14.1. INTRODUCTION

Cucumber (Cucumis sativus L.) is believed to have originated on the Indian subcontinent. Cucumbers are members of the cucurbit family and are related to gourds, gherkins, pumpkins, squash, and watermelon. The first horticultural types were selected in the 1700s following introduction into Europe. They were introduced to the Americas by Christopher Columbus, and have been cultivated in the United States for several centuries (Sargent & Maynard, 2009). Cucumbers are an important commercial and garden vegetable. China is the most important cucumber and gherkin producing country, with more than 25 million tons in production. Other important cucumber and gherkin producing countries are Turkey, Iran, Russia, and the United States (FAOSTAT, 2009) (Table 14.1).

There are three basic classes of cucumber marketed in the United States, i.e. field-grown slicers, greenhouse-grown slicers, and processing (pickling) cucumbers. Field-grown slicers (cucumbers for the fresh market) are larger and sweeter, and have a thicker skin than the pickling varieties. The United States produced 920,000 tons of cucumber for all uses in 2007, which are about equally split between the fresh and processing market. Hand (multiple harvests) and machine (once-over) harvesting are practiced in several growing regions of the United States. All fresh-market cucumbers are
Cucumber and gherkin production in thousand metric tons of selected top producing countries in the past three years

<table>
<thead>
<tr>
<th>Country</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>26,558</td>
<td>27,357</td>
<td>28,062</td>
</tr>
<tr>
<td>Turkey</td>
<td>1,745</td>
<td>1,800</td>
<td>1,876</td>
</tr>
<tr>
<td>Iran</td>
<td>1,721</td>
<td>1,721</td>
<td>1,720</td>
</tr>
<tr>
<td>Russia</td>
<td>1,414</td>
<td>1,423</td>
<td>1,410</td>
</tr>
<tr>
<td>United States</td>
<td>930</td>
<td>908</td>
<td>920</td>
</tr>
<tr>
<td>Others</td>
<td>10,591</td>
<td>10,857</td>
<td>10,623</td>
</tr>
<tr>
<td>World</td>
<td>42,958</td>
<td>44,066</td>
<td>44,611</td>
</tr>
</tbody>
</table>

Source: FAOSTAT (2009)

harvested by hand, while most pickling cucumbers are harvested by machine [Lucier & Lin, 2000]. Although the incidence of cucumber fruit injuries may be higher when harvesting by machine, the acreage planted for mechanically harvested cucumber continues to increase in the United States owing to the scarcity and cost of labor and the continued improvement of harvesting technology.

Cucumbers are prone to damage during fruit enlargements, harvest, transport, and processing, thus steps must be taken in order to minimize losses due to bruising. Severely damaged fruits are visually detected and discarded in cucumber processing plants; however, mechanical injury often causes hidden internal physical damage in the form of carpel separation which can lead to increased bloating in brine-stock cucumbers. Carpel separation is a serious product quality problem, resulting in economic loss for the pickle industry [Wilson & Baker, 1976]. Carpel separation in pickling cucumber fruit occurs when the sutures of the three fused carpels form a hollow through part or the entire length of the fruit. As the carpel-suture strength increases, the frequency of carpel separation in green stock would decrease, which in turn would reduce occurrences of carpel balloon bloater formation during fermentation. Bruising triggers numerous biochemical and physiological changes, leading to accelerated aging in harvested fruit already undergoing postharvest senescence [Miller, 1989, Miller et al., 1987]. Biochemical methods have been developed to detect and separate bruised fruit in a number of crop species. For example, a catechol test coupled with hydrogen peroxide can be used to detect bruising in whole cucumbers [Hammerschmidt & Marshall, 1991]. This test is based on increased peroxidase activity after bruising [Miller & Kelley, 1989]. Mechanical injury may result in changes in endogenous levels and rates of biosynthesis of ethylene, indoleacetic acid, zeatin, and elicitors [Miller, 1992], cell wall-degrading
enzymes and ethylene production (Miller et al., 1987), and sugar composition of cell walls (Miller, 1989). The aforementioned methods are destructive, not instantaneous, and therefore not suitable for automated grading and sorting in a modern commercial setting.

