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Application of hyperspectral imaging for nondestructive measurement of plum quality attributes

Bo Li[a,*], Magdalena Cobo-Medina[a,b], Julien Lecourt[a], Nicola Harrison[a,c], Richard J. Harrison[a], Jeremy V. Cross[a]

[a] NIAB EMR, New Road, East Malling, ME19 6BJ, UK
[b] University of Nottingham, Sutton Bonington, LE12 5RD, UK
[c] Agriculture and Horticulture Development Board (AHDB), New Road, East Malling, ME19 6BJ, UK

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ABSTRACT

Colour, firmness and soluble solid content (SSC) are three important quality attributes of fruit that affect consumer acceptance. However, measurement of these attributes largely relies on destructive manual assessment, which is time consuming, and can only be applied to small number of batches. In this study, two hyperspectral cameras in the visible and near infrared (VNIR) regions between 600–975 nm and the short wave near infrared (SWIR) region between 865–1610 nm were evaluated for the non-destructive quantification of colour (L*, a* and b*), firmness and SSC. In total, images of 354 'Victoria' and 'Marjorie's Seedling' plums were collected for the calibration and validation of partial least square regression (PLSR) models. The performance of the prediction models was compared for both the cultivars alone and in combination. The effect of a light scattering correction on spherical objects was also investigated. This study showed that the SWIR hyperspectral imaging could accurately predict SSC with correlation coefficients for prediction (r_p^2) greater than 0.8, while VNIR hyperspectral imaging showed a better correlation with colour with r_p^2 values greater than 0.7 for L* and a*. This study shows that the use of hyperspectral imaging is feasible to non-destructively predict the SSC and the colour of two plums cultivars with high accuracy.

1. Introduction

Colour, soluble solid content (SSC) and flesh firmness are used to measure fruit ripeness, and are used by producers and retailers to schedule delivery of fruit consignments into the marketplace (García-Ramos et al., 2005). These quality parameters of fresh produce can be determined by various commercial systems both for laboratory use and for commercial applications, but most of these instrumental techniques are destructive and laborious (ElMasry and Nakauchi, 2016). A range of non-destructive techniques, such as acoustic methods (Al-Haq and Sugiyama, 2004), 2D imaging (Goel and Sehgal, 2015; Al-Haq and Sugiyama, 2004), fluorescence imaging (Betemps et al., 2012), spectroscopy (Wang et al., 2015), multispectral imaging (Peng and Lu, 2006a) and hyperspectral imaging (Zhang et al., 2014), have been deployed for the assessment of fruit ripeness. Among these techniques, hyperspectral imaging, combining both 2D imaging and spectroscopic methods, produces a three-dimensional image data cube, and records the spatial and spectral information simultaneously (Wu and Sun, 2013). Line scanning hyperspectral cameras, which scan samples on a conveyor belt continuously in one direction, has received increasing interest, as it provides several advantages compared with other non-destructive methods, such as high-throughput assessment, simultaneous multiple measurements and real time decision making (Mahesh et al., 2015). The principle of this technique is that light scattering and absorption occur when incident light interacts with fruit tissue. Light scattering is influenced by tissue density, composition and cellular structures, while absorption is more related with chemical composition of fruit. The availability of hyperspectral imaging platforms in the visible and near infrared (VNIR) region, which is between 400 and 1000 nm, has enabled the incorporation of the measurements of fruit quality, including firmness, SSC, dry matter, moisture content (MC), pH and other physiological attributes into the harvest, storage and marketing protocols for crops such as apples (Peng and Lu, 2006b), pears (Khodabakhshian and Emadi, 2017), peaches (Lu and Peng, 2006), bananas (Rajkumar et al., 2012), strawberry (Tallada et al., 2006), mango (Sivakumar et al., 2006), tomato (Zhu et al., 2015) and persimmon (Wei et al., 2013). Leiva-Valenzuela et al. found the firmness and SSC of blueberry can be measured by VNIR hyperspectral imaging

* Corresponding author.
E-mail address: Bo.li@emr.ac.uk (B. Li).

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and the fruit orientation has little effect on the accuracy of the prediction (Leiva-Valenzuela et al., 2013). With a similar wavelength range, excellent predictions of firmness and SSC were found for apple in the study of Mendoza et al. (2011). However, the prediction of peach firmness was less accurate compared with that for apple, and the correlation was cultivar dependent in the study of Lu et al. (2006). Short wave infrared (SWIR) hyperspectral imaging, covering approximately 865–1610 nm, has not been reported as being applied for fruit quality measurements, but the spectroscopic method at this wavelength range has been widely applied (Sinelli et al., 2011; Wang et al., 2015) and it was found to be related to the vibration and combination overtones of primary structural components of organic molecules (Sinelli et al., 2011). Paz et al. (2008) used a spectrometer to determine the SSC and firmness of plum. Reflectance spectra between 515 and 1400 nm was found to best correlate with SSC ($r^2 = 0.83$) for 'Late Royal' but the correlation was lower for 'Fortune' with the same wavelength range ($r^2 = 0.64$). A weak correlation was found for the prediction of firmness with best r^2 of 0.52 at the wavelength range of 1100–1650 nm (Paz et al., 2008). The CIE Lab colour components (L*, a* and b*) are easier to be related to the perceived colour by naked eyes than other colour space, and it is often used in food industry. The tristimulus values of XYZ colour space can be calculated by the integrals over the whole visible spectrum, which can then be converted to L*a*b* colour components; however, the colour of beef expressed as L* and b* could be predicted with six and five key wavelengths in the SWIR region by PLSR models (Elmasry et al., 2012). Such results are promising and could to be further developed to a multispectral imaging system with a lower cost to generate multiple estimates of quality attributes. No study has reported the application of the hyperspectral imaging for the quality measurement of plums.

