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MORPHOLOGICAL AND COLORIMETRIC MODELING FOR DETERMINING THE RIPENING STAGES OF *Euterpe edulis* FRUITS

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ABSTRACT

Accurate characterization of the fruit maturation stage is essential for ensuring quality standards, uniformity, and added value in production. In this study, morphological and colorimetric characteristics of *Euterpe edulis* Mart. fruits were analyzed with the objective of developing a mathematical model capable of efficiently estimating the physiological maturation point. The evaluated variables included dimensional measurements of the fruit and seed, fresh weight, seed volume, pulp yield, and color attributes. Correlation analysis revealed significant associations among most of the variables, with coefficients ranging from weak to strong. Strong correlations were observed between seed size and its fresh weight, while the association between morphological and colorimetric characteristics was generally weak. On the other hand, the maturation stage showed a strong and significant correlation with color parameters, particularly those related to lightness, saturation, and hue. Based on these results, a multiple linear regression model was developed using colorimetric attributes as predictor variables. The final model demonstrated high predictive capacity and can be applied as a non-destructive tool to estimate the maturation stage of juçara fruits. This approach contributes to standardizing the harvest point, optimizing pulp utilization, and adding value to the species' production chain. Among the various multiple linear models generated using colorimetric indices, the best fit was achieved with the following model: $\hat{Y} = 4.93543 - 0.04511L - 0.11503C + 0.04952b + 0.02832a + 0.00097h$.

Keywords: Juçara; Colorimetric indices; Multiple linear models

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MODELAGEM MORFOLÓGICA E COLORIMÉTRICA PARA DETERMINAÇÃO DE ESTÁDIOS DE MATURAÇÃO DE FRUTOS DE *Euterpe edulis*

RESUMO A caracterização precisa do estádio de maturação de frutos é essencial para garantir padrões de qualidade, uniformidade e valor agregado à produção. Neste estudo, foram analisadas características morfológicas e colorimétricas de frutos de *Euterpe edulis* Mart., com o objetivo de desenvolver um modelo matemático capaz de estimar, de forma eficiente, o ponto fisiológico de maturação. As variáveis avaliadas incluíram medidas dimensionais do fruto e da semente, massa fresca, volume de sementes, rendimento de polpa e atributos de cor. A análise de correlação indicou associações significativas entre a maioria das variáveis analisadas, com coeficientes variando de baixos a elevados. Correlações fortes foram observadas entre o tamanho da semente e seu peso fresco, enquanto a associação entre características morfológicas e colorimétricas foi, em geral, baixa. Por outro lado, o estádio de maturação apresentou correlação alta e significativa com os parâmetros de cor, especialmente com os componentes relacionados à luminosidade, saturação e tonalidade. Com base nesses resultados, foi possível ajustar um modelo de regressão linear múltipla utilizando os atributos colorimétricos como variáveis preditoras. O modelo final demonstrou elevada capacidade de predição e pode ser aplicado como ferramenta não destrutiva para estimar o estádio de maturação dos frutos de juçara. Essa abordagem contribui para a padronização do ponto de colheita, otimizando o aproveitamento da polpa e agregando valor à cadeia produtiva da espécie. Dentre os diferentes modelos lineares múltiplos gerados com o uso dos índices colorimétricos, o que melhor se ajustou foi o modelo: $\hat{Y} = 4.93543 - 0.04511 * L - 0.11503 * C + 0.04952 * b + 0.02832 * a + 0.00097 * h$.

Palavras-Chave: Juçara; Índices colorimétricos; Modelos lineares múltiplos

1. INTRODUCTION

With the growing demand from consumer markets for higher-quality food products (Oliveira et al., 2015), there has been increasing interest in fruits exhibiting distinctive attributes such as aroma, flavor, texture, exotic appearance, and functional properties (Schwartz et al., 2010; Schreckinger et al., 2010). Among the species with emerging commercial potential, *Euterpe edulis* Mart. (juçara) stands out due to its high nutritional and functional value, being rich in fatty acids, proteins, fibers, vitamins, minerals, and anthocyanins (Schulz et al., 2016).

Despite its relevance, studies focused on the technological utilization of juçara fruits remain limited, particularly with regard to the determination of the optimal harvest point. In ecologically managed systems, harvesting typically prioritizes fully ripe fruits (Muller et al., 2013), and fruit maturity is generally estimated based on visual assessment of color (Oliveira et al., 2007). Although color is commonly used as a post-harvest indicator due to its association with developmental stage, this empirical method presents notable limitations.

The subjective nature of visual assessment, influenced by individual variability in perceiving color parameters such as hue, shade, and contrast (Lima et al., 2007), may undermine the reliability of maturity determination, thereby affecting the uniformity of fruit selection and harvest timing.

While it is well established that fruit maturation involves a series of morphological, biochemical, and physiological changes, the ideal harvest point for *E. edulis* has not yet been clearly defined. In other species, this stage can be identified based on traits such as color, size, odor, presence of predators or dispersers, and dehiscence (Mamede et al., 2013). However, these criteria are not universally applicable. Defining the ideal harvest point requires consideration of the specific physiological and morphophysiological patterns of each species (Farias et al., 2011), highlighting the need for more objective and standardized methods.

In this context, the present study aimed to evaluate the morphological and colorimetric characteristics of *E. edulis* fruits to develop a statistical model capable of accurately estimating the species' maturation stages.

2. MATERIAL AND METHODS

The fruits used in this study were collected from mother plants on a private rural property with an area of approximately 24 hectares, located in the municipality of Rio Novo do Sul, in the state of Espírito Santo, Brazil. After collection, the fruits were stored in plastic bags and transported to the Plant Sample Preparation Laboratory at CCAE-UFES, where they were washed, air-dried at room temperature, and visually classified into five groups according to their maturation stage (Figure 1).

A sample of 100 fruits was randomly selected for each maturation stage, with each fruit considered as a replicate. The equatorial (FDE) and longitudinal (FLD) diameters of the fruits, as well as the equatorial (SED) and longitudinal (SLD) diameters of the seeds, were measured using a digital caliper. The fresh weight of the fruits (FW) was determined in grams by individual weighing on an analytical balance. After manually removing the pulp with knives, the seeds were individually weighed to determine their fresh weight (SW). The volume of 25 seeds (SV) was calculated using the water displacement method, with 200 mL of distilled water in a graduated cylinder, measuring the change in displaced volume. The pulp yield (PY) was calculated using the following equation:

$$PY = \frac{FW - SW}{FW} X100 \quad \text{(Eq. 1)}$$

The seed moisture content (M) was calculated using the following equation:

$$M = \frac{FW - DW}{FW} X100 \quad \text{(Eq. 2)}$$

Where: M = seed moisture content (%), FW = fresh weight (g), DW = dry weight (g) (Brasil, 2009).

