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Detection of fruit fly infestation in pickling cucumbers using a hyperspectral reflectance/transmittance imaging system☆

Renfu Lu[a,*], Diwan P. Ariana[b,1]

[a] U.S. Department of Agriculture, Agricultural Research Service, Sugarbeet and Bean Research Unit, 224 Farrall Hall, Michigan State University, East Lansing, MI 48824, United States
[b] Department of Biosystems and Agricultural Engineering, Michigan State University, East Lansing, MI 48824, United States

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ABSTRACT

Fruit fly infestation can be a serious problem in pickling cucumber production. In the United States and many other countries, there is zero tolerance for fruit flies in pickled cucumber products. Currently, processors rely on manual inspection to detect and remove fruit fly-infested cucumbers, which is labor intensive and also prone to error due to human fatigue and the difficulty of visually detecting infestation that is hidden inside the fruit. In this research, a laboratory hyperspectral imaging system operated in an integrated mode of reflectance and transmittance was used to detect fruit fly-infested pickling cucumbers. Hyperspectral reflectance (450–740 nm) and transmittance (740–1000 nm) images were acquired simultaneously for 329 normal (infestation-free) and fruit fly-infested pickling cucumbers of three size classes with the mean diameters of 16.8, 22.1, and 27.6 mm, respectively. Mean spectra were extracted from the hyperspectral image of each cucumber, and they were then corrected for the fruit size effect using a diameter correction equation. Partial least squares discriminant analyses for the reflectance, transmittance and their combined data were performed for differentiating normal and infested pickling cucumbers. With reflectance mode, the overall classification accuracies for the three size classes and the mixed class were between 82% and 88%, whereas transmittance achieved better classification results with the overall accuracies of 88–93%. Integration of reflectance and transmittance did not result in noticeable improvements, compared to transmittance mode. The hyperspectral imaging system performed better than manual inspection, which had an overall accuracy of 75% and whose performance decreased significantly for smaller size cucumbers. This research demonstrated that hyperspectral imaging is potentially useful for detecting fruit fly-infested pickling cucumbers.

1. Introduction

Pickling cucumber is grown in many parts of the world. Pest infestation can be a serious problem during the production of pickling cucumber. Fruit fly is considered one of the most devastating pests, which can cause major economic loss to the crop. The United States and European Union countries have zero tolerance for fruit fly and other pests (either dead or live) in a glass jar of pickled products. Hence cucumber growers and pickle processors have to make great effort to ensure the pickled products are free of pest infestation. Growers have adopted integrated pest management strategies with biological and chemical approaches to control pest infestation during the growth of pickling cucumber. Even with the implementation of integrated pest management strategies, growers cannot guarantee 100% pest-free pickling cucumbers. Subsequently, processors have to inspect harvested cucumbers to prevent the infested fruit from entering the pickled products, which is largely done through manual inspection.

Fruit fly damages in pickling cucumbers usually occur in three ways: (1) oviposition injury by female fruit flies on fruit and vegetative parts of the plant, (2) larval feeding damage on ovaries and fruit pulp, and (3) decomposition of fruit tissue by invading saprophytic micro-organisms (Dhillon et al., 2005). Oviposition damage may occur in the form of punctures on the fruit made by the female fruit flies. Larval feeding damages often occur within the cucumber fruit without showing a clear symptom from the outside of the fruit until the maggot is nearly full-grown. The fruit tissue that is injured by fruit flies often turns brown. In severely infested cucumbers, larvae are often present. While many infested pickling cucumbers can be identified by visual inspection based on the presence of external pest marks, such as holes or punctures, on the cucumbers, there are cases in which no visible external marks or holes are present

☆ Mention of commercial products is only for providing factual information and does not imply endorsement by USDA over those not mentioned.

* Corresponding author. Tel.: +1 517 432 8062.
E-mail addresses: renfu.lu@ars.usda.gov, lur@msu.edu (R. Lu), diwanariana@gmail.com (D.P. Ariana).
[1] Formerly.

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for the damaged cucumbers. It is thus challenging to achieve 100% accuracy in detecting and removing infested cucumbers. Currently, computer vision technology is widely used for inspecting external characteristics of pickling cucumbers and other horticultural products, but it is not effective for detecting pest infested cucumbers.

