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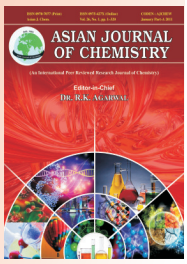

Sugar Contents and Firmness of Apples Based on Multi-Spectral Imaging Technology

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The paper proposed a prediction method of apple sugar content and firmness based on multi-spectral imaging. Firstly, four characteristic wavelengths (670, 750, 780 and 810 nm) were selected by correlation coefficient method. The gray images of samples at different wavelengths were collected by multi-spectral imaging system, then fitted with Lorenz function, modified Lorenz function, Gaussian function and polynomial function, respectively. It was found that the fitting effect of modified Lorenz function was best. Therefore, the experiment was performed by multiple linear regression and partial least square regression analysis of sugar content and firmness with the fitting parameters of modified Lorenz function. The result showed that the prediction of multiple linear regression model was better than partial least squares regression model. The modeling correction correlation coefficient, calibration standard deviation, the prediction correlation coefficient and predicted standard deviation of sugar content were 0.8568, 0.6736, 0.8395 and 0.7068, respectively. The modeling correction correlation coefficient, calibration standard deviation, the prediction correlation coefficient and the predicted standard deviation of firmness were 0.8660, 0.3275, 0.8407 and 0.3555, respectively. The results also showed that this method was feasible for the prediction of apple sugar content and firmness.

Keywords: Multi-spectral imaging, Apple, Sugar content, Firmness, Curve fitting, Multiple linear regression.

INTRODUCTION

Sugar content and firmness are important factors of fruit internal quality and also directly affect choice of consumers. Near-infrared spectroscopy (NIRS) is a common method used to detect the internal quality of fruit[1-8], but the detected information is one-dimensional and the large amount of data is also time-consuming. Moreover, the shape of the fruit tends to be irregular, the surface parts may also have differences in colour and characteristics of tissue and the location of fruit detected by fiber optic probe is limited, resulting in the information of the spectrum becoming incomplete. Spectral imaging technology consists of image analysis and spectral analysis technology. Spectral data can provide two-dimensional image information at each specific wavelength and the gray images at different wavelengths of the same pixel also provide spectral information, which can effectively reflect the information of the spectrum and the spatial characteristics of the sample. So it is a more comprehensive method to convey the spectral information[9-14]. Spectral imaging technology has been confirmed as a non-destructive method to predict the sugar content and firmness of apple, but the method is lack of the unified characteristic wavelength of the major internal quality[15-17]. This paper proposed a method which applied to predict the sugar content of apple and also the firmness. Firstly, characteristic wavelengths of sugar content and firmness were selected and the gray images of samples at different wavelengths were collected by the multi-spectral imaging system and then fitted with a variety of functions, to build the regression prediction models between fitting parameters and the value of sugar content and the value of firmness. The purpose of this paper was to provide methods and technology for realization of a real-time detection of apple internal quality.

EXPERIMENTAL

Red Fuji Apples as the experimental samples were procured from the fruit market. There was no obvious external defect on the surface of apples and the colour was uniform. The total number of apple samples was 50. Two points of each apple were measured. Every apple was marked before the experiment and then placed in the laboratory for 24 h to make the temperature of apple consistent with the environment temperature.

Apple multispectral images: Multi-spectral acquisition system which was based on the filtered sensitive wavelength was constructed and the obtained spectral images of apple were shown in Fig. 1. The system included a camera, lenses, a filter back wheel, 10 nm half-bandwidth optical filters with the center wavelength of 670, 750, 780 and 810 nm[18], a frame grabber, a halogen light source, a sample stage and so on.

