



Sweetness and Antioxidant Indices of Mango (*Mangifera indica* cv. *Nam Dok Mai Sithong*) using Red–Green–Blue and Near-Infrared Images

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Abstract: This study aimed to develop a simple method for the non-destructive evaluation of *Nam Dok Mai Sithong* mango quality indices. One hundred and fifty mangoes (*Mangifera indica* cv. *Nam Dok Mai Sithong*) were stored at room temperature for 10 days to evaluate image-based indices for non-destructive quality prediction. Physicochemical properties and image data were collected every two days. Red–green–blue (RGB) and near-infrared images were acquired using visible and infrared filters, respectively. RGB values were extracted using MATLAB. The *Nam Dok Mai Sithong* index (NDMSTI) was computed using the Normalized Difference Vegetation Index principle. Its predictive performance was compared with that of other RGB-based indices for mango chemical properties. Correlation analysis and partial least squares regression were applied. Model performance was validated using leave-one-out cross-validation. The models were evaluated using the coefficient of determination (R^2_{cv}) and root mean square error of cross-validation (RMSECV). Both the Normalized Green Blue Different Index (NGBDI) and NDMSTI showed statistically significant predictive performance for all chemical properties ($p < 0.01$). Performance was stronger for sweetness (total soluble solids) and antioxidants (ABTS). NDMSTI performed comparably to NGBDI, with slightly lower R^2_{cv} and slightly higher RMSECV. These results indicate that NDMSTI has potential as a non-destructive tool for monitoring mango quality during storage.

Keywords: RGB-based index; sweetness index; antioxidant index; mango quality; non-destructive assessment

1. Introduction

Fruit quality assessment is crucial in the food industry, particularly for international export. Mango (*Mangifera indica* L.) is the most popular tropical fruit consumed worldwide [1]. *Nam Dok Mai Sithong* (NDMST) mangoes are among the most widely exported Thai mango varieties [2]. The acceptability of exported mangoes in destination countries substantially depends on their eating quality, which is significantly influenced by harvest maturity. Mango maturity is commonly evaluated using visual indicators, such as skin color and chemical parameters, as well as total soluble solids (TSS), titratable acidity, and the ratio of solids to acids [3].

Beyond sensory and physicochemical attributes, fruit quality is increasingly evaluated based on its nutritional and functional properties, which are directly related to human health. Antioxidant content in fruits enhances immune function and reduces oxidative stress [4]. In mangoes, beta-carotene (BC) is a critical antioxidant that contributes to fruit color and has health benefits. This includes a reduced risk of chronic diseases such as heart disease and certain cancers, by reducing damage caused by free radicals to human cells [5]. Furthermore, the yellow hue of mango fruit is primarily determined by carotenoids, particularly BC, which accounts for approximately 70 % of the total carotenoid content in both the peel and pulp. This content increases as the fruit ripens [6]. Fruit grown in carbon paper bags has almost no chlorophyll or chlorophyll-related activities in its skin. For example, NDMST mango is normally wrapped in carbon-coated paper to maintain a consistently golden-yellow peel with minimal color changes during fruit ripening [1], thereby reducing damage from the oriental fruit fly and anthracnose [7–9]. The yellow color of mango skin may lead consumers unfamiliar with NDMST mangoes to assume that the mangoes are ripe. The color level of NDMST mangoes is also crucial for determining their taste and consumer satisfaction [3]. Although maturity determination by visual observation is unreliable and prone to error [3], this approach allows a thorough examination of relationships among quality attributes that might otherwise be obscured or disrupted [1].

Numerous non-destructive methods have been developed to evaluate mango quality reliably. These methods range from simple digital cameras to high-tech near-infrared spectroscopy (NIRS) and hyperspectral imaging (HSI) [3, 10–12]. Salengke and Murselim [3] used a digital camera to capture images of mango peels and applied image processing to obtain color values in CIELAB space, revealing that maturity indices can be predicted from color parameters. These values were plotted against quality attributes (TSS, TSS-to-total-acid ratio, or ripening index (RPI)). Rungpichayapichet et al. [12] found that NIRS and HSI exhibited potential for quality control in mango sorting, particularly for TSS, pH, RPI, and BC. Red–green–blue (RGB) and NIR imaging are also crucial in non-destructive analysis across various fields, particularly in food and fruit quality evaluation. To reconstruct the NIR spectral bands, Gkillas et al. [13] proposed a lightweight learning-based approach that reduced the cost of multispectral cameras by using only visible (RGB) data from an RGB camera and the Normalized Difference Vegetation Index (NDVI) calculated from the RGB and NIR images to track plant health. Kasimati et al. [14] reported a strong correlation among NDVI, grape yield, and TSS data at early and late growth stages. However, no significant relationship was observed with titratable acidity (TA) or pH.

