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Rapid Assessment of Badea (*Passiflora quadrangularis* L.) Maturity Degree by Digital Image Analysis and Multivariate Statistical Techniques

(Evaluación rápida del grado de madurez de badea (Passiflora quadrangularis L.) mediante análisis de imágenes digitales y técnicas estadísticas multivariantes)

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Abstract: Fruits and vegetables are essential for a healthy diet worldwide, but due to their perishable nature, they are among the most wasted foods. According to the Food and Agriculture Organization (FAO), approximately 45% of food is lost before reaching consumers. Proper handling during and after harvest is crucial to reducing this waste, including identifying the optimal ripening point for both harvest and sale. *Passiflora quadrangularis* (badea), a traditional South American crop rich in antioxidants, generates significant income for vulnerable communities. Determining the ripeness of badea is key to ensuring better quality and reducing post-harvest losses. In this study, a physicochemical characterization was carried out by days of ripening, and images of the badea were used at three stages of ripeness: green-ripe, early-ripe, and ripe. The physicochemical characterization suggests average pH values of 5,73 and a maturity index of 11,62%, as indicators of an early ripening stage suitable for harvest. These images were analyzed using multivariate statistical methods, including Principal Component Analysis (PCA) and Partial Least Squares Discriminant Analysis (PLS-DA), to identify visual patterns and classify ripeness levels. The model achieved a training accuracy of 100% and a validation accuracy of 83%. These methodologies offer a fast and non-invasive method for assessing fruit ripeness, facilitating informed decisions about the optimal time for harvest and helping to reduce post-harvest waste.

Keywords: Maturity index, multivariate analysis, tropical fruit, RGB, PLS-DA.

Resumen: Las frutas y verduras esenciales para una dieta saludable a nivel mundial son de naturaleza perecible. Según la Organización de las Naciones Unidas para la Alimentación y la Agricultura (FAO), aproximadamente el 45 % de los alimentos se pierden antes de su consumo. La identificación del punto óptimo de maduración, tanto para la cosecha como para la venta, y su manipulación adecuada permiten reducir este desperdicio. La *Passiflora quadrangularis* (badea) es un cultivo tradicional sudamericano rico en antioxidantes y de gran importancia económica para las comunidades. Determinar el grado de madurez de la badea es fundamental para garantizar la calidad y reducir las pérdidas postcosecha. En este estudio, se realizó una caracterización fisicoquímica por días de maduración y se utilizaron imágenes de la badea en tres etapas de maduración: verde-madura, madura para la cosecha y completamente madura. La caracterización fisicoquímica sugiere un pH promedio de 5,73 y un índice de madurez de 11,62 %, lo que indica un estado de maduración temprana, adecuado para la cosecha. Las imágenes fueron analizadas mediante algoritmos multivariantes, incluidos el Análisis de Componentes Principales (ACP) y el Análisis Discriminante de Mínimos Cuadrados Parciales (PLS-DA), con el fin de identificar patrones visuales y

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clasificar los niveles de madurez. El modelo alcanzó una precisión de entrenamiento del 100 % y de crosvalidación del 83 %. Estas metodologías ofrecen una manera rápida y no invasiva de evaluar la madurez de la fruta, facilitando la toma de decisiones sobre el momento adecuado para la cosecha y contribuyendo a reducir el desperdicio postcosecha.

Palabras clave: Índice de madurez, análisis multivariante, fruta tropical, RGB, PLS-DA.

1. INTRODUCTION

Fruits and vegetables are essential components of the human diet due to their richness in vitamins, minerals, fiber, and bioactive compounds that benefit health [1]. However, their perishability makes them one of the most wasted food categories globally. Approximately 45% are lost before reaching the consumer [2]. These figures reflect a significant challenge to food security, especially in developing countries, where post-harvest losses directly affect the economies of farming communities.

The badea (*Passiflora quadrangularis* L.) is a tropical fruit, its cultivation is traditional, typical of coastal regions of South America, not only has a high cultural and gastronomic value, but also constitutes an important source of income for low-income families [3]. Badea is appreciated for its content of bioactive compounds, including antioxidants. The fruit extract has been linked to sedative properties [4], characteristics that contribute to its nutritional and functional value, making it attractive for both local consumption and specialized markets.

