Journal of Innovative Optical Health Sciences
Vol. 8, No. 6 (2015) 1550032 (8 pages)
© The Author(s)
DOI: 10.1142/S1793545815500327

World Scientific
www.worldscientific.com

J. Innov. Opt. Health Sci. 2015.08. Downloaded from www.worldscientific.com
by 103.240.126.9 on 10/21/18. Re-use and distribution is strictly not permitted, except for Open Access articles.

Nondestructive determination of soluble solids and firmness in mix-cultivar melon using near-infrared CCD spectroscopy

Jie Lu*, Shuye Qi*, Ran Liu*, Enyang Zhou*, Wu Li†,
Shuhui Song† and Donghai Han*,‡
*College of Food Science and Nutritional Engineering
China Agricultural University, Beijing 100083, P. R. China
†National Engineering Research Center for Vegetables (NERCV)
Beijing 100097, P. R. China
‡handh@cau.edu.cn

Received 7 July 2014
Accepted 22 March 2015
Published 13 May 2015

Nondestructive evaluation of melon quality is in great need of comprehensive study. Soluble solids content (SSC) and firmness are the two indicators of melon internal quality that mostly affect consumer acceptance. To provide guidance for fruit classification, internal quality standards was preliminarily established through sensory test, as: Melon with SSC over 12° Brix, firmness 4–5.5 $\mathrm{kgf \cdot cm^{-2}}$ were considered as satisfactory class sample; and SSC over 10° Brix, firmness 3.5–6.5 $\mathrm{kgf \cdot cm^{-2}}$ as average class sample. The near infrared (NIR) nondestructive detection program was set as spectra collected from the stylar-end, Brix expressed by the average SSC of inner and outer mesocarp, each cultivar of melon was detected with its own optimum integration time, and the second derivative algorithm was used to equalize them. Using wavelength selected by genetic algorithms (GA), a robust SSC model of mix-cultivar melon was established, the root mean standard error of cross-validation (RMSECV) was 0.99 and the ratio performance deviation (RPD) nearly reached 3.0, which almost could meet the accuracy requirement of 1.5° Brix. Firmness model of mix-cultivar melon was acceptable but inferior.

Keywords: Melon; nondestructive detection; near-infrared; fruit quality; soluble solids content; firmness.

1. Introduction

For a long time, soluble solid content (SSC) was taken as the only melon quality indicator. Mutton *et al.*[1] recommended a minimum quality standard of 10° Brix for Australia market, and US recommended 9° Brix.[2] However, consumer acceptability for melon

‡Corresponding author.

This is an Open Access article published by World Scientific Publishing Company. It is distributed under the terms of the Creative Commons Attribution 3.0 (CC-BY) License. Further distribution of this work is permitted, provided the original work is properly cited.

J. Innov. Opt. Health Sci. 2015.08. Downloaded from www.worldscientific.com
by 103.240.126.9 on 10/21/18. Re-use and distribution is strictly not permitted, except for Open Access articles.

is determined by not only sugar concentration at harvest, but also its texture and maturity.[3] Tissue firmness of muskmelon fruit can decrease by 400% between 30 and 50 days post-anthesis measured by Lester, which was thought to affect both duration of shelf-life and intensity of sweetness.[4]

Most instrumental techniques measuring these properties are destructive and involve a considerable amount of manual work. For measuring firmness, which was generally by hand-held penetrometer, will leave a hole of ~3.5 mm diameter and 8 mm deep in the fruit, and the technique is time-consuming and subjective. Therefore, a rapid, noninvasive and on field analytical method that could determine melon internal quality will provide enormous advantage over conventional technique which is highly required.