The NDVI is a measure of vegetation greenness and density captured in a satellite image. It is calculated as the ratio difference between the measured canopy reflectance in the red and NIR bands of the vegetation image, as presented in Equation (1) [15]. NDVI values range from –1 to 1, depending on the absorption of red light by plant chlorophyll and the reflection of infrared radiation by water-filled leaf cells [16].

$$\text{NDVI} = \frac{\text{NIR} - \text{R}}{\text{NIR} + \text{R}} \quad (1)$$

During mango ripening, physicochemical changes such as fruit softening, color and flavor development, and increases in sugar content, TSS, and pigments, particularly carotenoids (with more red and orange color), occur at the mature stage [17, 18]. Carotenoids can absorb wavelengths between 400 and 600 nm, particularly at 520 and 540 nm [12]. RGB-based indices have been previously applied to assess fruit quality [19–21]. However, most previous studies have focused on green vegetation or green-skinned fruits, where NDVI is strongly associated with chlorophyll content. By contrast, studies on yellow-peel mango, such as NDMST, remain limited. Moreover, various destructive and spectroscopic methods have been developed to evaluate mango sweetness and antioxidant properties. However, these techniques are time-consuming, costly, and unsuitable for rapid or large-scale assessment. NDVI-based concepts offer a simple, ratio-based approach that is less sensitive to illumination variability. They can be adapted to low-cost RGB–NIR imaging systems, making them suitable for practical non-destructive applications. NDVI is widely used in vegetation monitoring. However, the potential to adapt the NDVI concept for developing a cultivar-specific index to assess internal quality attributes, such as sweetness and antioxidant content, in yellow-peel mangoes has not been systematically investigated.

This study aimed to develop a simple method for the non-destructive evaluation of NDMST mango quality indices. We focused on sweetness and antioxidant content, using RGB–NIR images captured with an RGB–IR camera. Additionally, we analyzed the color values from the RGB channels under visible and NIR filters to determine the optimal channel combination for constructing the NDMST index (NDMSTI) based on the NDVI concept. The results showed that an NDVI-based RGB–NIR index tailored to NDMST mangoes exhibits significant relationships with sweetness and antioxidant content during ripening and outperforms conventional RGB-based indices.

2. Materials and Methods

2.1 Sample Preparation

Export-grade NDMST mangoes from Petch Samrong Garden in Chachoengsao Province, Thailand, harvested 90–100 days after flowering, were screened for comparable physiological maturity using the 3% brine-floating method [23, 31]. This method is based on density differences related to maturity and soluble solid content. In this method, less mature mangoes with lower sugar levels float, while overripe mangoes with higher soluble solids tend to sink. Only mangoes that floated and did not sink to the bottom were selected. Therefore, the fruit did not exceed 90 % ripe, and its sweetness did not exceed 18 °Bx [22]. Temperature significantly affects mango growth, with the optimal range being 27–33 °C [24]. Therefore, 150 carefully selected mangoes were stored in the Packaging Laboratory of the Department of Science and Technology at Sukhothai Thammathirat Open University under ambient conditions over 10 days [11, 12] (27.8 ± 0.39 °C and $60.3 \pm 4.3\%$ relative humidity). These values represent the average measurements recorded over 10 days using a Tenmars TM-305U temperature and humidity data logger. Previous mango postharvest studies did not define a standard sample size because the number of fruits varied depending on the experimental design and analytical methods [11, 12]. In this study, 150 mangoes were used to ensure sufficient replication without compromising sample size. The experiment was conducted with five replicates. Each replicate comprised 30 mangoes ($n = 30$), a commonly accepted number to ensure statistical reliability and approximate normality according to the central limit theorem [25, 26]. All 150 mangoes were divided into five groups of 30 mangoes for each time of observation. Additionally, they were tested in two parts: 25 fruits for sweetness and antioxidant properties, as described in Section 2.3, and the remaining five fruits for color properties through visible and five NIR filters, as explained in Section 2.2. The experiment was performed with five replications at each time point (every two days), for a total of 10 days (Figure 1).