Traditionally, fruit ripeness is determined in the field through the empirical experience of producers. This approach is typically based on visual criteria, such as color change, fruit size, aroma, and tactile characteristics such as firmness and texture. Although rapid and straightforward, these practices present limitations in objectivity and reproducibility [5], [6]. Furthermore, environmental conditions, including climatic variables and agronomic management practices, can modify the physical and chemical characteristics of fruits during their development [7]. These factors can also threaten the organoleptic quality of fruits [8]. These fruits are generally found in Spanish-speaking communities, so it is necessary to standardize the terms used to describe the different common degrees of ripeness. The state of ripeness in which the fruit is unripe (the term "green") is used. The state of ripeness in which the color and texture begin to change in climacteric fruits, usually known as physiological rip is known as "pintón" [9]. In this document, "early ripening" is used; finally, the state in which the fruit is fully ripe is named "madura." [9], [10].

The laboratory's techniques used to determine ripeness measure total soluble solids (°Brix), titratable acidity, and the ripeness index (°Brix/acidity ratio). These methods provide quantitative and objective information on the fruit's development stage, allowing for more precise classification [11]. However, it requires considerable time to execute, trained personnel capable of performing the analyses correctly, and, in many cases, the destruction of the analyzed samples. The destructive nature of these techniques can be problematic in situations where samples are valuable or scarce [12], highlighting the need for alternative methods that are rapid, noninvasive, and cost-effective. Recent advances in non-invasive technologies, such as the use of visible and near-infrared (VIS/NIR) spectroscopy, have made it possible to analyze internal characteristics of fruits, such as the sugar content and phenolic compounds, without the need to destroy the samples [13].

Digital image analysis has also been used to assess fruit ripeness using parameters such as color, texture, and shape, which are associated with quality. Studies have shown that these techniques, combined with statistical models, can rapidly and nondestructively predict ripeness indices in products such as mangoes and tomatoes [14], [15].

Data from non-invasive devices have been combined with multivariate statistical analysis, which has proven to be a powerful tool for identifying patterns and classifying agricultural products based on specific attributes [16]. Methods such as Principal Component Analysis (PCA) and Partial Least Squares Discriminant Analysis (PLS-DA) have been successfully applied in the study of tropical fruits such as mangoes [17], limes [18] papayas [19], and bananas [20], demonstrating its ability to analyze complex data and provide relevant information for decision-making in the supply chain [21].

In this study, digital images were analyzed with PCA and PLS-DA to discriminate three badea ripeness categories—green-ripe, harvest-ripe, and ripe. The results suggest that these noninvasive techniques can be implemented as a practical tool for producers, enabling timely decisions during harvest. This approach not only benefits consumers by ensuring better-quality fruits, but also has a positive impact on the economic sustainability of producing families and on reducing food waste, thus contributing to the Sustainable Development Goals (SDGs), particularly those related to zero hunger, sustainable production, and reducing food losses and waste.

Thus, this work seeks to contribute to the knowledge and development of applicable tools in the post-harvest handling of tropical fruits, emphasizing badea, highlighting the importance of technology and innovation in sustainable agriculture.

2. MATERIALS AND METHODS

2.1 Fruit sampling

Trees with green fruit close to ripening were selected by simple random sampling from farms in the San Isidro area of the El Empalme canton, Guayas province. Images of these fruits were taken on the tree. Five samples were harvested on days 0, 1, 3, and 4, while three samples were collected on days 7, 8, 9, and 10. Fruits with no external damage from pests or physical harm, of approximately the same size, were selected and brought to laboratory conditions. A total of 30 fruits were harvested. The methodology adopted was proposed by [22].

2.2 Fruit physicochemical characterization-maturity index

The whole fruit was cleaned with potable water, and the size, weight, percentage of edible portion, and moisture content were measured.

2.2.1 Length and edible portion

The length and circumference were measured using a tape measure, following the guidelines of [23]. Fruit weight was obtained using a CAMRY brand digital scale with a 5 kg capacity.

