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Passive reflectance sensing and digital image analysis for assessing quality parameters of mango fruits

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ABSTRACT

Actual methods for assessing mango fruit quality are generally based on biochemical analysis, which leads to the destruction of fruits and is time consuming. Similarly, for valuating large quantities of mango fruits for export, numerous observations are required to characterize them; such methods cannot easily account for rapid changes in these parameters. The aims of this study to test the performance of hyperspectral passive reflectance sensing and digital image analysis was tested at various ripening degrees of mango fruits to assess their relationship to biochemical parameters (chlorophyll meter readings, chlorophyll *a*, chlorophyll *b*, total chlorophyll *t*, carotenoids, soluble solids content and titratable acidity) via simple linear regression and partial least square regression (PLSR) analysis. Models of PLSR included (i) spectral reflectance information from 500 to 900 nm, (ii) selected spectral indices, (iii) selected RGB indices from digital image analysis, and (iv) the combination of spectral reflectance indices and RGB indices information. The results showed that the newly developed index (NDVI-VARI)/(NDVI-VARI) showed close and highly significant associations with chlorophyll meter readings, chlorophyll *a* and chlorophyll *t*, with $R^2 = 0.78$, 0.71, and 0.71, respectively, while the normalized difference vegetation index (Red – Blue)/(Red + Blue) was highly significantly related to chlorophyll *b*, carotenoids, soluble solids content and titratable acidity, with R^2 values of 0.57, 0.53, 0.57, and 0.59, respectively. Calibration and validation models of the PLSR analysis based on the combination of data from six spectral reflectance indices and six RGB indices from digital image analysis further improved the relationships to chlorophyll meter readings ($R^2 = 0.91$ and 0.88), chlorophyll *a* ($R^2 = 0.80$ and 0.75), chlorophyll *b* ($R^2 = 0.66$ and 0.57) and chlorophyll *t* ($R^2 = 0.81$ and 0.80), while calibration and validation models of PLSR based on the data from the spectral reflectance range from 500 to 900 nm were most closely related to soluble solids content ($R^2 = 0.72$ and 0.48) and titratable acidity ($R^2 = 0.64$ and 0.49). In conclusion, the assessment of biochemical parameters in mango fruits was improved and more robust when using the multivariate analysis of PLSR models than with previously assayed normalized difference spectral indices and RGB indices from digital image analysis.

1. Introduction

Productive postharvest management and harvest time of mangos demand knowledge of the postharvest physiology or biochemical quality parameters to determine the best handling practices to maintain and create high fruit quality during the ripening stage. Ripening is actually part of the natural senescence regarding mango fruits. It is an irreversible process that contributes to organelle disruption and changes in chemical constituents, flavor and structure. There are different interesting biochemical parameters, such as chlorophyll *a* (Chl *a*), chlorophyll *b* (Chl *b*), total chlorophyll *t* (Chl t), carotenoids (carot), soluble solids content (SSC) and titratable acidity (T. Acid), which can be used as diagnostic indicators of mango quality. Actual methods for the assessment of mango fruit quality are generally based on biochemical analysis, which leads to destruction of fruits and is time consuming. Fruit analysis is important for detecting mango quality; nevertheless, destructive methods are not appropriate. Similarly, for valuating large quantities of mango fruits for export, numerous observations are required for their characterization; such methods cannot easily account for rapid changes in these parameters arising from changes in environmental conditions.

In contrast, high-throughput passive reflectance sensors using spectral reflectance measurements and digital image analysis have

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Table 1
Formula, index abbreviation and references of different spectral indices and RGB indices of digital image analysis used in this study.

Formula	Index abbreviation	References
$(R_{850} - R_{710})/(R_{850} + R_{710})$	HPS[a] 850_710	Datt (1999)
$(R_{780} - R_{570})/(R_{780} + R_{570})$	HPS 780_570	Rutkowski et al. (2008)
$(R_{780} - R_{550})/(R_{780} + R_{550})$	HPS 780_550 or GNDVI	Gutierrez et al. (2010)
$(R_{760} - R_{730})/(R_{760} + R_{730})$	HPS 760_730	Barnes et al. (2000)
$(R_{760} - R_{720})/(R_{760} + R_{720})$	HPS 760_720 or NAI	Rouse et al. (1974)
$(R_{750} - R_{710})/(R_{760} + R_{710})$	HPS 760_710	Zarco-Tejada et al. (2005)
$(R_{686} - R_{620})/(R_{686} + R_{620})$	HPS 686_620	this work
$(R_{570} - R_{540})/(R_{570} + R_{540})$	HPS 570_540	this work
(Green – Red)/(Green + Red – Blue)	VARI	Gitelson et al. (2003)
(Green – VARI)/(Green + VARI + Blue)	VARI1	this work
(VARI1 – VARI)/(VARI1 + VARI)	Norm (VARI, VARI1)	this work
(Red – Green)/(Red + Green)	NDVI	Aynalem et al. (2006)
(Red – Blue)/(Red + Blue)	NDVI1	Kawashima and Nakatani (1998)
(NDVI1 – VARI)/(NDVI1 + VARI)	Norm (NDVI1, VARI)	this work

[a] HPS indicates hyperspectral passive sensing.

the potential to provide more information for making better-informed decisions at the mango scale in real time. Passive sensor systems depend on sunlight as a source of light, which allows hyperspectral information to be obtained in the visible and near-infrared range (Elsayed et al., 2011; Erdle et al., 2011; Mistele et al., 2012; Elsayed et al., 2015a; Nagy et al., 2016).