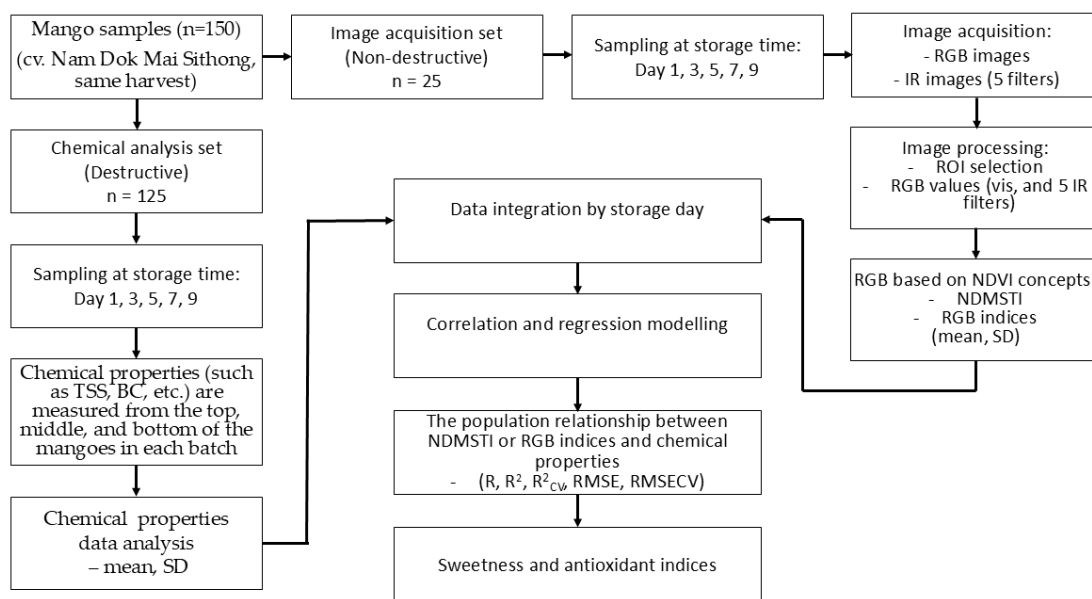


Figure 1. Workflow of data collection and analysis.

2.2 NDMST Mango Photography, Image Preparation, and RGB Value Analysis

The five representative mangoes from each group were photographed, prepared, and analyzed for RGB values according to the following steps.

2.2.1. NDMST Mango Photography and Image Preparation

Many digital cameras with CMOS sensors can be used as full-spectrum cameras (380–1000 nm) when their NIR-blocking filter is removed. Therefore, to capture NIR images for NDVI computation, we used a Canon EOS 5D Mark II camera, which was already available in our laboratory (at Chulalongkorn University) [27]. NDMST mangoes were photographed one at a time under IR. LED visible light was set to a color temperature of 6500 K. For every fruit photograph, six different types of filters were used: a visible filter; IR filters at 680 nm (IR 680), 720 nm (IR 720), 760 nm (IR 760), 850 nm (IR 850), and 950 nm (IR 950) [11, 12]. During each photoshoot, an X-Rite color checker pad was placed next to the mango. Each photo was captured in RAW format and processed for RGB and exposure corrections (white balance adjusted from the X-Rite ColorChecker Pad image in Photoshop). A total of 30 RGB and IR images, each from six filters, were created each time. Thus, a total of 150 images of the NDMST mangoes were obtained.

2.2.2. Analysis of RGB Values

The RGB values of the captured images were analyzed using MATLAB (R2023b). Each mango image was cropped into three parts: top, middle, and bottom [12]. The positions were initially checked in Photoshop. Subsequently, the cropped image positions were specified in MATLAB for image processing. The background was removed to obtain average color values based only on the RGB channels of the mango images. The results were presented as the average color values for R, G, and B, as shown in Figure 2. The NDVI values, calculated using Equation (1), were modified by subtracting each visible color value from the NIR value using either the R, G, or B channel rather than using only the R channel.