Several recent studies have been reported on using visible and near-infrared (NIR) spectroscopy for detection of pest infestation in horticultural products. NIR detection of pest infestation is primarily achieved through indirect detection of the changes in the spectral properties of infested tissues, rather than through direct detection of pests present in the tissue. Xing and Guyer (2008) applied visible and near-infrared spectroscopy (550–980 nm) in transmittance mode to detect plum curculio infestation in tart cherries and achieved the overall detection accuracies of 82–87%. Peshlov et al. (2009) compared three NIR instruments in diffuse reflectance mode, covering different spectral ranges between 600 nm and 1700 nm, for detection of wild blueberries infested with fruit fly larvae. The three instruments showed different infestation detection accuracies between 58% and 82%. Wang et al. (2011) evaluated three NIR sensing modes (i.e., reflectance, interactance and transmittance) for different spectral regions between 400 nm and 2000 nm for detection of insect infestation in jujubes. Their results showed that interactance for 1000–2000 nm and transmittance for 400–1000 nm had better performance compared to reflectance mode. X-ray technique has also been researched for pest infestation detection for horticultural products (Hansen et al., 2005; Jackson and Haff, 2006). But the technology is not currently in use for detecting internal infestation in fruit, because of its cost and difficulty in effectively differentiating normal and infested tissues.

Conventional visible/NIR spectroscopy is unable to provide spatial information, which is desirable or even needed in detecting properties or pest-infested tissues that are either spatially variable or are only confined to a small fraction of area or volume in whole products. Hyperspectral imaging has emerged as a new technology for food quality and safety inspection over the past decade (Chao et al., 2004; Lawrence et al., 2003; Lu, 2003). The technology provides both spectral and spatial information for each product item, which is advantageous for detecting internal quality attributes, minor or subtle defects, and contamination of horticultural products. Ariana and Lu (2008a, 2008b) developed a laboratory online hyperspectral imaging system operated in a simultaneous, integrated mode of reflectance (450–740 nm) and transmittance (740–1000 nm). This integrated sensing mode provides an effective means for detecting both internal (via transmittance) and external (via reflectance) quality or condition of whole pickles (Ariana and Lu, 2010a).

The objective of this research was therefore to investigate the feasibility of using the hyperspectral imaging system operated in an integrated mode of reflectance and transmittance to detect fruit fly infestation in pickling cucumbers. Specifically, three sensing modes (i.e., reflectance for 450–740 nm, transmittance for 740–1000 nm, and their combination for 450–1000 nm) were evaluated and compared with manual inspection for infestation detection in pickling cucumbers. This research was based on the hypothesis that there are differences in the spectral properties between pest-infested and normal cucumber tissues, and hyperspectral imaging in transmission and reflectance modes or their combination can, thus, be used to detect pest infestation in pickling cucumbers.

2. Materials and methods

2.1. Cucumber samples

Pickling cucumber samples were obtained from a commercial pickling cucumber company in India. All pickling cucumbers were first inspected by human inspectors and separated into normal (pest-free) and infested classes before they were packed into glass jars. There were large diameter and color variations among the cucumbers and many fruit were of irregular shape (i.e., curved or warped fruit, non-circular cross sectional area, or large diameter variation along the longitudinal axis). The cucumbers were classified into three size classes: 10–30 (with the mean diameter of 27.6 mm), 30–80 (with the mean diameter of 22.1 mm), and 80–120 (with the mean diameter of 16.8 mm). The size class labeling represents approximate numbers of cucumbers for each kilogram. Hence there were about 80–120 cucumbers per kilogram for the smallest size class 80–120, and approximately 10–30 cucumbers for size class 10–30. To meet the quarantine requirements for shipping across the border, the cucumbers were packed in glass jars with vinegar. Upon arrival at the USDA Agricultural Research Service postharvest engineering laboratory at Michigan State University in East Lansing, MI, these glass jars were kept in refrigerated air until they were ready for testing.

Prior to the imaging experiment, the cucumbers in the glass jars were drained and the water on the surface of the fruit was removed with the water-absorbing paper towel. These cucumbers were then hand placed, one after another, on the belt conveyor of the laboratory hyperspectral imaging system for imaging. After the image acquisition had been completed, all cucumbers were sliced into two halves along the longitudinal axis. The cucumber slices were then visually inspected to determine if they were infested with fruit flies. Each inspected cucumber was assigned to one of the four grades: 0 (pest free), 1 (presence of minor brown tissue but with no visible external damage), 2 (one visible hole on the fruit surface with the damaged tissue area less than ¼ of the fruit diameter), 3 (severely damaged). The inspection results from the sliced cucumbers provided the ground truth information for all tested cucumbers. Fig. 1 shows four normal and infested whole cucumbers of size 80–120, and cucumber halves showing the four infestation grades for two cucumber samples of each size class. For this study, a total of 329 cucumbers were tested; there were 25 normal and 33 infested cucumbers for size class 10–30, 45 normal and 60 infested cucumbers for size class 30–80, and 86 normal and 80 infested cucumbers for size class 80–120.

