Computer Based Data Acquisition and Control in Agriculture

Nondestructive Detection of Internal Insect Infestation in Jujubes Using Visible andNear-Infrared Spectroscopy

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ABSTRACT

This paper reports on a study of comparing three spectroscopic measurements (i.e., interactance, reflectance, and transmittance) in the Vis/NIR range for the detection of internal insect infestation with different damaged levels in jujubes. The stepwise discriminant analysis was used to derive the discriminant functions based on the effective wave lengths that had maximum discriminatory potential for the different internal conditions. The results show both of the interactance in the long-wave NIR (LWNIR) and the transmission in the visible and short-wave near-infrared (VSWNIR) wavelength ranges display an obvious advantage over the reflectance for every range in completely distinguishing infested jujubes from intact jujubes; however, interactance and reflectance in the VSWNIR wavelength range exhibited higher classification accuracies in sorting severely damaged jujubes from slightly infested and intact samples; furthermore, transmission had clear advantages over both interactance and reflectance for distinguishing slightly infested jujubes from intact jujubes in the VSWNIR range.

Keywords : *Jujube, Insect infestation, Spectroscopy, Interactance, Reflectance, Transmission*

Introduction

Internal insect infestations cause severe damage to, and affect the quality and yield of, jujube fruits. Infestations change the color of fruit as well as create holes and introduce insect larvae into the fruit, which contaminates the fruit tissue. Ancylis sativa Liu is a particularly confounding pest that causes internal damage to jujubes; its larvae often bore holes from the stem-end of the fruit into the interior of the jujube, wherein they feed until maturity. Internal insect infestation is difficult to quickly or accurately detect using manual detection; however, internal insect damage is the primary concern in the evaluation of the internal quality of jujube fruits. The presence of a few infested fruits in a shipment can render the entire shipment unmarketable. Therefore, it is important to identify fruits with insect damage before the fruits are shipped to the market.

Non-destructive methods of detecting the internal qualityof fruits, such as X-ray, machine vision, and NIR methods,have recently gained a great deal of attention. Although Xray techniques have provided promising results for determining the internal quality of fruits and other produce [1]-[3], this method is not practical to be implemented for online detection. Machine vision is typically used to detect the presence of infestation using information from the hole on the surface of an infested fruit. This technique also provides information regarding other kinds of surface damage, particularly at the location of the hole and at the stem-end of the fruit. Hyperspectral imaging method was used to detect early bruises in apple[4]. A great deal of research has been conducted using NIR spectroscopy to detect the internal quality of fruits, such as brown hearts in pears and apples[5], [6], internal disorders[7], [8], internal breakdown[9], and internal infestation[10], [11].

Different spectral measurements have been used to estimate internal fruit properties and to determine the method with the best classification potential based on differences in the characteristics of the fruits[12]. Reflectance-mode spectroscopy measures the light that is reflected or scattered from the surface and outer surface layers of a fruit, which gained a great deal of attention in surface quality [13], [14] and internal fruit-quality research[15],[16]. The transmission mode can detect both the external and internal properties of a sample. Transmission is preferable to reflectance measurements for detecting the internal qualities of some fruits [5], [16]; infested jujube fruits".

Materials and Methode

A. Jujube samples

240 intact "Lizao" jujubes (Hovenia acerba Lindl.) and another 220 jujubes with different internal insect-infested levels were collected from an orchard in Niigata, Japan, during the harvest period of 2008 and 2009. Every sample was labeled, and the morphological properties of each sample were measured and recorded before each spectroscopic measurement (Table 1). however, interactance is a method that can be used to obtain information on the inside of fruits when transmission measurements are difficult to obtain[17], [18]. Studies have indicated that the interactance spectra method provides the most accurate results among the three measurements when measuring the soluble solid content (SSC) of kiwifruit[15]. Because a jujube fruit has a stone that constitutes a relatively large percentage of its transverse area, interactance measurements were used to compare the transmitted and reflected abilities with transmission and reflectance measurements at each wavelength range. These measurements were also used to reveal the internal properties of infested jujube tissue, including symptoms of browning or darkening, dehydration, and the presence of larvae, contamination, and insect holes.