Researchers have explored various nondestructive methods for detecting mechanical injury in cucumber fruit. Sorting cucumbers by density has been proposed because damaged fruit have internal voids and may have different densities than undamaged fruit (Marshall et al., 1973). However, the rate of misclassification by density was high. Refreshed delayed light emission (RDLE) from chlorophyll was able to consistently distinguish bruised from non-bruised cucumber fruit (Abbott et al., 1991). Although the method is impractical for sorting individual pickling cucumbers owing to the time requirement for dark equilibrium and RDLE measurement, it has the potential to be used as an inspection tool by the processor. Visible/near-infrared light transmission measurement has been studied to evaluate internal quality of pickling cucumbers (Miller et al., 1995). Light transmission increased as the severity of mechanical stress applied to the fruit increased. The technique may be a valuable tool for detecting poor quality cucumbers before processing. Machine vision technology is currently used in many pickling cucumber processing plants, but the technology is designed for inspecting external characteristics, including size, shape, and color.

In recent years, hyperspectral imaging (also called imaging spectroscopy) has been used for quality evaluation and safety inspection of food and agricultural products. Hyperspectral imaging integrates conventional imaging and spectroscopy to obtain both spatial and spectral information from an object. The technique is thus useful for analyzing heterogeneous materials or quantifying properties or characteristics that vary spatially in food items (Park et al., 2006). Reviews on the applications of hyperspectral imaging for food quality and safety evaluation can be found in Gowen et al. (2007) and Wang & Paliwal (2007). This chapter presents the application of hyperspectral imaging for defect detection in pickling cucumbers.

### 14.2. DETECTION OF EXTERNAL BRUISE

The processing quality of cucumbers is a major concern of the pickling industry. Mechanical injury can cause physiological breakdown during postharvest storage and processing. Decreased cucumber quality as evidenced by tissue softening and deterioration has been linked to mechanical injury (Marshall et al., 1972). Miller et al. (1987) noted that water-soaked lesions were present in the skin of mechanically stressed cucumbers
immediately after treatment, indicating membrane damage at the cellular level. These water-soaked lesions are not very obvious in the visible (VIS) region of the electromagnetic spectrum.

A near-infrared (NIR) hyperspectral imaging system was developed to capture hyperspectral images from pickling cucumbers in the spectral region of 900–1700 nm (Ariana et al., 2006). The system consisted of an imaging spectrograph attached to an InGaAs (indium gallium arsenide) camera with line-light fiber bundles as an illumination source. Two cone-shaped sample holders were used to rotate pickling cucumbers thus scanning the entire surface of the fruits by a line-scan hyperspectral imaging system (Figure 14.1). Hyperspectral images were taken from the pickling cucumbers at 0, 1, 2, 3, and 6 days after they were subjected to dropping or rolling under load which simulated damage caused by mechanical harvesting and handling systems.

Knowledge about bruises and their locations on individual cucumber samples is required to determine the effectiveness of the bruise detection algorithm. The actual individual cucumber class (bruised or normal) was determined by visually comparing relative reflectance NIR images at 1200 nm before and after mechanical stress was applied. Bruised areas appeared as dark patches in the NIR images (Figure 14.2). Bruised and normal areas had the highest contrast at 1200 nm. If dark areas appeared on the NIR images only after bruising, the cucumber was designated to be in the bruised class. Rough skin areas, which appeared as dark areas on NIR images both before and after bruising, were not considered as bruised.
The mean reflectance of bruised tissue was consistently lower than that of the normal tissue over the spectral region of 950–1650 nm, except in the range of 1400–1500 nm where considerable spectral overlapping was observed for the two types of tissue. Water has strong absorption at 1450 nm (Osborne et al., 1993), which resulted in low reflectance for both normal and bruised tissue (Figure 14.3). The difference in the reflectance between normal and bruised tissue was the greatest in the region between 950 and 1350 nm. The reflectance of normal tissue was relatively constant over the period of the experiment. On the contrary, the reflectance of bruised tissue increased over time, approaching that of normal tissue (Figure 14.4). This characteristic might be due to the wound healing of the cucumbers in response to mechanical stress (Miller, 1992). Figure 14.2 shows the changes in bruised areas with time from the spectral images at 1200 nm taken over a period of 6 days. Within 2 hours after bruising (0 day), bruises appeared darker than normal tissue on the image. One day after stress was applied, the relative reflectance of bruised tissue showed the greatest difference from that of normal tissue. This fact is an advantage for machine vision-based sorting because freshly harvested cucumbers are usually sorted within 24 hours after harvesting. The spectral differences between the bruised and normal tissue decreased over time. Some bruise areas were no longer visible on the image after 6 days. Thus, sorting at later days is not desirable.