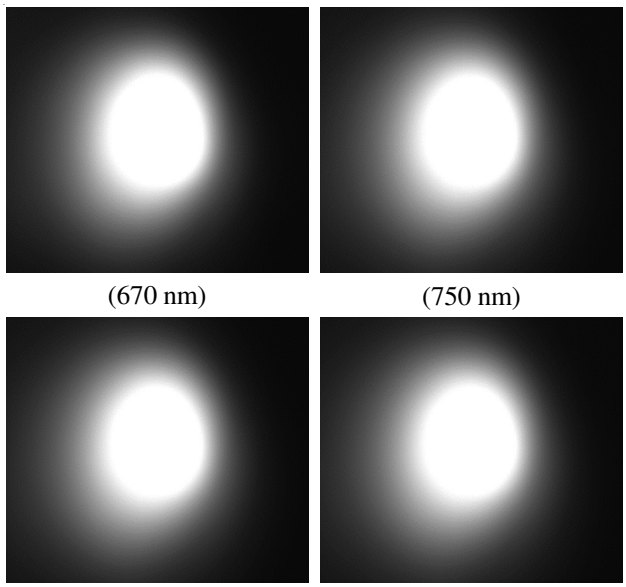


Fig. 1. Spectral images of apple

Measurement of sugar content and firmness: Sugar content was measured by PAL-1 digital refractometer, the incident point of each apple which was corresponding to light was picked as the measurement position and every position was measured three times, whose average value was taken as the final value of the sample.

Firmness was measured by GY-1 fruit firmness instrument. Similarly, the incident point of each apple which was corresponding to light was picked as the measurement position. Firstly, the peel of the measurement position was removed, then the instrument was inserted to the flesh uniformly with the depth of 10 mm and the maximum force in the process of flesh loaded was picked as the reference value. And each position was measured three times, whose mean value was taken as the firmness. The number of apple was 50 and each apple was measured in two points, so there was a total of 100 sets of data. The data would be divided into 70 modeling sets and 30 prediction. The statistics of sugar content and firmness value showed in Table-1.

Determination of fitting parameters: Since the spectral images acquired at the characteristic wavelengths was at radial asymmetric state with the light incident point as the center and intensity of the light decreased with the increase of the distance of the incident point. This paper firstly determined the center of spectral image of each band by centroid method, which was the light incident point (Fig. 2). In the spectral image acquired at each characteristic wavelength, the Euclidean distance between each pixel and their center pixel (*i.e.*, the incident point) was calculated according to formula (1):

$$dis((i_1, j_1),(i_0, j_0)) = \sqrt{(i_1 - i_0)^2 + (j_1 - j_0)^2} \quad (1)$$

where (i_1, j_1) represents the coordinates of any point of the image, (i_0, j_0) represents the coordinate of the center pixel of the image.

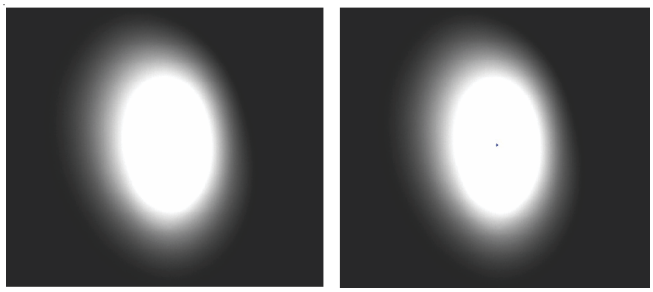


Fig. 2. Spectral image center

The average value of light intensity at each pixel of rings with the same width was calculated and the distribution of the scattering intensity of radius was obtained (Fig. 3).

