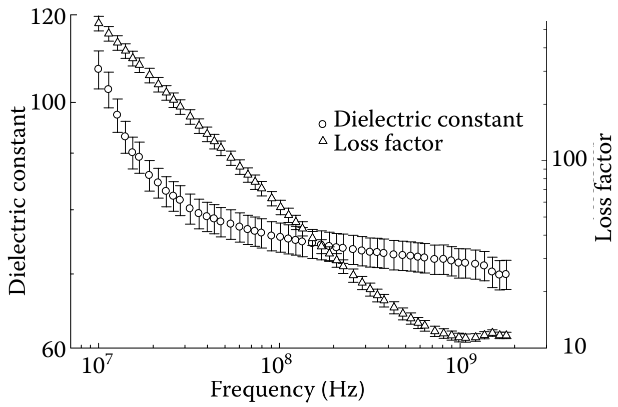

Figure 9. Log-log plot of the frequency dependence of honeydew melon dielectric properties (Nelson *et al.* 2006)

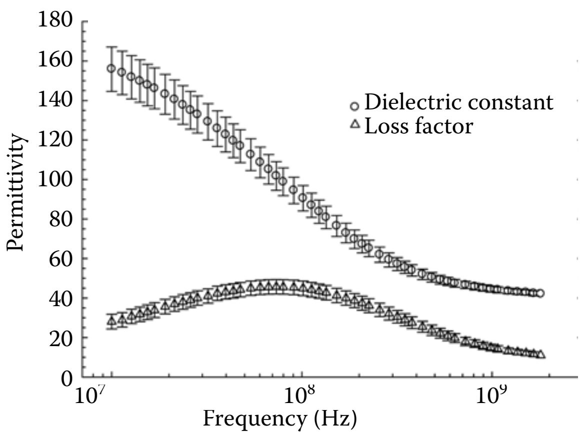

Figure 11. Mean values of dielectric properties from four probe measurements on the surface of a watermelon (Nelson *et al.* 2007)

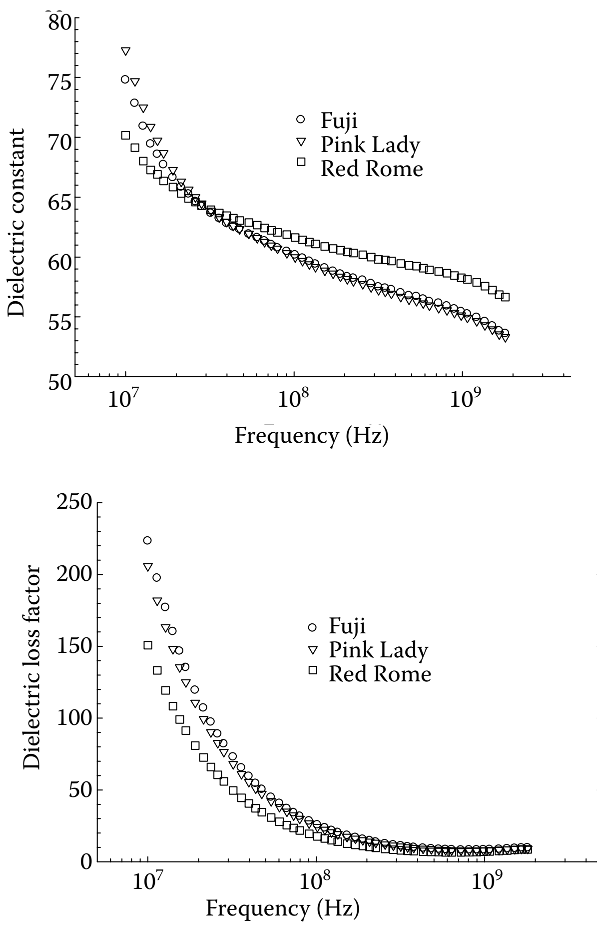

Figure 12. Comparison of dielectric properties from internal tissue measurements on three apple cultivars (Guo *et al.* 2007a).

