MEASURING DIELECTRIC PROPERTIES OF FRESH FRUITS AND VEGETABLES

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Introduction

Interest in the dielectric properties of agricultural products has been associated with only a few applications [1]. These have included the sensing of moisture content in grain [2], radio-frequency and microwave dielectric heating for pest control [3-5], seed treatment [6], product conditioning [7-9], remote sensing of crop condition [10], and potential uses for quality measurements other than moisture content [11, 12].

In this paper, the term "permittivity" implies the relative complex permittivity, i.e., the permittivity of a material relative to free space, sometimes called the complex dielectric constant, expressed as $\varepsilon = \varepsilon' - j\varepsilon''$, where ε' is the dielectric constant and ε'' is the dielectric loss factor. Here, all loss mechanisms, both those due to dipole relaxation and ionic conduction, are included in the dielectric loss factor ε''.

In connection with quality sensing in fruits and vegetables, the dielectric properties of mature-green and full-ripe peaches at 2.45 GHz were examined to see whether these properties might be useful in distinguishing degree of maturity [11]. The same kind of measurements were taken on normal sweet potatoes and those that had a hard-core condition induced by chilling injury in storage [11]. Permittivity measurements at the single frequency of 2.45 GHz did not appear to offer promise for detecting either of these quality factors. Following permittivity characterization measurements for twenty-three kinds of common fresh fruits and vegetables over the frequency range from 200 MHz to 20 GHz at 23 °C [13, 14], similar measurements were taken over a narrow range of peach maturity, and evidence was obtained for possible distinction of degree of maturity [12]. A permittivity-based maturity index was suggested, based on differences in both components of the permittivity, the dielectric constants at the low end of the frequency range and the loss factors at 10 GHz near the higher end of this frequency range. More research and developmental work was recommended for determining the potential for practical use of the technique, including measurements at frequencies lower than 200 MHz, since the curves for the dielectric constants of the two different maturities appeared to be diverging as they approached the lower end of the frequency range.

The objectives of the study being reported were to explore the frequency dependence of the dielectric properties of a few fruits and vegetables at frequencies below 200 MHz, and to obtain data on the temperature dependence of these properties as well, which are of interest in microwave heating and processing of such products. Permittivity measurements on a few different fruits and vegetables are presented here for background information on the variation of the dielectric constant and loss factor with both frequency (10 MHz to 1.8 GHz) and temperature (5 to 95 °C).

Materials and Methods

A few samples of nine different fresh fruits and vegetables were obtained at local grocery stores as needed for these measurements to study the variation of permittivity with temperature and frequency in the range from 10 MHz to 1.8 GHz. They included apple, avocado, banana, cantaloupe, carrot, cucumber, grape, orange, and potato.

The electrical measurements necessary for permittivity determination were obtained with an open-ended coaxial-line probe, an impedance analyzer, and a temperature-

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controlled stainless steel sample cup and water jacket assembly, designed and built for use with the probe [15]. Permittivities (dielectric constants and loss factors) were calculated with appropriate software that provided permittivity values from the reflection coefficient of the material in contact with the active tip of the probe [16].

Sample temperature control was provided by circulating water through the jacket surrounding the sample cup from a constant temperature circulator with a digital control module. Sample cup temperature was monitored with a thermocouple thermometer and a small thermocouple in the thin sidewall of the sample cup [15].

Prior to measuring fruit samples, some check measurements were run on a liquid of well-known dielectric properties, methanol [17]. Measured values for the dielectric constant agreed with the reference values within about 1 percent, and the loss factor values were very close as well. These values were well within the typical 5% accuracy specified by the manufacturer of the probe. Previous test measurements on distilled water showed that proper permittivity values were obtained at temperatures above and below 25 °C.

Samples to fit snugly in the 18.95-mm diameter stainless steel sample cup for efficient heat transfer were obtained from slices of the fruit about 1.5 cm thick with stainless steel cork-borer-type sample cutters fabricated for the purpose. If the fruit slice did not have parallel faces, the sample could be trimmed with a sharp knife using the cutting edge of the sample cutter as a guide to provide a right rectangular cylindrical sample for measurements.

Results and Discussion

The variation of the dielectric properties of samples from these fruits and vegetables with frequency and temperature were plotted as shown, for example, for avocado tissue in Fig. 1. The data shown were selected as typical of data obtained on several samples and show the general consistent trends. Both the dielectric constant and loss factor show monotonic decreases in value as frequency increases, which was true for all the fruits and vegetables. Trends with temperature were not so consistent. For example, at the lowest frequency, the dielectric constant and the loss factor both increased monotonically with temperature for the avocado (Fig. 1), cantaloupe, cucumber, and orange tissues. For apple, banana, carrot, grape, and potato, the dielectric constant increased as the temperature increased from 5 °C to 65 or 75 °C and then decreased as temperature continued to increase, probably as a result of some cooking action.

Tabular data for the permittivity of all nine fruits and vegetables are shown for a temperature of 25 °C at frequencies of 10 and 100 MHz and 1 GHz in Table 1.