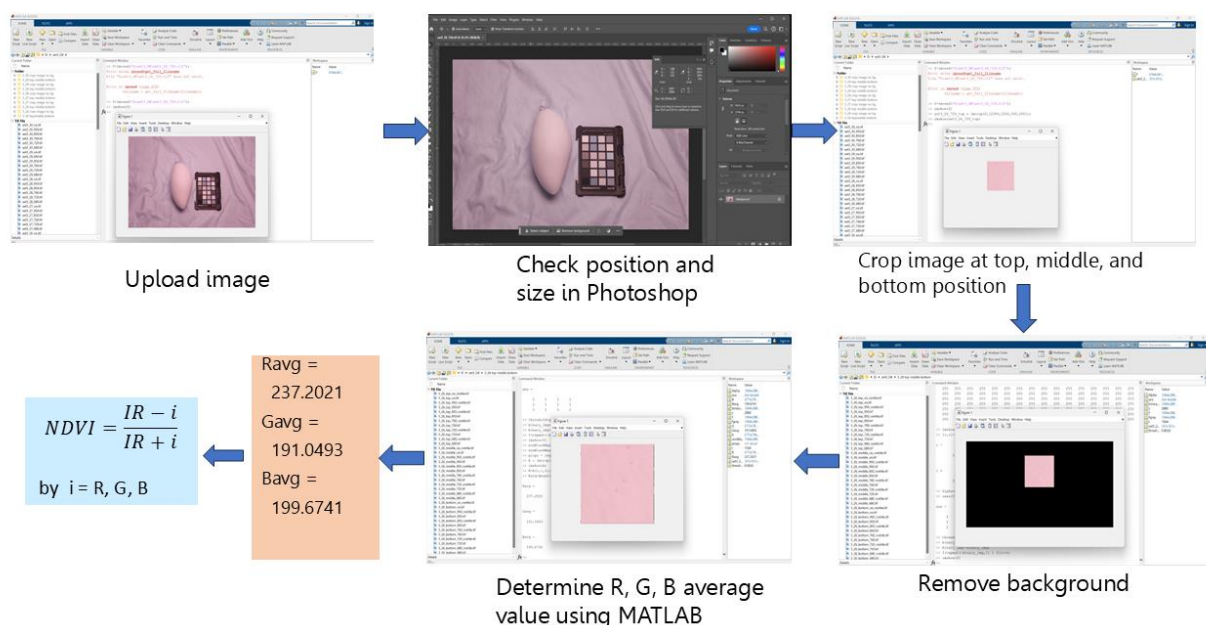


Figure 2. Analysis of RGB average value for NDVI calculation.

2.3 Analysis of Chemical Properties of NDMST Mango

To assess the sweetness and associated nutrients at the Analysis and Testing Service Unit, Rajamangala University of Technology Thanyaburi (RMUTT), Thailand, 25 NDMST mangoes from each period were cleaned, peeled, and divided into three parts (top, middle, and bottom). Subsequently, each part was ground to produce samples for further investigations of different values.

2.3.1. TSS

The Atago PAL-1 refractometer was used to measure TSS content (°Bx as a measure of sweetness).

2.3.2. Antioxidants

The BC and phenolic compounds were analyzed using a Thermo Helios Delta 9423 UVD 1722E UV-Visible Spectrophotometer. Antioxidant activity was assessed using the 1,1-diphenyl-2-picrylhydrazyl (DPPH) [28] radical scavenging assay and 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) [29] radical cation decolorization assay. All analyses were conducted at the Analysis and Testing Service Unit, RMUTT, Thailand.

2.3.3. Other Parameters

The pH, total sugar (TS), and TA were determined to evaluate the ripeness. The pH was measured using a Hanna HI2212 pH meter. The TS and TA were analyzed using the method of the Association of Official Analytical Chemists.

2.4 Data Analysis

Chemical and image measurements were obtained from different mango samples. Therefore, data integration was conducted at the population level, using storage time and mango position as common reference points. For each storage day and mango position, the mean and standard deviation (SD) of chemical properties and image features were calculated and combined into a single dataset. This approach allowed the evaluation of time-dependent relationships between non-destructive image features and destructive chemical measurements.

Owing to the small sample size, this study employed Spearman's rank correlation [30] for initial relationship analysis and partial least squares (PLS) regression combined with leave-one-out cross-validation to construct a stable model and reduce overfitting [31]. PLS regression was employed to develop individual prediction models for each image-derived index (NDMSTI or RGB-based) and for mango quality attributes (Table 1). This pairwise modeling approach enabled direct evaluation of each index's predictive capability for sweetness and antioxidant content. Robustness and predictive performance were assessed using cross-validation. The accuracy of each PLS model was evaluated by comparing predicted and measured values using the coefficient of determination from cross-validation (R^2_{cv}) and root mean square error of cross-validation (RMSECV). PLS with cross-validation was conducted using Minitab 18.