The percentage of edible portion was determined by weighing the fruit before and after peeling. The edible percentage was calculated using the Equation 1:

$$\%\ \text{Edible portion} = \frac{final\ weight}{initial\ weight} * 100 \qquad (1)$$

2.2.2 Moisture

A Merment brand sterilizing oven was used to determine moisture content. A crucible was weighed, then 5g of the sample (wet sample) was placed in the oven for 2 hours at 105°C (dry sample), and finally weighed.

The fruit's moisture percentage was determined using the Equation 2:

$$\%\ Moisture = \frac{Wet\ sample\ weight - Dry\ sample\ weight}{Wet\ sample\ weight} * 100 \qquad (2)$$

2.2.3 pH and acidity analysis

After the physical analyses were performed, before the chemical analyses, the pulp was extracted using a fruit extractor (UMCO, 6101 model, 1 L), filtered, and 50 mL of the juice was centrifuged at 3.400 rpm for 3 minutes. The soluble solids content (ºBrix) was determined using a digital refractometer (Atago Master) and the pH was determined using a pH meter (Starter Bio).

For acidity, 50 ml of the supernatant was taken. It was determined according to [24]. Calculations were made based on the citric acid content. The equation 3 was used:

$$\% \, Acidity = \frac{N * V * 0.67(meq.ac)}{ml} * 100 \qquad (3)$$

Where:
N: NaOH Normality
V: Titration flow rate (ml)
Meq.ac: milliequivalent of citric acid: (0,67)
Sample (ml): Total ml of the sample used.

2.2.4 Maturity index

The initial ripeness of the fruit was determined using the equation 4 [25]:

$$\textbf{Maturity Index (MI\%)} = \frac{Soluble\ solids\ content}{Titratable\ acidity} * 100 \qquad (4)$$

All analyses were done in triplicate during days 0, 1, 3, 4, 7, 8, 9 and 10 days in which 3 experimental units were analyzed.

2.3 Image analysis

Whole fruits were analysed, and the images were captured using a Samsung Galaxy A20 smartphone with a 13 MP f/1,9 + 5 MP f/2,2 rear camera, in JPG format. Image capture distances were standardized at 1 m in the field and 15 cm in the laboratory.

2.4 Statistical analysis

The determination of statistical differences between the days of analysis in the physicochemical variables was carried out using an ANOVA analysis of variance, in Statgraphics Centurion.

The images were analyzed using MATLAB V2018a software, and the PLS-DA was applied to the red (R), green (G), and blue (B) color coordinates. The dependent variable corresponds to maturity, with the classes: green (1), early-ripe (2), and ripe (3). Categories were derived from the maturity index outcomes; measurement procedures are detailed in Section 2.4.

3. RESULTS

3.1 Physicochemical characteristics of the badea

Table 1 presents the data corresponding to the weight, length and diameter of the badea. It is observed that, as the days go by, the weight increases progressively, reaching to a total of 2,51 kg. The length of the fruit also increased, going from 25,50 cm on day 1 to 27,67 cm on day 10, also the diameter varies slightly from 13,69 to 14,92. The statistical analysis indicates that the variables length and diameter show no significant differences.

Table 1. Means and standard deviation of physical variables.

		Weight (Kg)			Lenght (cm)			Diameter (cm)		
Maturity state	**Day**	**X**		**σ**	**X**		**σ**	**X**		**σ**
GREEN	0	2,12	±	0,0935	25,50	±	3,000	13,69	±	1,49
	1	2,15	±	0,0944	27,75	±	0,957	12,89	±	0,32
EARLY RIPE	3	2,15	±	0,0944	28,75	±	1,708	15,72	±	0,57
	4	2,20	±	0,0586	26,00	±	2,828	15,41	±	0,92
	7	2,31	±	0,1228	26,50	±	1,291	15,08	±	0,60
RIPE	8	2,43	±	0,1080	27,00	±	0,816	16,43	±	0,60
	9	2,45	±	0,1200	27,33	±	1,528	15,60	±	1,20
	10	2,51	±	0,1142	27,67	±	1,528	14,92	±	0,18

Table 2 presents the results of the chemical measurements. Statistically significant differences are observed in the °Brix values; starting on day 4, a notable increase is detected.

