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Prediction of tomato firmness using spatially-resolved spectroscopy

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ABSTRACT

This paper reports on evaluating the firmness of tomato fruit using a newly developed spatially-resolved spectroscopy (SRS) system with an illumination optic fiber and 30 detection optic fibers arranged at the source-detector distances of 1.5–36 mm. Spatially-resolved (SR) spectra of 550–1650 nm were acquired for 600 'Sun Bright' tomatoes at six maturity stages. The firmness of tomatoes was measured using acoustic/impact, compression and puncture tests. Partial least squares (PLS) models for individual SR spectra and their combinations were developed to determine optimal prediction models for the firmness parameters. The results indicated that firmness predictions varied with the light source-detector distance or SR spectra, and the optimal single spectrum was different for prediction of different firmness parameters. Those spectra acquired for the light source-detector distances of 6–24 mm resulted in better prediction results. Combinations of SR spectra gave consistently better predictions for the multiple firmness parameters than the optimal single SR spectra, with the correlation coefficients (r_p) of 0.760 and 0.911 for acoustic and impact measurement, r_p = 0.935 for compression, and r_p = 0.917, 0.948 and 0.859 for puncture maximum force, slope and flesh firmness. Overall, the SRS technique gave excellent predictions of firmness parameters for impact, compression and puncture tests that measured the local properties of tomato tissues, and combinations of SR spectra improved prediction results.

1. Introduction

Firmness of fresh tomatoes is a significant quality attribute that is of primary concern to the consumer, and it is also an important parameter in assessing tomato maturity, postharvest quality and shelf life (Hertog et al., 2004; Wu and Abbott, 2002). Like many parameters used for describing the textural properties of food, the term firmness is not a well-defined parameter, and it generally reflects the aggregate response of a whole fruit or a tissue section when subjected to a complicated form of mechanical load, which may involve compression, shearing and bending. Hence, over the years, researchers and practitioners have used different destructive and nondestructive techniques for measuring firmness of fruit like tomato. The Magness-Taylor (MT) puncture test is probably the most frequently used method for firmness evaluation, because it correlates well with the human's perception of firmness during the biting of a piece of fruit (Lu, 2013). The force/deformation curve is recorded during the MT test, as the probe punctures the sample for a specific depth, from which maximum force, along with other firmness parameters such as slope, is extracted as firmness measurements (Ali et al., 2010; Hertog et al., 2004; Pinheiro et al., 2013). The MT test, however, destroys the structural integrity of tomatoes, which is undesirable or unpractical in such applications as maturity assessment and quality inspection and monitoring during postharvest handling and storage and marketing. To overcome this main shortcoming, several nondestructive mechanical techniques have been developed and used for firmness evaluation for different application purposes. Quasi-static compression is a commonly used method, which primarily measures the turgor pressure or elasticity of tomatoes by applying two parallel plates to the whole fruit with small levels of deformation (usually less than 3% strain), such that no tissue failure would occur during the test (Barrett et al., 1998; He et al., 2005; Sirisomboon et al., 2012). Impact measurement is another nondestructive method for assessing fruit firmness; it records the response of a fruit subjected to a short pulse of force, in either time or frequency domain, which is sensitive to the elasticity of the local fruit tissue (De Ketelaere et al., 2006; Delwiche, 1987; Slaughter et al., 2009). The acoustic test is another firmness measurement method, which records the dynamic response of a fruit when subjected to an impact or sinusoidal vibration of different frequencies, from which resonant frequencies are extracted for estimating the fruit firmness (De Ketelaere and De Baerdemaeker, 2001b; Molina-Delgado

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et al., 2009; Zhang et al., 2014). Acoustic firmness measurements are related to the global elastic properties of the fruit and influenced by the mass and shape of the fruit (Lu and Abbott, 1997; Lu and Abbott, 1996). Other nondestructive mechanical techniques, such as relaxation and creep, have also been used for tomato firmness assessment (Barrett et al., 1998; Wu and Abbott, 2002).

These mechanical methods, either destructive or nondestructive, are based on different principles for firmness measurement, and each has its own limitations and therefore is not suited for all application purposes. Moreover, few studies have been reported on the correlations among the different firmness methods, which are expected to be variable or even low. Hence, it would be helpful to determine how these firmness measurement methods correlate with each other. More importantly, it would be highly desirable to have a new nondestructive method that can correlate well with these destructive and nondestructive methods for tomato firmness measurement. Recent studies have demonstrated that visible and near-infrared (Vis/NIR) spectroscopy provides an excellent tool for evaluating quality and composition of food products such as fruit, because it provides a large amount of data about the interaction of light with the tissue of food and biological materials over a wide spectral range (Clément et al., 2008; Nicolai et al., 2007). Vis/NIR technique has been reported for nondestructive measurement of tomato firmness (Kim et al., 2013; Shao et al., 2007; Sirisomboon et al., 2012). The technique is fast and requires no sample preparation. However, conventional Vis/NIR technique has limitations because it only acquires an aggregate amount of light reemitted from a specific area of samples without providing spatially resolved information. Fruit such as tomato are heterogeneous in structure and composition, consisting of cuticle, pericarp, septa, columella, placenta, seeds, and locular gel. Single-point Vis/NIR measurement is unable to provide accurate or comprehensive information about structural or compositional variation. It is well known that firmness is related to the cell turgor, intercellular space, cell wall components, and spatial arrangement of polymer constituents of the cell wall structure (Clément et al., 2008), and it varies with depth of tissue layers and tissue orientation and location (Abbott and Lu, 1996). Hence spatially-resolved measurement could be advantageous and is also desirable for assessment of tomato firmness.

