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Laser-light backscattering imaging for early decay detection in citrus fruit using both a statistical and a physical model

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ABSTRACT

The early detection of decay caused by fungi in citrus fruit is a primary concern in the post-harvest phase, the automation of this task still being a challenge. This work reports new progress in the automatic detection of early symptoms of decay in citrus fruit after infection with the pathogen *Penicillium digitatum* using laser-light backscattering imaging. Backscattering images of sound and decaying parts of the surface of oranges cv. 'Valencia late' were obtained using laser diode modules emitting at five wavelengths in the visible and near-infrared regions. The images of backscattered light captured by a camera had radial symmetry with respect to the incident point of the laser beam, these being reduced to a one-dimensional profile through radial averaging. Two models were used to characterise backscattering profiles: a statistical model using the Gaussian–Lorentzian cross product (GL) distribution function with five parameters and a physical approach calculating the absorption, μ_a, and reduced scattering, μ'_s, coefficients from Farrell's diffusion theory. Models described radial profiles accurately, with slightly better curve-fitting results ($R^2 \geqslant 0.996$) for the GL model compared to Farrell's model ($R^2 \geqslant 0.982$), both indicating significant differences in the parameters between sound and decaying orange skin at the five wavelengths. For dimensionality reduction purposes, feature selection methods were employed to select the most relevant backscattering profile parameters for the detection of early decay lesions. The feature vectors obtained were used to discriminate between sound and decaying skin using a supervised classifier based on linear discriminant analysis. The best classification results were achieved using a reduced set of GL parameters, yielding a maximum overall classification accuracy of 93.4%, with a percentage of well-classified sound and decaying samples of 92.5% and 94.3%, respectively. Results also pointed out application limits of Farrell's diffusion theory at 532 nm laser wavelength, for which high absorption of pigments occurred.

1. Introduction

Post-harvest decay in citrus fruit, due to *Penicillium* spp. fungi, causes severe economic losses world-wide in almost all regions where citrus is grown (Eckert and Eaks, 1989). Decayed fruit can propagate the fungal infection in the production, during long-term storage or fruit shipping to export markets. In practice, these infections are controlled by applying synthetic chemical fungicides, such as imazalil or thiabendazole. However, the widespread use of these fungicides has led to the resistance of the fungal pathogens (Eckert, 1990). Therefore, early detection of infected citrus fruit is regarded as a primary concern in commercial packinghouses. At present, the detection of infected fruit is performed visually by trained workers examining each fruit under ultraviolet (UV) illumination inside a dark chamber, since UV light triggers the excitation of fungal products, thus causing fluorescence emission in the blue (Momin et al., 2012). Nevertheless, this method has a high risk of human error and is harmful for the workers, since long exposure to UV radiation can lead to damage to the human skin, such as premature aging or cancer (Lopes et al., 2010).

The automation of these tasks using modern machine vision systems can be considered a valuable alternative to human inspection (Cubero et al., 2011). In this sense, vision systems based on colour cameras are currently used in the citrus industry to detect external defects that are visible at first glance (Blasco et al., 2007; Kim et al., 2009). However, decay in its early stages (before sporulation) is hardly detectable, since the appearance of the damage is very similar to sound skin, thus being barely visible to the human eye (Fig. 1). Other machine vision technologies have been proposed,

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such as the use of automated readings of UV-induced fluorescence. The systems based on UV radiation imitate the fluorescence technique used in the industry to detect decay in citrus by humans (Kurita et al., 2009). Nevertheless, the utilisation of UV light presents some disadvantages because not all cultivars of citrus show the same autofluorescence phenomenon due to differences in the peel composition (Momin et al., 2011, 2012) and, in addition, other defects like chilling injury can also lead to some degree of fluorescence (Slaughter et al., 2008). An alternative for detecting non-visible damage on citrus fruits is provided by hyperspectral and multispectral vision systems (Blasco et al., 2009; Gómez-Sanchis et al., 2012; Lorente et al., 2013c), since these systems are not limited to the visible part of the electromagnetic spectrum (Qin et al., 2013).