Before pulp removal, the fruit color was determined using a colorimeter (Konica Minolta®), based on the CIE 1976 L* a* b* (CIELab) color space, as established by the International Commission on Illumination. This system is based on three axes: L* (luminosity, ranging from 0 = black to 100 = white), a* (green-red axis, with positive values indicating redness), and b* (blue-yellow axis, with positive values indicating yellowness). From these values, the chromatic indices C* (chroma) and hº (hue angle) were calculated using the following formulas:

$$C^* = \sqrt{(a^2) + (b^2)} \quad \text{(Eq. 3)}$$

$$h^\circ = tan^{-1}\left(\frac{b^*}{a^*}\right) \quad \text{(Eq. 4)}$$

These three parameters (L*, C*, and hº) determine the position of the sample's color in the three-dimensional CIELab color space. The angle hº is always measured from +a*, in a clockwise direction (Figure 2).

The colorimetric parameters (L*, a*, b*, C*, and hº) were used as predictor variables

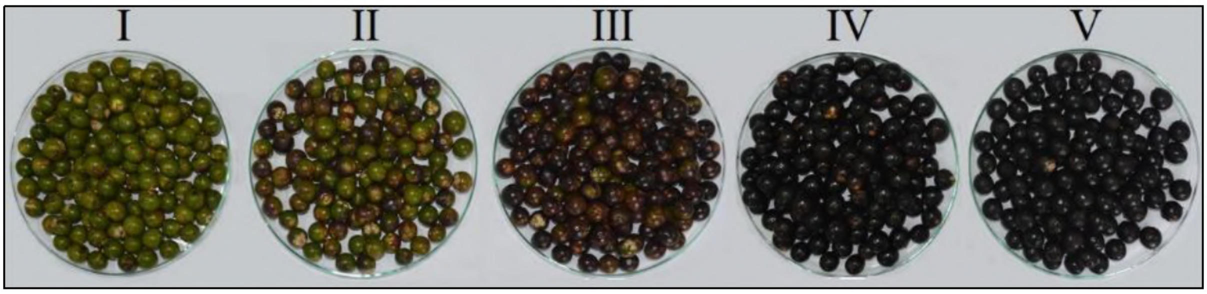

Figure 1. Maturation stages of *Euterpe edulis* fruits. Stage I: fruits with entirely green coloration; Stage II: green fruits with purple spots; Stage III: entirely purple fruits; Stage IV: entirely black fruits; Stage V: entirely black fruits with small cracks and easy pericarp removal

Figura 1. Estágios de maturação dos frutos de *Euterpe edulis*. Estágio I: frutos com coloração inteiramente verde; Estágio II: frutos verdes com manchas roxas; Estágio III: frutos inteiramente roxos; Estágio IV: frutos inteiramente pretos; Estágio V: frutos inteiramente pretos com pequenas rachaduras e fácil remoção do pericarpo

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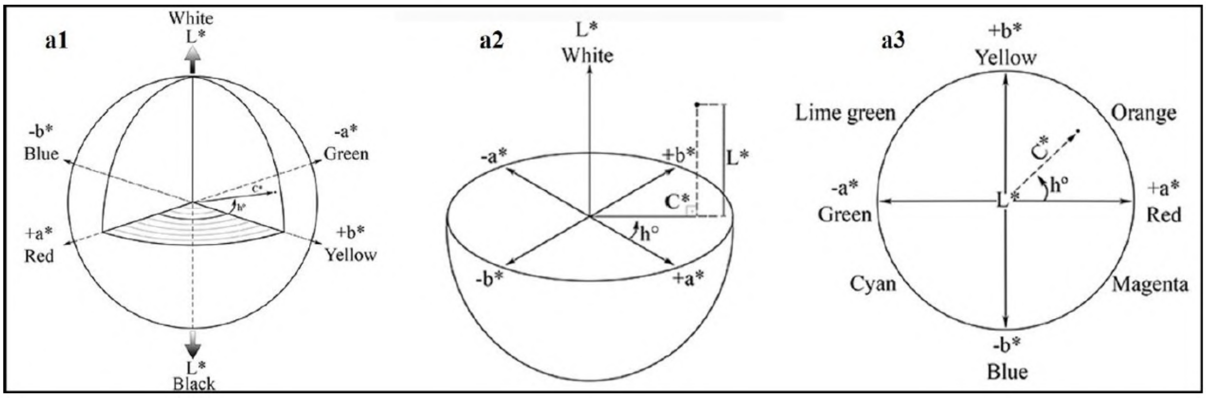

Figure 2. Cartesian plane in the color space of the CIELab system
Figura 2. Plano cartesiano no espaço de cores do sistema CIELab

in a multiple linear regression model, with the fruit maturation stage as the response variable. The model parameters were estimated using the following general equation:

$$Resp_i = \beta_0 + \sum_i^n \beta_i Vc + \varepsilon_i \qquad \text{(Eq. 5)}$$

Where: Respi is the response vector (maturation stage); β_0, β_1, ..., βn are the model coefficients; Vc are the colorimetric variables; and ε_i is the random error associated with the i-th observation.

To identify the most relevant predictor variables, the Stepwise selection method with bootstrapping (Breaux, 1967) was used. This technique is the first model selection procedure, which simplifies the choice of the model by addressing the issue of multiple possible combinations when the number of variables (p) is large (Desboulets, 2018). This method sequentially adds or removes variables from the model based on statistical criteria. In this regard, the Akaike Information Criterion (AIC) was used as the selection metric in the present study. The AIC evaluates the trade-off between model fit and simplicity, favoring models with lower values.

The model validation was performed through cross-validation, a technique that divides the dataset into subsets for training, testing, and validation. The dataset was partitioned into k = 15 subsets, with the process repeated 10 times to ensure greater robustness in the evaluation.

Multicollinearity among the variables was assessed using the Variance Inflation Factor (VIF), defined by the formula:

$$VIF_i = 1/(1 - R_i^2) \quad \text{i= 1, 2, 3, ... p} \qquad \text{(Eq. 6)}$$

Where: p is the number of predictor variables and R_i^2 is the multiple correlation coefficient of variable i with the others. Variables with a VIF greater than 10 were excluded from the analysis.

The refined dataset was subjected to multivariate analysis. The dissimilarity matrix was calculated based on the Standardized Euclidean Distance, and clustering was performed using the UPGMA (Unweighted Pair Group Method with Arithmetic Mean) method (Sneath & Sokal, 1973). All statistical analyses were conducted with the R software (R Core Team, 2017).

3. RESULTS

The variables related to fruit and seed color and size showed a significant association with the maturation stage (RS), standing out as good indicators for monitoring the harvest point. The correlations between RS and the analyzed characteristics ranged from 0.14** (low association between RS and FLD) to -0.92*** (strong negative association between RS and C*), as shown in Figure 3.

The highest correlations between the maturation stage (RS) and the colorimetric parameters were observed between RS and L* (-0.90***), RS and b* (-0.89***), and RS and C* (-0.92***). Among all the variables analyzed, the correlation coefficients ranged from 0.10* (between b* and hº) to 0.98*** (between b* and C*), with associations classified from weak to strong magnitude (Figure 3).

