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Quality assessment of tomato fruit by optical absorption and scattering properties

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ABSTRACT

This paper reports on the measurement of optical properties of tomato fruit over the wavelength range of 550–300 nm by means of a spatially-resolved diffuse reflectance technique, for assessing the firmness, soluble solids content (SSC) and pH. Spatially resolved diffuse reflectance spectra of 600 'Sun Bright' tomato samples harvested at six maturity stages were acquired using a newly developed spatially resolved spectroscopy (SRS) system, from which the reduced scattering (μ'_s) and absorption (μ_a) coefficients were estimated using an inverse algorithm for the diffusion theory model. Tomato firmness was measured using two reference methods, i.e., compression and puncture, while SSC and pH were measured using the standard refractometry and pH meter. Partial least squares (PLS) models were developed, based on μ'_s, μ_a and their combinations, for predicting the three quality parameters. While both μ'_s and μ_a were correlated with tomato firmness, SSC and pH, better prediction results were obtained for the multiplication of μ'_s and μ_a (i.e., $\mu_a \times \mu'_s$) except for puncture maximum force. PLS models gave good predictions of compression maximum force and puncture maximum force, slope and flesh firmness, with the correlation coefficients of 0.894, 0.915, 0.923, 0.835, respectively, while they had poor predictions of tomato SSC and pH with the correlation coefficients of 0.623 and 0.769, respectively. This research demonstrated that the SRS technique, along with the absorption and scattering coefficients, has potential for nondestructive measurement of quality attributes, especially firmness, of tomato fruit.

1. Introduction

Tomato is one of the most consumed fruit vegetables in the world. High quality tomatoes should have good appearance (color and shape), desired texture, and appropriate flavor and aroma. Firmness, as an important measure of fruit texture, directly affects postharvest quality and shelf life, while soluble solids content (SSC) and acidity (pH) determine the flavor of tomatoes. Conventional methods for quality measurement include the Magness-Taylor (MT) puncture and quasi-test compression for firmness, the refractometer for SSC, and the pH meter for acidity (Flores et al., 2010; Pinheiro et al., 2013; Tigist et al., 2013). However, these methods (except quasi-static compression) need to destroy the fruit and are time consuming. Therefore, non-invasive techniques are desired for measuring tomato quality attributes.

Various nondestructive sensing techniques have been developed over the years for measuring different quality attributes of horticultural and food products, which include, but are not limited to, acoustic, ultrasonic, electrical, spectroscopic and imaging. Visible and near-infrared (Vis/NIR) spectroscopy is one of the most successful nondestructive techniques for measuring chemical constituents and quality attributes of fruits and vegetables (Nicolai et al., 2007; Pan et al., 2015). Several studies were reported on using Vis/NIR technique to assess quality attributes (e.g., firmness, lycopene content, SSC, and acidity) of tomato fruit (Clément et al., 2008; Flores et al., 2009; He et al., 2005; Huang et al., 2018). de Oliveira et al. (2014) found that NIR spectroscopy covering 1000–2500 nm was not appropriate to evaluate the SSC and titratable acidity of tomato, and they attributed the poor results to the low levels of SSC and acidity in the tomato samples as well as poor light penetration for the spectral region, which could not adequately assess the heterogeneous structure of tomatoes. Sirisomboon et al. (2012) reported better NIR predictions of tomato firmness than for SSC.

The interaction between the light and biological tissue is dependent on the absorption and scattering properties, which are, in turn, related to the chemical composition and tissue structure. This is the basis for

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Vis/NIR spectroscopy for quality assessment of food products. However, conventional Vis/NIR spectroscopy only provides information on the aggregate effect of absorption and scattering, and it cannot offer separate information on the absorption and scattering properties of biological tissues, which could limit its ability of assessing quality of food and horticultural products.

Several techniques based on light transfer theory have been developed for the measurement of absorption (μ_a) and reduced scattering (μ'_s) properties of turbid biological materials (Hu et al., 2018; Nichols et al., 2012; Zonios et al., 2010). They include time-resolved, frequency domain, and spatially resolved. Time-resolved and frequency domain techniques are less convenient in measurement and still expensive in instrumentation, and they usually cover a narrower spectral region due to the limited wavelength-tuning capability. Hence their applications to food products have been limited. Spatially resolved spectroscopy (SRS) measures reflectance at different distances resulting from the illumination of a point light source of constant intensity, from which the absorption and scattering coefficients can be estimated by using an inverse algorithm for the diffusion approximation model (Cen et al., 2016). Compared with time-resolved and frequency domain methods, SRS is less complicated in instrumentation and also covers a broader spectral region. Hence, the technique has received much attention in food and agriculture in recent years (Hu et al., 2015). Several SRS configurations have been developed for measuring optical properties of food products. Xia et al. (2008) used a single-fiber configuration operated in contact mode to acquire spatially resolved spectra for beef muscles, from which the optical absorption and scattering spectra were estimated for predicting beef tenderness. Herremans et al. (2013) and Do Trong et al. (2014) developed a fiber-array probe with five optic fibers for simultaneous acquisition of spatially resolved reflectance spectra for evaluating quality of fruit. A hyperspectral imaging-based spatially resolved technique was developed for measurement of optical absorption and scattering properties of food products (Cen et al., 2012, 2013; Qin and Lu, 2008; Qin et al., 2009; Zhu et al., 2015). This technique allows fast, simultaneous acquisition of spatially resolved spectra in high pixel resolution, and it has been used for predicting quality of several horticultural and food products (Qin et al., 2009; Zhu et al., 2015). Backscatter imaging technique is yet another SRS configuration for measuring optical properties and quality of fruit (Adebayo et al., 2017; Mollazade and Arefi, 2017). The technique is, however, limited to single or a few selected wavelengths. Imaging-based techniques, either single wavelength, multispectral or hyperspectral, offer some advantages (e.g., high spatial resolution, non-contact sensing mode, etc.) over the fiber-based contact measurement configurations.

