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Early decay detection in citrus fruit using laser-light backscattering imaging

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ABSTRACT

Early detection of fungal infections in citrus fruit still remains one of the major problems in postharvest technology. The potential of laser-light backscattering imaging was evaluated for detecting decay in citrus fruit after infection with the pathogen *Penicillium digitatum*, before the appearance of fruiting structures (green mould). Backscattering images of oranges cv. Navelate with and without decay were obtained using diode lasers emitting at five different wavelengths in the visible and near infrared range for addressing the absorption of fruit carotenoids, chlorophylls and water/carbohydrates. The apparent region of backscattered photons captured by a camera had radial symmetry with respect to the incident point of the light, being reduced to a one-dimensional profile after radial averaging. The Gaussian–Lorentzian cross product (GL) distribution function with five independent parameters described radial profiles accurately with average R^2 values higher or equal to 0.998, pointing to differences in the parameters at the five wavelengths between sound and decaying oranges. The GL parameters at each wavelength were used as input vectors for classifying samples into sound and decaying oranges using a supervised classifier based on linear discriminant analysis. Ranking and combination of the laser wavelengths in terms of their contribution to the detection of decay resulted in the minimum detection average success rate of 80.4%, which was obtained using laser light at 532 nm that addresses differences in scattering properties of the infected tissue and carotenoid contents. However, the best results were achieved using the five laser wavelengths, increasing the classifier average success rate up to 96.1%. The results highlight the potential of laser-light backscattering imaging for advanced citrus grading.

1. Introduction

Decay caused by *Penicillium* spp. is among the main problems affecting postharvest and marketing processes of citrus fruit (Palou et al., 2011). Early detection of fungal infections still remains one of the major issues in packinghouses because a small number of decayed fruit can cause the infection of a whole consignment during storage and distribution. Currently, the detection of decayed fruit in packing lines is carried out visually by trained workers inspecting each fruit individually as it passes under ultraviolet (UV) light along a conveyor belt. However, this procedure has a high risk of human error and is potentially harmful for operators (Lopes et al., 2010). Machine vision systems potentially provide a means to detect decayed fruit automatically, thus preventing the drawbacks related to human inspection.

Although the use of technology based on colour cameras has spread rapidly for detecting skin damage of fruit and vegetables (cf. Zude, 2009; Cubero et al., 2011), its application to the external inspection of citrus fruit is only currently under research. For example, Kim et al. (2009) detected peel diseases in grapefruit using colour texture features based on HSI (Hue, Saturation, Intensity) and the colour co-occurrence method. Nevertheless, some defects, such as decay at very early stages, are virtually identical to the sound skin, thus very difficult to detect by the human eye, and consequently, by standard artificial vision systems, which are limited to the visible region of the electromagnetic spectrum (Blasco et al., 2009).

Various machine vision technologies have been incorporated for automatically detecting decay in citrus fruit imitating the fluorescence technique used in the industry by humans. Kurita et al. (2009) developed an inspection system based on two lighting systems

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Fig. 1. RGB images of a sound orange used for a control (*left*) and an orange showing early decay symptoms caused by *P. digitatum* (*right*).

(visible and UV) that should be powered alternatively using a stroboscopic mode since the fluorescence effect produced by UV light would be undetectable with a simultaneous use of both systems due to the high intensity of white light. However, the use of UV light has some limitations because not all decay lesions, and not all the citrus cultivars, present the same level of sensitivity to the fluorescence phenomena, and on the contrary, other defects like chilling injury can result in some fluorescence (Slaughter et al., 2008), thus reducing the performance of these systems. In this sense, the recent introduction of hyperspectral sensors for food inspection is a successful alternative to detect non-visible damages on fruit (Lorente et al., 2012b). In the particular case of citrus fruit, different research has been conducted to detect decay lesions. For instance, Gómez-Sanchis et al. (2012, 2013) and Lorente et al. (2012a, 2013) studied the feasibility of a hyperspectral vision system based on liquid crystal tuneable filters (LCTF; 460–1020 nm) for detecting decay in citrus fruit in early stages of infection using halogen lighting instead of the traditional inspection using UV lighting.

