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PREDICTING LYCOPENE AND *β*-CAROTENE CONTENT IN TOMATOES AND TOMATO PRODUCTS USING COLORIMETRIC PARAMETERS

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KEYWORDS

colorimetric parameters, non-destructive methods, carotenoids.

ABSTRACT

Image-based systems are designed to approximate human color perception, accounting for nonlinear nature of vision. Non-destructive methods predicting parameters traditionally obtained through destructive analysis enable larger sample sizes to be assessed with sufficient accuracy. This study developed a model to estimate lycopene and *β*-carotene levels in fresh and processed tomato varieties using non-destructive spectrophotometric parameters. Models showed strong agreement with observed values, yielding correlation coefficients of 0.71 for lycopene and 0.79 for *β*-carotene, with minimal associated error. These findings demonstrate that carotenoid levels can be reliably estimated through fruit color, reducing need for destructive analyses.

Practical Applications

Bioactive compounds in foods, particularly carotenoids in tomatoes, are associated with several health benefits, including enhanced antioxidant activity that prevents cellular damage, reduced risk of diseases such as cancer, immune system stimulation, and hormonal balance, owing to their antioxidant, antimicrobial, and anticarcinogenic properties. Understanding how these compounds behave during vegetable processing supports selection of suitable varieties for industrial use. Agro-industrial parameters that quantify carotenoids, combined with visual attributes such as color—one of the most critical traits for both consumers and processing industry—are essential to evaluate tomato varieties under thermal processing. Establishing reliable relationships between non-destructive and destructive parameters adds economic, environmental, and practical value. This approach reduces use of specialized reagents, standards, and sophisticated equipment, while minimizing reliance on highly trained labor. Moreover, it enables carotenoid quantification directly on classification lines, during production, or in the field, which is crucial for optimizing harvest, consumption, and processing.

INTRODUCTION

Among the main bioactive constituents of tomato fruits and processing by-products are carotenoids, predominantly lycopene ($C_{40}H_{56}$), followed by *β*-carotene and lutein. Because human body cannot synthesize these compounds, their absorption depends entirely on dietary sources (Szabo et al., 2022).

Lycopene is a highly potent antioxidant among carotenoids present in tomatoes. Its ability to neutralize free radicals underlies many of its health-promoting effects, including inhibition of several lifestyle-related diseases. Our study emphasizes lycopene's role as an antioxidant, preventing pathologies such as cardiovascular diseases, nervous system disorders, diabetes, liver diseases, and ulcerative colitis (Kulawik et al., 2023). Evidence suggests that consuming foods rich in lycopene reduces the risk of chronic diseases, including cancer, cardiovascular disorders, metabolic syndrome (Costa-Rodrigues et al., 2018), and dyslipidemia through regulation of blood lipid levels (Hsieh et al., 2022). Li et al. (2021), in a review of 174 studies, reported inverse associations between tomato intake and all-cause mortality, as well as mortality from coronary heart disease, cerebrovascular disease, prostate cancer, and gastric cancer. The widespread interest in tomato consumption is linked to its nutritional properties, supported by numerous studies demonstrating health benefits to humans (Monteiro et al., 2008). Overall, the literature indicates that lycopene supplementation holds

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strong potential for treating diseases associated with oxidative stress and chronic inflammation (Kulawik et al., 2023).

Lycopene and *β*-carotene concentrations in tomatoes vary widely depending on variety, color, ripeness, planting location, and climate. Processing conditions, particularly exposure time to high temperatures, can further influence bioavailability and digestibility (Wu et al., 2022).

In recent years, the advent of portable spectrometers has promoted the use of non-destructive devices to estimate food quality (*e.g.*, near-infrared, fluorescence meters, mid-infrared, and multispectral or hyperspectral imaging) (Betemps et al., 2012), along with reflectance and colorimetry stored in RGB, XYZ, CMYK, HEX, and CIELAB formats (Goisser et al., 2020). Non-destructive spectrophotometric methods for evaluating vegetables are advantageous because they allow larger sample sizes, multiple repetitions, and savings in raw materials, reagents, and time. Their association with quality parameters adds considerable economic and environmental value, as these methods reduce reagent consumption and enable quantification directly on grading lines or in the field—an essential feature for harvest management.

Accurately predicting changes in quality parameters for specific plant varieties remains a challenge. Based on L*, a*, and b* color values, several formulas and indices have been developed to identify the most appropriate predictors. For example, the a*/b* ratio has proven more effective than a* alone or the tomato color index (TCI = $2000a^*/L^*(a^{*2}+b^{*2})^{1/2}$) for distinguishing varieties (Gómez et al., 2001).

Given that lycopene and *β*-carotene levels can be estimated through non-destructive evaluation, we hypothesized that fruit color parameters could be modeled to predict carotenoid content. The aim of this study, therefore, was to establish associations between non-destructive colorimetric determinations—conducted with a portable colorimeter as predictor variables—and destructive analyses of lycopene and *β*-carotene levels in fresh and processed tomato fruits.

MATERIAL AND METHODS

Plant Material

The five tomato varieties used in this study were obtained from growers in the western region of São Paulo State, Brazil. The varieties included ‘Longa-vida,’ ‘Pizzadoro,’ ‘Grape,’ ‘Coquetel,’ and ‘Amarelo.’ Some are already established in terms of production and market acceptance, while others are still being evaluated by seed companies for these and related traits.