Significant phenotypic correlations observed between physical characteristics

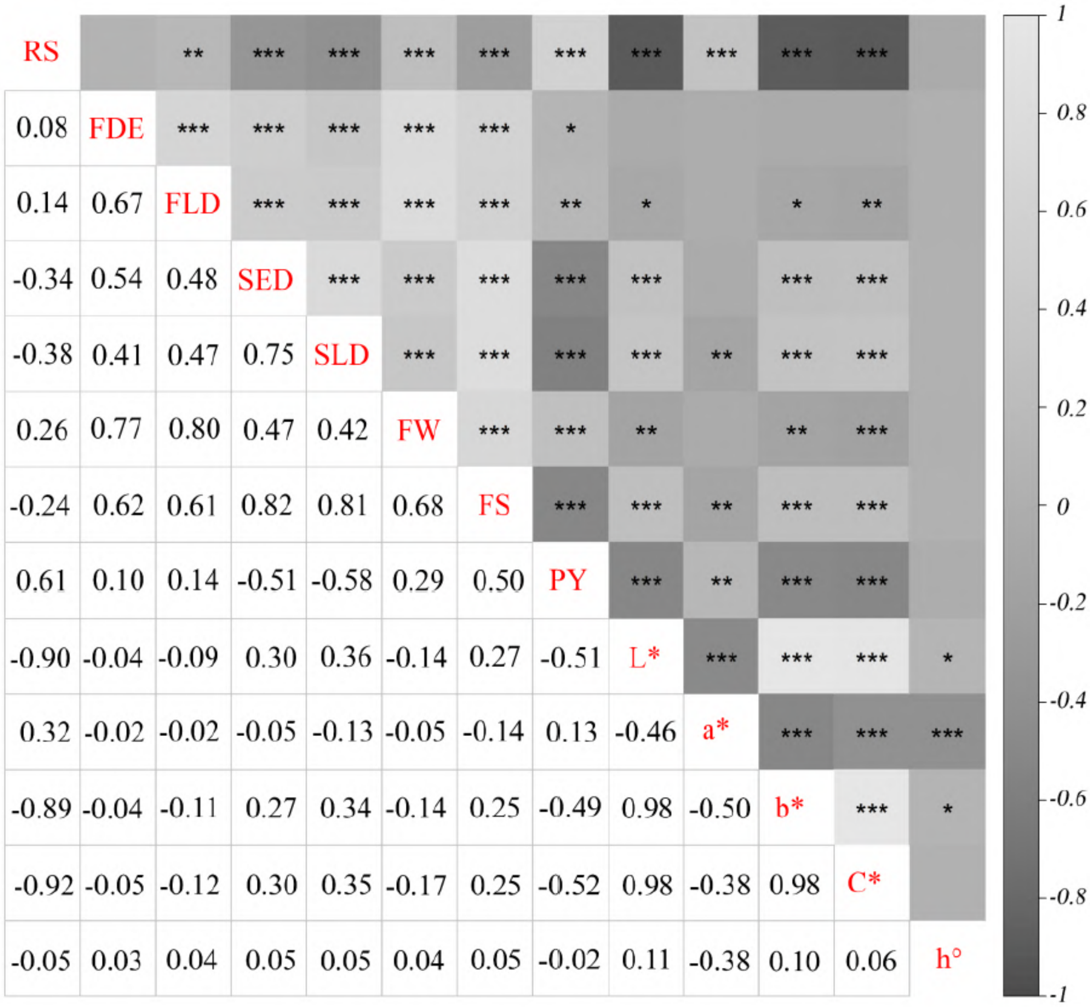

Figure 3. Phenotypic correlation between the maturation stage (MS), biometric variables (FED, FLD, SED, SLD, FW, SW, and PY), and colorimetric parameters (L, a, b*, C*, and hº) of *Euterpe edulis* fruits. The upper diagonal represents the significance and Pearson's correlation values, as follows: significant at 5%; significant at 1%; significant at 0.1%. The color gradient presented on the upper diagonal reflects the magnitude and sign of the correlations shown in the lower diagonal, which may range from -1 to 1. In this context, darker shades indicate negative correlations, while lighter shades represent positive correlations. MS: maturation stage of the fruit; FED: fruit equatorial diameter; FLD: fruit longitudinal diameter; SED: seed equatorial diameter; SLD: seed longitudinal diameter; FW: fruit fresh weight; SW: seed fresh weight; PY: pulp yield; L: luminosity; a: green-red axis; b: blue-yellow axis; C: chroma; hº: hue angle

Figura 3. Correlação fenotípica entre o estádio de maturação (MS), variáveis biométricas (FDE, FLD, SED, SLD, FW, FS e PY) e parâmetros colorimétricos (L*, a*, b*, C* e ho) dos frutos de *Euterpe edulis*. A diagonal superior representa a significância e os valores da correlação de Pearson, sendo: *significativo a 5%; **significativo a 1%; ***significativo a 0,1%. O gradiente de cor apresentado na diagonal superior reflete a magnitude e o sinal das correlações exibidas na diagonal inferior, que podem variar de -1 a 1. Nesse contexto, tonalidades mais escuras indicam correlações negativas, enquanto tonalidades mais claras representam correlações positivas. RS: estádio de maturação do fruto; FDE: diâmetro equatorial do fruto; FLD: diâmetro longitudinal do fruto; SED: diâmetro equatorial da semente; SLD: diâmetro longitudinal da semente; FW: peso fresco do fruto; SW: peso fresco da semente; PY: rendimento de polpa; L*: luminosidade; a*: eixo verde-vermelho; b*: eixo azul-amarelo, C*: cromaticidade; hº: ângulo de matiz

(FDE, FLD, SED, SLD, FW, SW, and PY) ranged from 0.10* (between PY and FDE) to 0.82*** (between SED and SW). A significant correlation of 0.68*** was also identified between FW and SW (Figure 3).

Pulp yield (PY) showed a progressive increase as the fruits advanced in maturation stages, with a significant difference between stages and a positive correlation of 0.61*** between RS and PY. The fresh weight of the fruits (FW) also increased at more advanced stages, as shown in Table 1.

Differences were observed between the maturation stages for the biometric variables FDE, FLD, SED, and SLD. The fresh seed weight (SW) showed a moderate negative correlation with pulp yield (PY), with r = −0.50***, indicating that fruits with lighter seeds had a higher pulp yield. In stage V, the fruits exhibited the lowest values of SW and seed volume (SV), which were associated with the highest pulp yield recorded (Table 1).

Regarding seed volume (SV), the lowest value was also observed in stage V. Although seed moisture content (M) did not differ statistically between stages, a slight reduction in moisture content was observed throughout maturation (Table 1).

The changes in fruit coloration during maturation, transitioning from green to black tones (Figure 1), were accompanied by variations in the colorimetric parameters. The variables L*, b*, and C* proved to be more effective in detecting these changes (Figure 3). Among them, L* allowed for distinguishing all maturation stages, showing higher values at earlier stages and lower values at more advanced stages, as the fruits darkened (Table 2).

The colorimetric indices b* and C* were effective in distinguishing between the fruit maturation classes. However, when the fruits reached black coloration, both indices failed to discriminate between stages IV and V. The colorimetric variables a* and hº showed lower efficiency in separating the maturation stages, with the a* index reaching its maximum value at stage III (Table 2).

The maturation of *E. edulis* fruits in the CIELab color space was primarily related to the variables L*, b*, and C*, as indicated by the separation of groups and the linear responses observed (Figure 4).

