Determination of fruit maturity and its prediction model based on the pericarp index of absorbance difference ($I_{AD}$) for peaches

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Abstract

Harvest maturity is closely related to peach fruit quality and has a very important effect on the fresh fruit market. Unfortunately, at present, it is difficult to determine the maturity level of peach fruits by artificial methods. The objectives of this study were to develop quadratic polynomial regression models using near-infrared spectroscopy that could determine the peel color difference, fruit firmness, soluble solids content (SSC), soluble sugar, organic acid components, and their relationships with the absorbance of chlorophyll (index of absorbance difference, $I_{AD}$) in late maturing ‘Xiahui 8’ peach and ‘Xiaguang’ nectarine fruits. The analysis was based on data for fruits at veraison, fruits at harvesting maturity, and all fruits. The results showed that firmness has the highest correlation coefficient with $I_{AD}$. Prediction models for fruit maturity were established between firmness and the $I_{AD}$ of the two cultivars using the quadratic polynomial regression method. Further variance analysis on the one degree term and quadratic term of each equation showed that every partial regression coefficient reached a significant or extremely significant level. No significant difference was observed between estimated and observed values after regression prediction. The regression equations seem to fit well. Other peach and nectarine varieties were used to test the feasibility of maturity prediction by this method, and it was found that maturity was successfully predicted in all the samples. The result indicated that the $I_{AD}$ can be used as an index to predict peach fruit maturity.

Introduction

In the peach market, the maturity at fruit harvest is always the main factor that restricts its commodity value. Accurately determining peach maturity plays an important role in its timely harvesting, classification, packing, transportation, and the guarantee of commodity quality [1]. As a respiration climacteric fruit, peaches release an increased amount of ethylene during ripening, and gene transcription also varies, which is often regulated by plant hormones [2–4]. During this process, fruit firmness, the composition and ratio of fruit inclusion, and the peel color change accordingly, and the quality related indicators are significantly different in fruits
Many studies have investigated the peach maturity level using destructive or non-destructive methods [1,6,7]. The correlation between soluble solids content (SSC) and maturity, and regression analysis of fruit SSC and quality indicators in ‘Hujingmilu’ peach, Zhang et al. [1] established prediction equations for firmness and SSC using the quadratic polynomial regression method. Nascimento et al. [8] used near-infrared spectroscopy to investigate peach maturity predictions by the partial least square (PLS) model of the SSC and fruit firmness in low-chilling peach. They created prediction models for SSC and fruit firmness, and established the optimization potential of the model. Matteoli et al. [9] proposed a spectral-based non-destructive method for the classification of peach maturity levels that estimates the firmness of the flesh to classify the maturity level by the reflectance spectra. They used multiple retrieval techniques and the fuzzy classification system, and this method lays the foundation for the automatic classification of peach fruit maturity.

The index of absorbance difference ($I_{AD}$) is an indicator that is based on the close relationship between the degradation of chlorophyll and the maturity of the fruit, which is determined by the difference between the absorption at 670 nm and 720 nm using near-infrared spectroscopy. It directly reflects the actual content of chlorophyll a [4]. The non-destructive measurement of $I_{AD}$ is not harmful to fruit, the reading is fast and convenient, and it is more desired than the destructive assays, such as firmness and SSC. Therefore, it is highly suitable for fruit quality estimation at the end of the supply chain. Currently, $I_{AD}$ prediction is carried out mostly on stone fruit trees, such as peach [10,11] and plum [12], etc. Gonçalves et al. [13] performed a non-destructive evaluation on seven peach and five nectarine varieties and found that there was an extremely significant linear regression relationship between the $I_{AD}$ value and fruit firmness, and that there were variations among different varieties. They also showed that there was no significant relationship between the $I_{AD}$ value and fruit SSC. Lurie et al. [14] collected the $I_{AD}$ at harvest of both early and late maturity peach varieties, carried out a non-linear regression analysis of the change in firmness during shelf time, and established the Logistic model of firmness change. They used time resolution reflectance spectroscopy to evaluate the degree of maturity and believed that the measurement of $I_{AD}$ at harvest might classify the fruits into various categories based their potential shelf time, which may ensure better fruit quality.

Previous studies mainly used SSC and titratable acid content as internal quality indicators for the prediction of peach maturity by the $I_{AD}$ value, but there have been few studies on the effect of composition content and its ratio on maturity. In addition, the relationship between peach maturity and firmness has rarely been investigated by previous studies. In peach production, it is common to choose peach fruits at veraison for long-distance transportation, but fruits at harvesting maturity are more suitable for the fresh fruit market. In this study, we used the peach variety ‘Xiahui 8’ and nectarine variety 'Xiaguang' at different maturity points to comprehensively analyze the peach color differences, firmness, internal quality indicators, and pericarp $I_{AD}$ value, and tried to establish a prediction model of fruit maturity in order to provide a scientific basis for fruit harvesting time.