Near infrared (NIR) spectroscopy, allied to multivariate calibration techniques, fulfill the above requirements. It has already been tested for nondestructive evaluation of firmness, acidity, soluble solids and other physiological properties of many fruits including apple,[5,6] kiwi,[7] Satsuma mandarin,[8] watermelon[9] and mango.[10] In melon, the very first publication was reported by Dull *et al.*[11] in assessing the SSC of intact cantaloupe with a root mean square error of prediction (RMSEP) of 2.18, by using the two wavelengths 896 and 860 nm in 1989. However, currently, Long and Walsh[12] found that, in the SSC calibration model, chemistry value assessed from outer tissue performs better than inner one; and calibration models highly varied among different cultivar populations. So far, even though pectin and cellulose, that mainly affect melon firmness, have NIR absorbance, no one has applied NIR technique on melon firmness detection. What is more, as the NIR spectroscopy is essentially composed of a large set of overtones and combination bands, to separate the irrelevant information and improve model robustness is a great challenge. There are many variable selection methods, such as genetic algorithms (GA), artificial neural networks (ANN), uninformative variable elimination (UVE) and successive projections algorithm (SPA), can be applied to variable selection. Among them, UVE and GA have been widely used in NIR spectra analysis recently.

In this work, we (i) found a mathematical technique, i.e., second derivative algorithm, to eliminate the energy spectra difference; (ii) set up a method for determining SSC and firmness in various melon cultivars, simultaneously and nondestructively, via NIR and multivariate calibration techniques; (iii) established sufficiently robust calibration model to correct the SSC and firmness of melon at postharvest stage. The NIR calibration model could be used to establish the classification standards.

2. Materials and Methods

2.1. *Samples*

Melon fruits (*Cucumis melo* L.) of four cultivars which were chosen to contrast fruit quality traits, such as color and physiological behavior, were organized for this study. Detailed properties of all the samples were summarized in Table 1. To ensure the consistency of the experiment condition, the fruits were all harvested by hand, transported and stored in a lab for 24 h at 25°C, before further analysis.

2.2. *Sensory evaluation*

References for sweetness and texture of different cultivars of melon fruits were measured at individual stations by a briefly-trained, 10-member preference panel. The number of tested melon fruits was 16, and the sensory index of each fruit was represented by the average score of each panelist. A 0–10 scale was used to rate the acceptability, [10, 8) represents satisfactory, [8, 6) average and [6, 0) dissatisfactory. The surrounded tissues of each evaluated position were crushed in a pressware and the resulting juice was assessed for SSC value

Table 1. Characteristic of four cultivars melon fruit.

Cultivar	Origin	Days after full bloom	Harvest time	Color of rind	Color of mesocarp
Elizabeth	Beijing, China	40–50	Jun, 2013	Yellow	White
M-1	Tianjin, China	45–55	Sep, 2013	Yellow	Orange
M-3	Tianjin, China	45–55	Sep, 2013	Green	Orange
M-5	Tianjin, China	45–55	Sep, 2013	Green	White

J. Innov. Opt. Health Sci. 2015.08. Downloaded from www.worldscientific.com
by 103.240.126.9 on 10/21/18. Re-use and distribution is strictly not permitted, except for Open Access articles.

(°Brix) on a digital refractometer (model: PR-101, ATAGO, Japan).

Fruit firmness was measured by a hand-held penetrometer (GY-1, China) with a 3.5 mm diameter plunger. Three measurements were made on each vascular region of melon equator, and were averaged to give mean value as the reference.

