

Hyperspectral Characteristics of Apple Leaves Based on Different Disease Stress

Xianyi Fang¹, Xicun Zhu^{1,2#}, Zhuoyuan Wang¹, Gengxing Zhao¹, Yuanmao Jiang³, Yan'an Wang⁴

1. College of Resources and Environment, Shandong Agricultural University, Tai'an 271018, China

2. National Engineering Laboratory for Efficient Utilization of Soil and Fertilizer, Tai'an 271018, China

3. College of Horticulture Science and Engineering, Shandong Agricultural University, Tai'an 271018, China

4. State Key Laboratory of Crop Biology, College of Life Science, Shandong Agricultural University, Tai'an 271018, China

#Email: zxc@sdau.edu.cn

Abstract

The hyperspectrum were measured on healthy apple leaves and infected leaves by brown spot, yellow leaves and mosaic virus at different severity levels in orchards of Qixia experimental sites, Shandong province. The objectives of this study were to (i) analyze and compare the hyperspectral reflectance characteristics of apple leaves infected by three diseases, (ii) confirm the sensitivity wave bands at different severity levels respectively and (iii) establish the diagnosing models of leaves infected by these three diseases at different severity levels. The results indicated that the hyperspectral reflectance of apple leaves at different disease stress was higher than that of healthy apple leaves in the visible region, lower in the near-infrared region and higher in the short wave infrared region compared with the hyperspectral reflectance of healthy apple leaves. The hyperspectral reflectance of apple leaves decreased with disease levels increasing in the near-infrared region. However, the hyperspectral reflectance of apple leaves increased with disease levels increasing in the short wave infrared region with disease levels increasing. The 422 nm~724 nm and 710 nm~724 nm could be used as sensitive bands for diagnosing apple leaves infected by brown spot, 410 nm~724 nm was the most sensitive region for diagnosing apple leaves infected by mosaic virus and 585 nm -709 nm was the sensitive bands for diagnosing apple leaves infected by yellow leaf disease at different severity levels. The visible region was the sensitive region for recognizing the disease severity levels of apple leaves at different disease stress. The logit model $y = 0.0039\ln(R_{755}) + 0.0076$ was better for diagnosing apple leaves infected by brown spot with R_{755} as the independent variable. The power model $y = 0.0067[(R_{516} \times R_{694})/R_{768}]^{0.4808}$ was the best model for diagnosing apple leaves infected by mosaic virus. The index model $y = 0.009e^{-0.6302(R_{961}/R_{759})}$ was proved to be the best model for diagnosing apple leaves infected with yellow leaf disease. The research provides theoretical basis and reference for diseases and pests monitoring and prevention in hyperspectrum for fruit trees.

Keywords: Apple Leaves; Disease Stress; Hyperspectral Characteristics; Diagnosing Models

1 INTRODUCTION

Brown spot, yellow leaves and mosaic virus are common diseases that threatening apple production in China. It can do harm to apple leaves and infect fruit and petiole, affecting apple production and quality. Therefore, timely, accurately and comprehensively methods or tools to get apple's disease information is necessary for preventing and curing apple diseases. Traditional plant diseases monitoring recognition mainly adopts artificial field investigation, which was accurate and reliable, but time-consuming, laborious and poor timeliness. It is difficult to meet the need of real-time, rapid, accurate and large area of monitoring apple diseases [1]. Using hyperspectral remote sensing technology to monitor plant diseases has become an important research direction [2]. After apple leaves infected with diseases, its physiological and biochemical parameters will have corresponding changes, thus affecting its hyperspectral characteristics. It provides a theoretical basis for monitoring apple diseases by using remote sensing technology. So far, many studies have focused on monitoring plant diseases at different severity levels, which is