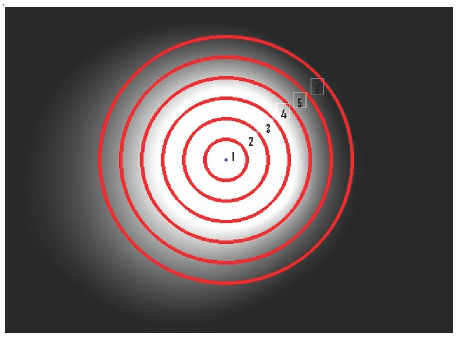


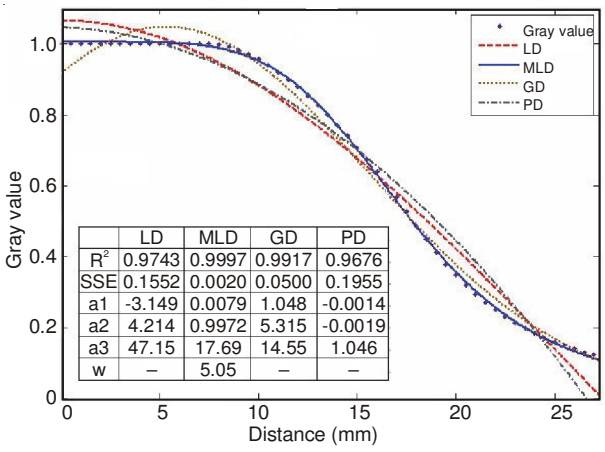
Fig. 4. Pixels selection in the image

Finally, the scattering intensity of radius was fitted with the Lorenz function (LD), modified Lorenz function (MLD), Gaussian function (GD) and polynomial function (PD), respectively and the fitting parameters were obtained, as shown in Fig. 4.

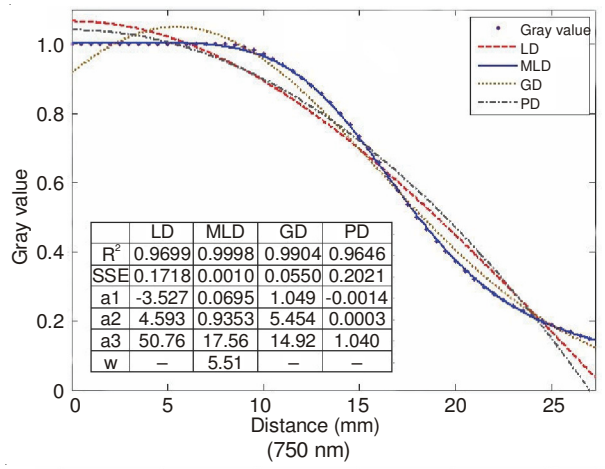
According to the distribution of light intensity values and curve fitting as shown in Fig. 4, it was found that the result of LD, GD and PD was poorer, but MLD could better fit the scattered light area. All light scattering images of other samples obtained the same result fitted with the four kinds of function (*i.e.* LD, MLD, GD and PD). Therefore, MLD was selected as the fitting method for the image at the characteristic wavelength of the samples to obtain fitting parameters.

TABLE-1
STATISTICS OF SUGAR CONTENT AND FIRMNESS VALUES

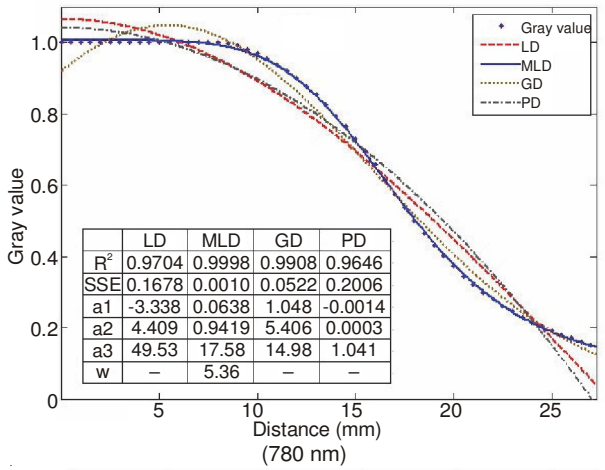
Index		Maximum	Minimum	Mean	Standard deviation
Sugar content	Modeling set	14.77	10.27	12.50	1.15
	Prediction set	14.10	11.15	12.60	0.85
Firmness	Modeling set	8.38	6.13	7.40	0.57
	Prediction set	8.62	6.48	7.70	0.65