FIGURE 1. Tomato varieties: ‘Longa-vida,’ ‘Pizzadoro,’ ‘Grape,’ ‘Coquetel,’ and ‘Amarelo.’

Fruits were harvested at physiological maturity, identified by bright red or yellow external color. They were transported to the Laboratory of Biology and Chemistry at UNESP College of Science and Engineering in Tupã-SP, Brazil, for pre-selection. After selection, fruits were washed with running tap water, sanitized in a 200-ppm chlorine solution, and divided into four batches corresponding to the heat treatments and control: T0 – fresh fruits; T1 – tomato sauce; T2 – dehydrated tomatoes; and T3 – freeze-dried tomatoes. Analyses were performed in five replicates, each consisting of enough fruits to prepare the processed products, totaling approximately 2 kg per treatment, including fresh samples. Immediately after acquisition, the fruits were separated into batches, subjected to the respective processing, and analyzed as fresh controls.

Processing

Sauce production: To prepare tomato sauce, skins and seeds were removed, and the pulp was ground in a food processor. The pulp was then cooked in a stainless-steel pot with a lid to prevent loss. Cooking was performed at ~95 °C, monitored with a digital thermometer. The soluble solids content (°Brix) was measured with a Palette PR–32 ATAGO digital refractometer. Cooking continued until the sauce reached 10–12 °Brix (Monteiro, 2008).

Sun-dried tomatoes: For production of sun-dried tomatoes, fruits were weighed and cut in half lengthwise using stainless steel knives. Drying was conducted in a Tecnal TE-394/3 MP oven with air circulation and renewal. Fruits were then placed on nylon screens to ensure forced airflow circulation at 70 °C for four days, following a method adapted from Araújo (2014). The endpoint of the dehydration process was determined using the following equation:

$$Pf = (Pi \times [100 - Ui]) / (100 - Uf) \quad (1)$$

Wherein:

Pf - final net weight for the product to reach the desired moisture content;

Pi - initial weight, obtained by weighing;

Ui - initial moisture content (93% *wb*);

Uf - desired final moisture content (64% *wb*).

After dehydration, the dryer’s heating system was turned off, and the fan remained on until the product reached room temperature.

Freeze-dried tomatoes: For freeze-drying, fruits were frozen at –80 °C and processed in a LIOBRAS K105 freeze dryer. The system included a control panel, drying chamber, heating tray, vapor condensation chamber, compressor, vacuum system, heat exchanger, air dryer, and drain outlet.

Drying was performed at approximately 200 mmHg with a chamber temperature of –103 °C, for up to seven days.

Sample storage: Fresh and processed fruit samples were stored in 15 mL Falcon tubes and kept at –80 °C in a deep freezer until analysis.

Destructive Analysis – Predictor Variables

Instrumental Color: Color was determined using a Nix™ Pro color sensor (Nix Team, Ontario, Canada). Measurements of fresh fruit were taken at the central region. The device contains an internal LED light source that activates during measurement, capturing the reflected color and converting it into multiple color parameters through a proprietary model (Borges et al., 2022). The Nix Pro™ spectrophotometer was operated via the Nix Pro™ Color Sensor app on an Android smartphone through Bluetooth connectivity. Data were stored in the smartphone memory and downloaded at the end of each measurement session, both for fresh fruit and processed products.

Color values were recorded in RGB, XYZ, CMYK, HEX, and CIELAB formats, but only CIELAB was used in this study. In this system, L* represents brightness, a* indicates chromaticity from red (+a*) to green (–a*), and b* indicates chromaticity from yellow (+b*) to blue (–b*). From these, chroma (C*) and hue angle (H°) were calculated as:

$$C^* = ([a^*]^2 + [b^*]^2)^{1/2} \quad (2)$$

$$H^o = \tan^{-1}(b^*/a^*) \quad (3)$$

Where:

H° is measured in degrees from 0 to 360° (Itle et al., 2009).

The device was calibrated in the Lab* system using a standard white ceramic plate, and readings were taken at the fruit center. For processed products, samples were placed in nine-centimeter Petri dishes until filled, and surface color was measured.

To assess correlations between quantified lycopene levels and colorimetric variables, the following indices proposed by Clemente & Boiteux (2012) were calculated for both fresh and processed samples:

$$a^*/b^* \quad (4)$$

$$(a^*/b^*)^2 \quad (5)$$

$$TCI = 2000a^*/L^*(a^{*2}+b^{*2})^{1/2} \quad (6)$$

Wherein:

TCI - Tomato Color Index.

Destructive Analysis – Response Variables

Quantification of Lycopene and β-Carotene: Lycopene was extracted using an acetone:hexane (4:6) solution, and absorbance readings were taken at 663, 645, 505, and 453 nm by spectrophotometry. Lycopene and β-carotene contents were then calculated according to Nagata & Yamashita (1992) using the following equations:

$$\text{Lycopene (mg } 100g^{-1}) = -0.0458A_{663} + 0.204A_{645} - 0.0806A_{453} \quad (7)$$

$$\beta\text{-Carotene (mg } 100g^{-1}) = 0.216A_{663} - 1.22A_{645} - 0.304A_{505} + 0.452A_{453} \quad (8)$$

Experimental design and data analysis

The experiment followed a completely randomized design in a 5 × 4 factorial arrangement (five varieties × four preparation methods, including three thermal processes plus a control), with five replicates. Data were first tested for normality and homogeneity of variances, then subjected to analysis of variance (ANOVA) to evaluate treatment effects.