easier to estimate, to give an indirect assessment of the degree of the plant diseases. Mirik et al [3] demonstrated that vegetation index could predict the density of wheat aphids. Delalieux et al [4] found that 1350 nm~1750 nm was the best wavelength range for distinguish healthy apple foliar and foliar that infected with scab. Prabhakar et al [5] established leafhoppers estimate models, which could effectively monitor the number of the cotton leafhoppers. Cao et al [6] have identified that wheat diseases index and canopy hyperspectral reflectance was strongly correlated with its chlorophyll contents. Qiao et al [7] found that the edge of red and green region played an important role in identifying powdery mildew, stripe rust and insect pests of the winter wheat. Luo et al [8] build winter wheat aphids hyperspectral indices and aphids levels inversion model. Guo et al [9] achieved better results with SD_r , NDVI, RVI and reflectance at 690 nm and 850 nm for monitoring wheat stripe rust. Jiang et al [10-12] studied the relationship between the canopy hyperspectral reflectance and canopy chlorophyll contents, water contents, canopy nitrogen contents under stripe rust stress. Sun et al [13] illuminated the differences between the healthy rice canopy hyperspectral reflectance and the hyperspectral reflectance of the rice foliar infected by rice *cnaphalocrocis medinalis*. Liu et al [14] compared the healthy foliar pigment contents, the hyperspectral reflectance, the hyperspectral characteristics parameters with foliar under rice *aphelenchoides besseyi* Christie. Li et al [15] achieved fast and accurate classification of several kinds of rice diseases by using principal component analysis and probabilistic neural network. Shi et al [16] established hyperspectral identification model based on support vector machine method, and can effectively identify the rice leaf damaged. Wang et al [17] used plant spectrometer to test hyperspectral reflectance changes of leaf damaged by aphids. Jiang et al [18] designed a new index $R_{500} \times R_{550} / R_{680}$ to identify the disease of soybean. Chen et al [19-21] systematically measured the spectrum and physical-chemical parameters of cotton leaves infected by aphids, the results showed that the thickness, water and Chla, Chlb and Cars decreased in leaves. Jing et al [22-23] found that 650 nm~700 nm was the best bands to recognize verticillium wilt severity of cotton leaf. Most studies have used remote sensing technology to monitor the crop and forest tree diseases. However, there was few research focused on apple diseases [24-25].

The objectives of the study were to reveal hyperspectral characteristics of the apple foliar that infected with brown spot, yellow leaves and mosaic virus by combining hyperspectral technology and photo images, through data transformation and analyzing to establish illness diagnosis models at different disease stress. It hopes to provide theoretical guidance and technical support for large area apple disease diagnosing and identification by using hyperspectral remote sensing technology.

2 MATERIALS AND METHODS

2.1 SITE DESCRIPTION AND SAMPLINGS

The experiments were conducted in Qixia county experimental sites of Shandong Province in China (120°33'E, 37°05'N). The district covers an area of 390.52 km² and its climate is defined as sub-humid continental monsoon. The average annual temperature is 11.3°C. The mean precipitation amounts to 650 mm per year of which 70% occurs in summer months.

Red Fuji apple is one of the most important economic trees in this district. Field samplings were carried out in June 2013. Healthy apple leaves and those infected with brown spot, yellow leaves and mosaic virus were randomly selected from different orchards. Apple leaves were collected on the same level. 90 samples were collected altogether, including 30 healthy leaf samples, 20 leaf samples that infected with brown spot, 20 yellow leaf samples and 20 mosaic virus leaf samples. All sampling plots were about 20 m away from adjunct road in order to avoid other possible effects.

2.2 HYPERSPECTRAL DATA COLLECTION AND CLASSIFICATION

2.2.1 HYPERSPECTRAL DATA COLLECTION

Hyperspectral reflectance was measured with ASD FieldSpec 3 (Analytical Spectral Devices Inc, Boulder, CO, USA). The ASD FieldSpec 3 spectrometer was configured to collect reflectance from 350 nm to 2500 nm. The sampling interval is 1.4 nm for the spectral region of 350 nm~1050 nm and 2 nm for the 1000 nm~2500 nm region. A barium sulfate (BaSO₄) standard whiteboard would be used for correction about 15 minutes. Hyperspectral measurements

were taken at the top, middle and bottom of the leaves and averaged to represent the reflectance of the sample.