2.3. *NIR spectroscopy and constituent (SSC and firmness) measurements*

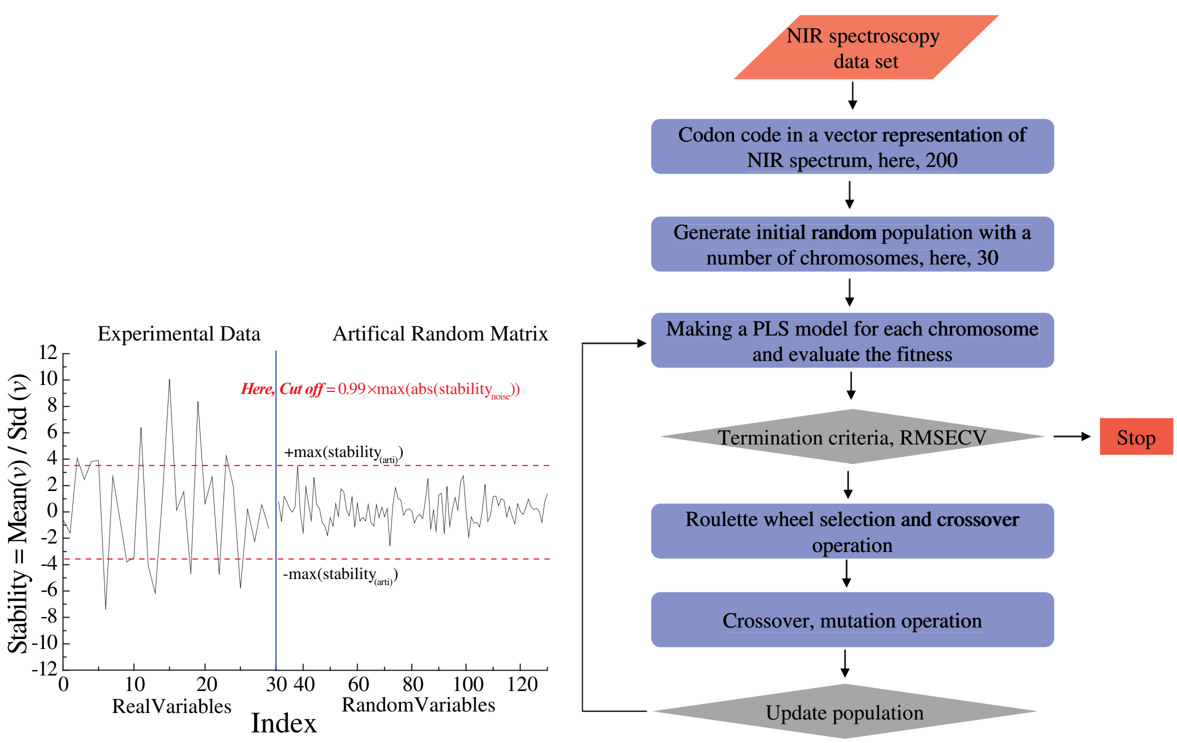
It is well known that the NIR spectroscopy below 1100 nm maintains long light penetration potential, which is suitable for internal quality detection of fruit. Meanwhile, the interactance detection mode of spectroscopy, where the detector is separated from the illuminated surface by light seal in contact with fruit surface,[13] can optimize the detection of intact fruit. For these reasons, K-BA100R (Kubota, Japan) spectrophotometer (500–1010 nm, spectra interval 2 nm), equipped with fiber-optic probe in interactance mode and charge-coupled device (CCD) line-array detector (Shimadzu, Japan), was chosen to measure the spectra of each intact melon. The spectrophotometer collects volt energy spectrum first, and then transfers the volt energy into absorbance spectrum by mathematics method. Finally, it shows the reference values by operating the preset calibration model.

Spectra were acquired from the stylar-end and two opposite equatorial positions of each intact melon. SSC was assessed from outer (defined as 0–20 mm in depth) and inner (defined as from 20 mm to the seed cavity) mesocarp of spectra-collected position.

2.4. *Feature wavelengths extraction and modeling*

To develop NIR spectroscopy available for mix-cultivar melon calibration model, four different methods of variable selection for PLS regression were investigated in this work. The methods are UVE, UVE–SPA, GA and UVE–GA, these algorithms were carried out in Matlab 7.0 work package (MathWorks Inc., USA). The optimization as well as predictive capability of calibration model was expressed by the indicators of correlation coefficient (R^2), root mean square error of cross validation (RMSECV) and RMSEP.

UVE was applied as: (1) An artificial noise matrix with 200 variables was appended to the spectra



(a) (b)

Fig. 1. Schematic diagrams for (a) the mechanism of UVE algorithm and (b) the operation process of GA-PLS.