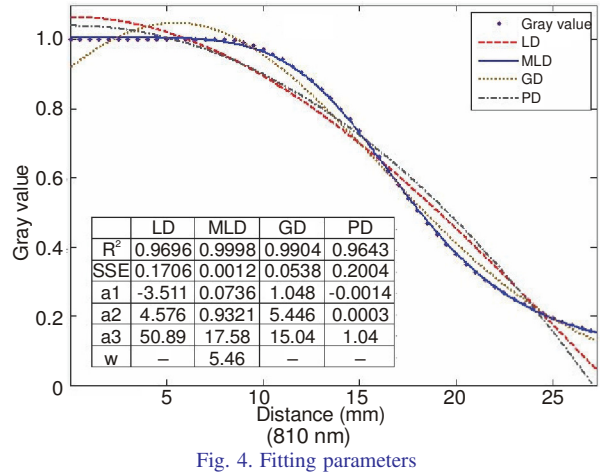
	LD	MLD	GD	PD
R^2	0.9743	0.9997	0.9917	0.9676
SSE	0.1552	0.0020	0.0500	0.1955
a1	-3.149	0.0079	1.048	-0.0014
a2	4.214	0.9972	5.315	-0.0019
a3	47.15	17.69	14.55	1.046
w	–	5.05	–	–



	LD	MLD	GD	PD
R^2	0.9699	0.9998	0.9904	0.9646
SSE	0.1718	0.0010	0.0550	0.2021
a1	-3.527	0.0695	1.049	-0.0014
a2	4.593	0.9353	5.454	0.0003
a3	50.76	17.56	14.92	1.040
w	–	5.51	–	–



	LD	MLD	GD	PD
R^2	0.9704	0.9998	0.9908	0.9646
SSE	0.1678	0.0010	0.0522	0.2006
a1	-3.338	0.0638	1.048	-0.0014
a2	4.409	0.9419	5.406	0.0003
a3	49.53	17.58	14.98	1.041
w	–	5.36	–	–



	LD	MLD	GD	PD
R^2	0.9696	0.9998	0.9904	0.9643
SSE	0.1706	0.0012	0.0538	0.2004
a1	-3.511	0.0736	1.048	-0.0014
a2	4.576	0.9321	5.446	0.0003
a3	50.89	17.58	15.04	1.04
w	–	5.46	–	–

Fig. 4. Fitting parameters

Establishment of the prediction model of sugar content

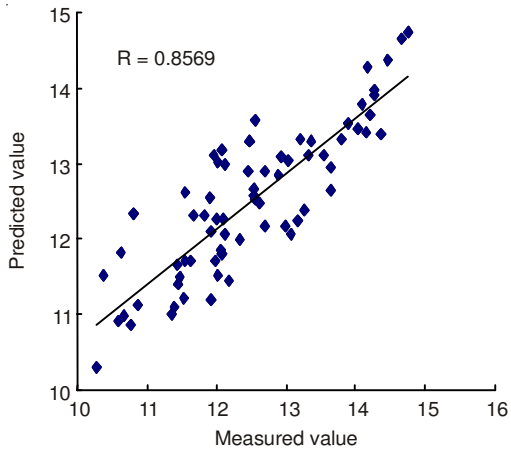
Multiple linear regression analysis: Multiple linear regression analysis of the measured values of sugar content with the fitting parameters of the spectral images at the four wavelengths by modified Lorenz function was performed and the prediction model was obtained as formula (2):

$$S = f_0 + \begin{bmatrix} f_{11} & f_{21} & f_{31} & f_{41} \\ f_{12} & f_{22} & f_{32} & f_{42} \\ f_{13} & f_{23} & f_{33} & f_{43} \\ f_{14} & f_{24} & f_{34} & f_{44} \end{bmatrix} \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ w_1 & w_2 & w_3 & w_4 \end{bmatrix}$$