2.2.2 CLASSIFICATION OF THE DISEASES SEVERITY LEVELS

Diseases severity levels were classified after the measurement of the hyperspectral reflectance. The apple foliar diseases severity levels were divided into four grades according to the blade incidence area percentage of the total leaf area, namely health (SL0): all leaf disease-free, disease spot area accounted for 0% of leaf area; mild (SL1): disease spot accounted for 0%~ 10% of leaf area; moderate (SL2): disease spot accounted for more than 20% of leaf area.

2.3 DATA PREPROCESS

The reflectance spectra were analyzed with ViewSpecPro software Version 5.0.19 (Analytical Hyperspectral Devices Inc, Boulder, CO, USA) to get the original hyperspectral reflectance data of the different disease severity leaf samples. Apple leaf photos were processed with Photoshop. Apple leaf disease severity levels were divided by calculating leaf incidence area percentage of the total leaf area.

3 RESULTS AND ANALYSIS

3.1 THE APPLE LEAF HYPERSPECTRAL REFLECTANCE CHARACTERISTICS

The hyperspectral curves of the apple leaves infected with brown spot, yellow leaves, mosaic virus and healthy were Fig.1. As shown in Fig.1, the hyperspectral curves showed similar change trends in 350 nm~2500 nm. But the hyperspectral reflectance displayed difference. The differences in visible wavelength (380 nm~760 nm) were more obvious than that in the near infrared and short-wave infrared region. The hyperspectral reflectance that infected with brown spot and mosaic virus were greater than the hyperspectral reflectance of the healthy apple leaves. The reason for this phenomenon was the chlorophyll contents in apple leaves decreased under disease stress, the absorption of green light and blue-violet reduced, thus the reflection enhanced. While the hyperspectral reflectance of the apple leaves that infected with mosaic virus was lower than the hyperspectral reflectance of the healthy apple leaves in near infrared reflection platform (800 nm~1300 nm). The hyperspectral information in the near-infrared region mainly reflected the internal structure of the plant. The hyperspectral reflectance of the apple leaves that infected with mosaic virus was slightly larger than the hyperspectral reflectance of the healthy apple leaves. This was because the disease destroyed the leaf cell membrane structure, resulting in the decrease of the plant water content, thus the hyperspectral reflectance increased. The hyperspectral shapes that infected with yellow leaves were similar in the near-infrared and short-wave infrared region. Its reflection was lower than that of healthy apple leaves. In the visible light region, the reflectance of the apple leaves that infected with yellow leaves at “green peak” were higher than those of healthy apple leaves, and in 490 nm~645 nm formed a steep slope.