Spatially-resolved spectroscopy (SRS) measures reflectance at different spatial distances resulting from a point light source that impinges on the sample, thereby enabling acquisition of information from the sample at different depths or distances from the illumination point. The technique has been used for measuring optical absorption and scattering properties of food products (Herremans et al., 2013; Qin and Lu, 2008; Xia et al., 2008b). While most reported studies on SRS have attempted to predict quality of food samples by using the optical absorption and scattering properties derived from the spatially-resolved reflectance, only a few considered using individual spatially-resolved (SR) spectra for quality assessment. Lu and Ariana (2002) applied an NIR spectrometer coupled with a specially designed detection probe with two optic fibers to obtain SR spectra for apple fruit at the source-detector distances of 3.5 mm and 5.5 mm, and they reported that the prediction results for firmness and soluble solids content (SSC) were influenced by source-detector distance. Do Trong et al. (2014) compared the prediction results of apple SSC and firmness between SR spectra and optical absorption and scattering spectra, which were acquired using a five-fiber SRS configuration at the source-detector distances of 0.3 mm–1.2 mm. They reported that only fiber 2 with a source-detector distance of 0.45 mm resulted in SSC and firmness prediction results comparable to those obtained using absorption spectra. These studies suggested that SRS could be advantageous for assessing the condition and properties of tissues at different depths or when the products to be measured are heterogeneous in structure and composition. Several configurations of SRS, in the form of single optic fiber, multiple optic fibers or hyperspectral imaging, have been developed (Cen, 2011; Herremans et al., 2013; Hu et al., 2017; Xia et al., 2008a); however, the SR spectra acquired by these systems are generally limited to within 10 mm source-detector distances, due to strong light attenuation in biological tissues. Moreover, the fiber-based SRS systems generally use flat, rigid detection probes, which are only suitable for samples with flat surface or limited to a very short distance from the light source. Many intact food products such as fruit are of irregular shape or curved surface, which would present challenges in the data acquisition and analysis with existing SRS measurement systems.

Recently, a new SRS system was developed (Huang et al., 2017), which enables acquiring 30 SR reflectance spectra of 550–1650 nm from samples with either flat or curved surface at the source-detector distances of 1.5–36 mm. The SRS system is designed for measuring optical absorption and scattering properties, and it can also be used for assessing quality of food samples using individual spatially resolved spectra. The overall objective of this research was therefore to assess firmness of tomatoes using this newly developed SRS system, with the following specific objectives:

- acquire SR reflectance spectra of tomatoes at different maturity stages over the spectral range of 550–1650 nm;
- measure the firmness of tomatoes using multiple mechanical techniques including acoustic/impact, compression and puncture, and determine correlations among the different firmness parameters; and
- develop partial least squares (PLS) regression models based on individual SR spectra and their combinations, and compare the PLS models for prediction of firmness parameters.

2. Materials and methods

2.1. Samples

A total of 600 tomatoes, 100 samples each of six maturity stages [green, breaker, turning, pink, light-red and red (USDA, 1991)], were hand picked from an experimental field at Michigan State University Horticultural Research and Teaching Center (Holt, MI, USA) in August 2016. SR spectra were acquired for each tomato sample using the SRS system over the spectral region of 550–1650 nm. Firmness of the samples was then measured in sequence, using acoustic/impact, compression, and puncture tests.

2.2. SR spectra measurement

SR spectra for each tomato sample were acquired using a specially designed SRS system, which was developed based on a multichannel hyperspectral imaging instrument (Model 1003B-10152, Headwall Photonics, Inc., Fitchburg, MA, USA). The multichannel hyperspectral imaging instrument consists of an imaging spectrograph, a Vis-InGaAs camera covering the spectral region of 550–1650 nm, 35 200-μm detecting fibers and associated optical hardware. Fig. 1 shows a schematic of the SRS system, which is comprised of a 910 nm illumination fiber and 30 light receiving fibers of three sizes (i.e., 50 μm, 105 μm and 200 μm) arranged in pair with symmetry to the illumination fiber over the source-detector distances of 1.5 to 36 mm. A detailed description of the SRS system and calibration procedure is given in Huang et al. (2017). The SRS probe was in direct contact with the equatorial region of tomato samples during the measurement. Thirty SR spectra were taken from the two opposite sides of each sample, and symmetric pairs of spectra were averaged, resulting in 15 spectra for further analysis. Following the same procedure, SR spectra were also acquired for a white cylindrical Teflon block of 50.5 mm height and 80 mm diameter as references for correcting sample spectra.