It is known that the spherical shape of the fruit samples influences the scattering profiles of light, which always results in darkening at the edges of the objects. Image pre-processing methods have been developed in previous studies to address this problem for the fruit quality measurement by hyperspectral imaging (Gómez-Sanchis et al., 2008; Peng and Lu, 2008). However, none of the studies showed how the spherical shape correction improved the prediction accuracy on fruit quality attributes. In this study, the automatic shape correction method developed by Gomez-Sanchis et al. (Gómez-Sanchis et al., 2008) was applied and the influence on the prediction model was also studied.

Based on previous work, this study aimed to:

1) Acquire hyperspectral images on two sides of 'Victoria' and 'Marjorie' plums using hyperspectral imaging systems in the VNIR (600–975 nm) and SWIR (865–1610 nm) regions.
2) Develop PLSR models for the prediction of colour components (L*, a* and b*), firmness and SSC of plum for the cultivars alone and in combination.
3) Investigate the influence of light scattering correction on the performance of prediction model.
4) Compare the performances of the prediction models with average spectra extracted from one side of each plum sample and two opposite sides.

2. Materials and methods

2.1. Plum samples

Plum (*Prunus domestica* L.) fruit of 'Victoria' (n = 174) and 'Marjorie's Seedling' (n = 180), were used in this experiment. Plums of each cultivar were harvested from eight trees of three different plots located at NIAB EMR, England, and the height of all the trees are around 2.5–2.7 m. Fruit at different ripeness stages were picked from random locations in the canopy with different exposure to sunlight. All fruit were stored in air at 4 °C for 7 d prior to the experiment. The fruit, which were free of visual defects, were selected at different ripening stages in order to generate adequate variability in ground-truth quality attributes.

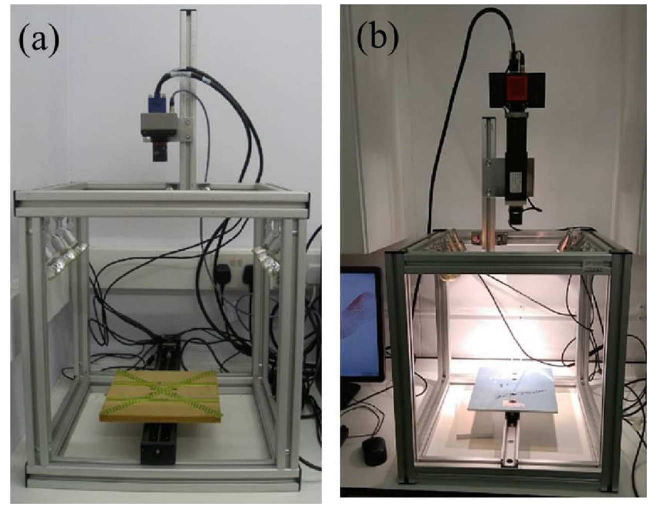

Fig. 1. Hyperspectral imaging platforms in VNIR (a) and SWIR (b) region. A line scanning hyperspectral camera is placed above a moving translation stage, illuminated by dimmable halogen lamps.

2.2. Standard assessment of plums quality attributes

Fruit quality attributes including colour, firmness and SSC were assessed manually as ground-truth data. The colour values (L*, a*, b*) were measured on two opposite sides of fruit samples using a Konica Minolta CR-400 colourimeter (Minolta Corporation, Ramsey, NJ) and the average values were used to correlate with spectral data. Firmness measurements were also carried out on two opposite sides of the fruit using the fruit texture analyser (Lloyd Instruments, Fareham, UK) and the average values were used as the ground-truth data. Two pieces of plum were cut from both sides, then the juice, extracted from both pieces, was used for the measurement of SSC with a digital Hanna refractometer (Hanna Instruments Inc., Woonsocket, R.I.).

2.3. Hyperspectral imaging acquisition

Two line scanning hyperspectral imaging systems (Fig. 1) were set up inside stainless frames and the details of both imaging systems are illustrated in Table 1. For each hyperspectral system, 6 plums were placed on a tray (15 cm × 8 cm) in two rows illuminated by tungsten halogen lamps at a 45° angle with respect to the horizontal plane. In this study, image scanning was taken for one side of the plum sample, then repeated the imaging after turning to the other side manually.

Due to the heterogeneous intensities of the light source across the whole wavelength range, reflectance calibration was performed before each measurement by taking the image of a piece of white reference standard with 95% reflectance (SphereOptics, Germany) and also a dark frame to reduce the effect of dark current. The reflectance

Table 1
Details of the two hyperspectral cameras used in this study.

Wavelength range	VNIR (600–975 nm)	SWIR (865–1610 nm)
Manufacture	IMEC Ltd (Gent, Belgium)	Specim Ltd (Oulu, Finland)
Sensor	CMOS	InGaAs
Bit depth	12 bit	12 bit
Spatial resolution	2048 × length of scan	640 x length of scan
Number of bands	98	448
Spectral resolution	< 10 nm	5 nm
Illumination	Six 12 W tungsten halogen lamps	Four 8 W tungsten halogen lamps
Integration time	25 ms	10.75 ms