Table 1. Tested RGB-based indices.

RGB indices	Formula	References
Woebbecke index (WI)	$(G - B)/(R - G)$	[32]
B index	B	[21]
Normalized Green Blue Difference Index (NGBDI)	$(G - B)/(G + B)$	[33]

3. Results and Discussion

This study aimed to determine the RGB–NIR images related to mango properties using the NDVI principle. The results showed that RGB color values from the visible-filtered images are suitable for predicting mango quality.

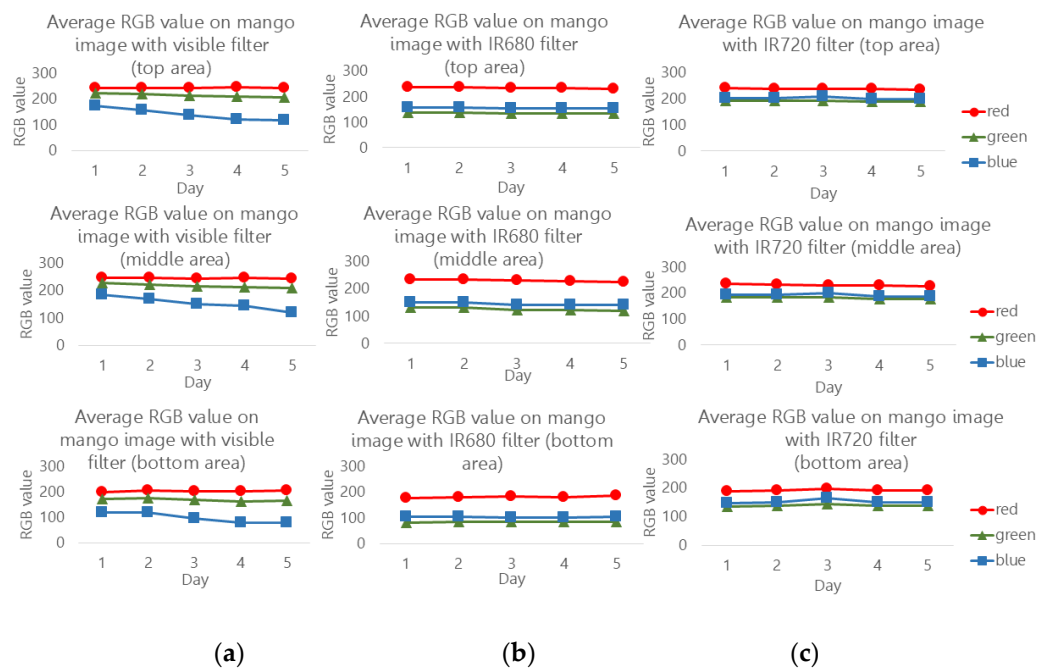
3.1 RGB Values from RGB and NIR Images

Figure 3 shows the RGB values of the mangoes photographed with a visible filter and five IR filters at different wavelengths (IR 680, IR 720, IR 760, IR 850, and IR 950). The images at each ripening stage were cropped and analyzed in MATLAB. The results showed that the color values of the B channel (blue) changed significantly across the ripening stages (Figure 4(a)), with a statistically significant effect [$F(3, 11) = 130.63$, $p < 0.001$]. As the storage age increased, the B channel color value of the mango photographs decreased, consistent with the results of a study by Min et al. [34]. The wavelength region between 400 and 600 nm, particularly at 520 and 540 nm, was strongly absorbed by carotenoids [12], exhibiting less reflection in the B

channel during ripening stages. However, after passing through the IR filters, no change in the R, G, and B color values was observed over the storage period (Figure 4(b)–(f)). Thus, the change in beta-carotene content in mangoes from yellow to orange cannot be precisely identified in the short-wavelength infrared range (680–950 nm) in this study, consistent with the observations of Rungpichayapichet et al. [35].



Figure 3. Cropped RGB images samples of NMDST (T- 1–29 indicates image code, T is top position, 1 is the first day and 29 is the number of mangoes) using the visible (Vis) and the five IR filters (IR 680, IR 720, IR 760, IR 850, and IR 950) at the top (T), middle (M), and bottom (Bo) positions.