The objectives of this study were: (1) to identify the effective wavelengths with the maximum discriminatory capability in the different wavelength ranges of the three spectra measurements, and (2) to compare three spectroscopic measurements (i.e., interanctance, reflectance and transmittance) for the detection of intact and pest

All jujube samples were measured using interactance, reflectance, and transmission spectroscopy at 20°C and 70% relative humidity. Following spectral measurements, the jujube samples were cut into halves for visual grading, with grades ranging from Level 0 (intact) to Level 3 (severe damage) based on the degree of infestation. Example images of jujubes at different infestation levels are shown in Fig. 1. In Level 1 samples, no visible larvae were present, and the tissues were slightly contaminated with only minor changes in color. In Level 2 samples, the tissues were obviously infested, with colors ranging from green or yellow to brown or dark brown, and also had clearly discernable small insect holes. In Level 3 samples, the fruit tissues had obvious insect holes and contamination, in addition to much larger larvae in comparison to those present in Level 2 samples. In the test, the number of each class from Level 0 to Level 3 includes 240, 73, 73, and 74 samples, respectively.

B. Spectral measurements

All spectra in interactance, reflectance, and transmission measmurements were obtained using two spectrophotometers with ranges from 310 to 1100 nm with a wavelength increment of 3.3 nm (a resolution of 0.3 nm), and from 1000 to 2150 nm with a 6.2-nm increment (a resolution of 0.6 nm), respectively (Handy Lambda Ⅱ & Solid Lambda NIR2.2t2, Spectra Co., Ltd., Japan; Fig. 2). The light sources for the interactance measurement (MHAA-100w, Moritex Co., Ltd., Japan) and for both of the reflectance and transmission measurements (HR-k2150N, Hiroshi industry Co., Ltd., Japan) consisted of two 100-W tungsten/halogen lamps that could be used in both the Vis and NIR regions. Under interactance mode, light was delivered (captured) from a fibre bundle (by a fibre receptor) positioned underneath the sample with a distance of 6 mm at an angle of 0° to the normal line. Under reflectance (transmission) mode, light was delivered from two halogen lamps positioned underneath (above) the sample with a distance of 160 mm at an angle of 30° to the normal line. Vis/NIR spectra were collected and transformed using Wave Viewer software (Spectra Co., Ltd., Japan). Reference and dark spectra were measured and stored prior to sample spectrum measurement by using a spectral white panel (2.5 mm thickness) to eliminate interference by the optical system itself (including light source and two spectrophotometers). Jujubes were placed centrally and were steadied on a fruit holder with the stem-calyx axis oriented horizontally such that spectra could be collected from three locations separated by 120° around the equator of each fruit.

C. Data analysis

The spectral data of each fruit were obtained by averaging three locations for each spectroscopic measurement. Due to the low signal at the two ends of the spectral curves, only spectral information from 440 to 1750 nm for interactance, from 500 to 1980 nm for reflectance, and from 680 to 1000 nm for transmission modes were analyzed in this study. In order to identify the effective wavelengths in each range through discrimination analysis, the above wavelength spectrum range was divided into three bands: (1) the visible and short-wave near-infrared (VSWNIR) range (440–1000 nm), (2) the long-wave nearinfrared (LWNIR) (1000–1980 nm), and (3) the entire spectrum (VNIR) from 440–1980 nm. The model-fitting procedure of the JMP 7.0 program (SAS Institute Inc., Cary, NC, USA) was used to select the effective wavelengths that could provide the maximum discriminatory capability. This procedure performs a stepwise discriminant analysis (DA) to select a subset from all obtained wavelengths for use in classification modes based on the significance level of a likelihood ratio test (LRT) among five class arrangements. Total 460 jujube samples with five different internal conditions are divided into five class arrangements ({0},{1}), ({0},{2}),

({ 0 } , { 1, 2, 3 }), ({ 0 } , { 3 }), and ({ 0, 1 } , { 2, 3 }). The stepwise discriminant analysis (SDA) with K-fold cross validation method was used for developing classification models. Here every class arrangement is divided into 10 subsets, therein, 1 of the 10 subsets was used as the test set and the other 9 subsets were put together to form a training set. Then the mean DA results from calibration and validation are computed after running the 10 models. The multivariate analysis of Variance (MANOVA) is conducted to observe if the differences between the classes being compared are true. It supports well to continue data analysis for the purpose of classification when the differences between the classes have significant level based on an F-test. DA was conducted in JMP 7.0 (SAS Institute Inc., Cary, NC).