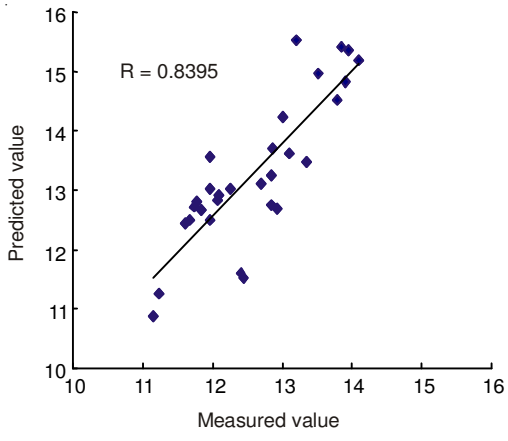
$$= 35.11 + \begin{bmatrix} 25.81 & -0.12 & -0.13 & -3.72 \\ 4.32 & -14.17 & 2.25 & 1.12 \\ -54.98 & 19.62 & -4.86 & -0.04 \\ 14.94 & -26.66 & 2.89 & 1.92 \end{bmatrix} \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ w_1 & w_2 & w_3 & w_4 \end{bmatrix} \quad (2)$$

where S is the sugar content to be predicted, a_{1i}, a_{2i}, a_{3i}, w_i (i = 1, 2, 3, 4) are curve fitting parameters of each wavelength obtained by MLD. The results predicted by the model were shown in Fig. 5.

As shown in Fig. 5, the correlation coefficient of modeling set and predicted set were 0.8569 and 0.8395, respectively, which indicated that the fitting parameters with sugar content obtained by MLD had good linear correlation and the model was feasible to predict the sugar content.



(a) Correlation plot of Modeling set



(b) Correlation plot of Predicted set

Fig. 5. Multiple linear regression analysis of sugar content

Partial least squares regression analysis: Partial least squares regression analysis of the measured value of sugar content with the fitting parameters of the spectral images at the four wavelengths by modified Lorenz function was performed and the prediction model was obtained as formula (3):

$$S = 12.08 + \begin{bmatrix} 24.19 & -0.56 & -0.77 & -3.50 \\ -4.57 & 2.68 & 2.09 & 2.64 \\ -5.34 & 0.93 & -3.59 & -2.33 \\ -4.65 & -3.47 & 2.51 & 2.52 \end{bmatrix} \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ w_1 & w_2 & w_3 & w_4 \end{bmatrix} \quad (3)$$

where S is the sugar content to be predicted, a_{1i}, a_{2i}, a_{3i}, w_i (i = 1, 2, 3, 4) are curve fitting parameters of each wavelength obtained by MLD. The results predicted by the model were shown in Fig. 6.