J. Innov. Opt. Health Sci. 2015.08. Downloaded from www.worldscientific.com
by 103.240.126.9 on 10/21/18. Re-use and distribution is strictly not permitted, except for Open Access articles.

one; (2) The stability of each variable was calculated through leave-one-out validation; (3) Variable with stability between cut-off thresholds (99%) was regarded uninformative and eliminated. GA was applied as follows: (1) A population of 30 chromosomes was generated by randomly combining components; (2) PLS analysis was conducted and the fitness (i.e., RMSECV) was compared; (3) The chromosomes with low RMSECV values were paired and reproduced by double cross-over (probability = 50%) and mutation (probability = 1%). Step 2 was again applied, after which Steps 2 and 3 were repeated until the RMSECV reaches an acceptable value. Schematic illustrations of UVE and GA–PLS were illustrated in Figs. 1(a) and 1(b), respectively.

After pretreatment of Savitzky–Golay smoothing (25, 3), second derivative and feature wavelength selection, spectra were analyzed by PLS program in TQ Analyst (TQ Analyst V9.0, Thermo Fisher Scientific Co., USA). Spectra outlier detection (Mahalanobis distance), calibration and prediction set separation (Kennard–Stone algorithm) were also executed in this work package.

3. Results and Discussion

3.1. *Standards of melon internal quality evaluation*

The statistics of sweetness and texture sensory indexes were shown in Figs. 2(a) and 2(b), respectively. As shown in Fig. 2(a), the sweetness sensory was highly correlated with SSC; melons with SSC over 12 °Brix were regarded as satisfactory by panelists, and over 10 °Brix as average. In Fig. 2(b), the texture sensory shows a high–low trend with the increase of mesocarp firmness. Panelists were satisfied with melon texture when the firmness is in the range of 4–5.5 $\text{kgf} \cdot \text{cm}^{-2}$, and can basically accept its texture when the firmness ranges from 3.5 to 6.5 $\text{kgf} \cdot \text{cm}^{-2}$. Though the accuracy of the experimental result might be limited due to the few testing samples and short-time trained panelist, it shows the similar trend with that Taniwaki *et al.*[14] reported in 2009. Therefore, by integration with previous investigations,[14] we may propose a standard, i.e., the guidance for classifying fruit by internal quality, as: Melon with SSC over 12 °Brix, firmness 4–5.5 $\text{kgf} \cdot \text{cm}^{-2}$ considered as satisfactory class sample; and SSC over 10 °Brix, firmness 3.5–6.5 $\text{kgf} \cdot \text{cm}^{-2}$ as average class sample.

3.2. *Nondestructive detection program*

3.2.1. *Equalization of spectra from different integration times*

The texture properties of melon rind and mesocarp vary heavily between different cultivars, which will lead to bad differences in the pathlength of NIR radiation and in the scatter profile of the samples.[14] Thus, using the same NIR spectroscopy scanning parameter, especially integration time, cannot obtain good spectral recording for all cultivars of melon as shown in Fig. 3. It can be seen that some of the M-1 melon spectra had overflew the response interval of the detector in Fig. 3(b). Thus, to date, different cultivars of melon were detected and modeled individually.[15] A high commercial cost is necessary for melon nondestructive detection if an effective technique could not be developed. As the difference in energy spectra could be equalized,