Among the multiple linear models presented in Table 3, model 7 achieved the

Table 1. Phenotypical means for the biometric characteristics of fruits and seeds in relation to the maturation stage of *Euterpe edulis* fruits
Tabela 1. Médias fenotípicas para as características biométricas de frutos e sementes em relação ao estádio de maturação dos frutos de *Euterpe edulis*

MS	FDE (mm)	FLD (mm)	SED (mm)	SLD(mm)	FW (g)	SW (g)	PY (%)	SV (cm^3)	M (%)
I	13.20b[1]	13.48b	12.49[a]	12.68a	1.55b	1.36a	12.35c	28.00a	45.555
II	13.05b	13.52b	12.40[a]	12.62a	1.51b	1.33a	11.98c	27.13ab	45.009
III	13.18b	13.54b	12.27[a]	12.18b	1.54b	1.23bc	19.78b	25.50ab	44.766
IV	13.58a	13.82a	12.43[a]	12.11b	1.66a	1.31ab	20.78b	27.13ab	44.136
V	13.14b	13.70ab	11.53b	11.77c	1.68a	1.19c	28.74a	23.75b	43.712

1Means followed by the same letter do not differ from each other at 5% of probability, by Tukey's test. Abbreviations: Maturation stages (MS) of *E. edulis*. I: fruits with entirely green coloration; Stage II: green fruits with purple spots; Stage III: entirely purple spots; Stage IV: entirely black fruits; Stage V: entirely black fruits with small cracks and easy pericarp removal; equatorial fruit diameter (FDE, mm); longitudinal fruit diameter (FLD, mm); equatorial seed diameter (SED, mm); longitudinal seed diameter (SLD, mm); fruit fresh weight (FW, g); seed fresh weight (SW, g); pulp yield (PY, %); volume of 25 seeds (SV, cm3), and seed moisture (M, %).
1Médias seguidas pela mesma letra não diferem entre si a 5% de probabilidade, pelo teste de Tukey. Abreviações: Estádios de maturação (MS) de *E. edulis*. I: frutos com coloração inteiramente verde; Estádio II: frutos verdes com manchas roxas; Estádio III: manchas inteiramente roxas; Estádio IV: frutos inteiramente pretos; Estádio V: frutos inteiramente pretos com pequenas rachaduras e fácil remoção do pericarpo; diâmetro equatorial do fruto (FDE, mm); diâmetro longitudinal do fruto (FLD, mm); diâmetro equatorial da semente (SED, mm); diâmetro longitudinal da semente (SLD, mm); peso fresco do fruto (FW, g); peso fresco da semente (SW, g); rendimento de polpa (PY, %); volume de 25 sementes (SV, cm3) e umidade da semente (M, %).

Table 2. Colorimetric indices in relation to the maturation stage of *Euterpe edulis* fruits
Tabela 2. Índices colorimétricos em relação ao estágio de maturação em frutos de *Euterpe edulis*

MS	L*	a*	b*	h°	C*
I	43.947a[1]	-4.030c	26.103a	98.839ab	26.469a
II	37.811b	1.130b	17.644b	81.006ab	18.721b
III	29.141c	7.644a	5.597c	35.707c	9.903c
IV	25.357d	1.610b	1.004d	101.855a	2.506d
V	24.077e	1.161b	0.721d	75.846b	1.784d

1Means followed by the same letter do not differ from each other at 5% of probability by Tukey's test. Abbreviations: MS: Maturation stages of fruits of *E. edulis*. I: fruits with an entirely green coloration; II: green fruits with purple spots; III: entirely purple fruits; IV: entirely black fruits; V: entirely black fruits with small cracks and easy pericarp removal; L*: total clarity; b*: coordinate of the blue-yellow axis; a*: coordinate of the red-green axis; C*: saturation or chroma and hº: hue angle.
1Médias seguidas pela mesma letra não diferem entre si a 5% de probabilidade pelo teste de Tukey. Abreviações: MS: Estádios de maturação dos frutos de *E. edulis*. I: frutos com coloração totalmente verde; II: frutos verdes com manchas roxas; III: frutos totalmente roxos; IV: frutos totalmente pretos; V: frutos totalmente pretos com pequenas rachaduras e fácil remoção do pericarpo; L: claridade total; b: coordenada do eixo azul-amarelo; a*: coordenada do eixo vermelho-verde; C*: saturação ou croma e hº: ângulo de matiz.

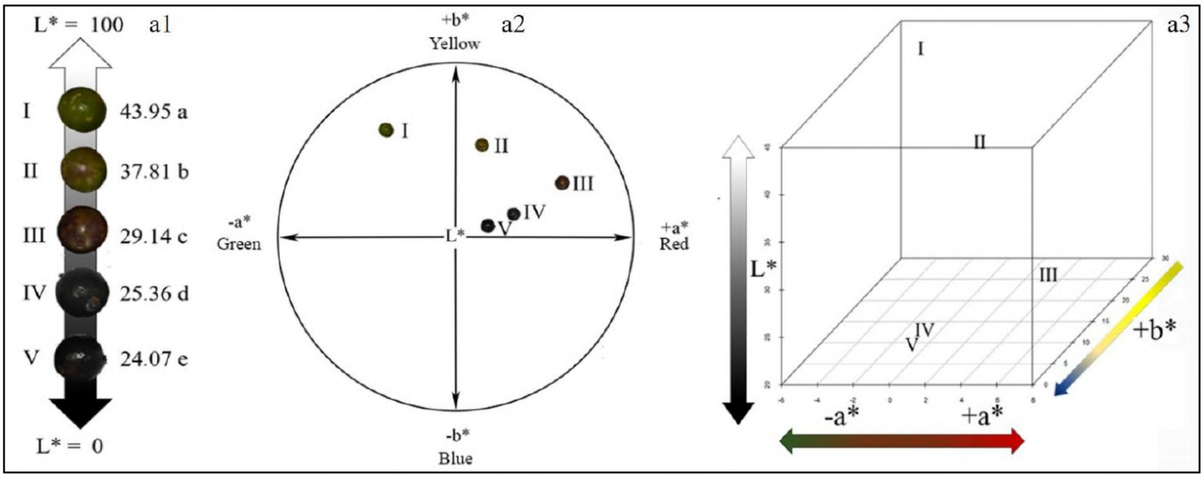

Figure 4. Average behavior of the maturation of fruits of *Euterpe edulis* in the color space of the CIELab system. 4.1a: Maturation stages and test of means in the luminosity axis; 4.1b: Behavior of the maturation stages in the xyz coordinates of the cartesian plane; 4.1c: Behavior of the maturation stage in the tridimensional space of the CIELab system. I: maturation stage I; II: maturation stage II; III: maturation stage III; IV: maturation stage IV, and V: maturation stage V
Figura 4. Comportamento médio da maturação de frutos de *Euterpe edulis* no espaço de cores do sistema CIELab. 4.1a: Estágios de maturação e teste de médias no eixo da luminosidade; 4.1b: Comportamento dos estádios de maturação nas coordenadas xyz do plano cartesiano; 4.1c: Comportamento do estádio de maturação no espaço tridimensional do sistema CIELab. I: estádio de maturação I; II: estádio de maturação II; III: estádio de maturação III; IV: estádio de maturação IV e V: estádio de maturação V

lowest AIC value (-695.72), indicating higher efficiency in estimating the maturation stage based on colorimetric indices.