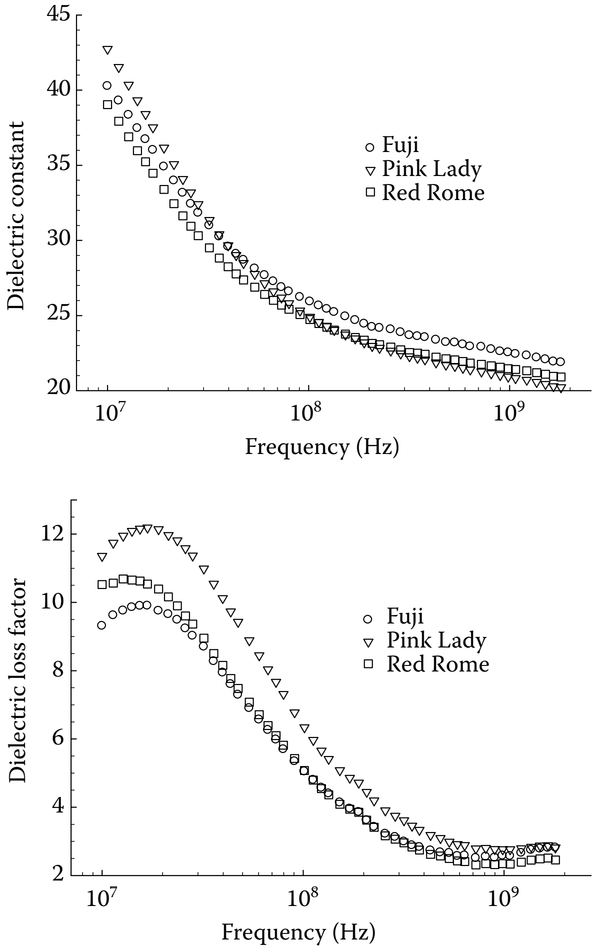

Figure 13. Comparison of dielectric properties from external surface measurements on three apple cultivars (Guo *et al.* 2007a)

the apples are shown in Figure 13. Considerable differences were noted among the three cultivars. These surface measurements also exhibited the dielectric relaxation phenomenon noted in surface measurements on watermelons, and are most likely related to the exocarp structure of the fruit. Dielectric properties of the apples remained relatively constant during the 10-week refrigerated storage period.

Dielectric properties of a commercial apple juice product were also measured over the 200-MHz to 20-GHz frequency range (Nelson & Bartley 2002). Because of the high water content of the apple juice, the dielectric relaxation of liquid water is clearly evident in Figure 14. The temperature dependence of the dielectric properties of the apple juice at the higher frequencies is also very similar to that of pure

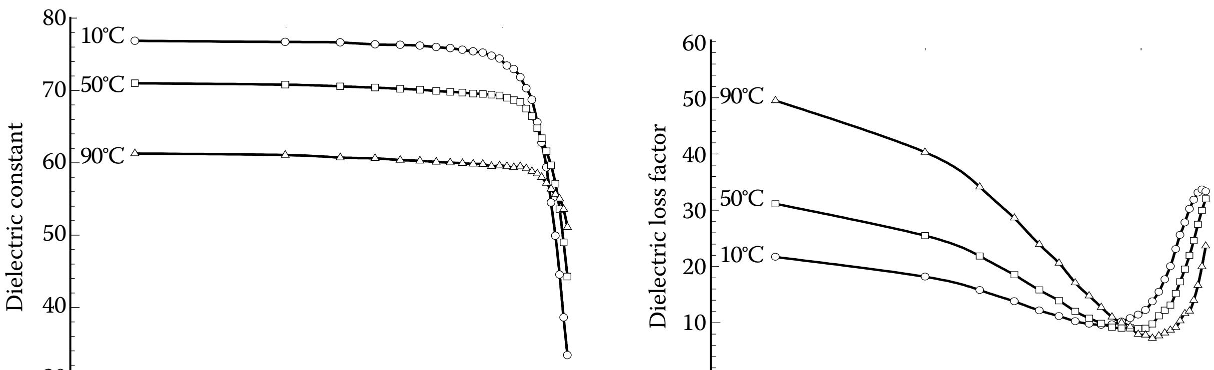

Figure 14. Frequency dependence of the dielectric properties of apple juice at indicated temperatures (88.5% water)

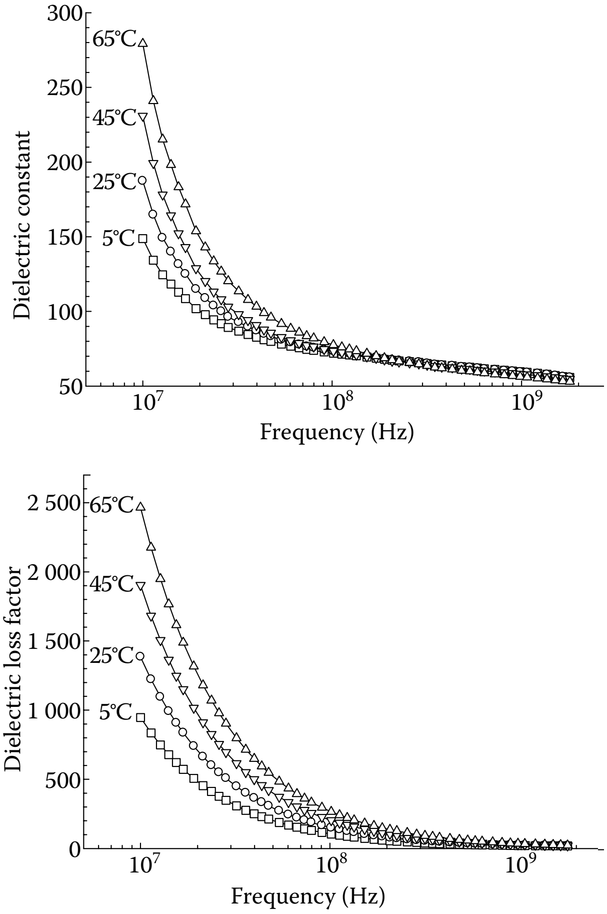

Figure 15. Frequency and temperature dependence of the dielectric properties of fresh chicken breast meat, *P. major,* deboned at 2 h postmortem (Zhuang *et al.* 2007)