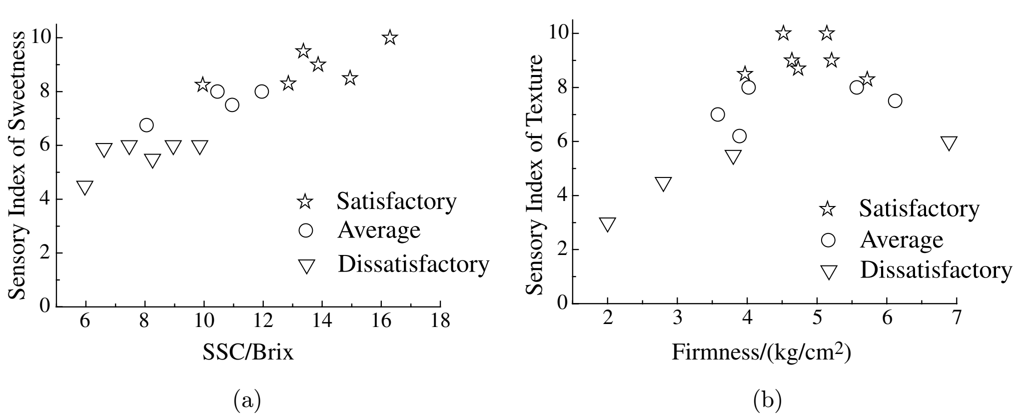


Fig. 2. The correlation of melon sensory index of (a) sweetness and (b) texture with reference.

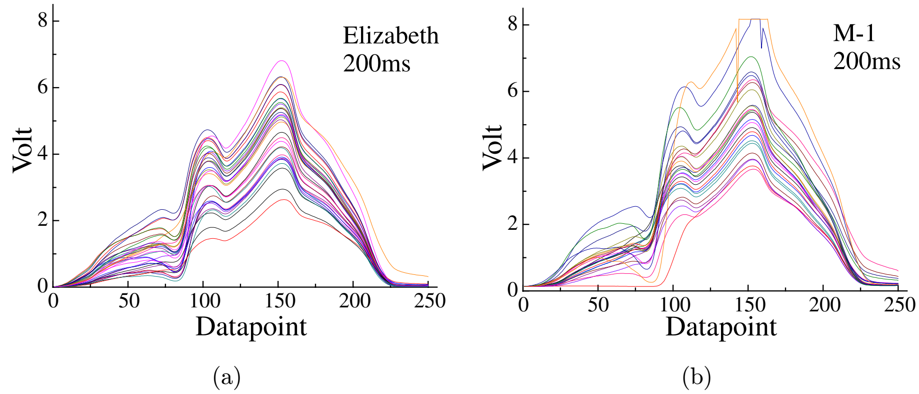


Fig. 3. Energy spectra of (a) Elizabeth and (b) M-1 melon (integration time of 200 ms).

when ignoring the small error cost by signal to noise ratio, difference in energy spectra could be equalized by measuring reference at each integration time and operating second derivation algorithm as shown in Fig. 4. Therefore, in this study, we will illustrate a mathematical strategy which is suitable to build a common calibration model for different melon cultivars.

3.2.2. *Sampling position*

As melon flesh is thick and heterogeneous with respect to SSC, effects of fruit "optical" and chemical sampling position need to be estimated. Ito *et al.*[16] chose to base spectroscopic assessment of melon on the stylar-end, as the flesh is thinner than other parts, whereas Guthrie *et al.*[17] chose to assess melon at an equatorial position, as it represents a large target area.

To evaluate the effect of sample position on mix-cultivar melon, SSC models are developed. Spectra were collected from the stylar-end and two opposite positions of equator for each melon, Brix reference values were separately determined for outer and inner mesocarp. Calibration statistics made up with full spectra were shown in Fig. 5. The RMSECVs of outer mesocarp models are consistently higher than average and inner mesocarp models whether the models were developed on stylar-end or equator. Models developed on stylar-end possess a higher R^2 of cross validation than equatorial position. The inaccuracy of inner mesocarp SSC models may be caused by the limited transmission of NIR radiation. The stylar-end which is unique and holds a higher correlation between inner and outer SSC model as shown in Fig. 6 could be set as the optimum sampling point for internal quality prediction. Brix expressed by the average of inner and outer SSC was set as the SSC reference method, as it represents more internal information than outer tissue. Meanwhile it has a similar R^2 in outer mesocarp SSC models.