Model 3 was selected as the most suitable based on both qualitative and quantitative methods, considering criteria such as the coefficient of determination (R^2), Akaike Information Criterion (AIC), Pearson's correlation coefficient (r), and structural simplicity. This model presented AIC values (-599.62), R^2 (0.8517), and r (0.9228), which were considered high and comparable to those of the other models tested, demonstrating good agreement between the estimated values and the observed data (Table 4).

Model 3 stood out due to its lower complexity, as it did not include interactions between variables, which favored its selection. The graphical analysis of the trend

Table 3. Predictive models of the fruit maturation stage for *Euterpe edulis*
Tabela 3. Modelos preditivos do estágio de maturação dos frutos para *Euterpe edulis*

Id.	Models		
1	Ŷ=4.5197-0.1296*C		
2	Ŷ=4.60549-0.16993*C+0.04041*b		
3	Ŷ=6.92129-0.14912*C+0.0938*b-0.09693*L		
4	Ŷ=8.02437-0.21665*C+0.03880*b-0.13931*L+0.00351*C*L		
5	Ŷ=8.87359-0.78205*C+0.58281*b-0.16953*L+0.02320*C*L–0.01890*b*L		
6	Ŷ=10.4950-0.8705*C+0.59602*b-0.23768*L+0.0273*C*L–0.01734*b*L-0.00456*C*b		
7	Ŷ=11.38-0.9045*C+0.3682*b-0.272*L+0.0293*C*L-0.01160*b*L+0.00528*C*b+0.00027*C*b*L		
Coefficients associated with the models			
Id.	**AIC**	**R^2**	**r**
1	-563.33	0.8392	0.9161
2	-570.43	0.8421	0.9180
3	-599.62	0.8517	0.9228
4	-642.51	0.8644	0.9292
5	-671.41	0.8725	0.9341
6	-681.96	0.8757	0.9357
7	-695.72	0.8796	0.9378

Abbreviations: Id.: model identification; L*: total clarity; b*: coordinate of the blue-yellow axis; C*: saturation or chroma; AIC: Akaike Information Criterion; R2: coefficient of determination of the model; r: Pearson correlation coefficient between the estimated values and the real values.
Abreviações: Id.: identificação do modelo; L*: claridade total; b*: coordenada do eixo azul-amarelo; C*: saturação ou croma; AIC: Critério de Informação de Akaike; R2: coeficiente de determinação do modelo; r: coeficiente de correlação de Pearson entre os valores estimados e os valores reais.

curve indicated a good overall correspondence between the estimated and observed values. However, the model showed lower efficiency in estimating maturation stage V (Figure 5).

The maturation stages of *E. edulis* were grouped into four classes based on the colorimetric parameters (Figure 6). Group II, which combined stages IV and V, showed low divergence in fruit coloration, limiting the differentiation between these stages using colorimetric variables. As a result, data from stages IV and V were consolidated, and a new model was developed to classify the fruits into stages I, II, III, and IV.

The new model, presented in Figure 7, demonstrated greater efficiency compared to Model 3, with a lower AIC value (-696.57)

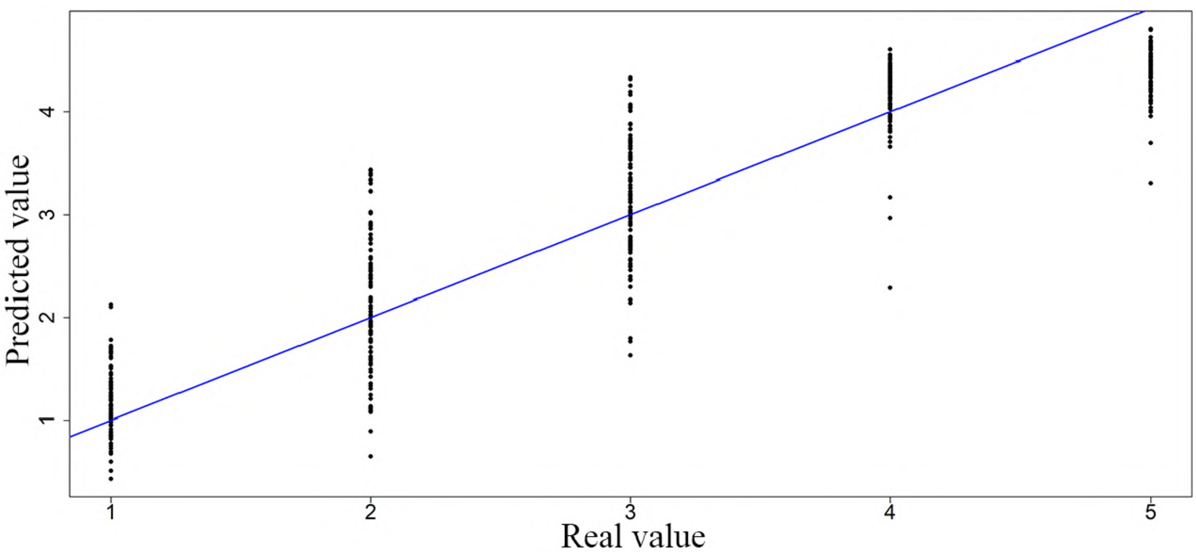

Figure 5. Trend curve of model 3 in relation to the estimated and real values
Figura 5. Curva de tendência do modelo 3 em relação aos valores estimados e reais

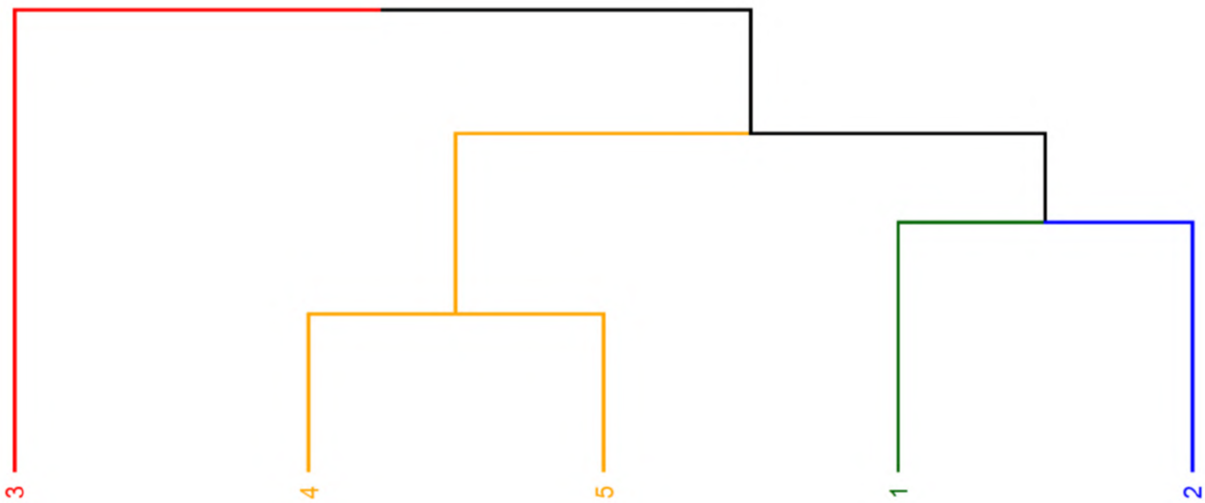

Figure 6. Representative dendrogram of the maturation degree among seeds of *E. edulis*
Figura 6. Dendrograma representativo do grau de maturação entre sementes de *E. edulis*

and higher R² (0.86) and r (0.93). This model utilized all the measured colorimetric variables and proved to be a robust estimator for classifying the maturation stages.