Table 1. Permittivities of fresh fruits and vegetables at indicated frequencies at 25 °C

Fruit or Vegetable	10 MHz		100 MHz		1 GHz	
	ε’	ε”	ε’	ε”	ε’	ε”
Apple	109	281	71	33	64	10
Avocado	245	759	66	89	56	14
Banana	166	834	76	91	65	18
Cantaloupe	260	629	70	72	63	14
Carrot	598	1291	87	157	72	23
Cucumber	123	361	80	39	77	9
Grape	122	570	78	60	73	13
Orange	197	617	78	69	72	14
Potato	183	679	73	77	62	16

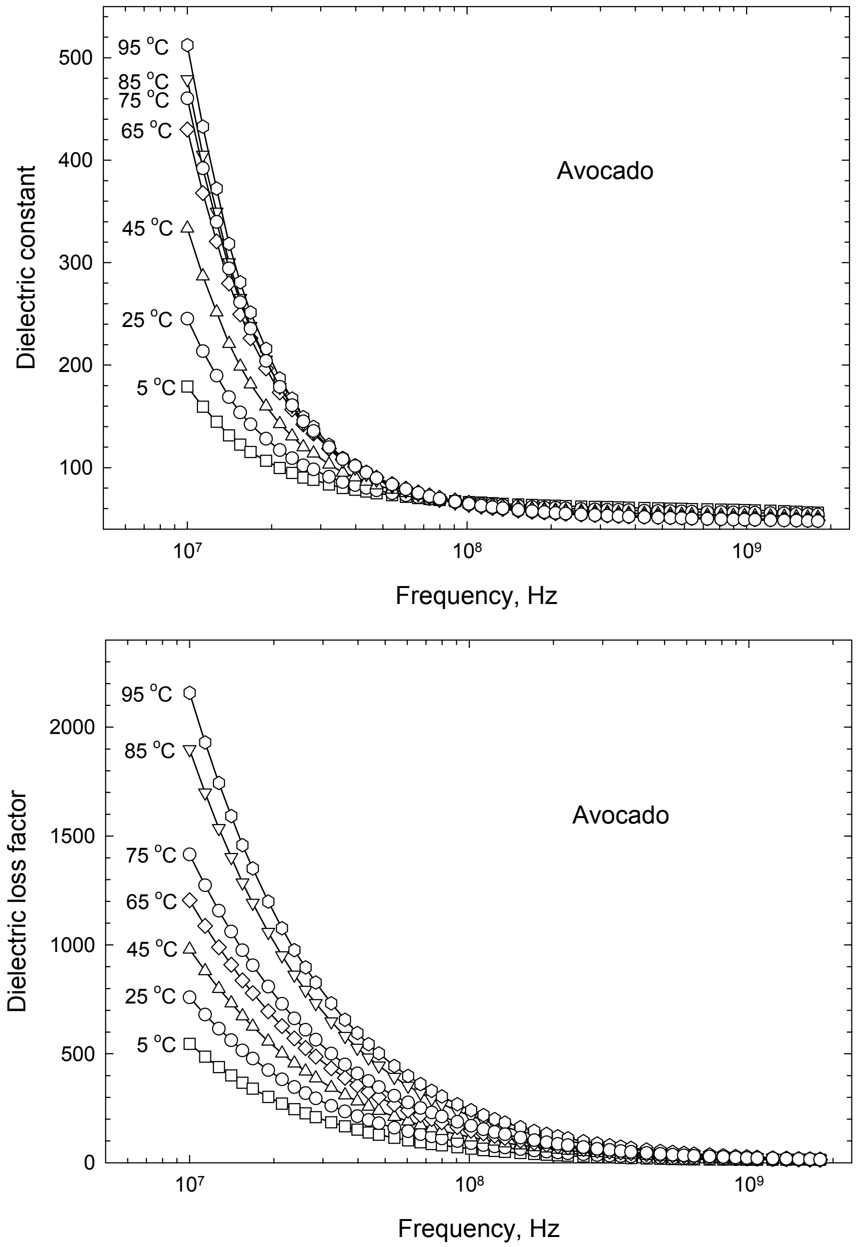

Figure 1. Frequency and temperature dependence of avocado permittivity

The very high values for ε' at the lower end of the frequency range are no doubt attributable to the polarization contributed by ionic conduction, while the behavior of ε' at the higher end of the frequency range is characteristic of dipolar relaxation. It is evident in Fig. 1 that at about 90 MHz the temperature dependence of ε' disappears, and the ionic conduction becomes the dominant mechanism influencing the value of ε' below that frequency. This phenomenon was noted for all the fruits and vegetables at some frequency in the 10- to 100-MHz range.

Data in Table 1 show considerable variation among the different fruits and vegetables. Both real and imaginary parts of the permittivity are particularly large for carrot tissue at the lower frequencies, but these differences largely diminish at microwave frequencies.

The new frequency and temperature dependence permittivity data provide information that can be useful in understanding the behavior of such materials exposed to radio-frequency and microwave dielectric heating. They also provide background information that may be useful in studies aimed at sensing fruit and vegetable quality through measurements that utilize the dielectric properties of these kinds of agricultural products.

Conclusion

The temperature and frequency dependence of the dielectric properties of fruits and vegetables can be efficiently measured with an open-ended coaxial-line probe, network analyzer, and suitable sample temperature control instrumentation. Measurements of the permittivities of samples cut from nine different fresh fruits and vegetables over the frequency range from 10 MHz to 1.8 GHz at temperatures ranging from 5 to 95 °C revealed dielectric constants decreasing from values of several hundred at 10 MHz to less than 100 at 1.8 GHz. Dielectric loss factors of several hundred to a few thousand in value at 10 MHz decreased regularly to much less than 100 at 1.8 GHz. The dielectric constants generally increased with temperature at lower frequencies in this range but decreased with temperature at higher frequencies. Loss factors generally increased with increasing temperature. For fruit and vegetable tissue samples, there was a point in the region between 10 and 100 MHz, where temperature dependence of the dielectric constant was minimal. At frequencies below this point, ionic conduction dominated the dielectric behavior, and at higher frequencies, dielectric relaxation losses were dominant. These measurements provide new information concerning the frequency- and temperature-dependent behavior of the dielectric properties that may be useful in dielectric heating applications and as background material in exploring the dielectric properties of fruits and vegetables for potential new quality sensing applications.

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