Univariate Analysis and Principal Component Analysis (PCA): Data analysis and determination of statistical significance for tomato varieties and processed products were conducted using Minitab software (version 18.1, Minitab Inc., Munich, Germany). One-way ANOVA followed by Tukey's test ($p = 0.05$) was applied, and Pearson's correlation coefficients were calculated. PCA was performed as an initial analysis to assess relationships between predictor and response variables. Based on this analysis, variables with the strongest potential associations were preselected to develop predictive models.

Linear Regression Analysis

Regression models were developed using predictor variables as inputs and response variables as outputs. Several models with multiple predictor variables were tested, with preference given to those not requiring additional calculations. Minitab software (version 18.1, Minitab Inc., Munich, Germany) was used for all analyses.

RESULTS AND DISCUSSION

Quantification of Lycopene and β-carotene

Due to their lipophilic nature, carotenoids such as lycopene and β-carotene are susceptible to degradation by light and temperature during processing. Thermal treatments often concentrate the product by reducing water content and increasing solids; however, they can also promote carotenoid degradation, as these compounds are thermolabile, highly reactive, and prone to isomerization and oxidation (Bemfeito et al., 2020). Figure 1 presents the contents of β-carotene (A) and lycopene (B) in the tomato varieties studied, both fresh and processed.

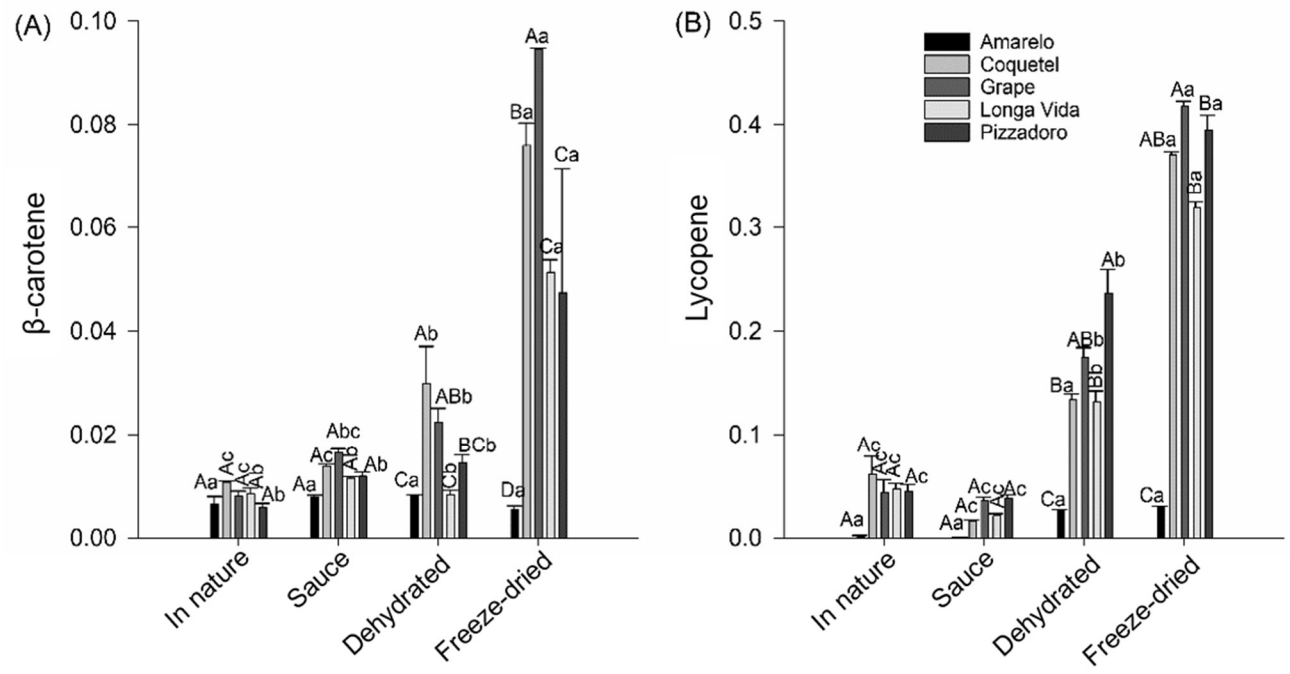

FIGURE 2. (A) and 2(B): *β*-Carotene and lycopene contents (mg 100 g^{-1}) in tomato fruits of the varieties 'Amarelo,' 'Coquetel,' 'Grape,' 'Longa Vida,' and 'Pizzadoro' subjected to different heat treatments: cooking (sauce), dehydration, and freeze-drying. Capital letters indicate differences among cultivars, and lowercase letters indicate differences among preparation methods, according to Tukey's test at $p < 0.005$.