For classifying the estimated values, a scale based on the quartiles of the maturation classes was created, as shown in Table 4.

4. DISCUSSION

The morphophysiological changes in the colorimetric variables of the CIELab system demonstrate a high potential for determining the optimal harvest point for *E. edulis* fruits. The colorimetric characteristics are strongly associated with the ripening stage, highlighting the efficiency of these parameters in detecting color changes linearly throughout the ripening process. These findings are consistent with previous studies, such as those by Li et al. (2015), Lim & Eom (2018), and Williams & Benkeblia (2018), which also reported relationships between changes in fruits and seeds during ripening.

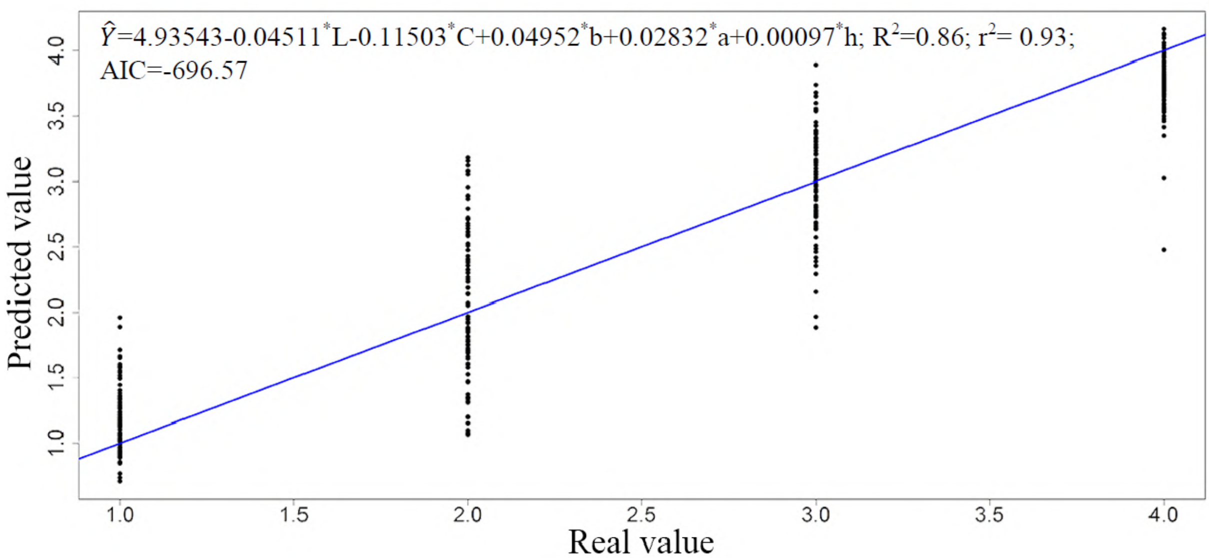

Figure 7. Trend curve of the new model in relation to the estimated and real values, for the four maturation classes determined
Figura 7. Curva de tendência do novo modelo em relação aos valores estimados e reais, para as quatro classes de maturação determinadas

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Table 4. Scale for the maturation classification of *Euterpe edulis* fruits
Tabela 4. Escala para classificação da maturação dos frutos de *Euterpe edulis*

Fruit maturation stages	Scale	Classficiation
I	0 to 1.51	Green fruits
II	1.52 to 2.62	Beginning of maturation
III	2.63 to 3.72	Nearly ripe
IV	> 3.73	Ripe fruits

Although the development of ripening indices is still in its early stages for various tropical fruits (Williams & Benkeblia, 2018), the use of coloration as a criterion is already well-established for species such as pomegranate (Manera et al., 2013), mango (Lalel et al., 2003), and tomato (Camelo and Gómez, 2004). The applicability of these techniques to *E. edulis* reinforces the potential of using colorimetric characteristics to optimize industrial processes and meet market demands for high-quality products.

The observed phenotypic correlation values were mostly lower than the genetic correlations reported in previous studies. Marçal et al. (2015) identified higher genetic correlations, such as 0.98 between fruit mass and fruit equatorial diameter, and 0.93 between seed mass and seed equatorial diameter, attributed to the elimination of environmental effects. Similarly, Oliveira et al. (2015) reported a correlation of 0.95 between the mass of 100 fruits and the mass of 100 seeds when controlling for environmental effects. These results highlight the influence of the environment on phenotypic associations and suggest that genetic analyses can complement fruit management and selection.

The progression of the ripening stage is directly associated with an increase in pulp yield, as evidenced by a positive correlation of 0.61***. This positive correlation between maturation and pulp yield is consistent with observations in other tropical fruits, where physiological maturation typically enhances pulp deposition (Vianna-Silva et al., 2008, Bonnet et al., 2013, Moreno et al., 2020, Vieira et al., 2024). Such a trend reinforces the importance of harvesting strategies that align with the biochemical maturity of the species, underscores the importance of management practices that prioritize harvesting at the optimal ripening point to maximize productivity and the economic value of the fruits. Furthermore, the data indicates the feasibility of integrating phenotypic and genetic analyses to enhance management and production strategies.

Although significant differences were observed among ripening stages for the variables FDE, FLD, SED, and SLD, the variations were minor. This pattern suggests that the increase in fruit size occurs predominantly during the developmental stages prior to ripening stage I, with physiological changes being more prominent in the subsequent stages.

The fruits analyzed at stage V were classified as small, with an average of 13.42 mm, falling within the class defined by Lin (1986) for fruits smaller than 13.5 mm. For the seeds, the average diameter observed in this study (11.65 mm) falls between the second and third size classes proposed by Martins et al. (2009), whose average values range from 10.31 mm to 13.49 mm, and above the average diameters of smaller seeds reported by Andrade et al. (1996), which range from 8.98 mm to 9.79 mm.

The average seed weight (1.19 g) was below the 1.51 g recorded by Andrade et al. (1996) for large fruits but above the average weight of 0.85 g for small fruits, highlighting the influence of genetic and environmental factors on the physical characteristics of fruits and seeds. As a monoecious species with cross-pollination (allogamy), *E. edulis* exhibits high genetic variability, contributing to the diversity of sizes observed among populations and studies (Martins et al., 2009).