Results and Discussion

A. Spectral analysis

Fig. 3 depicts average raw interactance, reflectance, and transmission spectra of internal jujube fruit conditions. Jujubes with the four degrees of tissue infestation yielded distinct differences in the spectra obtained in the different wavelength ranges. These internal conditions of the jujube fruit impact the spectral characteristics of light reflected from or transmitted through the fruit. Samples that were more seriously infected than others produced higher values in the VSWNIR wavelength range (except between Level 0 and Level 1 at 670 nm or lower) but lower values in the LWNIR wavelength range of both the interactance and reflectance measurements; however, the differences of those values in the VSWNIR wavelength range were larger than those in the LWNIR range. These changes in spectral appearance may

have been due to increased and decreased transmission abilities in the VSWNIR and LWNIR wavelength ranges, respectively. Transmission ability can be affected by wavelength ranges, degrees of infestation, and by stones that make up a relatively large percentage of the transverse area (Table 1). For the transmission measurement, light in the LWNIR wavelength range was not efficiently transmitted to the fiber receptor for both intact and infested fruits. Furthermore, more seriously infested jujubes appeared to have lower values in the VSWNIR wavelength range based on the increased transmissive properties of the infested tissues. As expected, more seriously infested jujubes exhibited higher absorbances in the interactance and reflectance measurements performed in the VSWNIR wavelength range in comparison to those of slightly damaged or intact fruits. This result was due to a decreased reflectance of the infested tissue, which allowed more incident light to be transmitted into the fiber receptor.

B. Discriminant Analysis

1. Interactance measurement

In the intera7ctance measurement, it was surmised that some light was reflected by the surface of the fruit stone after passing through the peel, the pulp, air cavities, larvae, and contaminants from the larvae; the remaining light was either scattered in different directions by other internal objects, or was captured by the fiber receptors. Four effective wavelengths in the VSWNIR wavelength range and two effective wavelengths in both the LWNIR and VNIR wavelength ranges were identified by the model-fitting procedure in each range (Table 2). The effective wavelengths contain the green (489 nm) and yellow (596 nm) regions,while peaks at approximately 832, 983, 1487, and 1497 nm correspond to water or OH functional groups. It is concluded that both the color and moisture of jujubes affect the discrimination of infested jujubes from intact jujubes but moisture content plays a more important role than color. The results of MANOVA show that the Wilks' Lambda test is always significant at the 0.0001 significance level, which indicates that there are indeed differences between the different classes of samples based on the extracted wavelengths to conduct discriminant analysis (Table 3). DA results indicate that the correct classification rates between intact (Level 0) and infested jujubes (from Level 1 to 3) were increased with infestation degree becoming serious and those in the LWNIR and VNIR ranges works better than in the VSWNIR range. Class arrangement Level (0+1) and (2+3) fruits were more accurately classified than Level 0 and (1+2+3) fruits in the VSWNIR range, but the reverse results were obtained in the LWNIR and VNIR ranges, wherein both exhibited the highest discrimination rates, with no infested fruits being misclassified as intact (Tables 4, 5). The above results revealed that light in the LWNIR range transmitted more useful information concerning the inside of the fruit tissue to the receptor in comparison to light in the VSWNIR range due to the enhanced light reflected by fruit and its stone (From transmission mode, it can be found that light in the LWNIR range was not efficiently transmitted to the fiber receptor, but was efficiently transmitted in the VSWNIR range). Therefore, it is likely the primary reason for the decreased correct classification rates between class arrangement Level (0+1) and Level (2+3) performed in the LWNIR wavelength range in the interactance mode that the spectral information of Level (0+1) fruits included slightly infested characteristics from Level 1 fruits. As a result, the effective LWNIR wavelengths less accurately distinguished Level (2+3) fruits from Level (0+1) fruits but could more accurately distinguish between intact and entire infested fruits.