The results showed that freeze-dried products contained higher levels of both carotenoids compared to dehydrated products and sauces. This outcome may be attributed to the low temperatures of freeze-drying, in which tomatoes are dried below the freezing point of water and moisture is removed by sublimation under controlled pressure. In this process, drying temperature plays a critical role in preserving the physical quality and stability of compounds. Freeze-drying proved suitable for several evaluated traits, with minimal impact on antioxidant activity, phenolic compound content, and color changes (Li et al., 2021).

Although thermal methods involving high temperatures, such as cooking, are more aggressive and lead to greater carotenoid degradation, they remain widely employed by the food industry to diversify tomato-derived products. Their continued use can be explained by the lower cost and greater accessibility of heat-based methods compared with more advanced, non-thermal technologies that minimize carotenoid degradation (Saini et al., 2015), as confirmed in this study, where fruits subjected to a lower freeze-drying temperature.

Like lycopene, *β*-carotene is prone to isomerization, oxidation, and degradation through cleavage reactions. During isomerization, the all-*trans* form converts to the *cis* form, which is more susceptible to oxidation and has lower biological activity (Li et al., 2021). Lycopene naturally occurs mainly in the *trans* isomers (Górecka et al., 2020), but in the human body it is predominantly found as *cis* isomers. Conversion between these forms occurs during storage, processing, and transportation of food products, as well as during metabolic processes in the human body (Imran et al., 2020). Heat treatments increase lycopene bioavailability by promoting its transformation from *trans* to *cis* isomers. Moreover, heating facilitates carotenoid release from the plant matrix, enhancing absorption in the human body (Doyle, 2020).

Dehydration is an ancient technique that, when properly applied, increases carotenoid concentration in the food matrix. However, processing and storing dehydrated products influence their nutritional characteristics, and carotenoid stability is primarily affected by isomerism, molecular conformation, and the surrounding matrix (Sevindik Baç et al., 2023). In this study, tomatoes subjected to dehydration showed an increase in *β*-carotene concentration.

A similar pattern was observed for lycopene. Reports in the literature on the effects of processing on lycopene concentration are often contradictory, with some suggesting that thermal treatments at milder temperatures increase lycopene levels in tomato products by enhancing its free and bioaccessible forms. Both temperature and heating duration strongly influence lycopene concentration. These inconsistencies may be explained by heat-induced isomerization of the all-*trans* form into the *cis* form, which is more susceptible to oxidation. Although isomerization does not alter total lycopene concentration, the *cis* form is more soluble in organic solvents, thereby improving extraction during quantification.

Despite the concentration of solids resulting from water evaporation, tomato sauce showed a reduction in lycopene, attributable to the high cooking temperature. In a study on different tomato varieties and processed products such as juice and ketchup in Korea, lycopene content ranged from 40.19 to 108.06 mg kg^{-1} (170% variation) in fresh fruits, from 116.59 to 254.98 mg kg^{-1} (118% variation) in ketchup, and from 9.90 to 54.21 mg kg^{-1} (445% variation) in juice (Park et al., 2020). These findings demonstrate that both varietal differences and processing methods directly affect carotenoid content.

Lycopene in tomato puree shows relatively high stability, with losses of about 20% (Hsieh et al., 2022). According to the same authors, unlike other bioactive compounds such as ascorbic acid, kaempferol, and quercetin, lycopene retains its integrity even after repeated sterilization and evaporation cycles. This stability may be linked to the presence of phenolic compounds and ascorbic acid in tomatoes, which inhibit lycopene isomerization and autooxidation, enhancing its resistance in the food matrix compared with isolated lycopene.

Colorimetry

Color changes in processed tomatoes result primarily from pigment degradation, non-enzymatic browning (Maillard reactions), and sugar hydrolysis. In this study, the L* parameter increased across all varieties after processing (Figure 3A), in contrast to the findings of Assad et al. (2024), who reported a 30% reduction in dehydrated tomatoes. Notably, freeze-drying led to increased luminosity.