The negative correlation between SW and PY (-0.50***) can be attributed to physiological and structural changes during fruit ripening, such as seed desiccation and greater incorporation of the endocarp (Chitarra & Chitarra, 2005). These changes are typical of fruits at advanced ripening stages, such as stage V, which exhibited the highest pulp yield.

The lowest SV values at ripening stage V (23.75 cm³) can be explained by the seed desiccation process that occurs during the full maturation of the fruits. This process is essential for preparing the fruit for detachment from the mother plant, as described by Firmino et al. (1996). The gradual reduction in seed moisture content, although not statistically significant, reflects physiological maturation and the transition to the final stage of development.

The observed colorimetric changes, with the reduction of L* as the fruits darken, highlight this variable as an effective indicator of the progress of ripening. The results confirm the practical applicability of the variables L*, b*, and C* to detect color changes and monitor the optimal harvest point, especially for fruits with a final black coloration.

The indices "b*" and "C*" proved to be useful tools for separating ripening classes in the early stages, but showed limitations in the final stages (IV and V), when the fruits acquire a black coloration. The "a*" index showed its highest value at stage III, which was expected, considering that this variable measures the variation on the green-red axis, and fruits at this stage are characterized by reddish tones. This characteristic confirms the sensitivity of "a*" to changes in tone associated with red pigments, but also reinforces its limitations in analyzing fruits at more advanced stages, where black tones predominate.

The lower efficiency of "a*" and "h°" in discriminating the different ripening stages reinforces the importance of prioritizing variables such as L*, b*, and C*, which proved to be more consistent in ripening analysis.

Although model 7 showed the lowest AIC value (-695.72), indicating a superior fit according to the Akaike Information Criterion (Manera et al., 2013), its performance in other selection criteria did not position it as the most suitable for practical application. This difference highlights the complexity in choosing the ideal model, a recurring issue in predictive analyses, as pointed out by Floriano et al. (2006). Considering multiple criteria is essential to balance simplicity, accuracy, and applicability.

The models presented in Table 3 are adapted to classify the ripening stage of the fruits, providing flexibility for use in different contexts. The application of these models helps in defining management and marketing strategies for *E. edulis* fruits, adjusting to the specific demands of each objective.

Model selection can be carried out using qualitative methods, which evaluate the interpretation and relationship of the model with the real process, and quantitative methods, which consider criteria such as fit, complexity, and generalization ability (Myung et al., 2003). The selection of model 3 was made using both methods, as recommended by Sit & Poulin-Costello (1994), considering the balance between simplicity, accuracy, and fitting capability.

Model 3 showed good AIC values (-599.62), R^2 (0.8517), and r (0.9228), comparable to the other models, but stood out for its lower complexity, as it did not include interactions between variables. This characteristic makes it easier to interpret and apply in practical analyses, aligning with the need for simple and efficient models for predictions in *E. edulis*.

Although the model showed good overall efficiency, the graphical analysis of the trend curve indicated limitations in estimating ripening class V. This difficulty can be attributed to the lower variability observed in the colorimetric parameters of this class, particularly in the L*, C*, and b* indices, which showed similar values. This limitation suggests the need for adjustments or the development of more specific models to capture variations in advanced ripening stage.

The formation of ripening groups based on colorimetric parameters reflects the behavior of these indices in relation to changes in the fruits during ripening. The merging of stages IV and V into group II is due to the low tonal divergence, as in these advanced stages, the color becomes more homogeneous, making it difficult for colorimeters to distinguish them, as they are more efficient at capturing chromatic variations in earlier stages. These results highlight the importance of integrating additional variables, such as chemical or structural characteristics, to improve

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discrimination between advanced ripening stages.

The grouping into four clusters, as shown in Figure 6, provides important insights for the practical classification of *E. edulis* fruits. and reinforces the applicability of colorimetric parameters for general discrimination, especially in the early and intermediate stages.

5. CONCLUSION

The ripening stage of *Euterpe edulis* fruits showed strong and consistent correlations with colorimetric indices, particularly L*, b*, and C*, which proved to be reliable predictors of maturation. Among the models tested, the selected multiple linear regression model demonstrated high accuracy ($R^2 = 0.85$; $r = 0.92$) and simplicity, making it suitable for practical application in fruit classification. This approach offers a reproducible and objective alternative to visual selection, contributing to improved harvest timing, quality control, and standardization in the processing of *E. edulis* fruits. Further refinement may be needed to enhance discrimination at late ripening stages, where chromatic variation is less pronounced.

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AUTHOR CONTRIBUTIONS

Canal, G. B.: Data curation, Formal analysis, Investigation, Writing – original draft; Alexandre R. S.: Supervision, Writing – review & editing; Silva Júnior, A. L da: Investigation, Writing – original draft; Guilhen, J. H. S.: Formal analysis; Caiafa, K. F.: Writing – review & editing, Visualization, Project administration; Ferreira, M. F. da S.: Investigation, Writing – original draft; Ferreira, A.: Supervision, Writing – review & editing.

DATA AVAILABILITY

The entire dataset supporting the findings of this study has been published within the article.

7. REFERENCES

Andrade, A. C. S., Venturi, S., & Paulilo, M. T. S. (1996). Efeito do tamanho das sementes de *Euterpe edulis* Mart. sobre a emergência e crescimento inicial. *Revista Brasileira de Sementes, 18*(2), 225–231. https://doi.org/10.17801/0101-3122/rbs.v18n2p225-231

Bonnet, C. B., Hubert, O., Mbeguie-A-Mbeguie, D., Pallet, D., Hiol, A., Reynes, M., & Poucheret, P. (2013). Effect of physiological harvest stages on the composition of bioactive compounds in Cavendish bananas. *Journal of Zhejiang University Science, 14*(4), 270–278. https://doi.org/10.1631/jzus.B1200177.

Brasil. (2009). Regras para análise de sementes. Ministério da Agricultura, Pecuária e Abastecimento, Secretaria de Defesa Agropecuária. Brasília: MAPA/ACS.

Breaux, Harold J. (1967). *On Stepwise Multiple Linear Regression.* Technical Report. Aberdeen: Army Ballistic Research Lab Aberdeen Proving Ground MD.

Camelo, A. F. L., & Gómez, P. A. (2004). Comparison of color indexes for tomato ripening. *Horticultura Brasileira, 22*(3), 534–537. https://doi.org/10.1590/S0102-05362004000300006

Chitarra, M. I. F., & Chitarra, A. B. (2005). *Pós-colheita de frutas e hortaliças: Fisiologia e manuseio.* Lavras: Universidade Federal de Lavras.

Desboulets, L. D. D. (2018). A review on variable selection in regression analysis. *Econometrics, 6*(4), 1–27. https://doi.org/10.3390/econometrics6040045.

Farias, J. F., Araújo Neto, S. E., Álvares, V. S., Ferraz, P. A., Furtado, D. T., & Souza, M. L. (2011). Maturação e determinação do ponto de colheita de frutos de envira–caju. *Revista Brasileira de Fruticultura, 33*(2), 730–736. https://doi.org/10.1590/S0100-29452011005000100.