All aforementioned SRS techniques are generally suitable for measuring food products with a relatively large flat surface. Problems will arise in measuring food products with curved or irregular surface, because the fiber-based probes are usually inflexible and cannot fit the sample well, while the imaging-based configurations do not need to contact the sample, the acquired spectral data would need be corrected for the effect of curved surface, which can be quite complicated. So far, these SRS systems only cover the wavelength range up to 1000 nm. Extension of the detection wavelengths beyond 1000 nm is desired in order to obtain more useful information about samples. The spectral region of 600–1300 nm, which is called 'diagnosis window' in the biomedical research, allows better interrogation of tissues at greater depth because the light in this spectral region has good penetration in biological tissues.

A new SRS system, which uses a multichannel hyperspectral imaging instrument as a platform, was recently developed for simultaneous acquisition of spatially resolved reflectance spectra from food samples over the wavelength range of 550–1650 nm (Huang et al., 2017). The system enables acquiring 30 spectra simultaneously over the distances of 1.5–36 mm, by using three different sizes of fibers arranged in a specific format. The SRS probe is flexible to accommodate food samples with either flat or curved surface. With proper calibration procedures, the SRS system can be used for measuring the optical properties of intact food samples for the spectral region of 550–1650 nm. The objectives of the current research were therefore to measure the absorption and reduced scattering properties of tomatoes using the newly developed SRS system over the spectral region of 550–1300 nm, and develop partial least squares regression models, based on the absorption coefficient, reduced scattering coefficient and their combinations, for predicting firmness, SSC and pH of tomato fruit.

2. Materials and methods

2.1. Samples

Six hundred 'Sun Bright' tomatoes, 100 each of the six maturity grades (i.e., green, breaker, turning, pink, light red, red) based on their surface color (USDA, 1991), were hand-picked from an experimental field at Michigan State University's Horticultural Research and Teaching Center in Holt, MI, USA in August 2016. Right after the samples had been transported to the laboratory, spectral measurements were taken for each tomato sample using the SRS system over the wavelength range of 550–1650 nm. Thereafter, the samples were evaluated for firmness, SSC and pH in sequential order. During the experiment, the samples were kept at room temperature (~24 °C) with no humidity control and the experiment was completed within 7 d of harvest.

2.2. Acquisition of spatially resolved reflectance spectra

Spatially resolved reflectance spectra for tomato fruit were acquired using the newly developed SRS system, as shown in Fig. 1. A detailed description of the SRS system and its calibration procedure is given in Huang et al. (2017). The SRS system was built by using a multichannel hyperspectral imaging instrument (Headwall Photonics, Inc., Fitchburg, MA, USA) as the platform. The multichannel hyperspectral imaging instrument consists of an imaging spectrograph, a Vis-InGaAs camera with a 14-bit frame grabber covering the spectral range of 550–1650 nm with a nominal spectral resolution of 4.85 nm, and associated optical hardware. It differs from conventional line-scanning hyperspectral imaging systems in that its entrance slit is mounted with 35 receiving fibers of 200 μm instead of an objective lens, which provide flexible arrangements for food quality assessment.

The SRS probe consists of a 910-μm fiber as a point light source and 30 light receiving fibers of three sizes (i.e., 50 μm, 105 μm and 200 μm) arranged in pairs with symmetry to the light source fiber over the spatial distances of 1.5 mm–36 mm, so as to obtain two replications for each measurement (Fig. 1b). The remaining five fibers of the multichannel system were not used, because the 30 fibers already cover a large distance. The use of the three sizes of fibers would enable obtaining better reflectance signals for a greater range of distances, because small fibers arranged at short distances are less likely to saturate, while the larger size fibers can acquire more signals at greater distances, which are often weak due to strong light attenuation in biological tissues. The illumination fiber and the 30 light receiving fibers are multimode fibers (Thorlabs, Inc., Newton, NJ, USA) with a numerical aperture (NA) of 0.22. The 30 fibers are permanently mounted on the individual metal blocks, which are bonded together using stretchable rubber bands so that they can be adjusted easily for maintaining good contact with the sample during measurement. The other ends of these detection fibers are connected to 30 of the 35 200-μm fibers with 0.22 NA, which are permanently connected to the entrance slit of the multichannel hyperspectral imaging system (Fig. 1). However, only 18 fibers over the spatial distances from 1.5 to 12.5 mm were actually used to analyze the absorption and reduced scattering properties of tomato fruit in this study, because the signal beyond 12.5 mm was too weak to be useful.