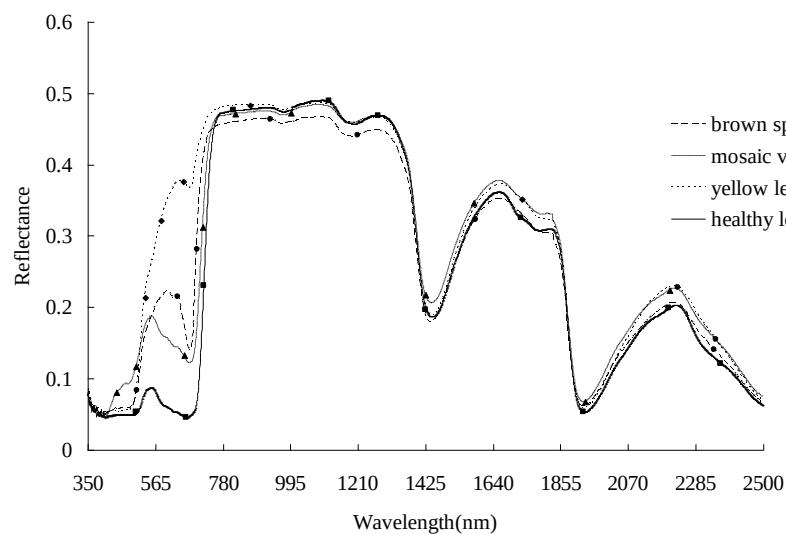


FIG.1 HYPERSPECTRAL CURVES OF THE APPLE LEAVES AT DIFFERENT DISEASES

3.2 THE APPLE LEAF HYPERSPECTRAL REFLECTANCE CURVES

Fig 2, Fig 3 and Fig 4 illustrates hyperspectral reflection curves of the apple leaves that infected with brown spot, mosaic virus and yellow leaves at different severity levels. The hyperspectral curves of the apple leaves under different diseases in different disease severity levels were different in the visible light region, while showed similar variation trends in the near-infrared and short-wave infrared region. The hyperspectral reflectance of the healthy apple leaves was lower than those infected with diseases in the visible light region (380 nm~760 nm), and their differences increased gradually with the increase of the disease severity levels. The hyperspectral reflectance of the apple leaves at different severity levels at “green peak ”and “red valley”increased obviously while contrasting them. The hyperspectral reflectance of the healthy apple leaves was greater than those under disease stress in the near-infrared region (800 nm~1300 nm), and the hyperspectral reflectance decreased with the increasing of the disease severity levels. The hyperspectral reflectance of the healthy apple leaves was lower than those infected with disease in 1300 nm~2500 nm. Meanwhile, the hyperspectral reflectance increased with the increasing of the disease severity levels, and showed obvious difference at 2200 nm. Thus the reflectivity could be considered as the foundation to identify the disease damage degree of the apple leaves.