Principal components of NIR hyperspectral images based on the optimum spectral resolution of 8.8 nm were analyzed in three different spectral regions, 950–1650 nm, 950–1350 nm, and 1150–1350 nm. Table 14.2 shows the classification accuracies of cucumber samples based on the first principal
CHAPTER 14: Hyperspectral Imaging for Defect Detection of Pickling Cucumbers

**FIGURE 14.3** Mean relative reflectance spectra of normal and bruised cucumber tissue and their standard deviation (SD) spectra (reproduced from Ariana et al., 2006. © Elsevier 2006)

**FIGURE 14.4** Mean relative reflectance changes on bruised tissue of the cucumbers over time periods of 0–6 days after mechanical stress (reproduced from Ariana et al., 2006. © Elsevier 2006)
components over the period of 0–6 days. The best classification accuracies were achieved under the spectral region of 950–1350 nm for all days after mechanical stress. This region represented wavebands where reflectance difference between normal and bruised tissue was the greatest. The classification accuracy within 2 hours of bruising was 94.6% and decreased over time to 74.6% at day 6 after bruising. Decreasing classification accuracy over time was also observed at the other two regions. This pattern was due to the decreased differences in reflectance between bruised and normal tissue.

Although only one component was used in the classification, the computation of the principal component included all spectral images for a spectral region. For real-time applications, it is more desirable to use fewer (two or three) wavelengths in order to accelerate the image acquisition and analysis process. Ratio or difference of two wavelengths followed by image segmentations using a threshold was used in this study. The best two wavelengths for the ratio and difference algorithm were found using correlation analysis of all possible wavelengths. For the ratio of two wavelengths, the best wavelengths are 988 nm and 1085 nm, as calculated by the following equation:

$$R = \frac{R_{988\text{nm}}}{R_{1085\text{nm}}}$$  \hspace{1cm} (14.1)

where $R_{988\text{nm}}$ and $R_{1085\text{nm}}$ are relative reflectance at 988 nm and 1085 nm, respectively. Wavelengths 1346 nm and 1425 nm were found to be the best for difference calculations:

$$D = R_{1346\text{nm}} - R_{1425\text{nm}}$$  \hspace{1cm} (14.2)

where $R_{1346\text{nm}}$ and $R_{1425\text{nm}}$ are relative reflectance at 1346 nm and 1425 nm, respectively. Classification accuracy based on $R$ and $D$ values
Classification accuracies (in percentage) based on ratio and difference of two NIR spectral images

<table>
<thead>
<tr>
<th>Calculation*</th>
<th>Days after bruising</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>( R = R_{988\text{nm}} / R_{1085\text{nm}} )</td>
<td>92.7</td>
</tr>
<tr>
<td>( D = R_{1346\text{nm}} - R_{1425\text{nm}} )</td>
<td>87.3</td>
</tr>
</tbody>
</table>

*\( R_{988\text{nm}}, R_{1085\text{nm}}, R_{1346\text{nm}}, \) and \( R_{1425\text{nm}} \) are relative reflectance images at their respective wavelengths.

Source: Ariana et al. (2006)

using threshold values of 0.79 and 0.16 respectively over a period of 0–6 days are shown in Table 14.3.

The classification accuracy based on the ratio of two wavelengths was slightly better than that based on the difference of two wavelengths for 0 and 1 days after bruising, whereas the difference of two wavelengths was superior for 3 and 6 days. Classification based on the first principal component over the region of 950–1 650 nm (Table 14.2) yielded higher accuracies at 0 and 1 day compared to classification based on \( R \) or \( D \) values (Table 14.3). However, its accuracy at 6 days after bruising was much lower than that from band difference or ratio. The general classification performance based on the first principal component was also inferior to that based on the \( R \) or \( D \) values. Classification accuracy based on the first principal component seemed more sensitive to the age of tissue bruising. Hence, the method of band ratio or difference is preferable because its classification accuracy was more stable over time.

### 14.3. DETECTION OF INTERNAL DEFECT

Adverse growing conditions and/or excessive mechanical load during harvest, transport, and postharvest handling are the major causes of internal damage in pickling cucumbers, which often occurs in the form of carpel separation or hollow centers (Miller et al., 1995). Figure 14.5 represents a typical cucumber slice from normal and defective pickling cucumbers. These defective cucumbers would cause a bloating problem during brining if not segregated prior to the brining process. Since the hollow center is largely hidden inside cucumbers, it is difficult to detect with current machine vision systems. Sorting for internal defect is not currently performed on fresh cucumbers but only on whole desalted pickles.
Defective pickles are separated from normal ones by visual inspection and/or hand touch of pickles moving on conveyor belts. Human sorting and grading of defective cucumbers is not cost-effective and is also prone to error due to speed demand and fatigue. Hence it is desirable that a machine vision system be used for removing defective pickling cucumbers from normal ones prior to brining.