3.3. *Modeling*

Melon from Beijing Orchard was scanned with the integration time of 200 ms and melon from Tianjin

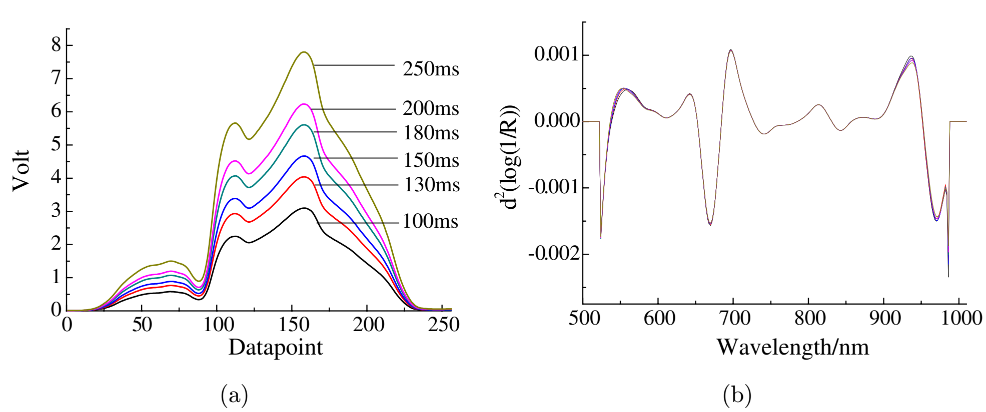


Fig. 4. (a) Energy spectra in different integration times and (b) transfer spectra after second derivative algorithm calculation.

J. Innov. Opt. Health Sci. 2015.08. Downloaded from www.worldscientific.com
by 103.240.126.9 on 10/21/18. Re-use and distribution is strictly not permitted, except for Open Access articles.

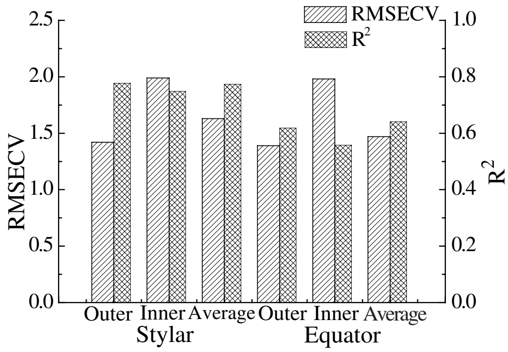


Fig. 5. Calibration statistic of SSC models using different spectra collecting method.

Orchard 150 ms, thus, all the spectra were pretreated by the second derivate algorithm for calibration modeling. To construct prediction model with simplicity and robustness, wavelength selection method could be used to reduce irrelevant information and improve the speed and accuracy of prediction.

The UVE method was first adopted to reduce irrelevant variables. As shown in Table 2, the UVE–PLS model is not only simplified, but also the performance was highly improved compared with full spectral model. But the variables selected by UVE are still redundant for the large number of variables and factors. So UVE–SPA, GA and UVE–GA were also applied in wavelength selection of melon internal quality prediction model.

In the optimization of SSC and firmness prediction models of mix-cultivar melon, the GA–PLS performed best, as it is an efficient algorithm for interrogating a large search space in which many combinations of wavelengths are possible, and can guarantee the reliability of the model. For SSC prediction, the RMSECV of 0.991 and the RMSEP of 0.825, can almost meet the accuracy standard

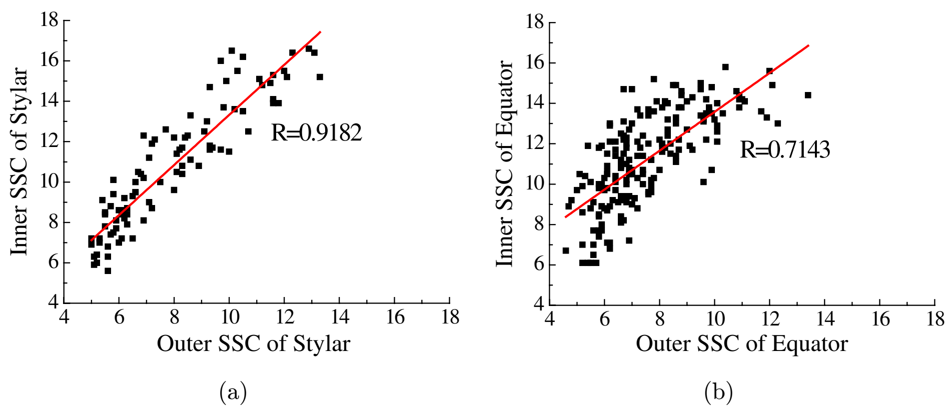


Fig. 6. The correlation between outer and inner SSC at (a) stylar and (b) equator.