Recently, light backscattering imaging (LBI) has been studied as an alternative machine vision technique for assessing fruit quality. When a light beam interacts with a fruit, reflectance, absorption and transmittance occur (Birth, 1976). Particularly, light reflectance (scattering) appears with two different geometries: Fresnel reflectance, which happens when photons are reflected on the surface of the sample; and diffuse reflectance (Meinke and Friebel, 2009). In the latter case, light enters the sample and interacts with the internal components of the fruit, and then it is scattered backward to the exterior tissue surface, thus carrying information related to the morphology and structures of the tissue additional to the absorption properties (Lu, 2004). In recent years, much work has focused on using LBI systems to assess quality of apples and other fresh fruit; however, no research has been reported to detect decay in citrus fruit using this technique. For example, Lu (2004) analyzed backscattering images from apples at multiple wavelengths in the visible and the near-infrared (NIR) region for predicting firmness and soluble solids content. In another study, the variation of moisture content of banana slices subjected to different drying conditions was evaluated by taking backscattering images at 670 nm (Romano et al., 2008). From experiments on bruised apples, Lu et al. (2010) suggested that the scattering analysis would provide good results.

Decay process in citrus fruit implies changes in enzymatic activity, resulting in an enhanced water-soluble pectin fraction, and consequently, weakening of the cell wall (Barmore and Brown, 1979). The subsequent water soaking of the tissue is an early visible symptom of infection in citrus (Barmore and Brown, 1981). Hence, since later changes in the pigment contents, and therefore in the optical properties of fruit tissue, can be expected, the LBI technique could be a promising tool for detecting decay in citrus fruit. The main objective of this research work was to evaluate the potential of laser-light backscattering imaging as a tool for the automatic detection of green mould caused by *P. digitatum* on citrus fruit. For this purpose, diode lasers emitting in the visible and NIR range were used to obtain backscattering images of citrus fruit aiming for the classification of fruit into two classes (sound and decaying oranges). The ultimate aim of this work was to evaluate and compare laser wavelengths in terms of their contribution to the detection of decay.

2. Materials and methods

2.1. Fruit and fungal inoculation

The experiments were carried out using sweet oranges (*Citrus sinensis* L. Osbeck) cv. Navelate collected during the 2012 harvest season from the field collection of the Citrus Germplasm Bank at the IVIA (Spain) (Navarro et al., 2002). A total of 100 fruit were used for the experiments: 50 oranges were superficially injured on the rind and inoculated with spores of *P. digitatum* and the other 50 were injured in the same way but treated with sterilized water for control purposes. *P. digitatum* isolate NAV-7, from the fungal culture collection of the IVIA CTP, was cultured on potato dextrose agar (PDA, Sigma–Aldrich Chemical Co., St. Louis, MA, USA) plates at 25 °C. Conidia from 7 to 14 day old cultures were taken from the agar surface with a sterile glass rod and transferred to a sterile aqueous solution of 0.05% Tween® 80 (Panreac, S.A.U., Spain). The conidial suspension was filtered through two layers of cheesecloth to separate hyphal fragments and adjusted to a concentration of 10^6 spores/mL using a haemocytometer. For inoculation, 20 μL of the conidial suspension was placed on the equator of each fruit by immersing the tip of a stainless steel rod, 1 mm wide and 2 mm in length, in the suspension and inserting it in the fruit rind. A concentration of 10^6 spores/mL of *P. digitatum* is the most appropriate to effectively infect citrus fruit in laboratory conditions (Palou et al., 2001). The fruit were stored for four days in a controlled environment at 20 °C and 65% RH. After this period, all the inoculated fruit presented lesions due to decay of an average diameter of 30 mm. Fig. 1 shows the images of a sound control orange and an infected orange.

2.2. Imaging system

In this work, a laser light backscattering imaging system was employed. This system mainly consisted of a CCD (charge-coupled device) based camera (JAI CV-A50 IR) with a zoom lens (F2.5 and