**Materials and methods**

**Fruit material**

The experiment was performed at the peach orchard of Jiangsu Academy of Agricultural Sciences in 2015 using the fruits of the 7a late maturity peach variety ‘Xiahui 8’ and late maturity nectarine variety ‘Xiaguang’ as experimental materials. At fruit maturation, 30 of the developmentally uniform fruits at veraison (maturity degree I) and 30 of fruits that had reached harvesting maturity (maturity degree II) were collected from the central periphery of the tree at different maturity levels [5].
8:00 am on a sunny morning. All the fruits were immediately brought back to the laboratory. Every fruit was numbered. The fruits were split and the middle of the two sides was labeled for each fruit. The $I_{AD}$ value, color difference, firmness, and SSC were sequentially determined, and then the flesh of the two sides was cut and homogenized to evaluate the soluble carbohydrate and organic acids using high performance liquid chromatography. The average of the two sides was used as the corresponding indicator for each fruit. The above-mentioned indicators for each fruit were one-to-one matched by ensuring the order of the assays. The tested trees showed moderate growth with an open vase form. They were planted north to south with ridge cultivation, and were managed by regular cultivation practices.

In 2016, 60 fruits for each variety ('Xiahui 8', 'Xiaguang') were chosen randomly during the ripening process to determine their firmness and $I_{AD}$ values. In addition, fruit firmness and the $I_{AD}$ values of three peach varieties ('Xiahui 5', 'Baihuashuimi', and 'Wanhujing') and three nectarine varieties ('Zijinhong 1', 'Zijinhong 2', and 'Huyou 018') were determined. For each variety, 30 fruits at veraison and 30 fruits at harvesting maturity were used.

**Index determination**

**Index of absorbance difference.** The index of absorbance difference ($I_{AD}$) can reflect the status of fruit maturity by measuring the changes in pericarp chlorophyll content, which is calculated as the difference between the absorption at 670 nm and 720 nm within the range of 0–2.2. The value 2.2 represents green, and 0 represents complete maturity [4,15]. The $I_{AD}$ value of the pericarp was determined by a DA-Meter (TR Turoni srl, Forlì, Italy).

**Color.** A Color Quest XE (Hunter Lab, Reston, VA, USA) color difference meter was used to evaluate the pericarp brightness ($L'$), where $a'$ represents “-green” to “+red” and $b'$ represents “-blue” to “+yellow”. Then, the chroma ($C'$), hue angle ($h$) [16,17], and $a'/b'$ were calculated.

**Firmness.** The firmness with and without the pericarp was determined by a TA-XT Plus texture analyzer (Stable Micro-Systems Texture Technologies Corp, Scarsdale, New York, NY, USA) with a probe diameter of 8 mm, a test depth of 5 mm, and a penetration rate of 1 mm s$^{-1}$.

**Soluble solids content.** Flesh SSC values were measured using a digital, hand-held pocket refractometer PAL-1 (ATAGO, Itabashi-ku, Tokyo, Japan). The SSC was expressed in Brix at 20˚C [18,19].

**Soluble sugar and organic acid components.** The sucrose, glucose, fructose, sorbitol, malic acid, quinic acid, and citric acid contents were measured by a Agilent 1100 high performance liquid chromatography (Agilent Technology, Santa Clara, CA, USA) [20]. The total sugar content was the content sum of four kinds of soluble sugars and the total acid content was the total content of four kinds of organic acids. The sugar/acid ratio was calculated from the total sugar and total acid contents.

**Data analysis**

In 2015, the average, standard deviation (SD), amplitude, range, and coefficient of variation (CV) for fruits with maturity degrees I and II were calculated for both varieties. The correlations between $I_{AD}$ value and the color difference, firmness, SSC, soluble sugar content, and organic acid indicators of the fruits at maturity degrees I and II and for all fruits were analyzed, and a regression analysis was performed on the indicators closely related to the $I_{AD}$ value to try and establish the equation for the prediction of peach fruit maturity. Data processing and analysis were carried out using Microsoft Excel 2010 (Microsoft Corp, Redmond, WA) and SPSS (Version 17.0, SPSS Inc., Chicago, IL, USA).
In 2016, both firmness and the \( I_{AD} \) for every fruit of 'Xiahui 8' and 'Xiaguang' were used to test the feasibility of the regression equations which were established in this study. Data for firmness and the \( I_{AD} \) values of other peach and nectarine varieties, respectively, were used to establish the regression equations.