2. Reflectance measurement

Unlike the interactance measurement, remitted light collected by a sensor, which was dominated by a scattering factor, was used as the information source in the reflective measurements. Three groups of effective wavelengths in the VSWNIR, LWNIR, and VNIR wavelength ranges were identified by a model-fitting procedure (Table 2). The peak at 673 nm corresponds to an absorption peak of chlorophyll,
whereas peaks at 579 nm and 726 nm belonged to the yellow and red regions respectively. Peaks at 759, 1905, and 1917 nm were attributed to water. The Wilks' Lambda test is significant at the 0.0001 significance level for five class arrangements in reflectance classification models (Table 3). For each class arrangement, the effective wavelengths in the VSWNIR wavelength range more accurately classified fruits than did those in the LWNIR and VNIR wavelength ranges, wherein far fewer infested fruits were misclassified as intact (Tables 4, 5). These results demonstrate that remitted light provide significantly more information on outer layer color change than on internal properties, such as fruit tissue dehydration. Both fruit color and moisture affect the identification and

separation of infested jujubes from the intact jujubes; however, color plays a more important role than moisture content, which is influenced to a greater extent by scattering than by absorption. Similar to what was observed for the aforementioned interactance measurements, Level (0+1) and (2+3) fruits were classified correctly more often than Level 0 and (1+2+3) fruits in the VSWNIR wavelength range; however, the opposite result was observed for LWNIR and VNIR ranges, more specifically, Level (0+1) and (2+3) fruits measured in the VSWNIR range were most accurately distinguished. These results further demonstrate that reflectance measurements do not provide more effective information regarding slight infestations inside the fruits. Therefore, the information received by the receptor from Level (1+2+3) fruits included similar characteristics as those provided by the outer layers of intact jujubes.

3. Transmission measurement

For transmission measurement, it was surmised that most of the light was reflected or absorbed after passing through the entire tissue of the jujubes as well as the objects in the way of the light path because no usable data were obtained from fruits measured in the LWNIR wavelength range. All three effective wavelengths (Table 2) can be attributed to water, which demonstrates that moisture content plays a more important role than color change in assessing fruit quality. The tests of significance show thatthe effect of classes is remarkable for transmission classification models (Table 3). Similar to the results obtained for interactance and reflectance measurements, the accuracies of fruits correctly classified increased with the degree of infestation. The opposite result was obtained for Level 0 and (1+2+3) fruits and Level (0+1) and (2+3) fruits in the same measurement range of the interactance and reflectance measurements (Tables 4, 5). The above results indicate that the light in the VSWNIR of the transmission measurement provided more information regarding the internal characteristics of slightly infested tissues. The spectral information of Level (0+1) fruits includes some slightly infested characteristics from Level 1 fruits, therefore, Level 0 and (1+2+3) fruits are more easily distinguished from each other in comparison to Level (0+1) and (2+3) fruits measured in the VSWNIR range. Correspondingly, no infested jujubes are misclassified as intact using this classification scheme.

C. Comparison of the discriminant analysis results for different spectral modes

Ideally, infested jujubes (Level 1–3) should be completely separated from intact jujubes as fresh food; however, slightly infested jujubes (Level 1) are hardly distinguishable from intact ones (Level 0) in the VSWNIR range of the interactance measurement and in the whole spectral band of the reflectance measurement but it works well in the LWNIR range of the interactance measurement and in the VSWNIR range of the transmission measurement. In fact, only a very slight infestation or tissue discoloration could be observed in the Level 1 samples, and no larvae were observed. Therefore, the high classification accuracy could not be achieved for infected vs. uninfected fruits, except for the wavelength ranges with strong transmission abilities. Of the three measurements, higher classification accuracies were obtained for Level (0+1) and (2+3) fruits in the interactance and reflectance measurements in the VSWNIR wavelength range, and from Level (0) and (1+2+3) fruits in the transmission measurements in the VSWNIR wavelength range and in interactance measurements in the LWNIR and VNIR wavelength ranges. The observed differences in the three spectral measurements in three of the wavelength ranges for every class arrangement may have been due to the intrinsic properties of fruit, the degree of infestation, and the typical transverse area of the fruit stone. Light in the VSWNIR wavelength range most likely is more effectively transmitted through the fruit stone than in the LWNIR wavelength range, resulting in decreased transmission and increased reflection in the LWNIR wavelength range. For different class arrangements, different wavelength ranges were demonstrated to have different classification potentials that would affect their detection rates in the industry. Both interactance in the LWNIR range and transmission in the VSWNIR range had clear advantages over the reflectance measurement in completely separating infested jujubes from intact jujubes; however, VSWNIR light could cause a larger percentage of slightly infested jujubes to be classified as intact for both interactance and reflectance measurements. In practice, Level 1 fruits are usually unmarketable as fresh food but can be used as dried food after being processed in a fruit processing plant. Based on the different demands for classifying jujubes as being fresh or dried food, a few suggestions based on discriminant accuracy for different modes in different wavelength range may help for the online detection in industry. An interactance mode can be used to detect insect infestation from intact jujubes as being fresh food by using the LWNIR range or as being dried food by using the VSWNIR range, respectively; in the VSWNIR range, both the interactance and reflectance modes are suit for sorting insect infestation jujubes as being fresh food but transmission mode works well for that as being dried food.