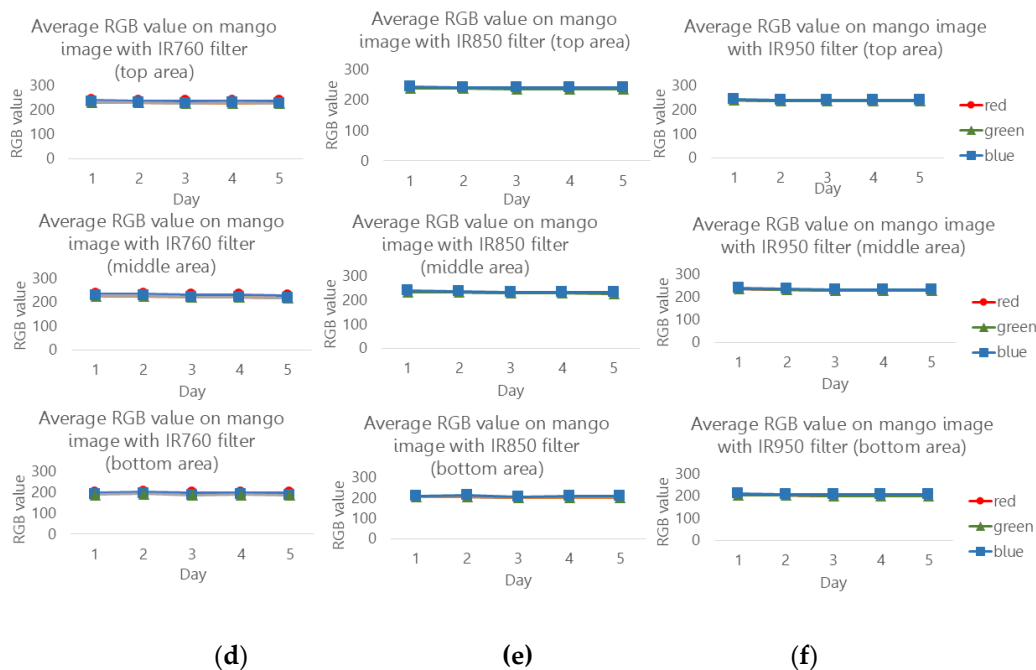


Figure 4. Average RGB values at the top, middle, and bottom of the NDMST mango (from top to bottom) across different ripening stages, (a) using a visible filter and (b) –(f) using NIR filters IR 680, IR 720, IR 760, IR 850, and IR 950, respectively.

In this study, the R-value obtained when applying the five IR filters was identical to that derived from the RGB image. Consequently, the R value can be used instead of the IR value in the NDVI formula. Equation (2) represents this novel concept. These findings are consistent with those of the NDVI1 investigation of Kawashima and Nakatani [20]. They determined the regression line for the relationship between chemical content and $(R - B)/(R + B)$, computed from data collected during the ripening stage.

$$\text{NDMST index} = \frac{R - B}{R + B} \quad (2)$$

3.2 Results of Regression Analysis Based on Indices (NDMSTI and RGB-based Indices) and NDMST Mango Properties

Table 2 presents correlation coefficients between chemical properties and image-based indices. The results show that image-based indices of NGBDI and NDMSTI are associated with nearly all mango chemical properties (β -carotene, TSS, TS, TA, ABTS, DPPH, and pH), except phenolic content (shown in bold). Phenolic acid content shows no relationship with any of the image-based indices because it remains constant throughout ripening. Therefore, NDMSTI and NGBDI were obtained from PLS regression of mango chemical properties, as presented in Table 3. Figure 5 shows samples from the regression plots of TSS content obtained from PLS models based on NDMSTI (Figure 5(a)) and NGBDI (Figure 5(b)). The circle dot represents the calibration data, while the square dot represents the cross-validation data. With a limited number of samples, the PLS models were intentionally constrained to a single latent variable (LV = 1) to reduce the risk of overfitting. The model resulted in moderate R^2_{cv} values, particularly for β -carotene, TS, TA, and DPPH. Therefore, while the models capture meaningful relationships between NDMSTI or NGBDI and chemical attributes, this variance is partially limited by sample variability and the narrow range of chemical composition represented in the dataset. By contrast, higher predictive performance ($R^2_{cv} > 0.50$) was observed for TSS, ABTS, and pH. These properties are more closely associated with mango visual attributes and surface color characteristics, which can be effectively captured by NDMSTI or RGB-based indices [1]. This finding is consistent with previous studies reporting stronger correlations between optical image features and physicochemical properties related to soluble solids and antioxidant capacity [19, 20, 36]. Although both