## Results

### Analysis of the variation on the fruit quality indicators

As shown in Tables 1 and 2, the fruit \( I_{AD} \), color difference, firmness, SSC, sucrose, fructose, sorbitol, citric acid, and total sugar contents of 'Xiahui 8' and 'Xiaguang' at maturity degree I showed similar trends when compared to those at maturity degree II. The fruit \( I_{AD}, L^*, b^*, h \), firmness with pericarp, firmness without pericarp, and sorbitol and citric acid contents were all lower for maturity degree II fruit than for those at maturity degree I, but the \( a^*, C^*, a^*/b^* \), SSC, sucrose and total sugar content measurements produced opposite results. Differences were observed in the glucose, malic acid, quinic acid contents, and the total acid and sugar acid ratio between the two varieties at the different maturity degree points. The glucose content and sugar acid ratio of 'Xiahui 8' at degree I were lower than at degree II, whereas the malic acid, quinic acid, and total acid contents were higher, but these indicators showed an opposite trend in 'Xiaguang'. These data indicate that a higher maturity degree results in a lower \( I_{AD} \) value, lower fruit firmness, a deeper red color, and a higher inclusion content, but the soluble sugar and organic acid compositions varied in the different varieties.

In addition, Tables 1 and 2 show that although manual classification of maturity was performed during fruit harvesting, fruits with the same maturity degree still showed significant differences for many indicators and a relatively large amplitude and CV.

### Table 1. Variation analysis of the fruit quality indexes for 'Xiahui 8' peach.

| Index                           | Maturity Degree I | Maturity Degree II |
|--------------------------------|-------------------|-------------------|
|                                | Mean   | SD     | Amplitude | Range  | CV    | Mean   | SD     | Amplitude | Range  | CV    |
| \( I_{AD} \)                   | 0.53   | 0.26   | 0.19–1.17 | 0.98   | 48.92 | 0.12   | 0.11   | 0–0.36   | 0.36   | 86.69 |
| \( L^* \)                      | 69.36  | 4.78   | 61.13–77.68 | 16.55  | 6.89  | 53.25  | 4.79   | 42.77–62.08 | 19.31  | 9.00  |
| \( a^* \)                      | 15.36  | 5.71   | 4.09–24.54 | 20.46  | 37.18 | 31.61  | 3.14   | 23.11–36.18 | 13.07  | 9.93  |
| \( b^* \)                      | 23.31  | 1.81   | 20.14–26.92 | 6.78   | 7.76  | 18.31  | 1.60   | 14.71–21.43 | 6.73   | 8.73  |
| \( C^* \)                      | 28.93  | 2.33   | 24.97–34.52 | 9.55   | 8.04  | 36.65  | 2.73   | 31.27–40.89 | 9.61   | 7.46  |
| \( h \)                        | 57.97  | 11.26  | 40.80–80.82 | 40.02  | 19.43 | 30.21  | 3.52   | 25.44–40.80 | 15.36  | 11.66 |
| \( a^*/b^* \)                  | 0.69   | 0.29   | 0.16–1.16  | 1.00   | 41.78 | 1.75   | 0.21   | 1.28–2.10 | 0.82   | 11.80 |
| Firmness with Pericarp (N)      | 173.16 | 15.96  | 140.24–203.85 | 63.61  | 9.22  | 89.00  | 36.19  | 26.60–145.14 | 118.50 | 40.66 |
| Firmness without Pericarp (N)   | 95.59  | 10.18  | 72.26–110.95 | 38.68  | 10.65 | 40.71  | 20.02  | 5.97–67.32 | 61.34  | 49.18 |
| SSC ('Brix)                     | 11.94  | 1.14   | 8.75–14.15 | 5.40   | 9.57  | 12.44  | 1.74   | 10.00–17.25 | 7.25   | 13.95 |
| Sucrose (g kg\(^{-1}\))        | 49.82  | 8.02   | 25.89–60.56 | 34.67  | 16.11 | 54.84  | 9.41   | 38.74–75  | 36.26  | 17.16 |
| Glucose (g kg\(^{-1}\))        | 13.18  | 1.61   | 6.39–16.24 | 9.85   | 12.22 | 14.97  | 1.29   | 12.39–17.44 | 5.05   | 8.61  |
| Fructose (g kg\(^{-1}\))       | 11.87  | 1.33   | 9.16–15.54 | 6.38   | 11.18 | 13.42  | 1.64   | 10.94–18.33 | 7.40   | 12.20 |
| Sorbitol (g kg\(^{-1}\))       | 6.25   | 1.97   | 1.18–9.87  | 8.69   | 31.49 | 2.58   | 1.79   | 0.58–7.56 | 6.98   | 69.33 |
| Malic Acid (g kg\(^{-1}\))     | 2.71   | 0.45   | 2.16–4.64  | 2.48   | 16.63 | 2.11   | 0.22   | 1.71–2.62 | 0.91   | 10.63 |
| Quinic Acid (g kg\(^{-1}\))    | 1.18   | 0.36   | 0.75–2.44  | 1.69   | 30.83 | 1.08   | 0.28   | 0.56–1.85 | 1.28   | 26.18 |
| Citric Acid (g kg\(^{-1}\))    | 0.35   | 0.13   | 0–0.55     | 0.55   | 35.52 | 0.02   | 0.05   | 0–0.15   | 0.15   | 228.50 |
| Total Sugar (g kg\(^{-1}\))    | 81.13  | 9.81   | 50.14–95.50 | 45.36  | 12.10 | 85.81  | 11.48  | 69.27–111.33 | 42.06  | 13.38 |
| Total Acid (g kg\(^{-1}\))     | 4.24   | 0.78   | 3.34–7.43  | 4.09   | 18.42 | 3.22   | 0.41   | 2.46–4.28 | 1.82   | 12.86 |
| Sugar Acid Ratio                | 19.75  | 3.86   | 9.86–27.27 | 17.41  | 19.56 | 27.00  | 4.08   | 18.98–34.97 | 15.99  | 15.10 |