2.2. Hyperspectral imaging system

Fig. 2 shows a schematic of the laboratory hyperspectral imaging system operated in an integrated reflectance (450–740 nm) and transmittance (740–1000 nm) mode (Ariana and Lu, 2008a). A 150-W tungsten halogen light source (Model Fiberlite A240P, Dolan-Jenner Industries, Lawrence, MA, USA) connected to a dual fiber optic line light was used to provide reflectance illumination. A short-pass blocking filter was installed in the light lamp housing to block the light with wavelengths longer than 740 nm. A 410-W tungsten halogen lamp (Model FXL/5, Eiko Ltd., Shawnee, KS, USA) installed beneath the conveyor's round belts provided transmittance illumination; the lamp housing was installed with a long-pass filter to block the light with wavelengths shorter than 740 nm. The hyperspectral imaging system consisted of a high performance CCD camera (Model Sensicam QE, The Cooke Corp., Romulus, MI, USA), coupled with a visible/near-infrared imaging spectrograph (Model ImSpector V10E OEM, Specim, Finland) which disperses the incoming light onto the 2D area array of the CCD detector covering the wavelengths of 400–1000 nm. The hyperspectral imaging system had a nominal spectral resolution of 0.5 nm/pixel and a spatial resolution of 0.25 mm/pixel.

The conveyor was set to run at a speed of 17 mm/s. The whole cucumber samples were hand placed on the round belt conveyor without consideration of their orientation. As each cucumber was passing the imaging area, the hyperspectral imaging system, which

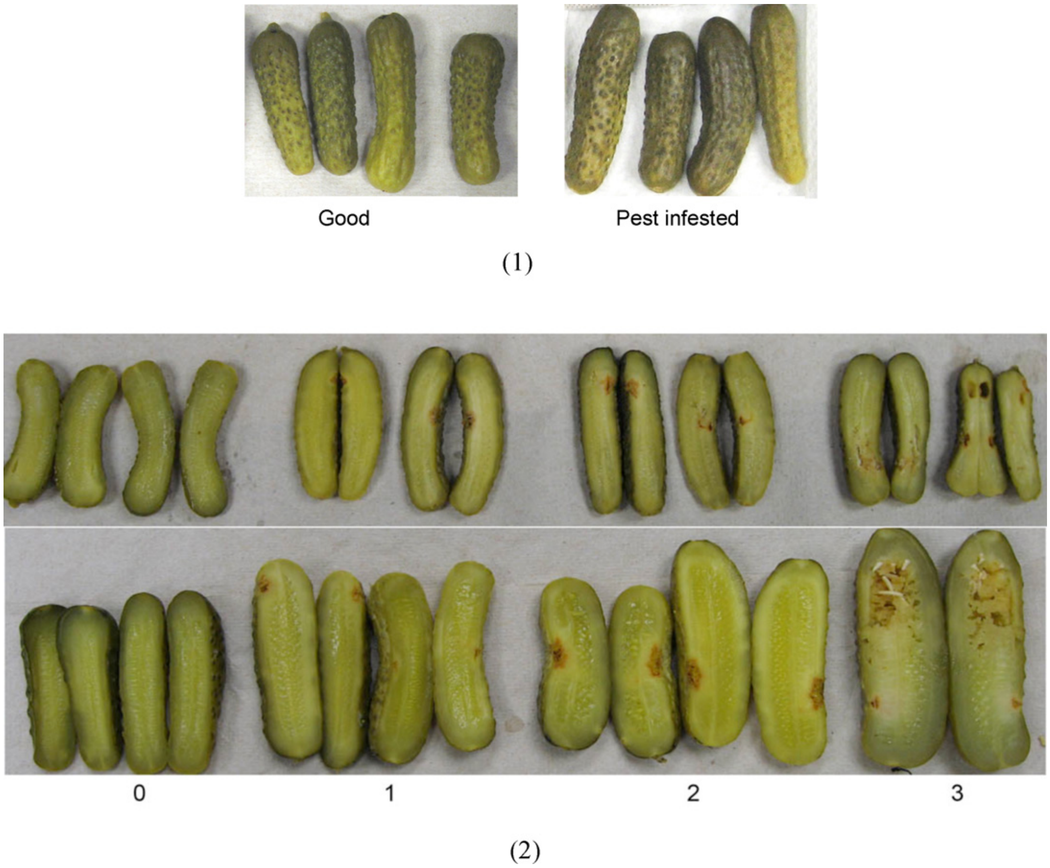

Fig. 1. (1) Normal and pest-infested whole cucumbers of size 80–120, and (2) visual classification of pest infestation in pickling cucumbers: 0 – no pest infestation, 1 – presence of minor brown tissue but with no visible external damage, 2 – one visible hole on the fruit surface with the damaged tissue area less than ¼ of the fruit diameter, and 3 – severely damaged.

was set to operate in continuous acquisition mode, line scanned the fruit to obtain 3D hyperspectral reflectance (450–740 nm) and transmittance (740–1000 nm) images simultaneously.