Table 2. Comparison of mix-cultivars of melon SSC and firmness calibration model performance developed by different wavelength selection methods and PLS.

Property				Cross Validation		Prediction	
s.d.	Method	No. of variables	Factor	RMSECV	R^2	RMSEP	R^2
SSC (1.9°Brix)	500–1010 nm	256	10	1.33	0.847	1.19	0.832
	UVE	103	10	1.20	0.879	1.01	0.884
	UVE-SPA	22	8	1.31	0.845	1.12	0.863
	GA	44	10	0.99	0.909	0.83	0.938
	UVE-GA	14	7	1.42	0.805	1.22	0.861
Firmness ($0.78\,\text{kgf}\cdot\text{cm}^{-2}$)	500–1010 nm	256	5	0.71	0.305	0.53	0.573
	UVE	63	8	0.58	0.631	0.43	0.611
	UVE-SPA	12	9	0.66	0.596	0.57	0.380
	GA	35	9	0.51	0.768	0.35	0.741
	UVE-GA	18	4	0.58	0.600	0.56	0.524

J. Innov. Opt. Health Sci. 2015.08. Downloaded from www.worldscientific.com
by 103.240.126.9 on 10/21/18. Re-use and distribution is strictly not permitted, except for Open Access articles.

J. Innov. Opt. Health Sci. 2015.08. Downloaded from www.worldscientific.com
by 103.240.126.9 on 10/21/18. Re-use and distribution is strictly not permitted, except for Open Access articles.

of 1.5 °Brix, following the report from Fujiwara and Sakakura.[18] The ratio performance deviation (RPD), which related the RMSEP to the standard deviation (std) of the original data, nearly reached 3.0. Based on such fine result, it is ready to conclude that spectra from different integration times can be used to construct generation model after pre-treatment with second derivative algorithm.

For firmness models, the predictive capacity was acceptable but lower than that recorded for SSC, as a number of authors have stressed the difficulties that occurred in its detection. This inaccuracy was probably because the physical characteristic such as firmness plus the chemical compositions that contribute to firmness such as pectin, hemicellulose are not that high in concentration, meanwhile the quite subjective testing value got by hand-held penetrometer.[6] To improve the accuracy of nondestructive detection of melon mesocarp firmness, an appropriate reference analysis method should be considered.

4. Conclusion

Herein, we found that the second derivative algorithm could eliminate the difference of energy spectra. Based on this algorithm, a robust calibration model to correct the SSC and firmness of various melon cultivars at postharvest stage was established, simultaneously and nondestructively, via NIR and multivariate calibration techniques. Although NIR combined with the second derivative algorithm already commercialized in Japan, the mathematical finding present in this work provides a good chance for China not only for quality control, but also for fruit classification by sugar content and firmness, for mix-cultivar melon. Meanwhile this research provides technical support and foundation for setting up of nondestructive quality evaluation program for other fruits.

Acknowledgments

This work was supported by the Special Fund for Agro-scientific Research in the Public Interest (Projected No. 201303075) and the Earmarked Fund for Modern Agro-industry Technology Research System (Projected No. CARS-26-22).The authors would like to express their gratitude to National Engineering Research Center for Vegetables (NERCV) for material and technical support.