SD, standard deviation. CV, coefficient of variation.

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The CVs for fruit $I_{AD}$, and sorbitol, quinic acid, and citric acid contents were relatively large in ‘Xiahui 8’ at both maturity degree points. Furthermore, the CVs for $a^*$, $h$, $a^*/b^*$, total acid, and the sugar acid ratio in fruits at degree I maturity, and firmness with pericarp and without pericarp in degree II fruit were also large (Table 1). Fruit $I_{AD}$, $h$, $a^*/b^*$, firmness with pericarp, firmness without pericarp, and the sorbitol, quinic acid, and citric acid contents of ‘Xiaaguang’ at both maturity degree points had relatively high CVs, as did the $a^*$ in degree I fruit and sucrose content of degree II fruit (Table 2). Our results suggest that $I_{AD}$ is the most sensitive indicator for determining peach maturity. Indicators with relatively high CVs showed a closer relationship with $I_{AD}$, and they had more significant effects on fruit maturity.

### Correlation analysis between the quality indicators of various fruit populations and $I_{AD}$ value

The correlation analysis between $I_{AD}$ value and the indicators for degree I fruits, degree II fruits, and all the collected fruits are shown in Table 3. In ‘Xiahui 8’, significant or extremely significant correlations were observed between $I_{AD}$ value and every tested indicator for all the fruits except for quinic acid content. The $I_{AD}$ value was significantly or extremely significantly correlated with color difference, firmness, and glucose and sorbitol contents in ‘Xiaguang’, but not with other indicators. The correlation analysis between $I_{AD}$ value and the indicators for the three fruit populations for each variety suggested that most indicators, such as $L^*$, $h$, $a^*/b^*$, sucrose, quinic acid, total acid, sugar acid ratio, etc., were significantly or extremely significantly correlated with the $I_{AD}$ value only at certain maturity degree points and that there was a poor consistency between varieties. The results demonstrated that the correlations between
IAD value and C, firmness with pericarp, firmness without pericarp, and sorbitol content were significant and extremely significant in the different fruit populations (except for the firmness with or without pericarp and the sorbitol content of ‘Xiahui 8’ degree I and degree II fruit, and the C of degree I ‘Xiaguang’ fruit), which indicated that these four indicators are more suitable for predicting peach maturity. The absolute value of the correlation coefficient between the firmness with or without pericarp and the IAD value was higher than that for C and sorbitol content, which suggested that fruit firmness is closely related to the maturity determination. The correlation coefficient between firmness with pericarp and without pericarp was 0.966 and 0.955 for ‘Xiahui 8’ and ‘Xiaguang’, respectively. Therefore, it should be possible to establish a maturity prediction model using a regression analysis of firmness data with or without pericarp and the IAD value.