NGBDI and NDMSTI exhibited comparable predictive performance, NGBDI consistently yielded slightly higher R^2 values and lower prediction errors. Given the small sample size and the absence of an independent external validation set, the observed differences between indices are indicative rather than conclusive. The results support the feasibility of using simple NDMSTI and NGBDI for non-destructive estimation of mango chemical properties. These indices are particularly useful for rapid screening and quality assessment, rather than as a replacement for conventional chemical analyses (destructive methods).

Table 2. Correlation coefficients between average chemical properties and average image-based indices at the same position and ripening stage (n = 15).

Chemical property	WI	B-index	NGBDI	NDMSTI
Gallic (phenolic) acid (mg/100 g fw)	−0.082 (0.771)	−0.150 (0.594)	−0.029 (0.919)	−0.018 (0.950)
β-carotene (μg/g fw)	0.364 (0.182)	−0.557 (0.031)	0.786 (0.001)	0.739 (0.002)
Total soluble solids (TSS) (°Brix)	0.500 (0.057)	−0.711 (0.003)	0.915 (0.000)	0.867 (0.000)
Total sugar (TS) (g/100 g fw)	0.404 (0.136)	−0.596 (0.019)	0.807 (0.000)	0.746 (0.001)
Titrateable acidity (TA) (%)	−0.576 (0.025)	0.382 (0.159)	−0.688 (0.005)	−0.618 (0.014)
ABTS (%activity)	0.350 (0.201)	−0.671 (0.006)	0.861 (0.000)	0.832 (0.000)
DPPH (%activity)	0.282 (0.308)	−0.457 (0.087)	0.700 (0.004)	0.661 (0.007)
pH	0.450 (0.092)	−0.521 (0.046)	0.777 (0.001)	0.728 (0.002)

Remark: Values are Spearman's rank correlation coefficients (ρ), with P-values in parentheses. Significant correlations are indicated in bold ($P < 0.05$).

Table 3. PLS regression performance of NDMSTI and RGB-based indices.

Chemical properties	Image-based indices	LV	R^2	RMSEC	R^2_{cv}	RMSECV	p-value
β-carotene (mg/g fw)	NGBDI	1	0.57	41.35	0.43	44.26	0.001
	NDMSTI	1	0.54	42.49	0.40	45.24	0.002
TSS (°Brix)	NGBDI	1	0.63	2.36	0.52	2.49	0.000
	NDMSTI	1	0.62	2.40	0.51	2.51	0.001
Total sugar (g/gfw)	NGBDI	1	0.56	3.31	0.43	3.50	0.001
	NDMSTI	1	0.55	3.37	0.42	3.55	0.002
TA (%)	NGBDI	1	0.55	0.46	0.45	0.48	0.002
	NDMSTI	1	0.52	0.48	0.43	0.49	0.002
ABTS (%)	NGBDI	1	0.71	15.38	0.64	15.92	0.000
	NDMSTI	1	0.69	15.91	0.62	16.39	0.000
DPPH(%)	NGBDI	1	0.54	12.03	0.43	12.41	0.002
	NDMSTI	1	0.52	12.24	0.41	12.62	0.002
pH	NGBDI	1	0.63	0.81	0.54	0.84	0.000
	NDMSTI	1	0.61	0.84	0.51	0.87	0.001

