ABSTRACT: Honeydew melons were grown and harvested with a range of maturities for measurement of tissue permittivities (dielectric constant and loss factor) to study possible correlations between the dielectric properties and soluble solids (sweetness) for nondestructive sensing of maturity. Permittivities of tissue samples from 38 melons were measured at 25°C over the frequency range from 10 MHz to 1.8 GHz along with refractometer determinations of soluble solids content (SSC), tissue density, and moisture content. A high correlation ($r = 0.96$) was found between SSC and the permittivity as expressed in a complex-plane plot of the two components of the relative complex permittivity, each divided by SSC. Through this mathematical relationship, SSC can be calculated from measured permittivity values independent of tissue density and moisture content. Moderate correlations were noted between dielectric constant and SSC at 10 MHz and between the loss factor and SSC at 1.8 GHz. Correlations between the dielectric properties and both moisture content and tissue density were very low. The correlation between tissue density and SSC was also very low. A high correlation was noted between SSC and moisture content, with SSC decreasing as moisture content increased. Problems in using the high correlation between permittivity and SSC for practical, nondestructive sensing of honeydew melon maturity as determined by SSC are also considered.

Keywords. Dielectric constant, Dielectric properties, Honeydew melons, Loss factor, Permittivity, Quality sensing, Soluble solids content.
18 August 2005, and measurements were taken on four melons each on those dates and on the remaining melons over the four days immediately following those harvest dates. Melons not measured on the harvest date were held at 4°C and removed from refrigerated storage the night before they were needed for measurements to equilibrate to about 25°C.

PERMITTIVITY MEASUREMENTS

The electrical measurements necessary for permittivity determination were obtained with a Hewlett-Packard 85070B open-ended coaxial-line probe, a Hewlett-Packard 4291A impedance/material analyzer, and a temperature-controlled, stainless-steel sample cup and water jacket assembly (fig. 1) designed and built for use with the 85070B probe (Nelson et al., 1997). Permittivities (dielectric constants and loss factors) were calculated with Agilent Technologies 85070D dielectric probe kit software, modified for use with the HP 4291A analyzer by Innovative Measurement Solutions, which provided permittivity values from the reflection coefficient of the material in contact with the active tip of the probe (Blackham and Pollard, 1997). Settings were made to provide measurements at 51 frequencies on a logarithmic scale from 10 MHz to 1.8 GHz. The 4291A analyzer was calibrated with an open, short, and matched load prior to the calibration of the open-ended coaxial-line probe with measurements on air, a short-circuit block, and glass-distilled water at 25°C. A personal computer was used to control the system and record resulting data.

PROCEDURES

Samples for measurements of the melon tissue were all taken from an equatorial slice, about 3 cm thick, cut with a sharp knife from the center of the melon perpendicular to the proximal-to-distal axis. From this slice, three cylindrical core samples were cut for the dielectric properties measurements, as shown in figure 2. Less variability in soluble solids content was expected for this orientation of the sample than for a sample with its axis in the radial direction (Peiris et al., 1999). Three more samples adjacent to the first samples were taken for moisture content determination. Moisture contents were determined by drying the triplicate samples in disposable 57-mm aluminum weighing dishes that were placed in a forced-air drying oven for 24 h at 70°C. Upon removal from the oven, the weighing dishes with samples were cooled in a desiccator over anhydrous CaSO₄ prior to reweighing for determination of moisture loss.

Samples were cut from the equatorial melon slice with a cylindrical cutter (Nelson, 2003) that provided samples of 18.6-mm diameter that fit well into the stainless-steel sample cup in the water jacket assembly. This provided rapid heat transfer for temperature control. The samples were held at 25°C for all of the permittivity measurements. Immediately after cutting the sample, the sample length was measured with a dial caliper and the sample was weighed on an analytical balance to determine its mass. Tissue density was then calculated from the mass and dimensions of the right circular cylindrical sample. From this sample, a length of about 1.5 cm was cut for insertion into the sample cup, and the sample cup and water jacket assembly was raised to bring the sample into firm contact with the open-ended coaxial-line probe for the permittivity measurements (Nelson, 2003). When that measurement was completed, the sample was removed, turned end for end, and reinserted into the sample holder for permittivity measurements on the other end of the sample. Thus, with measurements on each end of the three samples, six series of permittivity measurements at 51 frequencies from 10 MHz to 1.8 GHz were obtained to be averaged for each melon.

Upon removal from the sample holder, each sample was placed in a 1 oz. (30 mL) glass jar with screw-on cap and held a few hours for soluble solids content determination. The measurements of soluble solids were determined with an Atago Pallete Series model PR101 digital refractometer. Melon samples were placed in a garlic press with cheesecloth patches of several layers to strain the juice expelled for the refractometer measurements. Five readings were taken for each sample, and the composite soluble solids content determination for each melon was a mean of 15 readings.
RESULTS AND DISCUSSION

Typical results for the frequency dependence of the dielectric constant and loss factor for a honeydew melon are shown in figure 3, where mean permittivity values are plotted for the six measurements and the error bars show ±1 standard deviation. Figure 4 shows the same data plotted on a log-log scale, where the linear relationship between the log of frequency and the log of the loss factor is evident, as noted earlier for other fresh fruits and vegetables at frequencies where the ionic conduction is the dominant loss mechanism (Nelson, 2005).