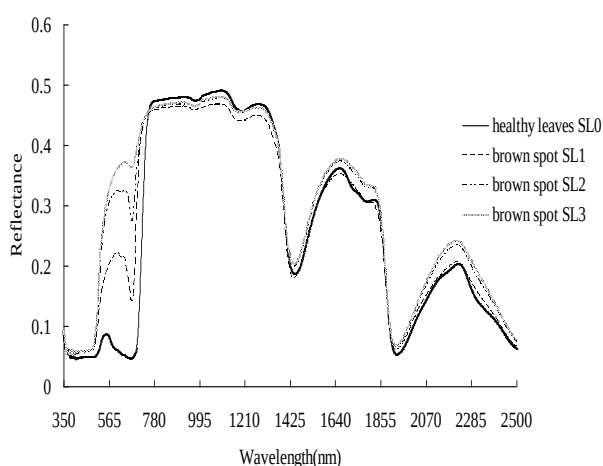


FIG. 2 REFLECTANCE SPECTRUM CURVES OF APPLE LEAVES INFECTED BY BROWN SPOT AT DIFFERENT SLs

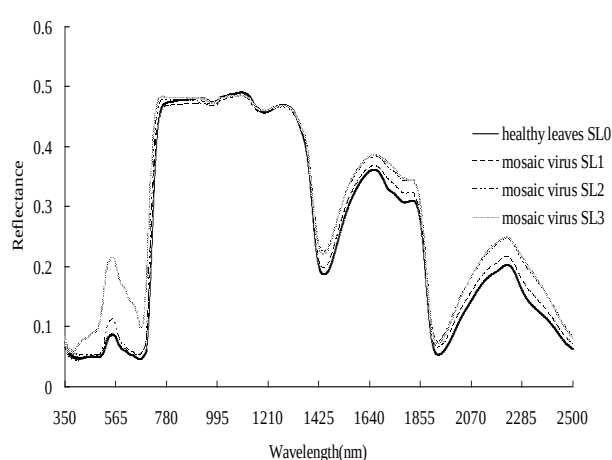


FIG. 3 REFLECTANCE SPECTRUM CURVES OF APPLE LEAVES INFECTED BY MOSAIC VIRUS AT DIFFERENT SLs

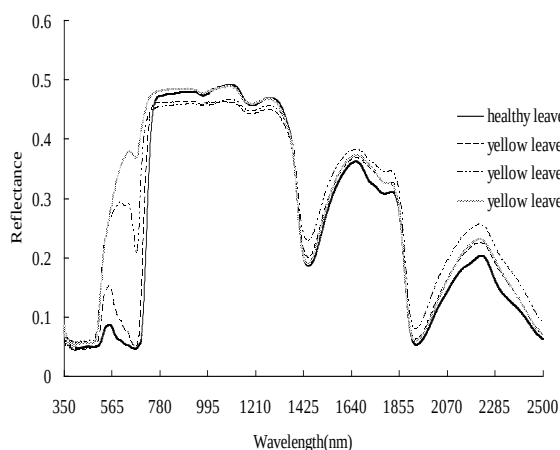


FIG. 4 REFLECTANCE SPECTRUM CURVES OF APPLE LEAVES INFECTED BY YELLOW LEAF DISEASE AT DIFFERENT SLs

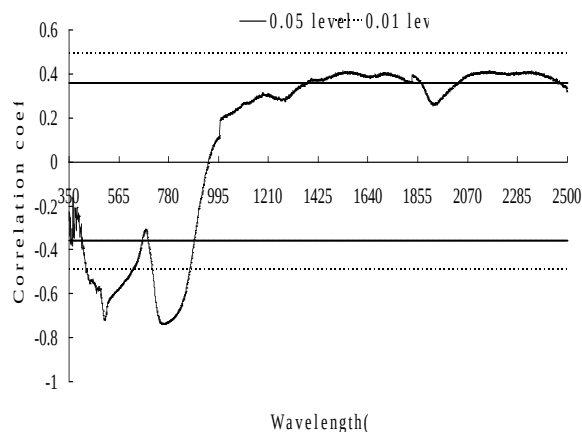


FIG. 5 CORRELATION COEFFICIENT BETWEEN THE PRIMITIVE HYPERSPECTRAL REFLECTANCE AND BROWN SPOT SLs

3.3 DISEASE SEVERITY LEVELS SENSITIVE BANDS

Selecting different disease severity levels apple leaves at different disease stress, and analyzing the relationships between the hyperspectral reflectance and different disease severity levels of apple leaves that infected with brown spot, yellow leaves and mosaic virus. As shown in Fig. 5, brown spot SLs of apple leaves were negatively related to

the reflectance in 350 nm~951 nm, the hyperspectral bands in 422 nm~621 nm and 710nm~870 nm were correlated significantly with brown spot SLs of apple leaves, brown spot SLs of apple leaves were positively related to the reflectance in 952 nm~2500 nm, the hyperspectral bands in 1377 nm~1864 nm, 2028 nm~2059 nm were correlated significantly with brown spot SLs of apple leaves. The highest correlation coefficient($r=-0.740$) was found at 755 nm. Thus the hyperspectral bands in 422 nm~621 nm and 710 nm~870 nm could be used as the sensitive bands monitoring brown spot SLs of apple leaves. 755 nm was the best wavelength monitoring brown spot SLs of apple leaves.