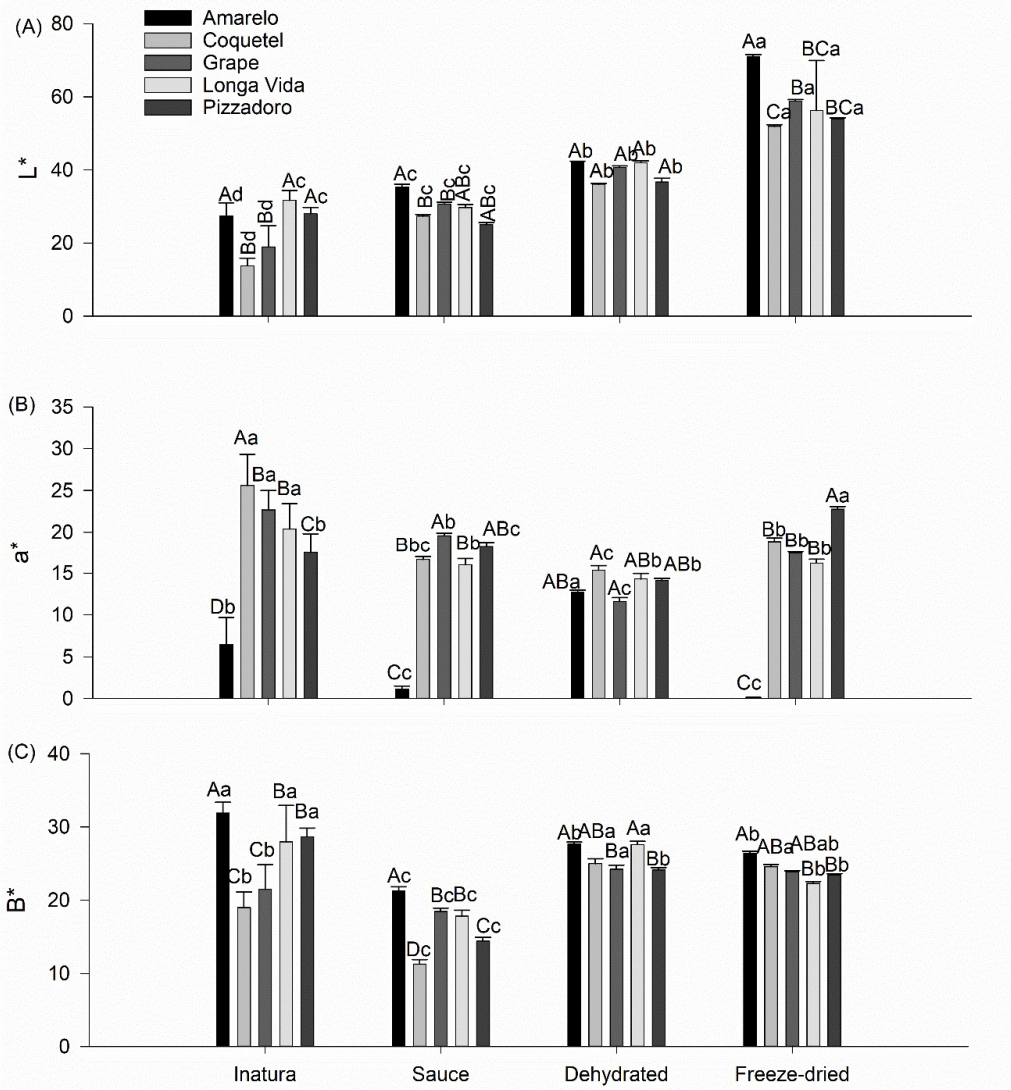

FIGURE 3. A, B, and C: Means and Tukey's test results (p = 0.05) for the colorimetric parameters L, a, and b* in tomato fruits of the varieties 'Amarelo,' 'Coquetel,' 'Grape,' 'Longa Vida,' and 'Pizzadoro' subjected to thermal treatments: cooking (sauce), dehydration, and freeze-drying. Uppercase letters indicate differences among cultivars, while lowercase letters indicate differences among preparation methods, according to Tukey's test at $p < 0.005$.

The decline in a* (Figure 3B) for processed products compared with fresh fruits was consistent with findings by Mayeaux et al. (2006), who reported a 27% decrease in a* for semi-dried tomatoes at 42 °C. In that study, tomato varieties showed an average 28% reduction in a* after semi-drying.

The color descriptor b* also decreased after the most severe heat treatment (cooking), while remaining stable in the other treatments for most varieties (Figure 3C). These results agree with Mayeaux et al. (2006), who observed a 41% reduction in b* for semi-dried tomatoes at 42 °C, and with Assad et al. (2024), who found reductions of up to 50% in certain varieties.

Figure 4 shows the hue angle (°Hue) and chroma (C*). °Hue remained stable for most varieties after processing (Figure 4A), whereas C* decreased, particularly in sauces (Figure 4B). In studies of ripening-related changes in tomato composition and color across different varieties, Shao et al. (2022) reported a significant decrease in °Hue, while C* changed little during ripening. Similar results were reported by Abdelhamid *et al.* (2020), who evaluated a non-destructive method for monitoring tomato ripening using chlorophyll fluorescence induction. However, data on the behavior of these colorimetric parameters under processing conditions remain limited.