2.3. Image processing and classification

The raw hyperspectral images were dark subtracted and corrected in real time, using the inline reflectance (450–740 nm) and transmittance (740–1000 nm) standards (Ariana and Lu, 2008a), to obtain the relative reflectance and transmittance images for all tested cucumber samples. An image mask was created based on the hue value with the threshold values of 45–90 to filter out background images. Thereafter, spectral data were extracted for each pixel on the two spatial dimensions within the masked hyperspectral image and were then averaged. According to the Beer–Lambert law (Splinter and Hooper, 2007), the attenuation of light in a tur-

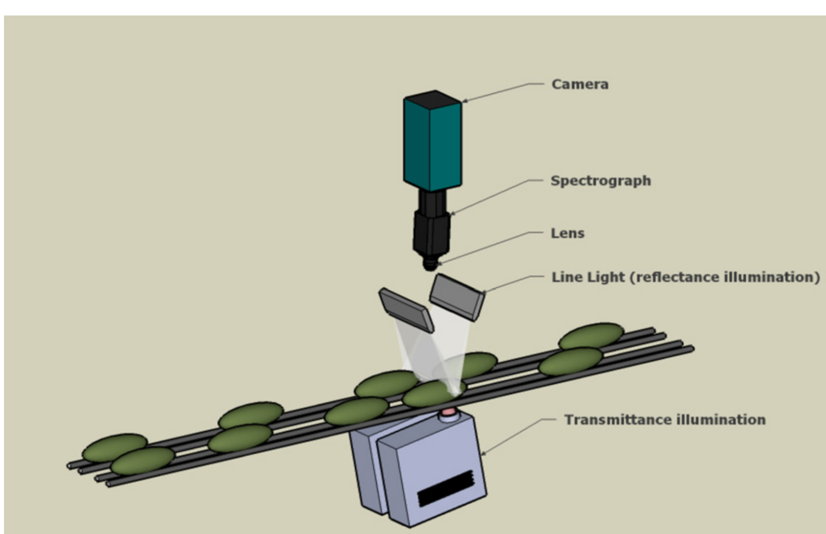

Fig. 2. A schematic of the laboratory hyperspectral imaging system operated in an integrated mode of reflectance (450–740 nm) and transmittance (740–1000 nm) for detecting pest infestation in pickling cucumbers.

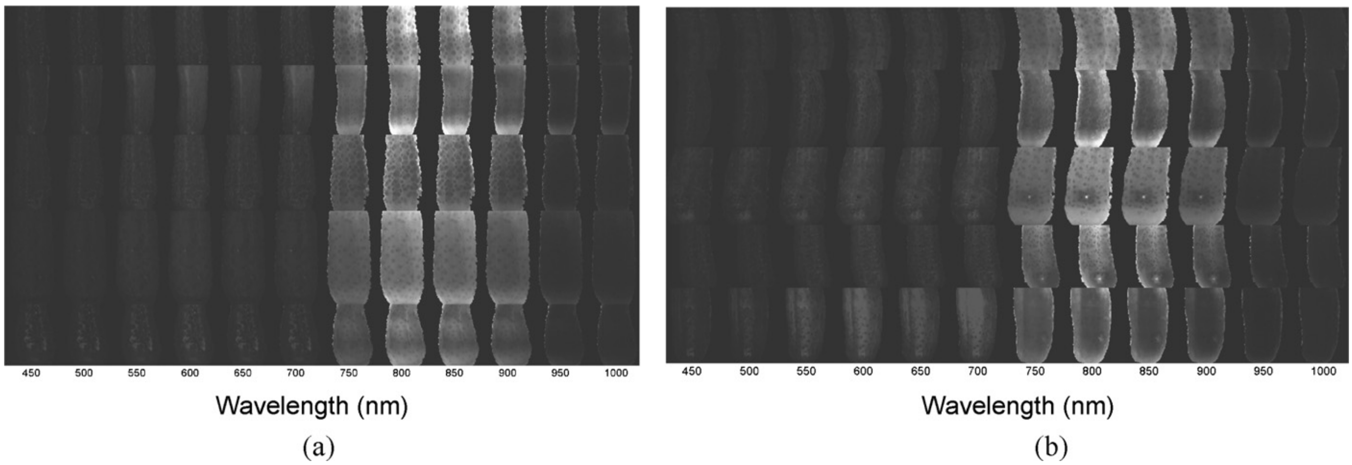

Fig. 3. Spectral images of five normal (a) and five infested (b) cucumbers for size class 10–30 for different wavebands of 450–1000 nm at 50 nm increments.