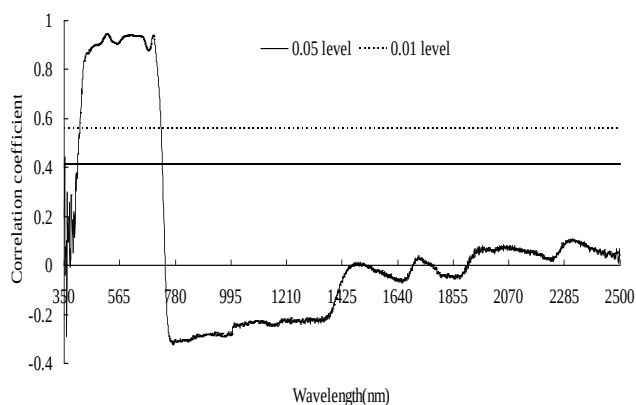


FIG. 6 CORRELATION COEFFICIENT BETWEEN THE PRIMITIVE HYPERSPECTRAL REFLECTANCE AND MOSAIC VIRUS SLs

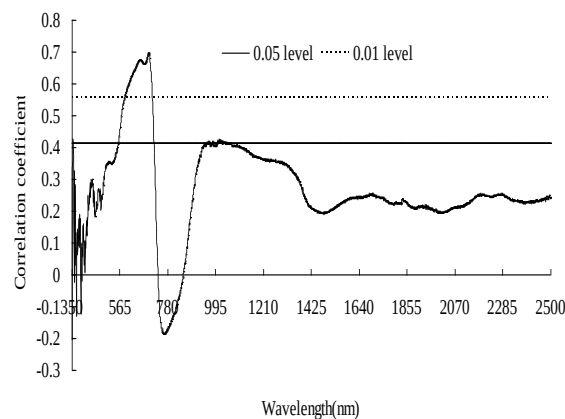


FIG. 7 CORRELATION COEFFICIENT BETWEEN THE PRIMITIVE HYPERSPECTRAL REFLECTANCE AND YELLOW LEAF DISEASE SLs

Fig. 6 showed that mosaic virus SLs of apple leaves were positively related to the reflectance in the visible light region 350 nm~739 nm, short-wave infrared region 1461 nm~1541 nm, 1699 nm~1769 nm and 1909 nm~2500 nm, the hyperspectral bands in 740 nm~1460 nm, 1515 nm~1698 nm and 1770 nm~1908 nm were negatively related to mosaic virus SLs of apple leaves. The hyperspectral bands in 410 nm~724 nm were correlated significantly with mosaic virus SLs of apple leaves. 516 nm had the largest $r(=0.945)$. We chose 410 nm~724 nm as the sensitive bands monitoring mosaic virus SLs of apple leaves.

Fig.7 illustrated the correlation coefficient between the hyperspectral reflectance and yellow leaves SLs of apple leaves. As shown in Fig.7, yellow leaves SLs of apple leaves were significantly related to the reflectance in 556 nm~717 nm, 1001 nm~1048 nm. The bands in 585 nm~709 nm were extremely significantly related to yellow leaves SLs of apple leaves. Thus this bands range could be used as the sensitive region monitoring yellow leaves SLs of apple leaves, with the highest r in 692 nm.

Comparing the correlation between the hyperspectral reflectance and the SLs of apple leaves at three disease stress, we found that although the correlation curves variation trends were different, but the highest value of the correlation coefficient were appeared in the visible light region, thus the visible light region could be served as the sensitive region to identify the SLs of apple leaves at different disease stress. The reason why the hyperspectral reflectance in 740 nm~780 nm were negatively related to the SLs of apple leaves at different disease stress was the disease destroyed mesophyll cells, the red edge slope reduce accordingly[23].

3.4 DIAGNOSING MODELS OF DISEASE SEVERITY LEVELS

In order to establish simple and practical disease SLs diagnosing models, 504 nm, 755 nm and 680 nm were used to build spectrum parameters R_{504} , R_{755} , R_{504}/R_{680} , R_{755}/R_{680} , $(R_{504}-R_{680})/(R_{504}+R_{680})$, $(R_{755}-R_{680})/(R_{755}+R_{680})$, $(R_{504} \times R_{755})/R_{680}$ for establishing brown spot disease SLs diagnosing models. In the same way, selecting 516 nm, 694 nm and 768 nm to build R_{516} , R_{694} , R_{516}/R_{768} , R_{694}/R_{768} , $(R_{516}-R_{768})/(R_{516}+R_{768})$, $(R_{694}-R_{768})/(R_{694}+R_{768})$, $(R_{516} \times R_{694})/R_{768}$ for establishing mosaic virus disease SLs diagnosing models. Choosing 692 nm, 961 nm and 759 nm to build R_{692} , R_{961} , R_{692}/R_{759} , R_{961}/R_{759} , $(R_{692}-R_{759})/(R_{692}+R_{759})$, $(R_{961}-R_{759})/(R_{961}+R_{759})$, $(R_{692} \times R_{961})/R_{759}$ for establishing yellow leaves disease SLs diagnosing models. The diagnosing models established by choosing the largest coefficients of determination were listed in Table.1. The model based on R_{755} had the highest coefficients of determination with

RMSE 0.001 and RE 0.007. The model $y = 0.0039\ln(R_{755}) + 0.0076$ was the best model for diagnosing brown spot disease SLs. The model based on $(R_{516} \times R_{694})/R_{768}$ had the highest coefficients of determination with RE 0.012. The model $y = 0.0067[(R_{516} \times R_{694})/R_{768}]^{0.4808}$ was the best model for diagnosing mosaic virus disease SLs. The model based on R_{961}/R_{759} had the highest coefficients of determination. It was regarded as the best model for diagnosing yellow leaves disease SLs of the apple leaves.