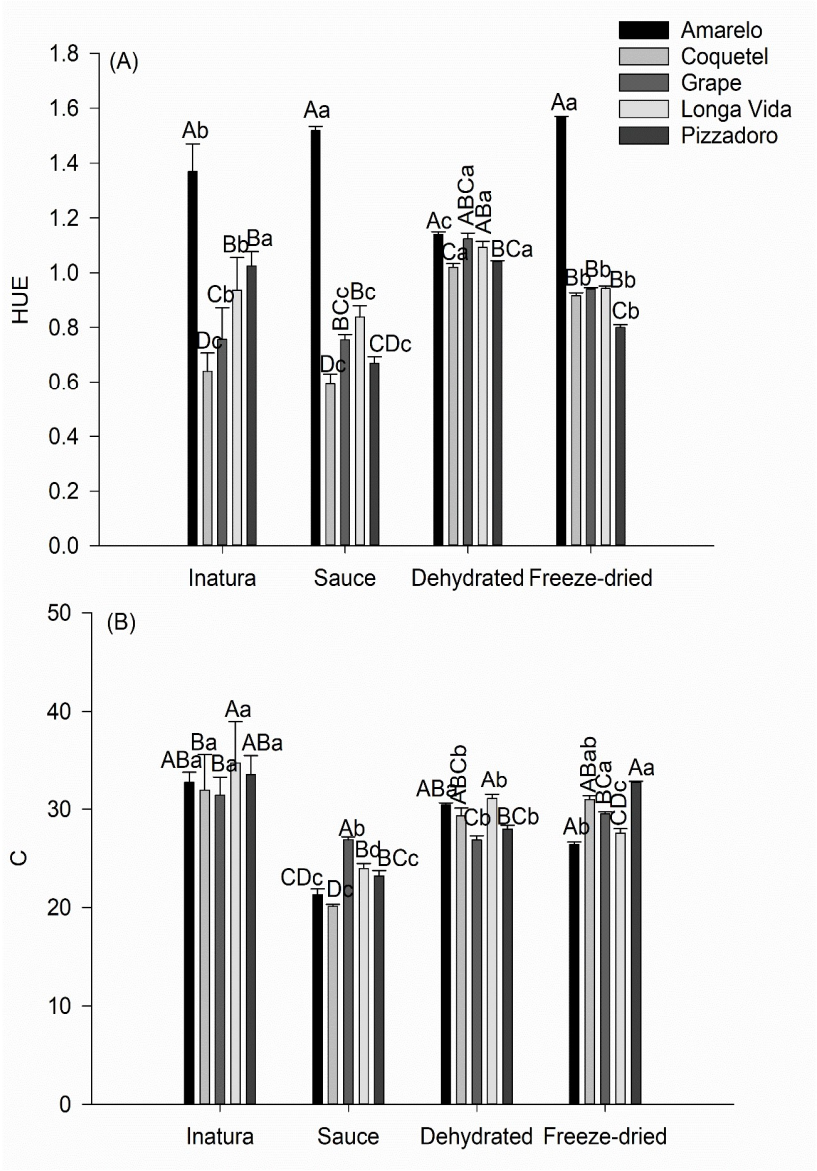

FIGURE 4. A and B: Means and Tukey's test results (p = 0.05) for hue angle (°Hue) and chroma (C*) in tomato fruits of the varieties 'Amarelo,' 'Coquetel,' 'Grape,' 'Longa Vida,' and 'Pizzadoro' subjected to thermal treatments: cooking (sauce), dehydration, and freeze-drying. Uppercase letters indicate differences among cultivars, while lowercase letters indicate differences among preparation methods by Tukey's test at $p < 0.05$.

Arias et al. (2000) highlighted that the relationship among color descriptors is often used as an indicator of tomato color quality, such as red brightness. These authors reported that the a*/b* ratio showed a strong linear correlation with tomato maturity stages (r = 0.95), while the $(a^*/b^*)^2$ ratio, also used as a ripeness index, had a slightly lower correlation (r = 0.92). In the present study, the a*/b* ratio increased after dehydration, consistent with findings by Mayeaux et al. (2006). Other ratios, however, decreased for most varieties compared with fresh fruits.