The first study for internal defect detection in pickling cucumbers using hyperspectral imaging was conducted under transmittance mode. Cucumbers were mounted on a rotating stage, illuminated from below, and hyperspectral transmission line scans were captured longitudinally from above using a CCD camera. Three hyperspectral line scans were obtained for each cucumber, separated by 120° [Ariana & Lu, 2008]. Examples of the hyperspectral transmittance images from a normal and a defective cucumber are shown in Figure 14.6.

Generally, the defective cucumber had a brighter image [higher pixel intensities] between 700 and 900 nm. The spatial profiles across the 800 nm line showed that transmittance was higher in the defective cucumber [Figure 14.6b] than in the normal cucumber [Figure 14.6a]. Further, defective cucumbers generally had a larger variation in transmittance along the scan line than normal cucumbers. Water-soaked lesions and tissue separation could account for increased light transmission in defective cucumbers. The light-scattering abilities of cellular components (e.g., cell walls, starch), which normally diffract or reflect light, might have decreased due to the fluid build-up from the ruptured cells [Miller et al., 1995]. When the refractive
Examples of hyperspectral transmittance images of (a) normal and (b) defective cucumber. Pixel intensities along the dotted line at 800 nm are presented in the graph below each image (reproduced from Ariana & Lu, 2008a. © American Society of Agricultural and Biological Engineers 2008).

Average classification accuracies of 93.2% and 90.5% were achieved using partial least squares-discriminant analysis (PLS-DA) and Euclidean distance measure respectively. Although resulting in lower accuracy, the Euclidean distance method is preferred because it is simple and requires only normal cucumbers for the model training.

Hyperspectral transmittance imaging is potentially useful for on-line detection of internal defect in pickling cucumbers. Further study to implement hyperspectral imaging for defect detection in an environment close to commercial line situations was conducted. A prototype on-line system using
belt conveyors to carry cucumbers, such as are commonly used in cucumber processing plants, was built (Figure 14.7).

The prototype included three major units: conveying, illumination, and imaging. It was designed to detect hollow center, a common internal defect in pickling cucumbers, as well as to evaluate external quality features, i.e., color and size. In the commercial setting, cucumbers are sized and sorted using multiple lanes of conveyor belts. With this consideration, the prototype was designed to operate in a two-lane mode at a rate of 1–2 pickling cucumbers per second per lane. While this sorting speed is still below that required for
commercial application, it would meet the needs of testing the design concept. The two-lane configuration could operate with a single camera and hence simplify the design. The prototype also has a unique feature of simultaneous reflectance and transmittance imaging and continuous measurements of reference spectra. Reflectance imaging in the visible region of 400–740 nm was intended for external quality evaluation such as color; whereas transmittance imaging in the red and near-infrared region of 740–1 000 nm was used for internal defect detection. Separation of the two imaging modes was possible by installing a shortpass filter with the cut-off wavelength at 740 nm in front of the reflectance light source. Spectral calibration references were built in the prototype for correction of each hyperspectral image to minimize the effect of light source fluctuations. In addition, the size of cucumbers was predicted from the hyperspectral images, which could be used for pathlength correction to improve detection accuracy for internal defect.

The camera was set to run continuously with 2 milliseconds exposure time and 8×8 binning, with a conveyor belt speed of 110 mm/s or approximately up to two cucumbers per second. A representative of hypercube data captured by the system at six selected wavelengths from 500 to 1 000 nm along with their corresponding color images is presented in Figure 14.8. Images at 500, 600, and 700 nm were reflectance images that carried mostly color information; meanwhile images at 800, 900, and 1 000 nm

![Image](http://www.elsevierdirect.com/companions/9780123747532/)

**FIGURE 14.8** Hyperspectral images for the normal (left) and defective (right) groups of pickling cucumbers and the corresponding RGB images (reproduced from Ariana & Lu, 2009. © American Society of Agricultural and Biological Engineers 2009). (Full color version available on http://www.elsevierdirect.com/companions/9780123747532/)
were transmittance images. The images on each row have been scaled for maximum contrast. For visual observation purposes, the RGB images (top row) were generated from the hyperspectral image cube in the 500–700 nm range by first computing CIE tristimulus values (X, Y, and Z) using the weighted ordinate method, followed by a conversion to RGB values. The intensity of images at 800 nm was higher (appeared brighter) compared to other wavebands. Furthermore, images at 800 and 900 nm appeared brighter in defective cucumbers than in normal cucumbers. In some severely defective cucumbers, bright areas appeared more intense compared to the surrounding pixels in the images at 800 nm (e.g., the second cucumber from the left for the defective group in Figure 14.8). These bright areas did not appear in the visible range.