Regression analysis based on the firmness and IAD value

Linear and quadratic polynomial regressions were performed between the firmness with or without pericarp and the IAD value for all fruits of both the ‘Xiahui 8’ and ‘Xiaguang’ varieties, and the results are shown in Table 4, Fig 1 and Fig 2. The P value of all the regression models was 0.0001, which indicated an extremely significant regression. The R² of the two polynomial regressions was higher than the linear regression for the same indicator and same variety, and its Durbin-Watson statistic value was closer to 2, which suggested that the model was more stable. The variance analysis of each quadratic term and linear term in the quadratic polynomial regression equation showed that the partial regression coefficient of the quadratic term and linear term in the firmness with/without pericarp model for ‘Xiahui 8’ and the firmness with the pericarp model for ‘Xiaguang’ reached a significant level (P < 0.01) (Table 5). However,

| Index                          | ‘Xiahui 8’ Maturity Degree I | ‘Xiahui 8’ Maturity Degree II | ‘Xiahui 8’ All Fruits | ‘Xiaguang’ Maturity Degree I | ‘Xiaguang’ Maturity Degree II | ‘Xiaguang’ All Fruits |
|-------------------------------|-------------------------------|-------------------------------|-----------------------|-----------------------------|-----------------------------|-----------------------|
| L⁻                            | -0.58**                      | -0.26                         | 0.47**                | 0.08                        | 0.05                        | 0.50**                |
| a⁻                            | 0.32                         | 0.44*                         | -0.52**               | -0.38*                      | -0.30                       | -0.65**               |
| b⁻                            | 0.09                         | 0.03                          | 0.63**                | 0.17                        | -0.06                       | 0.50**                |
| C₀                            | 0.43*                        | 0.43*                         | -0.46**               | -0.15                       | -0.63**                     | -0.34**               |
| H                             | -0.26                        | -0.32                         | 0.53**                | 0.36*                       | 0.12                        | 0.62**                |
| a⁻*b⁻                         | 0.24                         | 0.29                          | -0.58**               | -0.31                       | -0.18                       | -0.61**               |
| Firmness with Pericarp        | -0.13                        | 0.79**                        | 0.69**                | 0.84**                      | 0.90**                      | 0.91**                |
| Firmness without Pericarp     | -0.08                        | 0.61**                        | 0.69**                | 0.73**                      | 0.83**                      | 0.87**                |
| SSC                           | -0.73**                      | -0.24                         | -0.43**               | 0.36*                       | 0.41*                       | 0.12                  |
| Sucrose                       | -0.73**                      | -0.17                         | -0.52**               | 0.24                        | 0.09                        | -0.07                 |
| Glucose                       | 0.03                         | -0.07                         | -0.38**               | 0.32                        | 0.31                        | 0.29*                 |
| Fructose                      | 0.21                         | -0.12                         | -0.28*                | 0.24                        | 0.31                        | -0.14                 |
| Sorbitol                      | -0.57**                      | 0.25                          | 0.35**                | 0.47**                      | 0.86**                      | 0.71**                |
| Malic Acid                    | 0.16                         | 0.23                          | 0.56**                | 0.31                        | 0.30                        | 0.21                  |
| Quinic Acid                   | -0.09                        | -0.36*                        | 0.54**                | 0.31                        | 0.14                        |                      |
| Citric Acid                   | 0.25                         | 0.41**                        | 0.72**                | 0.47**                      | 0.06                        | 0.04                  |
| Total Sugar                   | -0.68**                      | -0.12                         | -0.46**               | 0.35                        | 0.36*                       | 0.19                  |
| Total Acid                    | 0.09                         | -0.07                         | 0.49**                | 0.57**                      | 0.35                        | 0.20                  |
| Sugar Acid Ratio              | -0.48**                      | -0.06                         | -0.65**               | -0.34                       | 0.03                        | -0.03                 |

Coefficients followed by one (*) and two asterisks (**) are significant at P < 0.05 and P < 0.01, respectively.

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the partial regression coefficients were extremely significant \((P < 0.01)\) and significant \((P < 0.05)\) for the linear term and quadratic term in the firmness without pericarp model for ‘Xiaguang’, respectively. The regression prediction was not significantly different for the difference between the estimated value and the observed value, which suggested that the regression equation had a good fit.

**Model verification**

In 2016, after determining the firmness and I\(AD\) of every fruit for ‘Xiahui 8’ and ‘Xiaguang’, we found that there was still no significant difference between the estimated and observed values. In addition, maturity prediction models for other peach and nectarine varieties were also established using firmness and I\(AD\) values respectively, and all quadratic polynomial regression equations fitted well.

**Discussion**

During the maturation of peach fruit, the internal SSC rises, firmness declines [21,22], the red color appearance increases, and the green color in the pericarp fades [20]. In this study, both ‘Xiahui 8’ and ‘Xiaguang’ had relatively high SSC, \(a^*\), and \(a^*/b^*\) values, and a low fruit firmness
at maturity degree II, which indicated that the $I_{AD}$ for degree II fruit was lower than that for degree I. The $a' / b'$ value can reflect the true color of the fruit [23,24], and was 2.54-fold and 1.94-fold higher in the degree II fruit than degree I ‘Xiahui 8’ and ‘Xiaguang’ fruit, respectively. This is consistent with the opposite change in $I_{AD}$, which indicated that the pericarp $I_{AD}$ value is closely related to the color of the pericarp. A significant difference in pericarp color, $I_{AD}$ value, and most quality indicators was seen in the fruits at the different maturity degree points. This suggested that light absorption and scattering are the main impacting factors on $I_{AD}$, which will further affect the pericarp pigment and the change in fruit texture [4,25,26].