Acidity showed statistically significant differences; the highest acidity value was observed in the green fruit, which progressively decreased over the days. Unlike the variations observed in pH and °Brix, acidity experienced a continuous decrease from day 1 to day 10.

Table 2. Means and standard deviation of chemical variables.

		pH			ºBrix			Acidity (%)			IM (%)		
State	**Day**	**X**		**σ**	**X**		**σ**	**X**		**σ**			**σ**
GREEN	0	5,58	±	$0,06^{a}$	4,33	±	$0,39^{a}$	0,737	±	$0,042^{a}$	5,94	±	$0,7022^{a}$
	1	5,54	±	$0,05^{a}$	4,54	±	$0,33^{a}$	0,673	±	$0,021^{b}$	6,75	±	$0,4952^{a}$
EARLY-RIPE	3	5,67	±	$0,03^{b}$	4,79	±	$0,33^{b}$	0,571	±	$0,024^{c}$	8,42	±	$0,7696^{b}$
	4	5,71	±	$0,04^{c}$	5,70	±	$0,25^{c}$	0,547	±	$0,018^{d}$	10,43	±	$0,6513^{c}$
	7	5,83	±	$0,03^{d}$	5,82	±	$0,24^{c}$	0,364	±	$0,018^{e}$	16,00	±	$0,8341^{d}$
RIPE	8	6,03	±	$0,06^{e}$	6,28	±	$0,25^{d}$	0,317	±	$0,014^{f}$	19,82	±	$1,1586^{e}$
	9	6,16	±	$0,06^{f}$	6,84	±	$0,21^{e}$	0,259	±	$0,007^{g}$	26,43	±	$1,0295^{e}$
	10	6,31	±	$0,04^{g}$	7,29	±	$0,21^{f}$	0,176	±	$0,022^{h}$	42,07	±	$5,5139^{g}$

IM: Maturity Index; σ: standard deviation, ^{a} letters that represent differences in significance.

The fruit maturity index (MI %) ranges from 5,94 (green) to 42,07 (ripe) on day 10, corresponding to an increase in soluble solids and a decrease in acidity. A high standard deviation is observed on day 10, indicating that the content of soluble solids and acidity, as well as the variability between samples, increases. The exponential trend in the maturity index from day 4, as shown in Figure 1, indicates that ripening does not follow a linear pattern but accelerates over time, especially after physiological changes, which may be relevant for defining the optimal time for harvesting or consumption.

