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Determination of soluble solids content and firmness of pears during ripening by using dielectric spectroscopy

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ABSTRACT

To investigate the feasibility of dielectric spectroscopy as a nondestructive technique in determining soluble solids content (SSC) and firmness of pears during ripening period, the dielectric constants and dielectric loss factors of 105 "Dangshansu" pears with different maturities were obtained at 201 discrete frequencies from 20 MHz to 4500 MHz with an open-ended coaxial-line probe and a vector network analyzer. The joint *x*–*y* distances sample set partitioning (SPXY) method was applied to divided all samples into calibration set (70 pears) and prediction set (35 pears). Nineteen and 13 characteristic variables were extracted for SSC and firmness, respectively, from the full dielectric spectra by using successive projection algorithm. The nonlinear model, i.e., least squares support vector machine, extreme learning machine (ELM) and generalized regression neural network, and linear models, i.e., multiple linear regression and partial least squares regression, were used to establish SSC and firmness determination models based on the full dielectric spectra and extracted characteristic variables by SPA. Results showed that SPA-ELM was the best model for SSC and firmness prediction, with the correlation coefficient and root-mean-square error of prediction set of 0.838 and 0.464 for SSC, and of 0.865 and 0.362 for firmness. The study indicates that dielectric spectroscopy combined with artificial neural network might be applied in developing portable SSC and firmness detectors of intact pears during on-tree ripening.

1. Introduction

Appropriate harvest is important for offering fruits with good quality. Too early harvest makes the fruits have lower sugar content and worse flavor, since sugars content and flavor increase while total acids decrease during late ripening (Etienne et al., 2002; Vizzotto et al., 1996). However, too late harvest makes the fruits have light flavor and soft flesh, leading to losses in the marketing chain. Although the skin color of many fruits can indicate the degree of ripeness, for pear, its skin color changes very little during on-tree ripening. It is very difficult to determine the pear maturity based on skin color. Therefore, evaluation of pear ripeness is an important issue in pear industry. The assessment of ripeness, a major part of quality evaluation, depends on several factors such as soluble solid content (SSC), firmness, acidity, sugars, organic acids, ethylene rate, and color (de Oliveira et al., 2014). For pear, SSC and firmness are the most important internal quality attributes (Nicolaï et al., 2008). The traditional method used to measure fruit SSC requires juice extracted from the fruit pulp, and is carried out by using digital refractometer or Abbe refractometer. The firmness is usually measured by a penetrometer to penetrate fruit flesh to a depth. These traditional methods can offer precise measurement results, but they are destructive. There is a need for nondestructive techniques for the assessment of internal quality attributes to instruct pear planting and harvesting.

The SSC and/or firmness have been determined on pears using near-infrared spectroscopy (Blanke, 2013; Cavaco et al., 2009; Fan et al., 2014; Li et al., 2013; Liu and Ying, 2007; Ying and Liu, 2008). However, all of these studies applied the postharvest pears as samples. Few reports have been noted on predicting internal qualities of pears during ripening before harvest. Dielectric properties of materials are those electrical properties that determine the interaction of the materials with electric fields. Dielectric spectroscopy is a rapid, easy, and nondestructive detection technique that can be a suitable substitute for traditional methods. It has been applied in determining some qualities of foods, such as protein content in milk (Zhu et al., 2015), fat content in meat (Ng et al., 2008), sucrose or sugar content in honey (Guo et al., 2011a, 2010b), water content in milk, legume, and cheese, etc. (Fagan et al., 2005; Guo et al., 2010a; Zhu et al., 2013). At present, no clear linear correlation between permittivities at a single frequency and an internal quality attribute has been noted in either external surface measurements or internal tissue measurements in apples

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(Guo et al., 2011b), watermelons (Guo et al., 2008; Nelson et al., 2007), peaches (Guo and Chen, 2010), honeydew melon (Nelson et al., 2006), and cantaloupes (Guo et al., 2008). Nelson et al. (1995) indicated that a permittivity-based maturity index, the ratio of the loss tangents at 10 GHz and 0.2 GHz, could be used to distinguish peach maturity (Nelson et al., 1995). Shang et al. (2013) applied dielectric spectroscopy to predict SSC of postharvest nectarines, and reported that SSC of nectarines could be predicted based on obtained dielectric spectra. However, to our knowledge, no attempt has been made to predict the SSC and firmness of pears during ripening using dielectric spectroscopy.

In this study, pears during ripening were used for permittivity (dielectric constant and dielectric loss factor) measurements over the frequency range from 20 to 4500 MHz, along with the measurement of SSC and firmness of pears. Dielectric spectroscopy technique combined with modeling methods were used to predict the SSC and firmness. The specific aims of this research are (1) to select the characteristic dielectric variables from full spectra (FS) of permittivities by using successive projections algorithm (SPA); (2) to develop different models to quantitatively predict SSC and firmness; and (3) to assess the feasibility of dielectric spectroscopy technique in determining SSC and firmness of intact pears with different maturities.