The relationship between SSC and fruit maturity is controversial. The SSC prediction for peach fruit by visible/near infrared spectroscopy combined with PLS showed that all the prediction models had a high coefficient of determination, and its prediction accuracy was high for the tested varieties [27,28]. However, Pinto et al. [29] did not observe a significant relationship between SSC and the indicators for maturity. In this study, an extremely significant negative correlation was seen between SSC and $I_{AD}$ in ‘Xiahui 8’, but there were no significant positive correlations. Furthermore, there was no correlation for ‘Xiaguang’, which indicated that SSC was a fruit quality indicator but cannot be used to determine harvesting timing [13,30,31]. Previous investigations into the relationship between SSC and fruit maturity showed that it varied depending on the climate zone of the test, the chilling requirements, and the variety tested [8,32].

Soluble sugars and organic acids are important components of soluble solids. In this study, the soluble sugar and organic acid contents were determined when we measured the $I_{AD}$, color

![Regression curve between fruit firmness and the $I_{AD}$ of ‘Xiaguang’ nectarines.](https://doi.org/10.1371/journal.pone.0177511.g002)

| Table 5. Variance analysis of the regression coefficients for quadratic polynomial regression. |
|-------------------------------------------------|
| **Index**                   | **Variety** | **Variable** | **Partial Correlation** | **t test** | **P** |
|----------------------------|-------------|--------------|-------------------------|------------|-------|
| Firmness with Pericarp     | ‘Xiahui 8’  | $r(y, x)$    | 0.8237                  | 10.9675    | 0.0001|
|                           |             | $r(y, x^2)$ | -0.7239                 | 7.9222     | 0.0001|
|                           | ‘Xiaguang’  | $r(y, x)$    | 0.7313                  | 8.0944     | 0.0001|
|                           |             | $r(y, x^2)$ | -0.4175                 | 3.4690     | 0.0010|
| Firmness without Pericarp  | ‘Xiahui 8’  | $r(y, x)$    | 0.7675                  | 9.0390     | 0.0001|
|                           |             | $r(y, x^2)$ | -0.6396                 | 6.2818     | 0.0001|
|                           | ‘Xiaguang’  | $r(y, x)$    | 0.6317                  | 6.1522     | 0.0001|
|                           |             | $r(y, x^2)$ | -0.3237                 | 2.5828     | 0.0123|

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difference, firmness, and SSC for every fruit of both varieties. There was no positive correlation between SSC and \( I_{AD} \), but the sorbitol content was closely related to \( I_{AD} \). The correlation coefficient between sorbitol and \( I_{AD} \) was 0.35 and 0.71 in ‘Xiahui 8’ and ‘Xiaguang’, respectively, with determination coefficients (\( R^2 \)) of 0.1225 and 0.5041, respectively. Thus, a prediction model for peach maturity based on the relationship between \( I_{AD} \) and sorbitol is feasible. Nevertheless, other indicators, such as firmness with or without pericarp, showed a higher correlation coefficient with \( I_{AD} \) than with sorbitol. Therefore, they may improve the establishment of a stable prediction model.

The establishment of a prediction model for fruit maturity is of great significance when attempting to determine fruit maturity and timely harvesting. It has been demonstrated that a prediction model based on the quality indicators for one variety is more feasible than that based on multiple varieties [1,29,33], but other studies show that the multiple varieties dependent prediction model gives a more accurate determination of fruit maturity [34,35]. The large numbers of different peach varieties mean that the size, color, flesh texture, solids content, mature period, and retention time vary, so it is difficult to create a prediction model that is suitable for all varieties. A prediction model built for a specific variety is more feasible and more accurate. Peach fruit firmness is closely related to harvest maturity, which is the main factor affecting the postharvest storage characteristics of the fruit [36]. Fresh peach market supply and long-distance transport should be combined with fruit hardness when developing an appropriate harvesting system. Gonçalves et al. [13] studied the relationship between fruit firmness and \( I_{AD} \) using 12 peach varieties and found positive correlations between the firmness without pericarp and \( I_{AD} \) for all varieties with a minimum \( R^2 \) of 0.108 and a maximum \( R^2 \) of 0.65. In this study, the \( P \) value for the linear regression model between fruit firmness with or without pericarp and \( I_{AD} \) was 0.0001 for both varieties and their Durbin-Watson statistic did not significantly deviate from 2, which indicated that the linear relationship between fruit firmness and \( I_{AD} \) can be used to predict fruit maturity. However, we also demonstrated that the \( R^2 \) of the prediction model had a better quadratic polynomial regression fit between firmness and \( I_{AD} \). Furthermore, the variance analysis of each quadratic term and linear term showed that their partial regression coefficients reached significant or extremely significant levels, and that the model was more stable than the linear regression model.