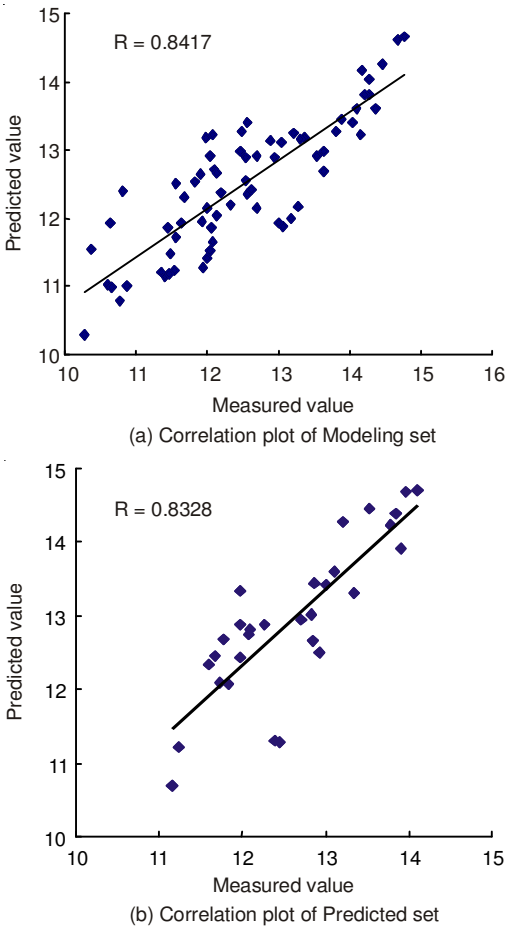


Fig. 6. Partial least squares regression analysis of sugar content

The correlation coefficient of modeling set and predicted set were 0.8417 and 0.8328, respectively, the result of the PLS was worse than MLS.

Establishment of the prediction model of firmness

Multiple linear regression analysis: Similar analysis with the sugar content, multiple linear regression analysis of the measured value of firmness with the fitting parameters of the spectral images at the four wavelengths obtained by modified Lorenz function was performed and the prediction model of the firmness was obtained as formula (4):

$$S = f_0 + \begin{bmatrix} f_{11} & f_{21} & f_{31} & f_{41} \\ f_{12} & f_{22} & f_{32} & f_{42} \\ f_{13} & f_{23} & f_{33} & f_{43} \\ f_{14} & f_{24} & f_{34} & f_{44} \end{bmatrix} \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ w_1 & w_2 & w_3 & w_4 \end{bmatrix}$$

$$= 7.22 + \begin{bmatrix} 5.93 & 0.96 & 0.05 & -0.40 \\ -21.26 & 22.58 & -0.14 & 1.60 \\ 1.12 & 6.01 & -1.91 & -1.88 \\ 16.48 & -30.08 & 2.19 & 0.17 \end{bmatrix} \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ w_1 & w_2 & w_3 & w_4 \end{bmatrix} \quad (4)$$

where F is the firmness to be predicted, a_{1i}, a_{2i}, a_{3i}, w_i (i = 1, 2, 3, 4) are curve fitting parameters of each wavelength obtained by MLD. The result predicted by the model was shown in Fig. 7.

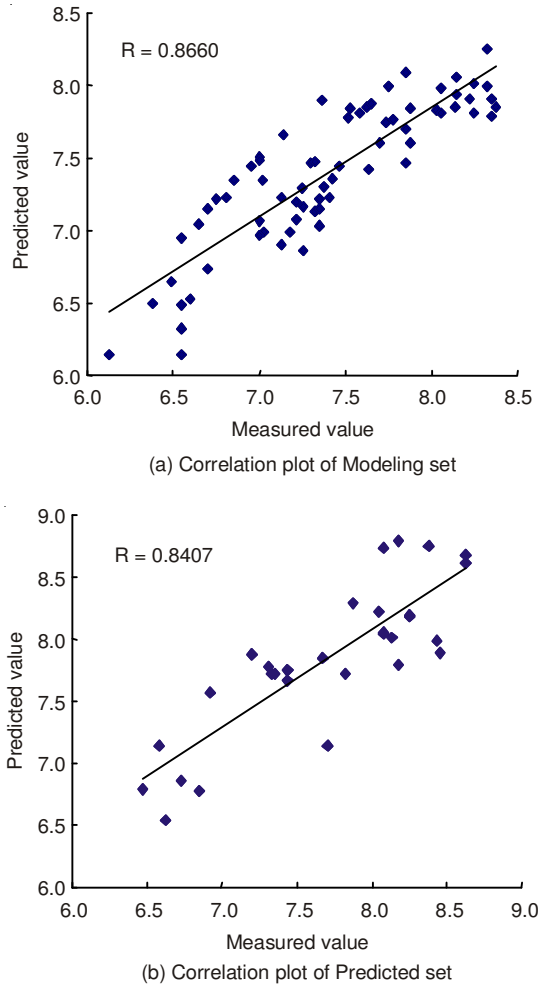


Fig. 7. Multiple linear regression analysis of firmness

As shown in Fig. 7, the correlation coefficient of modeling set and predicted set were 0.8660 and 0.8407, respectively, which indicated that the fitting parameters obtained by MLD with firmness had good linear correlation and the model was feasible to predict firmness.