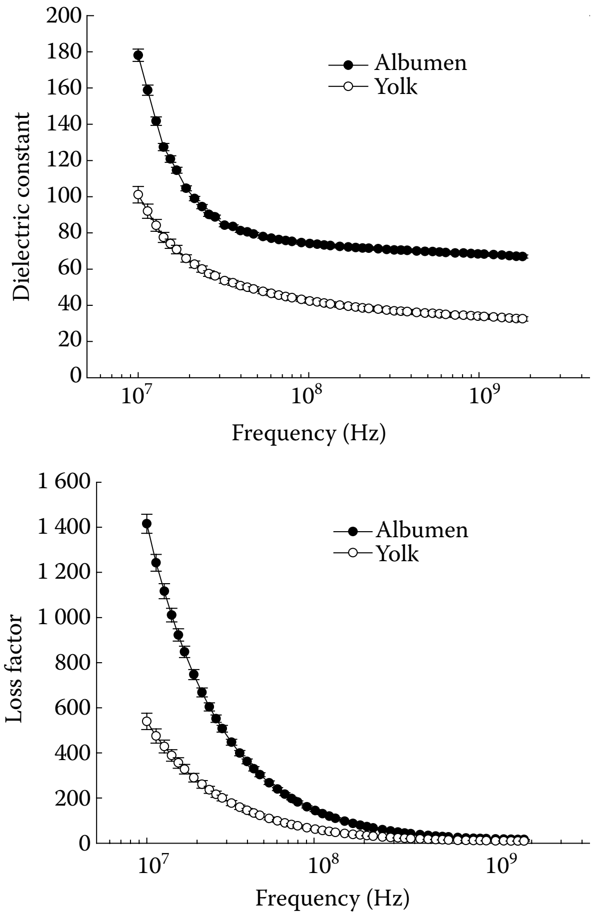

Figure 16. Frequency dependence of the loss factor of fresh egg albumen and yolk at 24°C; error bars indicate ± one standard deviation (Guo *et al.* 2007b)

liquid water, with the relaxation frequency for pure water shifting from below 20 GHz to higher frequencies as temperature increases (Hasted 1973).

Poultry products

Some dielectric spectroscopy measurements have been taken recently on poultry products in exploratory work on quality sensing (Zhuang *et al.* 2007). Dielectric properties values for fresh chicken breast meat in the 10 to 1800-MHz frequency range at temperatures from 5°C to 65°C are shown in Figure 15. These curves show frequency dependence of the dielectric properties similar to those for tissues of fruits and vegetables. Probable potential for using dielectric properties to assess meat quality characteristics was indicated.

Dielectric spectroscopy measurements were also taken on the albumen and yolk of fresh chicken eggs at weekly intervals during 5 weeks of storage (Guo *et al.* 2007b). Dielectric properties from 10–1800 MHz for the fresh eggs are shown in Figure 16, where the albumen has higher values for both the dielectric constant and loss factor than the yolk at any given frequency. Dielectric properties changed during the storage period, but they did not correlate well with traditional quality factors for the eggs.

SUMMARY

The importance and usefulness of the dielectric properties of agricultural products are discussed briefly, pointing out their use in the rapid sensing and measurement of moisture content in grain and seed and in governing the behaviour of materials subjected to RF and microwave electric fields for dielectric heating applications. Sources of information on the dielectric properties of such products are provided, and values of the dielectric constants and loss factors are presented graphically for a number of products, including grain, fruits and vegetables, and poultry products. These examples provide information not only on typical values of the dielectric properties, but also on their dependence on such variables as frequency of the alternating fields applied, moisture content

and temperature of the products. A few additional applications for dielectric properties information are also discussed briefly.

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Abstrakt

Nelson S.O. (2008): **Dielektrické vlastnosti zemědělských produktů a některé jejich aplikace.** Res. Agr. Eng., **54**: 104–112.

Je stručně diskutováno použití dielektrických vlastností pro detekci vlhkosti zrna a semen a využití těchto poznatků pro radiofrekvenční a mikrovlnný ohřev. Hodnoty dielektrických vlastností několika produktů, včetně zrna a semen, ovoce a zeleniny, drůbežích produktů (masa a vajec) jsou uvedeny graficky s cílem ukázat závislosti těchto vlastností na frekvenci použitých vln a vlhkosti a teplotě produktů. Jsou diskutovány také možnosti užití dielektrických vlastností k určení jiných faktorů kvality produktů než je jejich vlhkost.

Klíčová slova: permitivita; radiové frekvence; mikrovlny; reálná složka relativní permitivity; ztrátový faktor; frekvenční závislost; vlhkost; zrno; semena; ovoce; zelenina; drůbeží produkty

Corresponding author:

Prof. Stuart O. Nelson, U.S. Department of Agriculture, Agricultural Research Service, Richard B. Russell Agricultural Research Center, Athens, Georgia, USA 30604-5677
e-mail: sonelson@qaru.ars.usda.gov