bid medium is exponentially related to the pathlength of the light transmitting through the medium. Hence transmittance is affected by the diameter of the cucumber, and it was therefore necessary to correct for the fruit size effect the spectral transmittance data for 740–1000 nm. Diameters of the cucumbers were estimated from the masked images and were then used for correcting the spectral data for each cucumber. After evaluation of different diameter correction methods, it was found that the following diameter correction equation was suitable to remove or minimize the fruit diameter effect on the spectral data:

$$F = \left(\frac{d_s}{d_m}\right)^{1.3} \tag{1}$$

where F = diameter correction factor for the cucumber, d_s = the original diameter of the cucumber, d_m = the mean diameter of all tested cucumbers. The transmittance of each fruit was then corrected by multiplying it by the diameter correction factor F given in Eq. (1) to obtain the diameter-corrected transmittance spectra. No diameter correction was applied to the reflectance spectra of 450–740 nm since they were not directly affected by fruit diameter.

The corrected spectra were then used for classification of the cucumber samples into two classes: normal (i.e., pest free) and infested. Partial least squares discriminant analysis (PLS-DA) coupled with cross validation was applied to the spectral data. The PLS method relates two data matrices **X** (independent variables or wavelengths in the case of this study) and **Y** (dependent variables or predictive values) to each other through a linear multivariate model. It provides an effective means for analyzing data with noisy, collinear, and even incomplete variables in both **X** and **Y**. The PLS method is used extensively in the analysis of spectral data. PLS-DA is a variant of PLD modeling, which is used to find the variables and directions in a multivariate space that discriminate the known classes in the calibration set. In the current study, each sample was assigned to a binary value of either 0 (normal) or 1 (infested) for the **Y** matrix. PLS-DA was performed for three spectral regions: 450–740 nm for reflectance, 740–1000 nm for transmittance, and 450–1000 nm for both reflectance and transmittance. The analyses were performed using the PLS Toolbox (Eigenvector Research Inc., Wenatchee, WA, USA) and MATLAB software (The MathWorks Inc., Natick, MA, USA). The results for these three sensing modes were then compared with those obtained from manual inspection.

3. Results and discussion

3.1. Hyperspectral images

Fig. 3 shows spectral images for five size class 10–30 cucumbers each of the normal and infested grade for the spectral region of 450–1000 nm at 50 nm increments. Transmittance images for 750–900 nm were brighter than those for the visible region of 450–700 nm and above 900 nm. It was difficult to visually differentiate the images of normal and infested cucumbers, except for the three cucumbers that showed small bright spots on their images, which were attributed to holes or punctures generated by the fruit flies in the cucumbers. Although the holes for these cucumbers were quite distinctive on the spectral images of the near-infrared region, they could become invisible if the cucumbers were placed in a different orientation. In this study, we only used the spectral information for infestation detection, without considering the spatial information.

3.2. Diameter-corrected spectra data

Fig. 4 shows the diameter distribution of cucumbers for each size class, estimated from the hyperspectral images of the cucumbers. The mean diameters of normal and infested cucumbers were 16

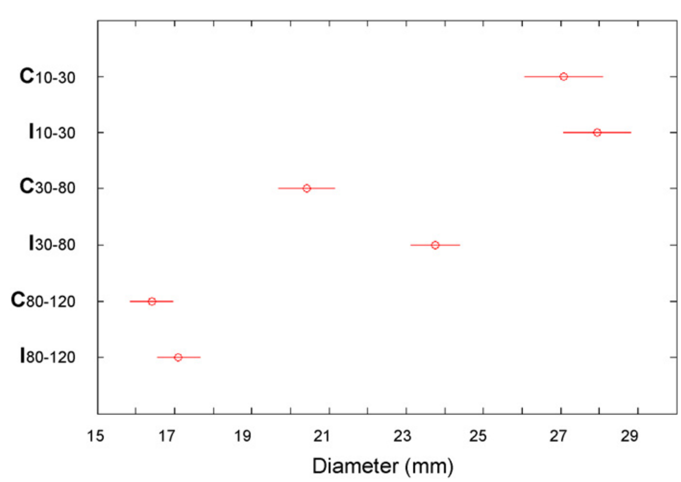

Fig. 4. Mean diameters (open circles) and variations (solid lines) for 95% of normal (denoted as '**C**') and infested (denoted as '**I**') cucumbers estimated from the hyperspectral images for each size class of 10–30, 30–80, and 80–120.

and 17 mm for size class 80–120, 20 and 24 mm for class 30–80, and 27 and 28 mm for class 10–30, respectively. The normal and infested cucumbers did not show significant differences in their fruit diameter for size classes 10–30 and 80–120. However, there was a significant difference in diameter between the normal and infested cucumbers for size class 30–80; the infested cucumbers were larger in diameter than the normal cucumbers.

