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Nondestructive detection of chilling injury in cucumber fruit using hyperspectral imaging with feature selection and supervised classification

Haiyan Cen[a,b,*], Renfu Lu[c], Qibing Zhu[d], Fernando Mendoza[e]

[a] College of Biosystems Engineering and Food Science, Zhejiang University, 866 Yuhangtang Road, Hangzhou 310058, PR China
[b] Department of Food Science and Human Nutrition, Michigan State University, East Lansing, MI 48824, USA
[c] USDA/ARS, 105A/224 Farrall Hall, Michigan State University, East Lansing, MI 48824, USA
[d] Key Laboratory of Advanced Process Control for Light Industry, Jiangnan University, Wuxi 214122, Jiangsu, PR China
[e] Department of Crop, Soil and Microbial Sciences, Michigan State University, East Lansing, MI 48824, USA

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ABSTRACT

Chilling injury, as a physiological disorder in cucumbers, occurs after the fruit has been subjected to low temperatures. It is thus desirable to detect chilling injury at early stages and/or remove chilling injured cucumbers during sorting and grading. This research was aimed to apply hyperspectral imaging technique, combined with feature selection methods and supervised classification algorithms, to detect chilling injury in cucumbers. Hyperspectral reflectance (500–675 nm) and transmittance (675–1000 nm) images for normal and chilling injured cucumbers were acquired, using an in-house developed online hyperspectral imaging system. Three feature selection methods including mutual information feature selection (MIFS), max-relevance min-redundancy (MRMR), and sequential forward selection (SFS) were used and compared for optimal wavebands selection. Supervised classifications with naïve Bayes (NB), support vector machine (SVM), and k-nearest neighbor (KNN) were then implemented for the two-class (i.e., normal and chilling) and three-class (i.e., normal, lightly chilling, and severely chilling) classifications based on the spectral and image analysis at selected two-band ratios. It was found that the majority of the optimal wavebands selected by MIFS, MRMR, and SFS for both two-class and three-class classifications were from the spectral transmittance images in the short-near infrared region. The SFS feature selection method together with the SVM classifier resulted in the best overall classification accuracy of 100%, and the overall accuracy of 90.5% for the three-class classification, based on the spectral analysis. The classification results based on the textural features (first-order statistics and second-order statistics features) extracted from the optimal two-band ratio images were comparable to those achieved using the spectral features, with the best overall accuracies of 100% and 91.6% for the two-class and the three class classifications, respectively. These results demonstrated the potential of hyperspectral imaging technique for online detection of chilling injury in cucumbers.

1. Introduction

Chilling injury (CI) is a physiological disorder caused by improper storage temperatures that results in the damage of fruit cell membranes. Cucumbers are susceptible to chilling injury when subjected to temperatures below 7–13 °C (Fernandez-Trujillo and Martinez, 2006). The incidence and severity of CI symptoms depend on the duration and temperature of chilling and post-chilling treatments as well as the fruit maturity stage. However, visual symptoms may not develop until after the fruit is returned to a warmer temperature. The main CI symptoms are surface lesions, internal discoloration, tissue collapse, pitting, translucent water-soaked spots, water-soaked areas in mesocarp, and off-flavor (Chen and Yang, 2013; Kang et al., 2002). The damaged cucumber will further decay resulting from fungi and bacteria growth, and eventually could infect the whole consignment, which can cause serious health problems to the consumer especially when cucumbers are eaten as a basic salad ingredient. Chilling injury not only reduces the quality and shelf life of fruit, but also causes economic losses during transportation, storage and marketing.

* Corresponding author.
E-mail address: hycen@zju.edu.cn (H. Cen).

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Therefore, it would be beneficial if a rapid, reliable, and nondestructive technique is implemented for early detection and diagnosis of chilling injury, so as to remove the damaged and infected fruit from the postharvest storage and marketing chain, and increase consumer satisfaction and industry profitability. Nondestructive optical technique is considered the most promising for meeting these requirements.

Optical techniques that are based on imaging and spectroscopy have been widely used for quality assessment and safety inspection of fresh agricultural commodities. Several studies have been reported on detection of internal wooliness and browning in nectarines caused by CI, and on the chilling temperature effect on the lycopene content of red ripe tomatoes (Farneti et al., 2012; Lurie et al., 2011). Since chilling damage in the fruit cell membranes affects the overall quality attributes, the susceptibility of fruit to chilling injury is usually evaluated by such quality indexes as flesh color, soluble solids content, dry matter, firmness, and pigment content. Hashim et al. (2013) conducted a study on the detection of chilling injury symptoms in bananas by monitoring changes in the pigment content and the texture of exocarp with backscattering imaging technique. Their classification errors for control and chilling injured bananas were 6% and 8% for early detection, and 0.67% and 1.33% for after-storage detection, respectively. Burdon et al. (2014) reported the challenges of using near-infrared spectroscopy (NIR) to detect the CI in kiwifruit at-harvest. They pointed out that the environmental conditions and/or orchard management practices were an important factor in determining the susceptibility of fruit to chilling injury. Chilling injury detection is challenging because of the delayed appearance of CI symptoms and the lack of quantifiable physiological parameters related to the low temperature tolerance.