Typically, the transmittance signal of pickling cucumbers was stronger in the NIR region than in the visible region (Figure 14.9). Both normal and defective spectra exhibited strong absorption at 680 and 950 nm due to chlorophyll and water absorption respectively. Local maxima at 550 nm represented the green color of cucumbers. The overlapping spectra in the visible region of 500–725 nm for normal and defective cucumbers suggested that both classes had similar color. Hence it would be difficult to segregate defective cucumbers from normal ones using hyperspectral reflectance images.
Hyperspectral imaging provides spectral information about a product item in addition to spatial features. Most hyperspectral imaging applications use a pushbroom sensing configuration to build 3-D hyperspectral image cubes, which contain spectral information for each pixel in the 2-D space. This would require a great amount of time for acquiring, processing, and analyzing images, making the technique impractical for on-line sorting and grading applications. In addition, hyperspectral image cubes are high-dimensional data and exhibit a high degree of interband correlation, leading to data redundancy that can cause convergence instability in classification models. Therefore, the use of fewer wavebands is preferable for more stable classification and easier implementation in a multispectral imaging system to meet the speed requirement of a sorting line.

Many techniques are available for selecting wavebands from hyperspectral images. One of them is correlation analysis, a common method to evaluate the relationship between input features and output. The method was proved effective in removing redundant features, and it has been used successfully for defect detection in apples and mandarins (Gomez-Sanchis et al., 2008; Lee et al., 2008). The waveband ratio of 940 and 925 nm resulted in an overall classification accuracy of 85.0%. The best classification accuracy was achieved using the difference of two wavebands at 745 and 850 nm with an overall classification accuracy of 90.8% (Ariana & Lu, 2009).

Representative images for the classification results are shown in Figure 14.10. Coloration was added to the cucumbers and defective areas to

![FIGURE 14.10](http://www.elsevierdirect.com/companions/9780123747532/)

Segmented images of normal and defective cucumbers (damage areas are denoted with red color) images (reproduced from Ariana & Lu, 2009. © American Society of Agricultural and Biological Engineers 2009). (Full color version available on http://www.elsevierdirect.com/companions/9780123747532/)
enhance visual observation. Most of the defective areas in the segmented images appeared large, although smaller areas were also identified, which might have been due to damage in the form of water soak lesions in the mesocarp region near the surface. Severely defective cucumbers would transmit more light because they had a substantial portion of the endocarp missing, which was consequently filled with air.

14.4. CONCLUSIONS

Automated sorting and grading of fruits and vegetable can reduce industry dependence on human inspectors, reduce production cost, and improve product consistency and wholesomeness. Many pickling cucumber processors are currently using machine vision systems in their lines for sorting cucumbers based on size, shape, and color. The systems are not designed for detection of external or internal damage in cucumbers, therefore they are incapable of detecting bruise damage in pickling cucumbers in the form of water soak lesions, carpel separation or hollow center. With the stringent quality control requirements, the presence of external and/or internal defect can lead to rejection and make the processor liable for economic loss.

Studies on the application of hyperspectral imaging for detection of defects in pickling cucumbers show a potential to use the technology in commercial lines. The simultaneous hyperspectral reflectance and transmittance imaging system can simplify the operation and reduce cost by having multiple inspections (size, shape, color, external, and internal bruise) in one station. However, further research is needed to make the technology applicable in the industry. While hyperspectral data are rich in information, processing the hyperspectral data poses several challenges regarding computation speed requirements, information redundancy removal, relevant information identification, and modeling accuracy. Hyperspectral imaging studies are often conducted as a precursor to the design of a multispectral imaging system using 3–4 wavebands for real-time applications.

NOMENCLATURE

Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCD</td>
<td>charge-coupled device</td>
</tr>
<tr>
<td>CIE</td>
<td>Commission internationale de l'éclairage (International Commission on Illumination)</td>
</tr>
<tr>
<td>InGaAs</td>
<td>indium gallium arsenide</td>
</tr>
</tbody>
</table>
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NIR  near infrared  
PLS-DA  partial least squares-discriminant analysis  
RDLE  refreshed delayed light emission  
RGB  red, green, blue

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