Fig. 5a shows means and 95% confidence intervals for the relative reflectance and transmittance spectra for the three size classes of normal cucumbers, before the diameter correction method was applied. The mean relative spectra for the three size classes were significantly different; as the fruit size increased, transmittance decreased. The smallest size class 80–120 had the highest relative transmittance compared with the two larger size classes. As shown in the figure, values of the relative reflectance for 450–740 nm were much lower than those of transmittance for 740–1000 nm. The relatively low values for reflectance in the visible region were not due to actual low reflectance from the cucumbers. Instead, this was primarily attributed to a particular light setting used for reflectance measurements and the two different inline reflectance and transmittance standards used for correcting the original, raw hyperspectral images. This showed that adjustments or changes to the two reference standards are needed in order to produce similar scales of relative reflectance and transmittance. Because of the significant diameter effects on the transmittance spectra, it was therefore necessary to use Eq. (1) to correct the spectra for all cucumber samples.

The spectra of mean relative reflectance and transmittance for the normal cucumbers of three size classes (i.e., 10–30, 30–80, 80–120) after the diameter correction (for the transmittance portion only) are shown in Fig. 5b. Differences in the transmittance spectra between the three size classes almost disappeared after the diameter correction. There were no statistically significant differences (at the 0.05 level) in the corrected mean transmittance spectra between the three size classes.

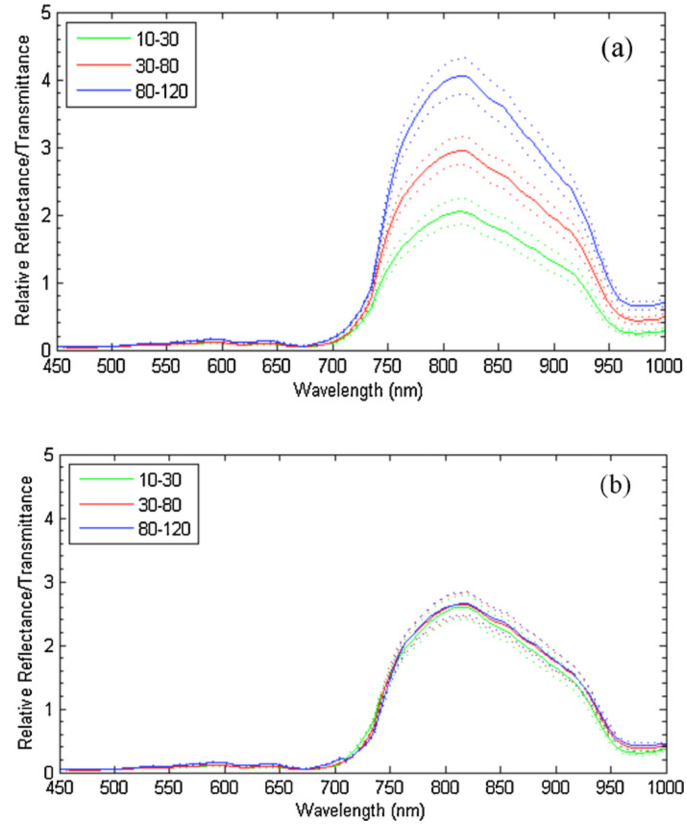

Fig. 5. Spectra of relative reflectance (450–740 nm) and transmittance (740–1000 nm) for normal cucumbers of the three size classes (i.e., 10–30, 30–80, and 80–120) before (a) and after (b) the diameter correction using Eq. (1). Solid lines denote mean spectra, whereas dotted lines represent 95% confidence intervals.