TABLE 1 DIAGNOSING MODELS AND TESTING FOR APPLE LEAVES INFECTED BY DIFFERENT DISEASE WITH DIFFERENT SLs

<i>Disease type</i>	<i>Spectral parameters</i>	<i>Model</i>	<i>R²</i>	<i>RMSE</i>	<i>RE</i>
Brown spot	R_{504}	$y = 0.0022\ln(x) + 0.0099$	0.835* *	0.002	0.057
	R_{755}	$y = 0.0039\ln(x) + 0.0076$	0.954* *	0.001	0.007
	R_{504}/R_{680}	$y = 0.0029x^2 - 0.0037x + 0.0049$	0.133	0.001	0.137
	R_{755}/R_{680}	$y = 0.0001x^2 - 0.001x + 0.0054$	0.210	0.001	0.203
	$(R_{504}-R_{680})/(R_{504}+R_{680})$	$y = 0.0045x^2 + 0.0026x + 0.0042$	0.101	0.001	0.122
	$(R_{755}-R_{680})/(R_{755}+R_{680})$	$y = 0.0075x^2 - 0.0069x + 0.0053$	0.212	0.001	0.144
	$(R_{504} \times R_{755})/R_{680}$	$y = 0.0004\ln(x) + 0.0047$	0.081	0.001	0.131
Mosaic virus	R_{516}	$y = 0.0098x^{0.9569}$	0.922* *	0.001	0.008
	R_{694}	$y = 0.0011\ln(x) + 0.0036$	0.932* *	0.001	0.067
	R_{516}/R_{768}	$y = 0.0046x + 0.0001$	0.974* *	0.001	0.136
	R_{694}/R_{768}	$y = -0.0081x^2 + 0.0084x - 0.0004$	0.976* *	0.001	0.075
	$(R_{516}-R_{768})/(R_{516}+R_{768})$	$y = 0.0035x + 0.0034$	0.979* *	0.001	0.029
	$(R_{694}-R_{768})/(R_{694}+R_{768})$	$y = 0.0034x + 0.0033$	0.974* *	0.001	0.078
	$(R_{516} \times R_{694})/R_{768}$	$y = 0.0067x^{0.4808}$	0.989* *	0.001	0.012
Yellow leaves	R_{692}	$y = -0.0509x^2 + 0.04x - 0.003$	0.862* *	0.004	0.757
	R_{961}	$y = -1.2169x^2 + 1.1673x - 0.275$	0.831* *	0.001	0.059
	R_{692}/R_{759}	$y = 0.0151x^2 - 0.0216x + 0.012$	0.125	0.003	0.636
	R_{961}/R_{759}	$y = 0.009e^{-0.6302x}$	0.976* *	0.045	0.039
	$(R_{692}-R_{759})/(R_{692}+R_{759})$	$y = 0.0458x^2 + 0.0153x + 0.0056$	0.150	2.611	1.980
	$(R_{961}-R_{759})/(R_{961}+R_{759})$	$y = 0.0048e^{-1.7908x}$	0.972* *	0.048	0.037
	$(R_{692} \times R_{961})/R_{759}$	$y = 0.0762x^2 - 0.0554x + 0.0144$	0.124	1.221	0.912