In recent years, hyperspectral imaging has been extensively researched as a useful tool for quality evaluation, and defect and disease detection, of food and agricultural products. Unlike conventional spectroscopic or imaging systems, hyperspectral imaging obtains spectral information at each spatial pixel, and the hypercube image data contains both spectral and spatial information, which is critical for reliable and comprehensive analysis of product properties or characteristics. Many applications have been reported for food and agricultural products, such as soluble solids content and firmness assessment of apples, peaches, bananas, and blueberries (Cen et al., 2013; Leiva-Valenzuela et al., 2014; Noh and Lu, 2007; Rajkumar et al., 2012), bruise detection in apples and pears (Baranowski et al., 2013; Lee et al., 2014; Lu, 2003), defect and disease detection in citrus fruit, cherry tomatoes, cucumbers, onions, and mushroom (Cen et al., 2014; Cho et al., 2013; Gowen et al., 2009; Lu and Ariana, 2013; Qin et al., 2009; Wang et al., 2012), and poultry carcass disease and fecal contamination detection (Lawrence, 2001; Park et al., 2006). However, due to the speed limitations in image acquisition and processing, hyperspectral imaging has so far been primarily used as a research tool, with only a few studies (Chao et al., 2011) being reported for real-time, online inspection.

To design an effective optical system for monitoring and/or detecting CI developments and symptoms in cucumbers and, ultimately, for online sorting and grading of cucumbers, we need to determine important wavebands through the dimensionality reduction and/or feature selection for hyperspectral image data. Feature selection has been used extensively in hyperspectral image processing to reduce redundant image features, retain most of the original information in fewer features, improve the image processing speed and, at the same time, achieve the maximum classification accuracy. The most common approaches include correlation analysis (CA) (Lee et al., 2008; Qin et al., 2011), principal component analysis (PCA) (Cheng et al., 2004), genetic algorithm (GA) (Kawamura et al., 2010), sequential forward selection (SFS) (Serpico and Bruzzone, 2001), minimum redundancy-maximum relevance (MRMR) (Peng et al., 2005), and receiver operating characteristic (ROC) curve (Fawcett, 2006). Meanwhile, a robust classifier is needed in identification and classification of fresh and chilling injured cucumbers. Supervised classification methods, such as Bayesian classifier, k-nearest neighbor, support vector machine, neural network, and linear discriminant analysis, were effective in distinguishing apple bruised tissue from normal tissue (Baranowski et al., 2013), identifying defective cucumbers from normal ones (Cen et al., 2014), and classifying the mango skin as damaged or sound (Rivera et al., 2014). In addition, combining the classifier with a proper feature selection method also improves the detection or identification capability. Therefore, this research was aimed to develop automated feature selection and classification algorithms for a hyperspectral imaging system to detect chilling injury in cucumbers, with the ultimate goal of developing a general inspection platform that is capable of sorting and grading cucumbers for multiple quality attributes/defects. The specific

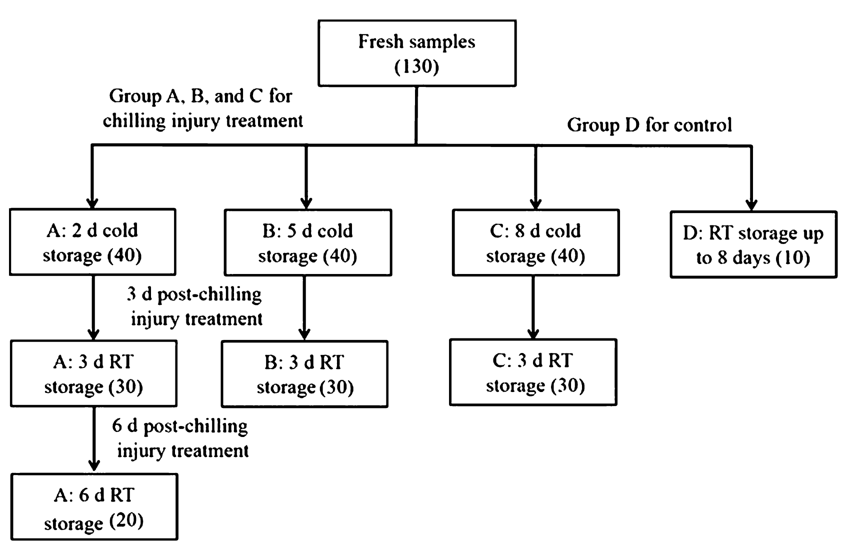

Fig. 1. Chilling and post-chilling injury treatments for pickling cucumbers (RT: room temperature at 22 °C).