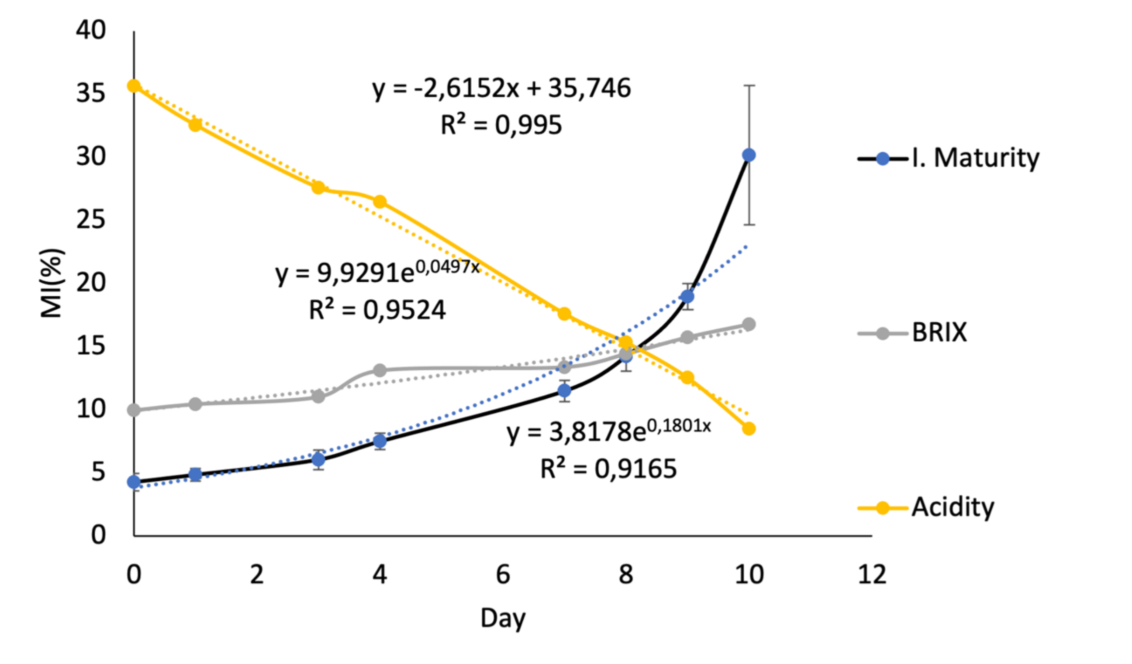

Figure 1: Variation of the badea maturity index vs. harvest days.

3.2 Fruit ripeness classification by image analysis

Figure 2 shows the biplot of the PLS-DA analysis, which displays the dispersion of the RGB data for the samples in the space defined by two latent variables (LVs). These variables represent linear combinations of the original data that maximize discrimination between predefined groups (fruit maturity states). The first LV explains 22,59% of the variability in the data, and the second LV explains 25,55% of the variability. The groupings between the samples indicate how the variability of the first LV is due to patterns found in green, early-ripe and ripe fruits. It is observed that in LV 1 the green fruits are in the space with positive values, while the ripe fruits obtain negative values. In the case of the early-ripe fruits, they are in the negative space of LV2, while the dispersion of the ripe samples, some also obtain positive values in this LV, which would allow discriminating between these 2 categories (early-ripe and ripe). Finally, the spread observed in the ripe data likewise indicates higher internal variability, likely due to variation in the final degree of maturity among samples within the group.

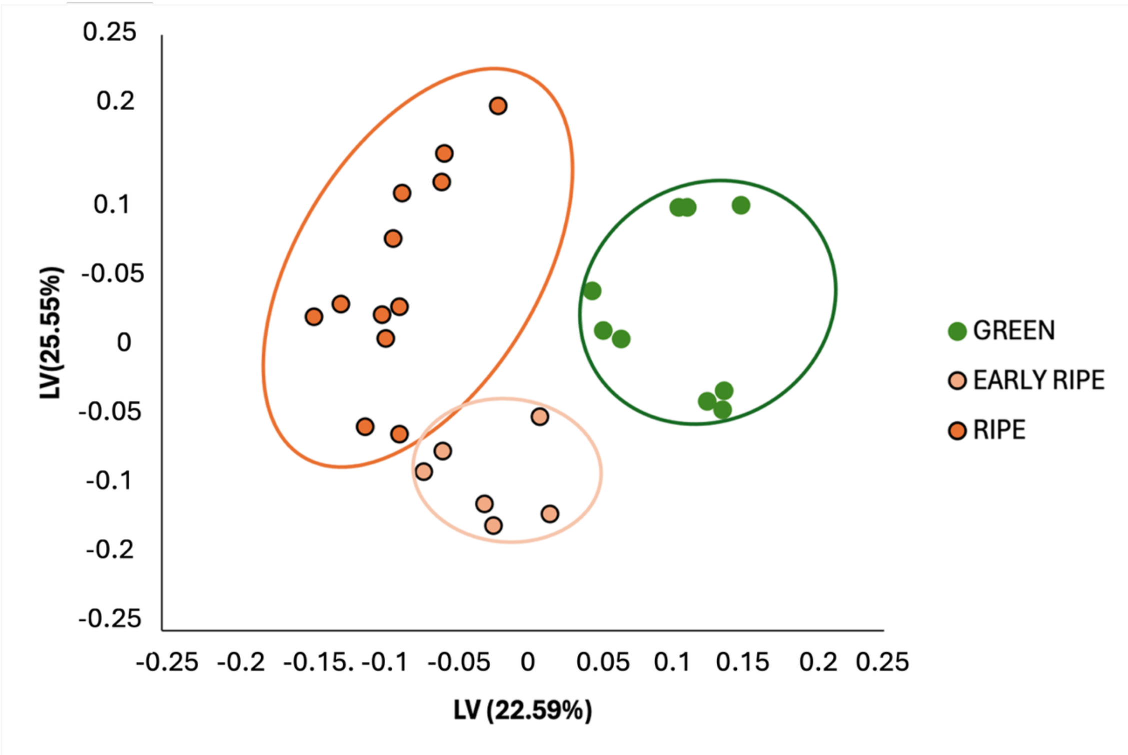

Figure 2. Scatter plot - classification by degree of ripeness of green, ripe, and ripe fruit.