Overall, the quadratic polynomial regression method can be used to explore the relationship between fruit quality indicators and maturity degrees. It can also be used to establish a regression equation with good stability and high prediction accuracy, which is of great significance when attempting to determine the maturity of peach fruit and harvest timing. \( I_{AD} \) values can serve as non-destructive indicators to assay peach maturity, but they have a closer relationship to fruit firmness. The regression relationship between firmness and \( I_{AD} \) can be used to predict the maturity of other peach and nectarine varieties.

**Supporting information**

S1 File. Experimental data file. https://figshare.com/s/65769c208399484a1deb. (DOCX)

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References
1. Zhang BB, Cai ZX, Xu JL, Li F, Qian W, Guo L, et al. (2014) Prediction of soluble solid content of Hujing-milu peach based on regression analysis. Food Sci 35: 68–71.
2. Tonutti P, Casson P, Ramina A (1991) Ethylene biosynthesis during peach fruit-development. J Am Soc Hort Sci 116: 274–279.
3. Trainotti L, Taddei A, Casadoro G (2007) The involvement of auxin in the ripening of climacteric fruits comes of age: the hormone plays a role of its own and has an intense interplay with ethylene in ripening peaches. J Exp Bot 58: 3299–3308. https://doi.org/10.1093/jxb/erm178 PMID: 17925301
4. Ziosi V, Noferini M, Fiori G, Taddei A, Trainotti L, Casadoro G, et al. (2008) A new index based on vis spectroscopy to characterize the progression of ripening in peach fruit. Postharvest Bio Technol 49: 319–329.
5. Crisosto CH (1994) Stone fruit maturity indices: a descriptive review. Postharvest News Inform 5: 65–68.
6. Herrero-Langreo A, Fernández-Ahumada E, Roger JM, Palagós B, Lleó L (2012) Combination of optical and non-destructive mechanical techniques for the measurement of maturity in peach. Food Eng 108: 150–157.
7. Onelli E, Ghiani A, Gentili R, Serra S, Musacchi S, Citterio S, et al. (2015) Specific changes of exocarp and mesocarp occurring during softening differently affect firmness in melting (MF) and non melting flesh (NMF) fruits. PLoS ONE 10: e0145341. https://doi.org/10.1371/journal.pone.0145341 PMID: 26709823
8. Nascimento PAM, Carvalho LCD, Júnior LCC, Pereira FMV (2016) Robust PLS models for soluble solids content and firmness determination in low chilling peach using near-infrared spectroscopy (NIR). Postharvest Bio Technol 111: 345–351.
9. Matteoli S, Diani M, Massai R, Corsini G, Remorini D (2015) A spectroscopy-based approach for automated non-destructive maturity grading of peach fruits. IEEE Sens J 15: 5455–5464.
10. Shinya P, Contador L, Predieri S, Rubio P, Infante R (2013) Peach ripening: segregation at harvest and postharvest flesh softening. Postharvest Bio Technol 86: 472–478.
11. Bonora E, Noferini M, Vidoni S, Costa G (2013) Modeling fruit ripening for improving peach homogeneity in planta. Sci Hort 159: 166–171.
12. Infante R, Contador L, Rubio P, Mesa K, Meneses C (2011a) Non-destructive monitoring of flesh softening in the black-skinned Japanese plums ‘Angeleno’ and ‘Autumn beaut’ on-tree and postharvest. Postharvest Bio Technol 61: 35–40.
13. Gonçalves RG, Couto J, Almeida DPF (2016) On-tree maturity control of peach cultivars: Comparison between destructive and nondestructive harvest indices. Sci Hort 209: 293–299.
14. Lurie S, Friedman H, Weksler A, Dagar A, Zerbini PE (2013) Maturity assessment at harvest and prediction of softening in an early and late season melting peach. Postharvest Bio Technol 76: 10–16.
15. Farneti B, Gutierrez MS, Novak B, Busatto N, Ravaglia D, Spinelli F, et al. (2015) Use of the index of absorbance difference $I_{AD}$ as a tool for tailoring post-harvest 1-MCP application to control apple superficial scald. Sci Hort 190: 110–116.
16. Voss DH (1992) Relating colorimeter measurement of plant color to the Royal Horticultural Society Colour Chart. HortScience 27: 1256–1260.