Some previous studies assessed the quality parameters of fruits by using spectroscopic measurements (Rutkowski et al., 2008; Deng et al., 2010; Moghimi et al., 2010; Jha et al., 2012). Rutkowski et al. (2008) found that the index of anthocyanin (NAI), calculated as $(R_{780} - R_{570})/(R_{780} + R_{570})$, was significantly correlated with the fruit firmness and titratable acidity in 'Golden Delicious' apples. Partial least square regression based on spectral reflectance from 400 to 1000 nm, processed with SNV, median filter and 1st derivative, was used to predict the acidity in kiwi fruits (Moghimi et al., 2010). Jha et al. (2012) applied reflectance spectroscopy to measure SSC and pH in seven mango cultivars. The optimal results were obtained by using PLSR models based on 2nd derivative spectra in the 1600–1799 nm range. The reflectance spectrum at 988 nm was significantly correlated with the soluble solids content and vitamin C content of oranges (Deng et al., 2010).

The application of digital cameras and image processing techniques is less expensive than the use of other techniques, such as passive and active reflectance sensing and technologies of satellite imagery. A color camera output can be de-coded into three images to represent the red, green and blue (RGB) components of the full image. The three components of the color image can be recombined using software or hardware to produce intensity, saturation and hue images, which can be more convenient for subsequent processing. Color is considered a fundamental physical property of agricultural products and foods (Ismail and Razali, 2012). The application of digital cameras by using color images has been proven to be a potential source for estimating several fruit quality parameters because the loss of green color is an obvious sign of fruit ripening in many mango cultivars. The development of the optimum skin color usually defines mango quality. Some mango cultivars retain a green color after ripening. Depending on the cultivar, the skin color can change from dark to olive green; sometimes reddish, orange-yellow or yellowish hues appear from the base color. Changes in eight mango selections during ripening included reductions in fruit weight, volume, length, thickness, firmness, pulp content, pulp:peel ratio, starch, and vitamin C and increases in TSS, pH, total sugars, sugar:acid ratio and carotenoid content (Gowda and Huddar, 2000). RGB-based image analysis has been applied in agriculture to detect the chlorophyll and carotenoids of orange fruits (Fouda et al., 2013), sugar content and pH of mangoes (Kondo et al., 2000), total soluble solids, total carbohydrates, titratable acidity and firmness of mango fruits (Domingo et al., 2012), chlorophyll contents of lettuce, broccoli, and tomatoes (Ali et al., 2012), nitrogen status of pepper plants (Yuzhu et al., 2011), and seed color for the identification of commercial seed traits (Dana and Ivo, 2008) and for the estimation of the chlorophyll content in micro propagated plants (Yadav et al., 2010; Dutta Gupta et al., 2013).

For example, applied to relatively few samples of oranges, the R/G band, averages of RGB and the Visible Atmospheric Resistant Index, VARI, showed a sensitive band ratio to different orange properties, such as chlorophyll and carotenoids (Fouda et al., 2013). The average values of red, green and blue of mango fruits under different levels of skin color from green to yellow were correlated with total soluble solids, total carbohydrates, titratable acidity and firmness (Domingo et al., 2012).

The scientific hypothesis raised in this study investigates whether changes in biochemical quality parameters can be reflected by changes in spectral reflectance measurements and digital images analysis based on the change in skin color of mango fruits from dark green to light green. Previous studies have been conducted to evaluate biochemical parameters using PLSR based on spectral reflectance from different bands, but only very few were focused on mango fruits. This study therefore evaluates different models of PLSR based on the full spectral reflectance range, spectral indices, RGB indices of digital image analysis and data combinations from spectral indices and RGB indices to predict biochemical parameters of mango fruits from dark green to light green.

The purpose of this work is to compare the performance of passive reflectance sensing and digital image sensing to assess whether spectral reflectance indices and indices of digital image analysis can reflect the change in biochemical parameters of mango fruits from dark green to light green and to compare the performance of four models of PLSR based on (i) the spectral reflectance from 500 to 900 nm, (ii) the six spectral indices HPS850_710, HPS760_730, HPS760_720, HPS750_710, HPS 686_620 and HPS 570_540 (Table 1), and (iii) six RGB indices of images analysis, namely, the VARI, VARI1, Norm (VARI, VARI1), Norm (NDVI1, VARI), NDVI and NDVI1 (Table 1), as well as (iv) the combination of data from six spectral reflectance indices and six RBG indices, to assess the quality parameters of mangoes.

2. Material and methods

2.1. Experimental information

The experiments were conducted at the Research Station of Sadat City University in Egypt (Latitude: N 30° 2′ 41.185″, Longitude: E 31° 14′ 8.1625″). Mango fruits of the Zabdia cultivar were taken from farms of the research station of Sadat City University. The fruit samples of the mango cultivar were selected at different