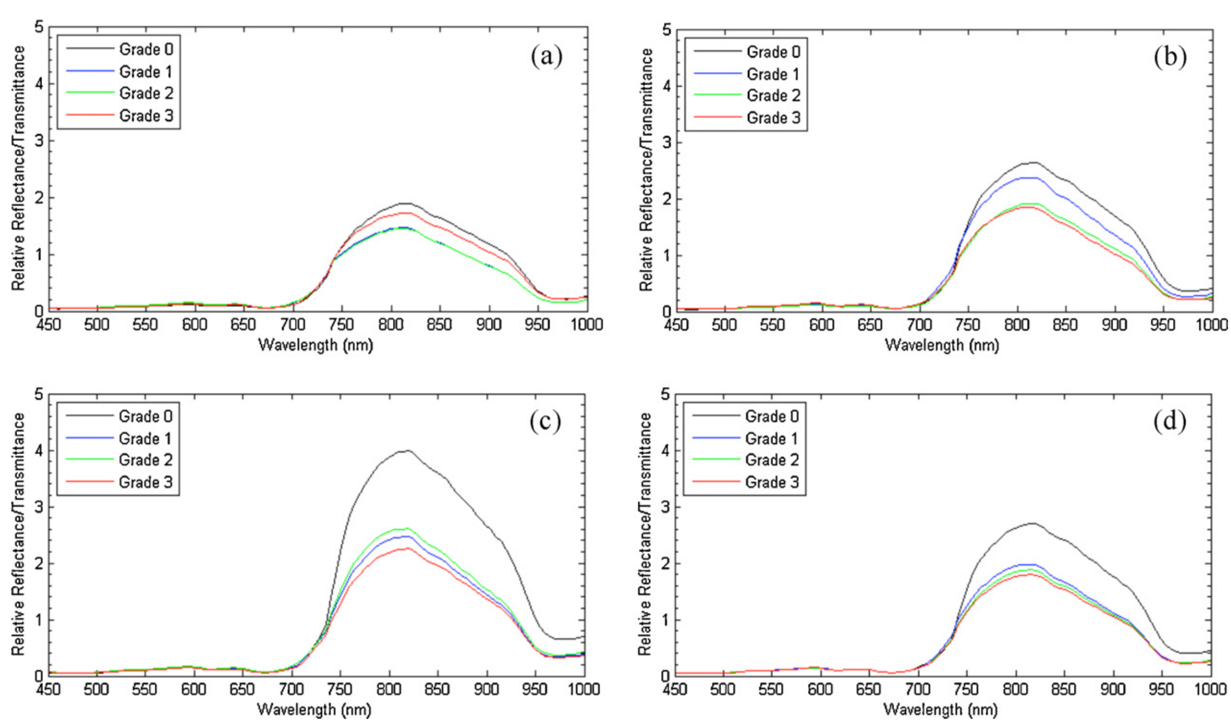

Fig. 6. Mean reflectance (450–740 nm) and transmittance (740–1000 nm) spectra for cucumbers of the four infestation levels or grades for three size classes and all pooled data: (a) size 10–30, (b) 30–80, (c) 80–120, and (d) mixed size. Infestation grade 0 represents normal or pest-free cucumbers and the infestation increased from the least level of 1 to the most severe level of 3.

Table 1
Classification accuracies for normal and infested cucumbers using partial least squares discriminant analysis.

Sensing mode	Size class	Normal	Infested	Overall
Reflectance 450–740 nm	10–30	89.7	86.2	87.9
	30–80	87.5	82.5	84.8
	80–120	85.5	85.6	85.5
	Mixed size	87.1	79.2	82.4
Transmittance 740–1000 nm	10–30	96.6	89.7	93.1
	30–80	91.7	84.2	87.6
	80–120	92.7	88.3	89.8
	Mixed size	90.9	85.8	87.8
Reflectance + transmittance 450–1000 nm	10–30	93.1	86.2	89.7
	30–80	91.7	84.2	87.6
	80–120	90.9	89.2	89.8
	Mixed size	92.4	85.8	88.5

Subsequently, the diameter correction method [Eq. (1)] was also applied to the infested cucumbers of the three size classes. Fig. 6 shows mean reflectance (450–740 nm) and diameter-corrected transmittance (740–1000 nm) spectra for cucumbers of the four infestation levels for each size class. Mean transmittance decreased as the level of infestation increased; the normal cucumbers had the highest mean transmittance within each size class. Pest infestation changed the optical properties of cucumbers and decreased the capability of the fruit tissue to transmit the near-infrared light. Fig. 6 further shows that the spectral differences between the normal and infested cucumbers were more pronounced for the smallest size class (i.e., 80–120) than for the other two size classes. This may be due to the fact that the infested area relative to the normal or uninfested tissue area in a small fruit was greater than that for a larger fruit for the same level of infestation, thus causing more significant changes in the mean transmittance spectra in the small fruit.

3.3. Classification results

Table 1 summarizes PLS-DA results for three sensing modes (i.e., reflectance, transmittance and their combination) for differentiating normal cucumbers from infested ones. For reflectance mode, the classification results for normal and infested cucumbers were quite consistent for the three size classes; they ranged between 85% and 90% for normal cucumbers and between 79% and 86% for infested cucumbers. And the overall classification accuracies were between 82% and 88%. These results are quite impressive, since the reflected light had only interacted with a portion of the fruit tissue.