To examine the correlations between dielectric properties and the soluble solids content (SSC) of the 38 different melons tested, eight frequencies were selected with nominal values of 10, 20, 40, 100, 200, 400, 1000, and 1800 MHz. These were selected to cover the total frequency range with reasonably uniform spacing on the logarithmic frequency scale. Then linear regressions were run for all 38 melons at each frequency. Correlations were low for both the dielectric constant and the loss factor at most frequencies, but the results for the highest correlation coefficients (r = 0.60 and 0.72) are shown in figures 5 and 6, respectively. These two values represent the dielectric constant at the lowest frequency measured (10 MHz) and the loss factor at the highest frequency (1.8 GHz), respectively. Larger differences in dielectric constant at lower frequencies and larger differences in loss factor at higher frequencies were noted with respect to maturity in peaches for which permittivities were measured from 200 MHz to 20 GHz (Nelson et al., 1995).

Correlations of dielectric constant and loss factor with moisture content were very low, since the moisture contents were quite uniform (between 89% and 94%, wet basis). Correlation of dielectric constant and loss factor with tissue density (ranging from 0.91 to 0.98 g/cm³) was also very low, as was the correlation between density and SSC. A high correlation was observed between SSC and moisture content (r = 0.92), and this is shown in figure 7. This relationship could be expected because, in a given melon, the SSC (percent of sugars) will be higher as the moisture content decreases, resulting in a higher concentration of sugars.

The correlations shown in figures 5 and 6 may not be high enough to justify attempts at sensing quality through these individual properties in honeydew melons at these frequencies, 10 MHz and 1.8 GHz. However, the use of a complex-plane plot of the dielectric constant ($\varepsilon'$) and the loss factor ($\varepsilon''$), each divided by SSC, shows a much higher correlation, $r = 0.96$ at 1.8 GHz (fig. 8). Thus, by combining the real and imaginary parts of the complex relative permittivity in such a plot, the soluble solids content may be
obtained from the values of $\varepsilon'$ and $\varepsilon''$ alone in the same way that density is provided by such plots for granular materials (Trabelsi et al., 1997, 1998). Use of the complex-plane plot for the two permittivity components, divided by the variable of interest, reveals the interchangeability of moisture content and temperature. For wheat and other grain and seed, bulk density is provided independent of moisture content and temperature (Trabelsi et al., 1997; Trabelsi and Nelson, 2006). Because of the interchangeability of moisture and temperature in their influence on permittivity plots in the complex plane, the SSC in melons will also most certainly be provided independent of moisture content and temperature. Referring to figure 7, the equation of the straight line can be written as:

$$\frac{\varepsilon^*}{s} = a_f \left( \frac{\varepsilon'}{s} - k \right)$$

where $s$ represents soluble solids content, $a_f$ is the slope of the line, and $k$ is the ($\varepsilon'/s$) = 0 intercept. Values for the regression constants $a_f$ and $k$ are provided by the regression calculation. Therefore, solving equation 1 for $s$ provides SSC in terms of the dielectric properties as:

$$s = \frac{a_f \varepsilon' - \varepsilon^*}{a_f k}$$

At a given frequency, slope $a_f$ and $k$ are constants for a given material. Therefore, SSC is dependent only on the two measured components of permittivity. The dependence of these permittivity components on temperature and moisture content will be taken into account when they are measured. Thus, determining $\varepsilon'$ and $\varepsilon''$ by any measurement technique makes it possible to predict soluble solids content based on the high correlation represented in figure 8. This would be most useful, because SSC is expected to be provided by equation 2 independent of temperature, tissue density, and moisture content.

There are challenges to be overcome for practical use of this correlation for nondestructive measurement of SSC. The principle problem is the attenuation of waves used in sensing the dielectric properties from an external source. This attenuation is described by the attenuation constant ($\alpha$) in terms of the dielectric properties as follows:

$$\alpha = \frac{2\pi}{\lambda_0} \sqrt{\frac{\varepsilon'}{2} \left[ 1 + \left( \frac{\varepsilon^*}{\varepsilon'} \right)^2 \right] - 1} \text{ nepers/m} \quad (3)$$

where $\lambda_0$ is the free-space wavelength. For expression of attenuation in decibels per cm, $\text{dB/cm} = 0.08686 \times \text{nepers/m}$. Therefore, the attenuation to be expected in honeydew melon tissue was calculated with the measured dielectric constant and loss factor data for the lower and upper frequencies of the range used in these measurements. The resulting attenuation at 10 MHz and 1.8 GHz was 0.9 dB/cm and 7.1 dB/cm, respectively. Thus, signal penetration, as expected, would be about 8 times better at the lower frequency. The depth of penetration, $l/(2\alpha)$, is about 5 cm at 10 MHz and about 6 mm at 1.8 GHz. However, the best correlation ($r = 0.96$) was obtained at the highest frequency, 1.8 GHz, as illustrated in figure 8. The correlation coefficient for a plot similar to figure 7 at 10 MHz was only 0.76. Thus, it remains to be determined whether sufficiently high correlations may be achieved at lower frequencies or whether sufficient penetration can be achieved for practical purposes at the higher frequencies.

**CONCLUSIONS**

The permittivities (dielectric constant and loss factor) of mature honeydew melon tissue have been measured at 25°C over the frequency range from 10 MHz to 1.8 GHz along with refractometer determinations of soluble solids content (sweetness), and tissue density and moisture content. A high correlation was noted between soluble solids content (SSC) and the permittivity as expressed in a complex-plane plot of the two components of the relative complex permittivity, each divided by SSC. Through this mathematical relationship, SSC can be calculated from measured permittivity values independent of tissue density and moisture content. Moderate correlations were noted between dielectric constant and SSC at 10 MHz and between loss factor and SSC at 1.8 GHz. Correlations between the dielectric properties and both moisture content and tissue density were very low. The correlation between tissue density and SSC was also very low. A high correlation was noted between SSC and moisture content, with SSC decreasing as moisture content increased. Problems in using the high correlation between permittivity and SSC for practical nondestructive sensing of honeydew melon quality as determined by SSC were also considered.
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