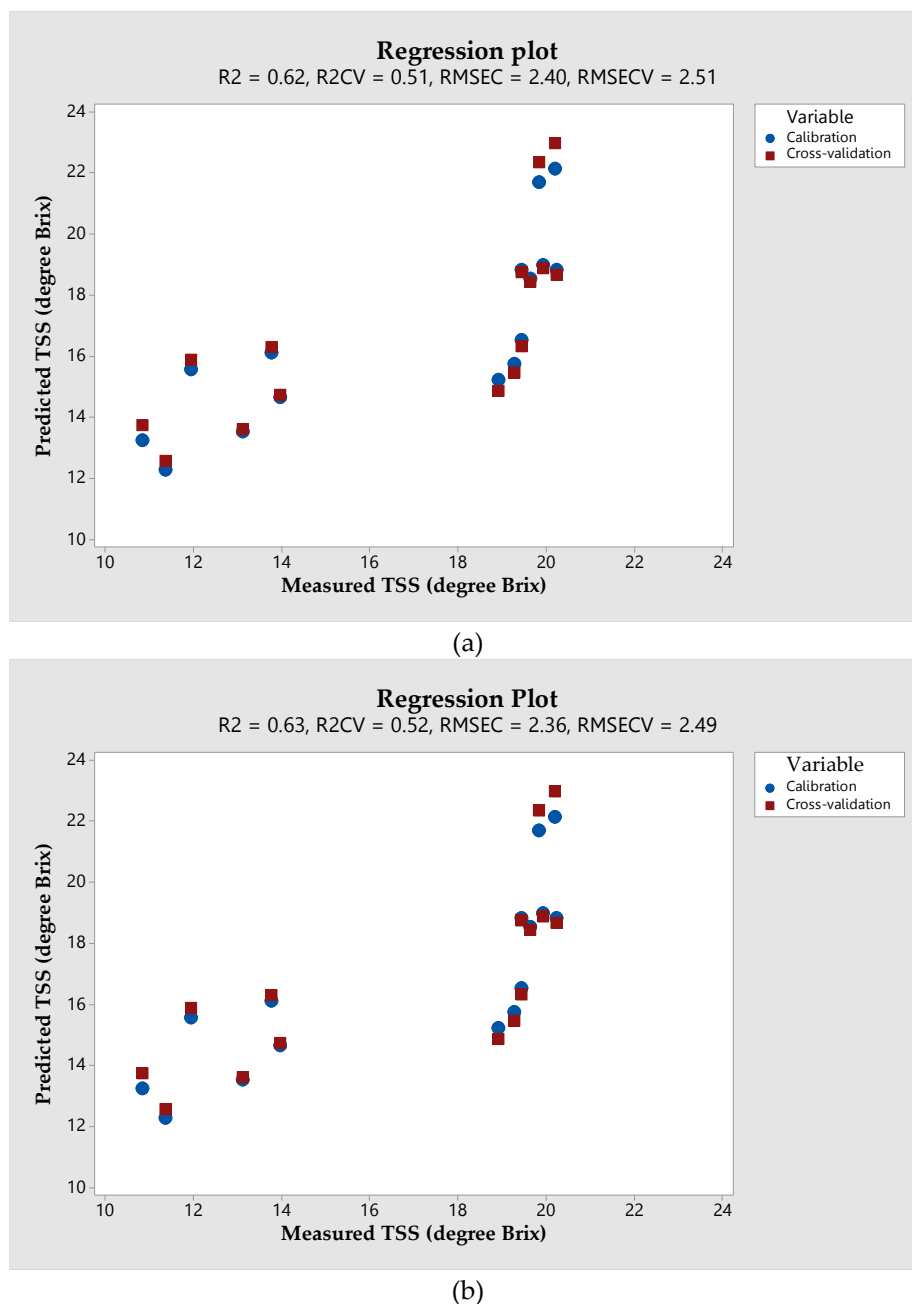


Figure 5. Relationship between measured and predicted TSS content (°Brix) obtained from PLS models based on (a) NDMSTI and (b) NGBDI.

4. Conclusions

In this study, we developed a non-destructive NDVI-based index using a digital camera. The NDMSTI values obtained from RGB–NIR images of mango peels were used to assess the sweetness and antioxidant content. The results showed that both NGBDI and NDMSTI demonstrated statistically significant predictive performance for all chemical properties ($p < 0.01$). NGBDI consistently provided slightly higher R^2 and R^2_{cv} values and lower prediction errors than NDMSTI, indicating marginally superior performance. The results indicate that image-based indices (NGBDI and NDMSTI) can predict all investigated chemical properties with statistical significance ($p < 0.01$). However, prediction accuracy varied across properties, with higher performance for TSS, ABTS, and pH, whereas β -carotene, TS, TA, and DPPH showed moderate predictive ability. Despite the small sample size ($n = 15$), this study demonstrated the potential of image-based indices

combined with PLS regression as a rapid, non-destructive tool for estimating mango chemical properties. Additionally, it provides a foundation for further model refinement and validation in future research. However, to address these limitations, future research should expand the initial sample size to maintain a higher number of observations after data integration.

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