2. Materials and methods

2.1. Pears

Pears, variety 'Dangshansu', one of the most famous pear cultivars planted in China widely, were picked at about 15-day intervals from August 5 to September 22, 2013, from a local orchard, located at 34°21′ north latitude, 108°10′ east longitude, and at an elevation of 455 m in Yangling, Xi'an, Shaanxi Province, China. The sampling dates were August 5, August 22, September 6, and September 22, 2013. At each sampling time, more than 30 pears were randomly picked from the pear orchard in the afternoon the day before measurement. After the pears were washed with tap water to remove any foreign materials on surface, they were kept at room temperature (22 ± 2 °C) and allowed to equilibrate overnight. About 25 pears with regular shape, without damage or defects, were measured at each sampling time. Totally, 105 pears were used in the study.

2.2. Dielectric properties measurements

The system used to acquire dielectric spectra consisted of an E5071C vector network analyzer, an 85070E open-ended coaxial-line probe, 85070 dielectric probe kit software (Agilent Technologies, Penang, Malaysia), a computer and a laboratory jack. The schematic diagram of the dielectric properties measurement system is shown in Fig. 1. The dielectric constant ε' and dielectric loss factor ε'', real and imaginary parts, respectively, of the complex permittivity relative to free space $\varepsilon = \varepsilon' + j\varepsilon''$ are the principal permittivities used in this study. They were calculated from the reflection coefficient of the material in contact with the active tip of the coaxial-line probe (Blackham and Pollard, 1997). Settings were made to provide measurements at 201 discrete frequencies on a logarithmic scale from 20 MHz to 4500 MHz. It means that there were two dielectric spectra, i.e., dielectric constant spectrum and dielectric loss factor spectrum, for each sample. Therefore, each sample had 402 values of permittivities, including 201 dielectric constant values and 201 dielectric loss factor values. In this study, the 201 dielectric constant values were numbered from 1 to 201, and the other 201 dielectric loss factors were numbered from 202 to 402 when the frequency increased from 20 to 4500 MHz. The permittivity data for each sample was a 402-dimensional vector.

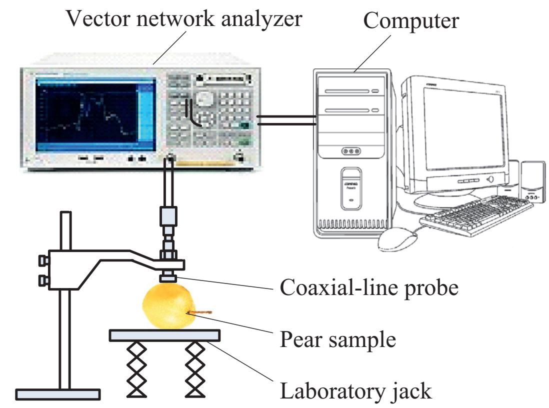

Fig. 1. The schematic diagram of the dielectric properties measurement system.

2.3. Determination of firmness and soluble solids content

The pear pulp firmness was measured with a GY-3 fruit penetrometer (Sundoo Instruments, Zhejiang, China) with an 8-mm-diameter penetrometer tip. Before measuring the tissue firmness, a peeler was used to remove the peel in the equatorial region of pear to a depth of about 2 mm. An even force was applied to the penetrometer tip to penetrate the pear pulp. When the probe advanced into the tissue to the required scale, the force was removed, and the force gage reading, in kg/cm^2, was recorded.

Soluble solids content, being mostly sugars (i.e., 80–85%) in fruits, was used as a measure of sugar content, and was determined from measurements on juice, which was expressed from pear pulp in a garlic press with cheesecloth patches. A digital refractometer (Model PR101a, Atago Co. Ltd., Tokyo, Japan) was used to measure SSC. The refractometer readings are frequently referred to as °Brix readings, which are expressed in percent total soluble solids by weight (Nelson, 2003).

2.4. Procedures

The E5071C network analyzer was warmed up for at least 1 h for stabilization, followed by calibrating with an open, short, and matched load in sequence at the port used for the dielectric properties measurement. Then the network analyzer and the 85070E open-ended coaxial-line probe were connected with a cable for the probe. The probe was calibrated using air, short-circuit, and 25 °C deionized water. A measurement was made on 25 °C deionized water to verify that proper permittivity values were being obtained.

The permittivity measurements of intact pears were made with the probe in firm contact with the surface of pears, supported by a laboratory jack, in the equatorial region at four points about 90° apart around the perimeter of the fruit. Firm contact implies the elimination of any air gaps between the probe and the fruit measured without application of force to otherwise deform or bruise the fruit pulp.

After completion of the permittivity measurements on intact pears, the firmness and SSC were measured on four points where the dielectric properties were measured. The means of repeated measurements for dielectric constant, dielectric loss factor, firmness and SSC values of each pear were calculated and used in the study.