Partial least squares regression analysis: In the same way, partial least squares regression analysis of the measured value of sugar content with the fitting parameters of the spectral images at the four wavelengths by modified Lorenz function was performed and the prediction model was obtained as formula (5):

$$F = 7.95 + \begin{bmatrix} 5.80 & 0.96 & 0.07 & -0.39 \\ -20.53 & 22.61 & -0.10 & 1.58 \\ -0.88 & 5.44 & -1.99 & -1.87 \\ 17.18 & -30.19 & 2.20 & 0.18 \end{bmatrix} \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ w_1 & w_2 & w_3 & w_4 \end{bmatrix} \quad (5)$$

where F is the firmness to be predicted, a_{1i}, a_{2i}, a_{3i}, w_i (i = 1, 2, 3, 4) are curve fitting parameters of each wavelength obtained by MLD. The result predicted by the model was shown in Fig. 8.

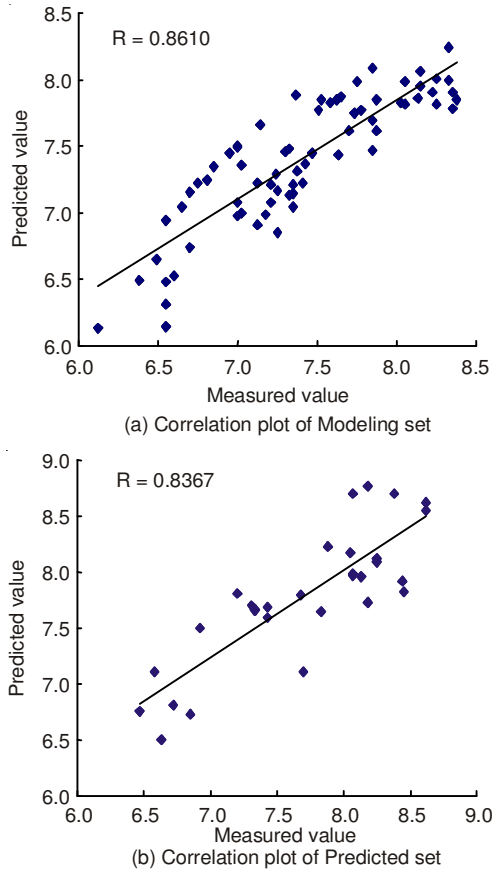


Fig. 8. Partial least squares regression analysis of firmness

The correlation coefficient of modeling set and predicted set were 0.8610 and 0.8367, respectively. But the result of the PLS was worse than MLS.

Conclusion

Through combining the analysis of light scattering intensity distribution of the spectral images under the four wavelengths (670, 750, 780 and 810 nm), with the fitting parameters obtained by MLD and the prediction models built by multiple linear regression and partial least square regression analysis of sugar content and firmness with the fitting parameters of MLD, we could conclude that the result of the MLS was better than PLS. The modeling correlation coefficient, calibration standard deviation, the prediction correlation coefficient and predicted standard deviation of sugar content were 0.8568, 0.6736, 0.8395 and 0.7068, respectively. The modeling correction correlation coefficient, calibration standard deviation, the prediction correlation coefficient and the predicted standard deviation of firmness were 0.8660, 0.3275, 0.8407 and 0.3555, respectively. Future research is to investigate the feasibility of using these four characteristic wavelengths to detect apple acidity, in order to build a real-time portable device for detecting the internal quality of apple. Clearly, multispectral imaging technology, which is a simple, inexpensive, rapid non-destructive testing technique to detect the internal quality of fruit, can be generalized to detect internal quality of other agricultural products.

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