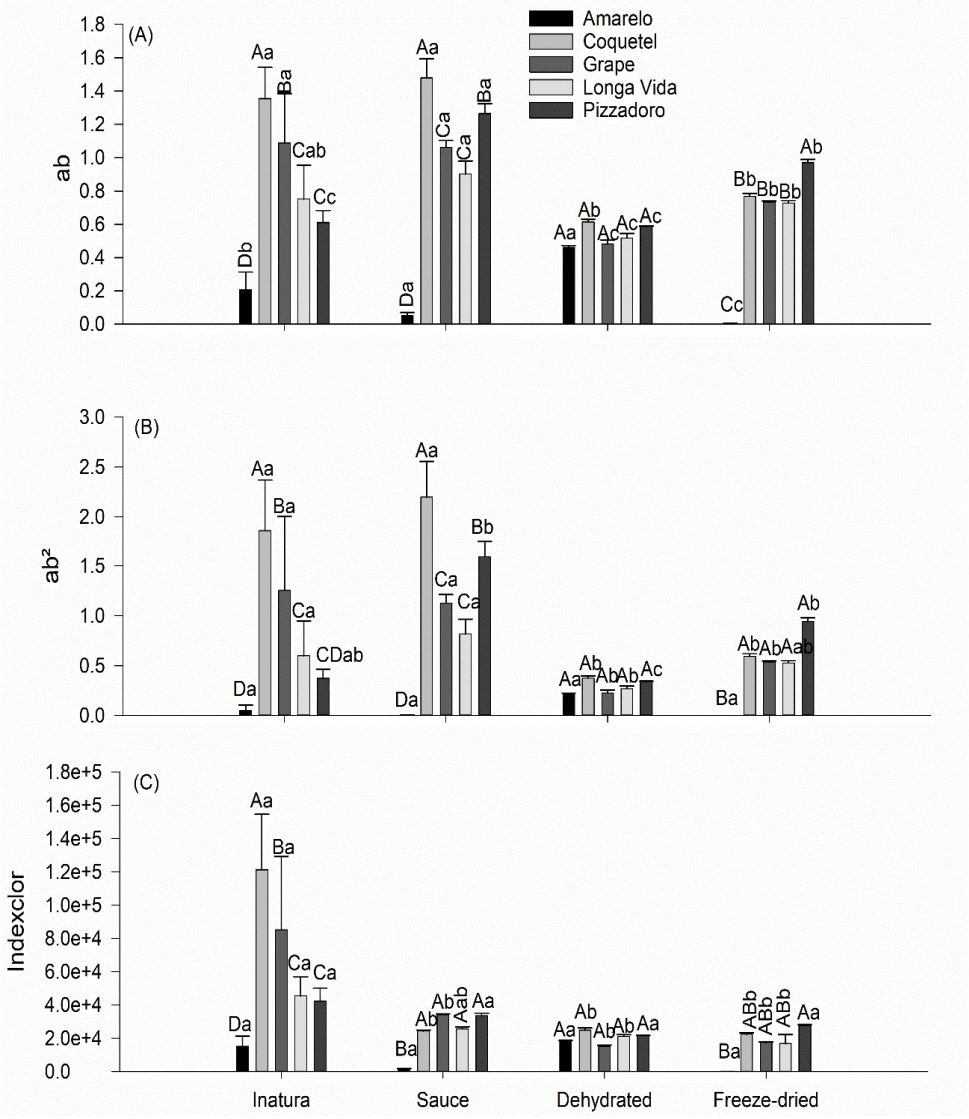

FIGURE 5. Color indices: (A) a/b, (B) $(a^*/b^*)^2$, and (C) Tomato Color Index (TCI). Uppercase letters indicate differences among cultivars, while lowercase letters indicate differences among preparation methods, according to Tukey's test at $p < 0.005$.

A Principal Component Analysis (PCA) model was constructed to examine associations between non-destructive variables (color parameters) and destructive variables (carotenoids) measured in fresh and processed tomato fruits. Figure 6 shows the projection of variables in the two-dimensional space defined by the first two principal components (PC1 and PC2), which together explained 63.83% of the total variance (PC1 = 24.09%; PC2 = 39.74%).

Carotenoids (lycopene and β-carotene) clustered near the PC1 axis, indicating that this component was strongly associated with destructive variables and represented the concentration gradient of these compounds across treatments. In contrast, the color parameters a*, a*/b*, and $(a^*/b^*)^2$ were located closer to PC2, suggesting that this component reflected variation in external fruit color.

The vectorial proximity and similar orientation of lycopene and β-carotene underscored their correlation, consistent with shared metabolic pathways and comparable behavior during thermal processing. The orthogonal or opposite placement of color parameters relative to carotenoids further highlighted the discriminative capacity of PCA, which separated two clusters of variables with complementary variation patterns.

Overall, PCA proved effective for visualizing interactions between chemical and physical attributes of tomato fruits, demonstrating the contribution of color parameters to carotenoid prediction. As an unsupervised method, PCA provided a realistic overview of natural correlations among variables without prior assumptions, helping to clarify processing-induced changes and supporting the use of non-destructive methods as a reliable analytical alternative.

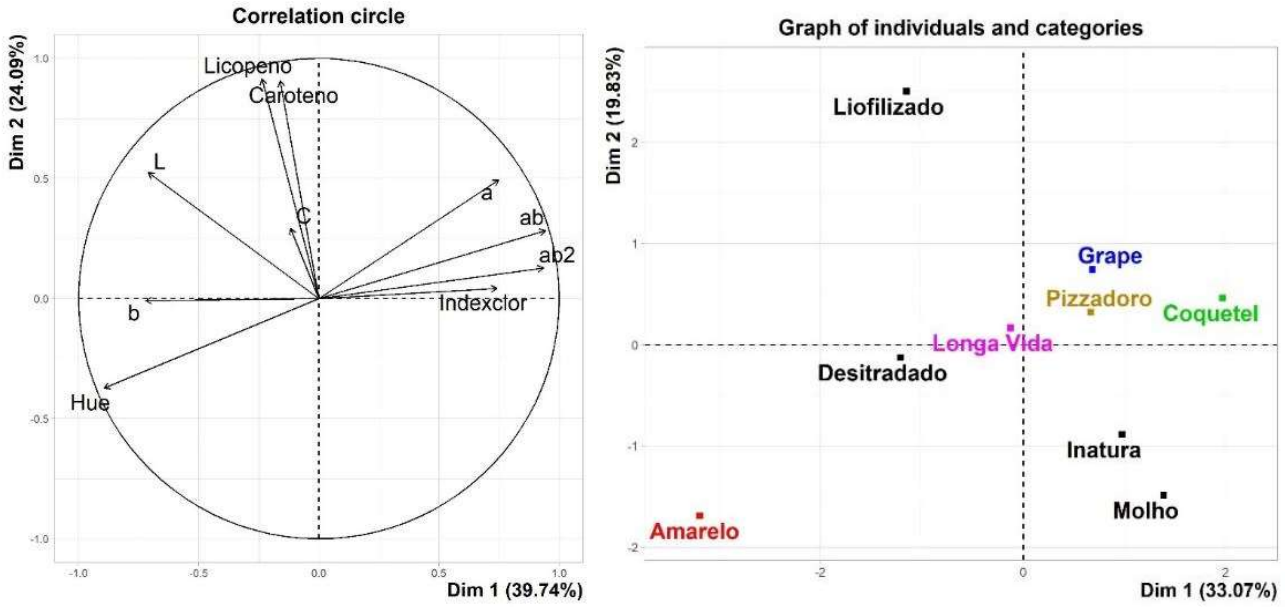

FIGURE 6. Principal Component Analysis (PCA) of non-destructive predictor variables (color parameters) and destructive response variables (carotenoids) in fresh and thermally processed tomato fruits.