Conclution

This study reports on comparing the performance of interactance, reflectance, and transmission spectroscopy at different wavelength ranges of Vis/NIR light in the detection evaluation of different degrees of internal insect infestation in jujubes. The wavelengths with the maximum discriminatory power were identified, and a discrimination function was developed based on three spectral measurements in different wavelength ranges for each class arrangement. The following conclusions can be drawn from our results: (1) The effective wavelengths in the LWNIR wavelength range of interactance measurement and in the VSWNIR wavelength range of transmission measurement had substantial discriminatory power, permitting infested jujubes to be completely separated from intact jujubes. Furthermore, both of these measurements at these wavelength ranges demonstrated a marked potential as means to classify jujubes as fresh food. (2) Transmission measurement performed in the VSWNIR wavelength range exhibited clear advantages over both interactance and reflectance measurements performed in the same wavelength range in distinguishing intact and slightly infested jujubes. (3) Interactance and reflectance measurements performed at VSWNIR wavelengths range were preferable to classifying jujubes as dried food that derived from their high discriminatory potential to distinguish acceptable fruits (Level (0+1)) from the seriously infested fruits (Level (2+3)). Future research will investigate the impact of stone size on the accuracy of internal quality assessments using different spectroscopy modes at different wavelength ranges.

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Figures and Tables

Table 1. Morphological Properties of the Jujube Samples Studied

Stone/ Fruit	Diameter (mm)	Height (mm)	Transverse area (mm2)	Ratio of area (%)
Range	(5.5–18.3)/(19.1–44.0)	(9.5–29.9) /(20.7–40.6)	(46.2–293.6)/(346.2–1402.3)	0.10–0.54
Mean value	11.1/30.2	16.9/29.9	150.1./ 717.0	0.22

Table 2. The Effective Wavelngths Selected by the Model-fitting Procedure within the Wavelength Ranges Based on the Interactance, Reflectance, and Transmission Modes.

	Interactance			Reflectance			Transmission
	VSWNIR	LWNIR	VNIR	VSWNIR	LWNIR	VNIR	VSWNIR
Wavelengths (nm)	596 832 489 983	1487 1497	1487 1497	673 579 759 726	1097 1905 1917	673 1905 1029 1917	986 766 960
R^2	0.73 0.83 0.94 0.97	0.67 0.93	0.67 0.93	0.67 0.88 0.90 0.93	0.65 0.72 0.92	0.67 0.74 0.93 1.00	0.90 0.92 0.95
LRT	86.967 33.346 46.255 6.402	333.60 127.25	333.60 127.25	287.78 9.79 11.65 5.26	273.97 38.72 17.81	287.78 32.28 51.15 33.55	22.74 6.07 5.76

Table 3. Wilks' lambda Test Results from the Manova Procedure for the Interactance, Reflectance, and Transmission Spectral Data with the Consideration of Different Class Arrangements

Class arrangement	Interactance		Reflectance		Transmission	
	Wilks' lambda	P > F	Wilks' lambda	P > F	Wilks' lambda	P > F
{0} , {1}	0.46	< 0.0001	0.47	< 0.0001	0.45	< 0.0001
{0} , {2}	0.44	< 0.0001	0.45	< 0.0001	0.42	< 0.0001
{0} , {3}	0.38	< 0.0001	0.37	< 0.0001	0.36	< 0.0001
{0} , {1, 2, 3}	0.40	< 0.0001	0.44	< 0.0001	0.39	< 0.0001
{0, 1} , {2, 3}	0.49	< 0.0001	0.48	< 0.0001	0.47	< 0.0001