Compared to reflectance for 450–740 nm, transmittance for 740–1000 nm yielded better classification results for both normal (between 91% and 97%) and infested (between 84% and 90%) cucumbers (Table 1). The overall accuracies for transmittance were between 88% and 93%. These results suggest that transmittance had advantages over reflectance in detecting pest infestation in cucumbers.

When the reflectance and transmittance data were combined, no improvements in the classification results were observed compared to transmittance mode alone. The overall classification accuracies for the integrated mode were between 88% and 90%. These results seemed to suggest that there was considerable redundant information between the reflectance and transmittance spectra. However, since these results were obtained by using simple image processing and classification algorithms, further investigation is needed to confirm whether the integration of reflectance and transmittance is not advantageous over transmittance for infestation detection in cucumbers.

Table 2 shows classification results from manual inspection of the freshly harvested cucumbers, in comparison to the pickled cucumbers that were used in the imaging analysis. It is interesting to notice that the human inspectors did an excellent job in correctly identifying normal and infested cucumbers in the largest size class 10–30, achieving 100% accuracy for infested cucumbers and an overall accuracy of 93%. However, human inspection results were affected by fruit size. Human inspection accuracy decreased significantly as the fruit size decreased. For the smallest size class (80–120), the human inspectors only had an overall classification accuracy of 62%, which was far lower than those obtained using the hyperspectral imaging system (Table 1). Overall, human inspection was not as good as the hyperspectral imaging system, operated in one of the three sensing modes (i.e., reflectance, transmittance or their combination), for infestation detection in cucumbers.

This paper presents results on the classification of normal and infested cucumbers by hyperspectral imaging technique. The algorithms used to process and analyze the hyperspectral image data are relatively simple and considerable improvements in the image processing and classification algorithm are thus needed, which should further improve the performance of the hyperspectral imaging system for pest infestation detection. For instance, we only used mean spectra extracted from each cucumber for PLS-DA classification, which may not be most suitable because these spectra were averaged over a large number of spatial pixels that had likely contained both normal and infested fruit tissue. Further studies are thus needed to determine the optimal number and size for the areas of interest to calculate mean spectra for each cucumber. Moreover, it may also be advantageous or even necessary to incorporate spatial features available in the hyperspectral images, so as to meet the stringent zero tolerance requirement for pest infestation detection. In addition, it would be necessary to determine the optimum spatial and spectral resolutions for fruit fly pest detection, so that faster imaging and spectral processing and analysis can be achieved. Finally, due to the restriction of shipping fresh cucumber samples with live fruit flies across the border, this study only tested those cucumber samples that have been submerged in vinegar solution, which had effectively killed all fruit flies. This canning process was expected to change the optical properties of the samples. Our previous study (Ariana and Lu, 2010b) showed that it was easier for light to transmit through brined pickling cucumbers and fresh pickling cucumbers. That study found that better detection results for internal defect (i.e., bruises, hollow or split center or watery tissue) were obtained from fresh cucumbers than from brined cucumbers. Further study should be considered to evaluate the hyperspectral imaging system for pest infestation detection in fresh pickling cucumbers.

Table 2
Manual classification accuracies for normal and infested cucumbers.

Size class	Normal	Infested	Overall
10–30	86.2	100.0	93.1
30–80	77.2	97.9	86.7
80–120	60.4	65.5	62.1
Overall	69.0	84.9	75.4

4. Conclusions

Pest infestation has changed the optical properties of pickling cucumbers tissues. Transmittance in the fruit fly-infested cucumbers for the spectral region of 740–1000 nm was lower compared to normal or pest-free cucumbers. Transmittance was significantly affected by fruit diameter and the proposed diameter correction equation was effective to remove or minimize the effect of fruit diameter on transmittance measurements. Reflectance mode for 450–740 nm was able to achieve overall classification accuracies between 82% and 88% for the three size classes of cucumbers, whereas transmittance for 740–1000 nm was superior with the overall classification accuracies between 88% and 93%. The integration of reflectance and transmittance produced classification results similar to those for transmittance. Overall, the hyperspectral imaging system performed better than human inspection, which had an overall accuracy of 75% and whose accuracy decreased significantly with the decreasing cucumber diameter. This research showed that hyperspectral imaging technique is potentially useful for detecting pest infestation in pickling cucumbers. However, improvements in the imaging processing and classification algorithms, such as incorporating image features, are needed in order to meet the stringent zero tolerance requirement for pest infestation in picked products.

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