Table 1 presents the regression models used to predict *β*-carotene and lycopene contents based on the color parameters L*, a*, b*, and C* as predictors. All parameters included in the models had $p < 0.05$, indicating statistically significant contributions to carotenoid prediction.

For lycopene, all variables (L*, a*, b*, and C*) had $p < 0.001$. The model yielded a correlation coefficient (R) of 0.790, demonstrating good explanatory power. Error statistics confirmed the robustness and accuracy of the model: mean absolute error (MAE = 0.012), mean square error (MSE = 0.0002), and mean absolute percentage error (MAPE = 1.17%). All variables were retained, as each contributed significantly to reducing model error.

For *β*-carotene, the model showed a slightly lower correlation coefficient (R = 0.710) but still satisfactory performance. All predictors were significant, with L* and a* showing $p < 0.001$ and relatively high coefficients (1.241 and 3.665, respectively), indicating stronger contributions to *β*-carotene variation. Variable C* had a borderline p value (0.024), but its inclusion improved overall model fit by reducing RMSE (0.082) and MAPE (17.66%), justifying its retention.

Overall, variable inclusion was statistically justified based on significance levels (p), correlation coefficients (R), and error indicators (RMSE, MAE, MSE, and MAPE). No arbitrary or subjective criteria were applied, and retention of all predictors strengthened the robustness of the developed regression equations.

TABLE 1. Regression equations for predictor (non-destructive) and response (destructive) variables in fresh and thermally processed tomatoes.

β-carotene = -26.812 + (1.241 * L) + (3.665 * a) + (2.870 * b) - (4.183 * C)			
Parameter	***p*-value**	**Fit**	**Value**
Constant	0.006	RMSE	0.082
L	<0.001	MAE	0.069
a	<0.001	MSE	0.006
b	0.004	MAPE	17.660
C	0.024	R	0.710
Model	P<0.005		
Lycopene = -0.210 + (0.00684 * L) + (0.0250 * a) + (0.0259 * b) - (0.0316 * C)			
Parameter	***p*-value**	**Fit**	**Value**
Constant	0.003	RMSE	0.0160
L	<0.001	MAE	0.0120
a	<0.001	MSE	0.0002
b	<0.001	MAPE	1.1700
C	<0.001	R	0.7900
Model	P<0.001		

Arias et al. (2000), investigating correlations between colorimetric parameters and lycopene content during tomato ripening, reported values ranging from 0.05 for L* in a linear regression equation to 0.96 for a* and the a*/b* ratio in exponential regression equations. For the linear regression of a*, they suggested that color changes correspond to the transition from green to red. Goisser et al. (2020), in a comparative study using different food scanners for non-destructive prediction of lycopene content in tomatoes, found R^2 values ranging from 0.00 for b* to 0.88 for the Tomato Color Index. In their study, non-destructive colorimetric parameters were applied individually to develop linear regression equations. Earlier, D'Souza et al. (1992), working with three cultivars across ripening stages from green to red, obtained R^2 values of 0.64–0.82 when using L* alone. Other studies that monitored ripening with linear regressions of L* reported lower performance, with R^2 ranging from 0.29 (Hyman et al., 2004) and 0.50 (Tilahun et al., 2018) to 0.67 (Carvalho et al., 2005).

CONCLUSIONS

Several studies have used colorimetric parameters to predict bioactive compounds in fruits. Most of these, however, have been restricted to isolated variable analyses and to monitoring fresh fruit ripening. Comprehensive studies considering the effects of thermal processing and integrating destructive with non-destructive parameters remain limited, though such approaches show promise for identifying varieties best suited to different processing methods and for optimizing non-destructive techniques in industrial and research applications.

In this study, regression equations achieved satisfactory fits between observed and predicted values (R^2 = 0.71 for β-carotene and R^2 = 0.79 for lycopene), demonstrating the feasibility of estimating carotenoid contents with good precision from spectrophotometric and colorimetric parameters. These results highlight the potential of non-destructive methods as practical alternatives to conventional quantification, which requires time, reagents, and sample destruction.

It should be noted, however, that the models are dependent on the experimental conditions adopted, including the tomato varieties and processing methods employed. Extrapolation to other cultivars, environmental conditions, or processing technologies will require further validation to ensure robustness and broad applicability. Our findings reinforce the relevance of models developed for estimating β-carotene and lycopene in tomatoes and tomato products and importance of non-destructive tools for quality assessment. Nonetheless, we only tested five tomato varieties; therefore, a wider range of cultivars should be validated and under industrial-scale conditions. Future work should aim to expand the models to incorporate additional quality parameters and to apply this approach to other food matrices, thereby enhancing its practical applicability.

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DATA AVAILABILITY STATEMENT

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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