17. Koukounaras A, Siomos AS, Stakiotakis E (2009) Impact of heat treatment on ethylene production and yellowing of modified atmosphere packaged rocket leaves. Postharvest Bio Technol 54: 172–176.
18. Mitchell F, Mayer G, Maxie E, Coates W (1974) Cold storage effects on fresh market peaches, nectarines & plums estimating freezing points using low temperatures to delay internal breakdown. Calif Agric 28: 12–14.
19. Infante R, Contador L, Rubio P, Aros D, Peña-Neira Á (2011b) Postharvest sensory and phenolic characterization of ‘Elegant Lady’ and ‘Carson’ peaches. Chil J Agric Res 71: 445–451.
20. Zhang BB, Guo JY, Ma RJ, Cai ZX, Yan J, Zhang CH (2015) Relationship between the bagging micro-environment and fruit quality in ‘Guibao’ peach [Prunus persica (L.) Batsch]. J Hort Sci Biotech 90: 303–310.
21. Dabbou S, Lussiana C, Maatallah S, Gasco L, Hajlaoui H, Flamini G (2016) Changes in biochemical compounds in flesh and peel from Prunus persica fruits grown in Tunisia during two maturation stages. Plant Physiol Bioch 100: 1–11.
22. Spadoni A, Cameldi I, Noferini M, Bonora E, Costa G, Mari M (2016) An innovative use of da-meter for peach fruit postharvest management. Sci Hort 201: 140–144.
23. Stewart I, Wheaton TA (2002) Carotenoids in citrus. Their accumulation induced by ethylene. J Agric Food Chem 20: 448–449.
24. Rodrigo MJ, Zacarias L (2007) Effect of postharvest ethylene treatment on carotenoid accumulation and the expression of carotenoid biosynthetic genes in the flavedo of orange (Citrus sinensis L. Osbeck) fruit. Postharvest Bio Technol 43: 14–22.
25. Zerbini PE, Vanoli M, Grassia M, Rizzolo A, Fibiani M, Cubeddu R, et al. (2006) A model for the softening of nectarines based on sorting fruit at harvest by time-resolved reflectance spectroscopy. Postharvest Biol Technol 39: 223–232.
26. Muhua L, Peng F, Renfa C (2007) Non-destructive estimation peach SSC and firmness by multispectral reflectance imaging. New Zeal J Agric Res 5: 601–608.
27. Ying YB, Liu YD, Wang JP, Fu XP, Li YB (2005) Fourier transform near-Infrared determination of total soluble solids and available acid in intact peaches. Trans ASAE 48: 229–234.
28. Shao YN, Bao YD, He Y (2011) Visible/near-infrared spectra for linear and nonlinear calibrations: a case to predict soluble solids contents and pH value in peach. Food Bioprocess Technol 4: 1376–1383.
29. Pinto C, Reginato G, Shinya P, Mesa K, Díaz M, Atenas C, et al. (2015) Skin color and chlorophyll absorbance: indices for establishing a harvest date on non-melting peach. Sci Hort 192: 231–236.
30. Lewallen KS, Marini RP (2003) Relationship between flesh firmness and ground color in peach as influenced by light and canopy position. J Am Soc Hort Sci 128: 163–170.
31. Cantín CM, Gogorcena Y, Moreno MA (2009) Analysis of phenotypic variation of sugar profile in different peach and nectarine [Prunus persica (L.) Batsch] breeding progenies. J Sci Food Agric 89: 1909–1917.
32. Golding JB, Satyan S, Liebenberg C, Walsh K, McClasson WB (2006) Application of portable NIR for measuring soluble solids concentrations in peaches. Acta Hort 713: 461–464.
33. Golic M, Walsh KB (2006) Robustness of calibration models based on near infrared spectroscopy for the in-line grading of stonefruit for total soluble solids content. Anal Chim Acta 555: 286–291.
34. Louw ED, Theron Ki (2010) Robust prediction models for quality parameters in Japanese plums (Prunus salicina L) using NIR spectroscopy. Postharvest Biol Technol 58: 176–184.
35. Tiwari G, Slaughter DC, Cantwell M (2013) Nondestructive maturity determination in green tomatoes using a handheld visible and near instrument. Postharvest Biol Technol 86: 221–229.
36. Infante R, Aros D, Contador L, Rubio P (2012) Does the maturity at harvest affect quality and sensory attributes of peaches and nectarines? New Zeal J Crop Hort Sci 40: 103–113.