Among the statistical parameters of the PLS-DA model is accuracy, which was 100% overall, indicating that all samples were correctly classified into their respective categories during model adjustment. After cross-validation, the model's total accuracy was 83%. Individually, the accuracy for unripe fruits was 83%, indicating that most samples were correctly classified, although 17% were misclassified. In the early-ripe phase, the accuracy was lower at 75%, suggesting that this category is the most difficult for the model to classify correctly, possibly due to fewer distinctive features or greater internal variability. Accuracy for ripe fruits was highest after training at 90%, indicating that the model classifies this category well.

4. DISCUSSION

In this study, consistent patterns were identified in the physicochemical and image data, allowing for the classification into three maturity categories: green, early-ripe, and ripe. The similarity of the categories with those studied according to reference [26] reinforces the validity of the method used, demonstrating that physicochemical analyses such as image-based techniques are reliable and complementary tools to determine the state of maturity of the fruit.

The physicochemical results obtained in this study fall within the ranges reported by [20], who indicated that the length of the badea ranges from 12 to 25 cm, with its diameter ranging from 8 to 16 cm across the three maturity stages studied (green, early-ripe, and ripe) [21]. This finding aligns with observations by other authors who also found no significant variation in fruit length and diameter between ripening stages, but variations in internal characteristics.

The Brix values obtained in this study are consistent with those reported by [27], who found a value of 4.78 °Brix in the pulp. However, [28] found that total solids values reached a maximum of 6º Brix, reflecting a slight difference in cultivation conditions or fruit variety. This variability is also reflected in the range of soluble solids observed, which is within the interval reported by [29], with values of 5.83 and 6.23 °Brix for fruits grown under organic and conventional practices, respectively.

Regarding acidity, the results obtained are in line with those reported by [26], who reported an acidity range of 0,36% to 0,49% in the badea pulp. This range suggests that acidity does not vary significantly between ripeness stages but may be a key indicator of the fruit's organoleptic quality.

The variation in the maturity index (MI) is consistent with the trend observed by [30], who reported similar behavior in strawberry ripening studies. Additionally, the exponential behavior observed in Figure 1 is comparable to the findings of [31], who explained that in climacteric fruits, the MI increases sharply after the peak respiration rate is reached, leading to rapid degradation of organic acids and accelerated fruit deterioration.

Regarding classification with PLS-DA, the results obtained are comparable to those reported by [30] for models calibrated with smartphone algorithms, which achieved an average accuracy of 91,98%, with validation accuracies ranging from 86% to 93%. Similarly, our results align with those obtained by [31] in the classification of granadillas, where a total accuracy of 93% was reported, with 96,6% accuracy for ripe granadillas and 86,6% for 'green-purple' passion fruits. Furthermore, [32] reported an accuracy of 91,52% for passion fruit classification using depth imaging. These results reinforce the robustness and reliability of the model proposed in this study, as they are within a comparable range of predictive performance reported in similar studies.

5. CONCLUSIONS

The physicochemical characteristics of *Passiflora quadrangularis L.* harvested close to ripeness were determined. The fruit showed significant variations in weight, which increased notably, but no significant variations in length and diameter, with average values of 2,29 kg, 27 cm in length, and 14,96 cm in diameter. The chemical parameters found were consistent with previous studies, and the average values of the early-ripe stage, suggested as optimal for harvest, were: pH 5,7, Brix 5,6, acidity 0,49%, and a maturity index of 11,62%. The image analysis results indicate that RGB coordinates can be used to fit models based on multivariate algorithms, such as PLS-DA classification. This allowed for the identification of patterns for classifying badea fruit into green, early-ripe, and ripe with 100% accuracy. The results can be used as an intuitive tool for production, leading to a reduction in post-harvest fruit losses. Reducing post-harvest waste contributes to sustainable development goals, such as zero hunger and poverty reduction.

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