4 DISCUSSION

Plant leaves play an important role in photosynthesis. When leaves suffered from disease stress, its chlorophyll content and biomass decreased. Therefore, the foliar biochemistry changed correspondingly. Hyperspectral remote sensing provides a new method to detect the changes of leaves' interior structure and growth status caused by disease stress that could induce the abnormalities in the spectrum [26-27]. Compared with the hyperspectral reflectance in the near-infrared region, the reflectance of the visible light region showed more significant differences. Thus the visible light region was more sensitive to disease stress, which was the same as the result of the study. In this study, we analyzed and compared the hyperspectral reflectance characteristics of apple leaves infected by three diseases, sensitivity analysis enables the selection of optimal spectral bands most indicative of leaf chlorophyll content and structural variations that caused by disease stress. The results showed that the precision of the models based on bands combination may not be higher than that of single band models, the result was different from the study of Chen [21]. Maybe different disease caused different damage to plants, resulting in the different hyperspectral reflectance. The specific diagnosing models based on different bands combination should be judged whether the combination was the best independent variables according to different plants or different disease characteristics.

This study was conducted in the field to focus on the stress induced by brown spot, mosaic virus and yellow leaves. The experiment has demonstrated the potential for distinguishing the injured plants from the healthy ones by using the hyperspectral remote sensing techniques applicability in the field. Whereas, this paper only studied the apple

leaves hyperspectral characteristics that infected with one disease. When leaves infected with more than one disease, its hyperspectral curves would become more complicated. We would expand sampling areas and extend the research scale to canopy scale by airborne or space-borne so as to provide theoretic evidence for the identification of the plant diseases in future.

5 CONCLUSIONS

The primitive spectrum of the apple leaves that infected with brown spot, mosaic virus and yellow leaves was higher than the healthy apple leaves hyperspectral reflectance in the visible light region (380 nm~760 nm), lower than the healthy apple leaves hyperspectral reflectance in the near infrared region (800 nm~1300 nm), but higher than the healthy apple leaves hyperspectral reflectance in 1300 nm~2500 nm, the primitive hyperspectral reflectance showed a trend of high-low-high. In the visible light region (380 nm~760 nm), the difference value between the healthy apple leaves hyperspectral reflectance and the hyperspectral reflectance of the apple leaves that under disease stress increased gradually with the increasing of the disease severity levels. The hyperspectral reflectance of the apple leaves decreased gradually with the increasing of the disease severity levels in the near infrared region (800 nm~1300 nm). The hyperspectral reflectance of the apple leaves increased with the increasing of the disease severity levels. 422 nm~621 nm, 710 nm~870 nm were the sensitive bands for diagnosing the brown spot of the apple leaves. 755 nm could be considered as the best wavelength to monitor the disease severity levels of the apple leaves that infected with brown spot. 410 nm~724 nm was the sensitive bands for diagnosing the mosaic virus of the apple leaves, 516 nm could be regarded as the best wavelength to monitor the disease severity levels of the apple leaves that infected with mosaic virus; 585 nm~709 nm was the sensitive bands for diagnosing the yellow leaves of the apple leaves, 692 nm could be taken as the best wavelength to monitor the disease severity levels of the apple leaves that infected with yellow leaves. The best sensitive bands varied along with different disease, but the sensitive bands appeared in the visible light region, thus the visible light region could be considered to be the sensitive region to identify the disease severity levels of the apple leaves. The brown spot SLs logarithm model $y = 0.0039\ln(R_{755}) + 0.0076$ based on R_{755} had highest coefficients of determination ($R^2=0.954$), lowest RE ($RE=0.007$) and could be used as the best model for estimating the SLs of the apple leaves that infected with brown spot; $y = 0.0067[(R_{516} \times R_{694})/R_{768}]^{0.4808}$ was the best diagnosing model for monitoring the SLs of the apple leaves that infected with mosaic virus; $y = 0.009e^{-0.6302(R_{961}/R_{759})}$ could be taken as the best model for diagnosing the SLs of the apple leaves that infected with yellow leaves.

ACKNOWLEDGMENT

This paper was supported by Shandong Province Natural Science Fund (ZR2012DM007), the National Nature Science Foundation of China (41271369) and Youth science and technology innovation fund of Shandong Agricultural University (23731).

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