Light backscattering imaging (LBI) has recently emerged as an alternative machine vision technique for fruit inspection combining spectroscopic and imaging approaches. The spatial modes of light interaction with turbid biological materials can provide distinct information related to the chemical and structural properties of the sample. It is assumed that, when a light beam interacts with a fruit, a small portion of only about 4–5% is reflected on the surface of the sample (Fresnel scattering) and the rest penetrates into the tissue (Birth, 1976). In the tissue, the entering light is partly scattered backwards to the exterior tissue surface after interacting with the internal components of the fruit (diffuse scattering or backscattering), whereas the remaining radiation is absorbed by tissue or transmitted further out of the fruit in different direction (Meinke and Friebel, 2009). The optical analyses can be used to characterise fruits (Salguero-Chaparro et al., 2014), particularly by two optical properties: the absorption coefficient ($\boldsymbol{\mu}_a$) and the reduced scattering coefficient ($\boldsymbol{\mu}_s'$) (Tuchin, 2000). Light absorption is mainly related to the chemical components of the fruit, such as amino acids, inorganic ions, carbohydrates, water or pigments (Williams and Norris, 2001). The spectroscopic technology has been successfully used to classify fruits in sorting lines, considering e.g. the soluble solids content (SSC). In contrast, light scattering is affected by the structural properties of the tissue, such as density, particle size and cellular structures (Seifert et al., 2014a). Here, light scattering, recorded by an imaging system, can be useful as an indirect measure of the histology of fruit, such as flesh firmness. If spectral and additional spatial imaging information is available, combined analyses of texture and chemical composition can be done. Accordingly, many studies have reported work on assessing the quality of different fresh fruit by LBI systems. For example, Qing et al. (2007) predicted firmness and SSC in apples from backscattering images acquired using laser light at five different wavelengths in the visible and near-infrared (NIR) regions (680, 780, 880, 940 and 980 nm). In other research, the variation of moisture content of banana slices subjected to different drying conditions was evaluated by taking backscattering images using a laser diode emitting at 670 nm (Romano et al., 2008). In order to detect bruises on apples, Lu et al. (2010) determined the optical properties (the absorption and the reduced scattering coefficients) of normal and bruised tissues, as well as their changes with time after bruising, using backscattering images acquired in the range of 500–1000 nm with a hyperspectral imaging system.

Fig. 1. Orange showing early decay symptoms caused by *Penicillium digitatum* fungus.

The process of decay in citrus fruit is characterised by the weakening of the cell walls due to changes in enzymatic activity (Barmore and Brown, 1979). Thus, the subsequent accumulation of liquid in the apoplast of the epidermis is an early visible symptom of infection in citrus (Barmore and Brown, 1981). In consequence, since structural changes in fruit tissue, and therefore changes in the optical properties, are expected, the LBI technique may have the potential for decay detection. In previous research (Lorente et al., 2013b), backscattering images obtained using laser light at several wavelengths in the visible and NIR ranges (532, 660, 785, 830 and 1060 nm) were analysed, for the first time, in order to detect decay caused by fungi in citrus fruit. The Gaussian–Lorentzian cross product (GL) distribution function with five independent parameters was used to describe backscattering profiles from backscattering images in that research. However, there also exists a physical, instead of statistical model for characterising the backscattering profiles. This physical approach consists in extracting optical properties (the absorption and reduced scattering coefficients) of fruits by Farrell's diffusion theory (Farrell et al., 1992), which provides a faithful description of the shape of the backscattering profiles (Qin and Lu, 2007; Qin et al., 2009). In order to continue the research line of the previous work (Lorente et al., 2013b), the present study advances in the automatic detection of an economically dangerous post-harvest disease of citrus fruit, such as fungal decay caused by *Penicillium digitatum*, by means of laser-light backscattering imaging. Particularly, this research aimed at evaluating and comparing the two profile modelling approaches (i.e., statistical and physical) and different feature selection methods in terms of their performance in the classification of orange skin into sound or decaying in an early stage, this appearing as the next step in the direction towards a potential automation. The additional advantage of the physical profile modelling approach, compared to the statistical one, is that it also allows to measure and separate the absorption and scattering properties of biological products, which is useful for quantitative analysis of light-tissue interactions. In this sense, an ultimate objective of this research work was the measurement and separation of the optical properties of sound and decaying skin of citrus fruit at different wavelengths, in order to extract more knowledge about the underlying optical properties associated with the decaying process in citrus fruit.

2. Material and methods

2.1. Fruit used in the experiments

Sweet oranges (*Citrus sinensis* L. Osbeck) cv. 'Valencia late', grown in Spain, were purchased from a local market in Potsdam (Germany). These oranges came from organic production, thus ensuring the absence of chemicals, such as synthetic waxes or fungicides, commonly applied on fruit during the post-harvest phase in conventional crop production. For the experiments, a total of 40 fruits were superficially punctured on the rind and inoculated