Table 4. The Mean Calibration Results Based on 10-fold Cross Validation in Distinguishing Infested Jujubes from Intact Jujubes for Different datasets Using Interactance Reflectance and Tranmission Modes

Model	Interactance (%)			Reflectance (%)			Transmission (%)
	VSWNIR	LWNIR	VNIR	VSWNIR	LWNIR	VNIR	VSWNIR
{0} , {1}	89.1	100	100	84.2	86.7	88.4	93.6
{0} , {2}	97.2	100	100	94.0	89.1	89.2	95.3
{0} , {3}	98.6	100	100	97.1	96.9	99.7	97.2
{0} , {1,23}	87.3	100	100	90.2	85.2	85.4	96.5
{01} , {23}	94.3	83.5	83.5	92.3	83.5	83.5	84.7

Table 5. The Mean Prediction Results Based on 10-fold Cross Validation in Distinguishing Infested Jujubes from Intact Jujubes for Different datasets Using Interactance Reflectance and Tranmission Modes

Model	Interactance (%)			Reflectance (%)			Transmission (%)
	VSWNIR	LWNIR	VNIR	VSWNIR	LWNIR	VNIR	VSWNIR
{0} , {1}	88.9	100	100	84.0	86.8	88.3	93.8
{0} , {2}	97.1	100	100	94.2	89.4	89.4	95.2
{0} , {3}	98.4	100	100	97.0	97.0	100	97.0
{0} , {1,23}	87.5	100	100	89.9	85.0	85.2	96.8
{01} , {23}	94.1	83.2	83.2	92.0	83.2	83.3	85.1

Fig.1. Examples of Jujubes with Different Levels of Internal Damage

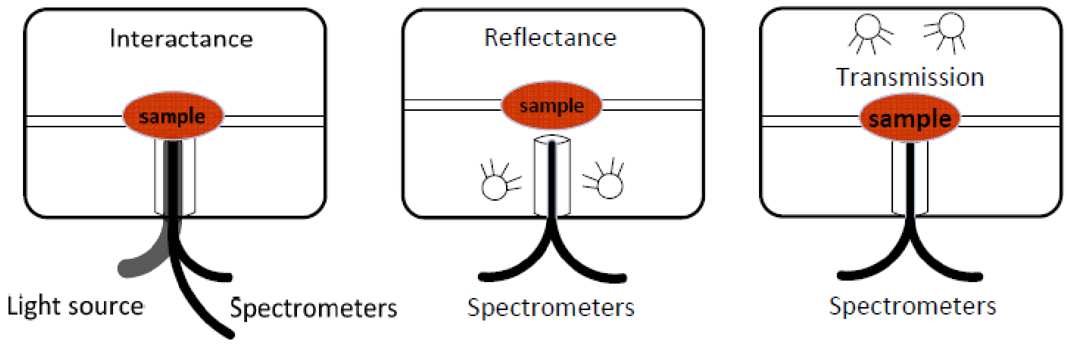

Fig. 2. Scematic of Interactance (a) Reflectance, (b) Transmission, and (c) Measurements

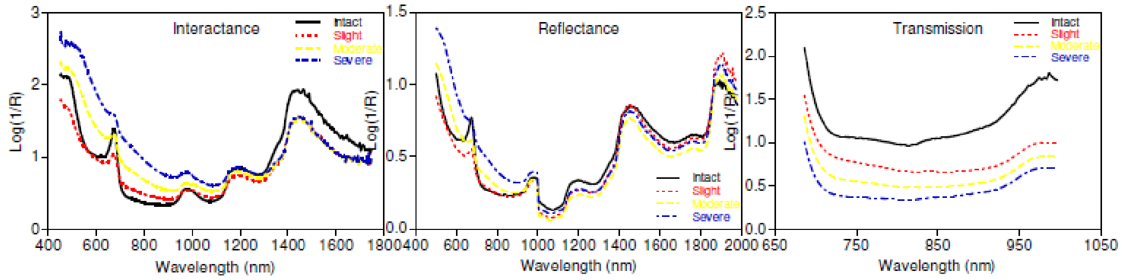

Fig. 3. Average Spectral Curves for Different Internal Conditions