Firmino, J. L., Santos, D. S. B., & Santos Filho, B. G. (1996). Características físicas e fisiológicas de sementes de cerejeira (*Torresia acreana* Ducke) quando as sementes foram coletadas do chão ou do interior dos frutos. *Revista Brasileira de Sementes, 18*(2), 28–32.

Floriano, E. P., Müller, I., Guimarães Finger, C. A., & Schneider, P. R. (2006). Ajuste e seleção de modelos tradicionais para série temporal de dados de altura de árvores. *Ciência Florestal, 16*(2), 177–199. https://doi.org/10.5902/198050981898

Lalel, H. J. D., Singh, Z., & Tan, S. C. (2003). Maturity stage at harvest affects fruit ripening, quality and biosynthesis of aroma volatile compounds in 'Kensington Pride' mango. *Journal of Horticultural Science & Biotechnology, 78*(2), 225–233. https://doi.org/10.1080/14620316.2003.11511610

Li, W. Q., Hu, Q. P., & Xu, J. G. (2015). Changes in physicochemical characteristics and free amino acids of hawthorn (Crataegus pinnatifida) fruits during maturation. *Food Chemistry, 175*, 50–56. https://doi.org/10.1016/j.foodchem.2014.11.125

Lim, Y. J., & Eom, S. H. (2018). Kiwifruit cultivar 'Halla gold' functional component changes during preharvest fruit maturation and postharvest storage. *Scientia Horticulturae, 234*, 134–139. https://doi.org/10.1016/j.scienta.2018.02.036

Lima, V. L. A. G., Mélo, E. A., & Guerra, N. B. (2007). Correlação entre o teor de antocianinas e caracterização cromática de polpas de diferentes genótipos de aceroleira. *Brazilian Journal of Food Technology, 10*(1), 51–55.

Lin, S. S. (1986). Efeito do tamanho e maturidade sobre a viabilidade, germinação e vigor do fruto de palmiteiro. *Revista Brasileira de Sementes, 8*(1), 57–66.

Mamede, M. E. O., Suzarth, M., Jesus, M. A. C. L., Cruz, J. F. M., & Oliveira, L. C. (2013). Avaliação sensorial e colorimétrica de néctar de uva. *Brazilian Journal of Food and Nutrition, 24*(1), 65–72.

Manera, F. J., Legua, P., Melgarejo, P., Brotons, J. M., Hernández, F., & Martínez, J. J. (2013). Determination of a colour index for fruit of pomegranate varietal group "Mollar de Elche". *Scientia Horticulturae, 150*, 360–364. https://doi.org/10.1016/j.scienta.2012.11.036

Marçal, T. S., Ferreira, A., Oliveira, W. B. S., Guilhen, J. H. S., & Ferreira, M. F. S. (2015). Correlações genéticas e análise de trilha para caracteres de fruto da palmeira juçara. *Revista Brasileira de Fruticultura, 37*(3), 692–698. https://doi.org/10.1590/0100-2945-163/14

Martins, M. P. C., Fialho, L. E. B., Zambiazi, D. C., & Konzen, E. R. (2009). Análise da diversidade genética de populações de palmiteiro (*Euterpe edulis* Martius) através de marcadores isoenzimáticos. *Revista Ceres, 56*(2), 204 – 212.

Moreno, J. L., Tran, T., Cantero-Tubilla, B., Lopez-Lopez, K., Becerra Lopez Lavalle, L. A., & Dufour, D. (2020). Physicochemical and physiological changes during the ripening of Banana (Musaceae) fruit grown in Colombia. *International Journal of Food Science and Technology, 56*(3), 1171-1183. https://doi.org/10.1111/ijfs.14851

Müller, A. E., Rother, D. C., Brancalion, P. S., Naves, R. P., Rodrigues, R. R., & Pizo, M. A. (2013). Can overharvesting of a non-timber forest product change the regeneration dynamics of a tropical rainforest? The case study of *Euterpe edulis*. *Forest Ecology and Management, 324,* 117–125. https://doi.org/10.1016/j.foreco.2013.09.001

Myung, I. J., Pitt, M. A., & Kim, W. (2003). *Model evaluation, testing and selection.* Columbus: Ohio State University, Department of Psychology.

Oliveira, M. S. P., Farias Neto, J. T., & Pena, R. S. (2007). *Açaí: Técnicas de cultivo e processamento.* Fortaleza: Instituto Frutal.

Oliveira, W. B. S., Ferreira, A., Guilhen, J. H. S., Marçal, T. S., Ferreira, M. F. S., & Senra, J. F. B. (2015). Análise de trilha e diversidade genética de *Euterpe edulis* Martius para caracteres vegetativos e de frutos. *Scientia Forestalis, 43*(106), 303–311.

R Core Team. (2017). R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria. https://www.R-project.org/

Schreckinger, M. E., Lotton, J., Lila, M. A., & de Mejia, E. G. (2010). Berries from South America: A comprehensive review on chemistry, health potential, and commercialization. *Journal of Medicinal Food, 13*(2), 233–246. https://doi.org/10.1089/jmf.2009.0233

Schulz, M., Borges, G. S. C., Gonzaga, L. V., Costa, A. C. O., & Fett, R. (2016). Juçara fruit (*Euterpe edulis* Mart.): Sustainable exploitation of a source of bioactive compounds. *Food Research International, 89*, 14–26. https://doi.org/10.1016/j.foodres.2016.07.027

Revista ÁRVORE
ISSN 1806 – 9088

Schwartz, E., Fachinello, J. C., Barbieri, R. L., & da Silva, J. B. (2010). Avaliação de populações de *Butia capitata* de Santa Vitória do Palmar. *Revista Brasileira de Fruticultura, 32*(3), 736–745. https://doi.org/10.1590/S0100-29452010005000089

Sit, V., & Poulin-Costello, M. (1994). *Catalog of curves for curve fitting* - Handbook 4. Victoria: Ministry of Forests, Forest Science Research Branch, Biometrics Information.

Sneath, P. H. A., & Sokal, R. R. (1973). Unweighted pair group method with arithmetic mean. In *Numerical Taxonomy*. San Francisco: W.H. Freeman and Company.

Vianna-Silva, T., Resende, E. D. D., Pereira, S. M. D. F., Viana, A. P., Rosa, R. C. C., Carlos, L. D. A., & Vitorazi, L. (2008). Influência dos estádios de maturação sobre as características físicas dos frutos de maracujá-amarelo. *Bragantia, 67*, 521-525. https://doi.org/10.1590/S0006-87052008000200029

Vieira, J. N., Silva, T. I., Costa, F. B., Macêdo, L. F., Nascimento, A. M., Sales, G. N. B., Souza, P. A., Santos, S. C. L., Ribeiro, W. S., & Candeia, R. A. (2024). Postharvest characterization of *Passiflora cincinnata* fruit pulp at different ripening stages. Agriculture, *Agribusiness and Biotechnology, 67*, e24230788. https://doi.org/10.1590/1678-4324-2024230788

Williams, R. S., & Benkeblia, N. (2018). Biochemical and physiological changes of star apple fruit (*Chrysophyllum cainito*) during different "on plant" maturation and ripening stages. *Scientia Horticulturae, 236*, 36–42. https://doi.org/10.1016/j.scienta.2018.03.007