References

1. L. Mutton, B. Cullis, A. Blakeney, "The objective definition of eating quality in rockmelons (Cucumis melo)," *J. Sci. Food Agriculture. Rev.* **32**(4), 385–391 (1981).
2. A. Kader, "Standardization and inspection of fresh fruits and vegetables," *Postharvest Technology of Horticultural Crops*, A. A. Kader, Ed., pp. 287–299, University of California, Oakland, California (1985).
3. T. Sun, K. Huang, H. Xu, Y. Ying, "Research advances in nondestructive determination of internal quality in watermelon/melon: A review," *J. Food Eng. Rev.* **100**(4), 569–577 (2010).
4. G. Lester, J. Dunlap, "Physiological changes during development and ripening of 'Perlita' muskmelon fruits," *Scientia Horticultuae. Rev.* **26**, 323–331 (1985).
5. C. Clark, V. McGlone, R. Jordan, "Detection of Brownheart in 'Braeburn' apple by transmission NIR spectroscopy," *Postharvest Biol. Technol. Rev.* **28**(1), 87–96 (2003).
6. G. Fan, J. Zha, R. Du, L. Gao, "Determination of soluble solids and firmness of apples by Vis/NIR transmittance," *J. Food Eng. Rev.* **93**(4), 416–420 (2009).
7. V. McGlone, S. Kawano, "Firmness, dry-matter and soluble-solids assessment of postharvest kiwifruit by NIR spectroscopy," *Postharvest Biol. Technol. Rev.* **13**(2), 131–141 (1998).
8. A. Gomez, Y. He, A. Pereira, "Non-destructive measurement of acidity, soluble solids and firmness of Satsuma mandarin using Vis/NIR-spectroscopy techniques," *J. Food Eng. Rev.* **77**(2), 313–319 (2006).
9. H. Ito, S. Morimoto, R. Yamauchi, K. Ippoushi, K. Azuma, H. Higashio, "Potential of near infrared spectroscopy for non-destructive estimation of soluble solids in watermelons," *Acta Horticulturae. Rev.* **588**, 355–356 (2002).
10. S. Saranwong, J. Sornsrivichai, S. Kawano, "Prediction of ripe-stage eating quality of mango fruit from its harvest quality measured nondestructively by near infrared spectroscopy," *Postharvest Biol. Technol. Rev.* **31**(2), 137–145 (2004).
11. G. Dull, G. Birth, D. Smittle, R. Leffler, "Near infrared analysis of soluble solids in intact cantaloupe," *J. Food Sci. Rev.* **54**(2), 393–395 (1989).
12. R. Long, K. Walsh, "Limitations to the measurement of intact melon total soluble solids using near

infrared spectroscopy," *Crop Pasture Sci. Rev.* **57** (4), 403–410 (2006).
13. P. Schaare, D. Fraser, "Comparison of reflectance, interactance and transmission modes of visible-near infrared spectroscopy for measuring internal properties of kiwifruit (Actinidia chinensis)," *Postharvest Biol. Technol. Rev.* **20**(2), 175–184 (2000).
14. M. Taniwaki, M. Takahashi, N. Sakurai, "Determination of optimum ripeness for edibility of postharvest melons using nondestructive vibration," *Food Res. Int. Rev.* **42**(1), 137–141 (2009).
15. M. Golic, K. Walsh, "Robustness of calibration models based on near infrared spectroscopy for the in-line grading of stonefruit for total soluble solids content," *Anal. Chim. Acta Rev.* **555**(2), 286–291 (2006).
16. H. Ito, S. Morimoto, R. Yamauchi, "Potential of near infrared spectroscopy for non-destructive estimation of soluble solids in growing melons," *II Int. Symp. on Application of Modelling as an Innovative Technology in the Agri-Food Chain*, MODEL-IT 566 (2001).
17. J. Guthrie, C. Liebenberg, K. Walsh, "NIR model development and robustness in prediction of melon fruit total soluble solids," *Crop Pasture Sci. Rev.* **57** (4), 411–418 (2006).
18. T. Fujiwara, H. Sakakura, "The difference of Brix value to distinguish sweetness of melon," *Nippon Shokuhin Kagaku Kogaku Kaishi. Rev.* **46**(9), 609–612 (1999).

J. Innov. Opt. Health Sci. 2015.08. Downloaded from www.worldscientific.com
by 103.240.126.9 on 10/21/18. Re-use and distribution is strictly not permitted, except for Open Access articles.