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Influence of Anthocyanin Concentration on the Performance of Papaya Freshness Indicator

Indrawan Cahyo Adilaksono[1], Rijanti Rahaju Maulani[2,✉], Putri Safina Jasmine[2], Rika Alfianny[2], Laras Putri Wigati[3]

[1] Agricultural Engineering Study Program, School of Life Sciences and Technology, Bandung Institute of Technology, Sumedang, INDONESIA
[2] Postharvest Technology Study Program, School of Life Sciences and Technology, Bandung Institute of Technology, Sumedang,, INDONESIA
[3] Microbial Biotechnology Research Group, School of Life Sciences and Technology, Bandung Institute of Technology, Sumedang, INDONESIA

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Corresponding Author:
✉ rijanti@itb.ac.id
(Rijanti Rahaju Maulani)

ABSTRACT

Indonesia is one of the world's largest producers of papaya (Carica papaya L.); however, its consumption rate remains relatively low. Papaya is rich in vitamins, especially vitamin A, and is commonly processed into fresh-cut fruit to improve convenience. However, fresh-cut papaya is susceptible to quality deterioration due to tissue damage caused by minimal processing, resulting in a shorter shelf life. Smart packaging with freshness indicator labels can be used to monitor freshness changes in fresh-cut fruit during storage. In this study, anthocyanin extracted from purple sweet potato waste (Ipomoea batatas L.) was used as a natural pH-sensitive dye for freshness indicator labels. This study aimed to determine the effect of different anthocyanin concentrations (0.5%, 1.0%, 1.5%, 2.0%, and 2.5%) on the color change of freshness indicator labels during 7 days of fresh-cut papaya (Carica papaya L. var. Calina) storage at 4±2 °C. The results showed that anthocyanin concentration did not significantly affect the color change of the indicator labels during storage ($p > 0.05$). However, the label color response was more closely associated with freshness parameters, particularly CO_2 concentration in the packaging headspace and fruit firmness. These findings indicate that anthocyanin-based freshness indicator labels have potential for monitoring freshness changes in fresh-cut papaya, although their performance is influenced by the physicochemical changes occurring in the packaged fruit during cold storage.

1. INTRODUCTION

Indonesia has a relatively high papaya (*Carica papaya* L.) production volume. However, consumption levels are still low. In 2022-2023, papaya production increased from 1,089,578 tons to 1,238,692 tons. Conversely, the per capita per year consumption rate of papaya in Indonesia decreased by 1.92% during the 2022-2023 period (Kementerian Pertanian, 2023). The high production volume of papaya needs to be accompanied by an increase in per capita consumption per year in Indonesia. One effort to reach this goal is to process the fruit into ready-to-eat cut fruit (Tarancón *et al*., 2021).

Practicality and convenience have become some of the main goals of the food industry in recent years. Therefore, the industry has tried to achieve this by processing various food products. Fresh-cut fruit products undergo several processing steps, such as washing, cutting, packaging, and cooling, before reaching the consumer. Therefore, this process adds value through its practicality and convenience for consumers (Tarancón *et al*., 2021).

Among the various types of fresh-cut fruit on the market, papaya is among the most popular due to its high nutritional content (Rong *et al*., 2024a). Papaya is rich in vitamins (A, B1, B2, and C), essential minerals, and natural sugars, containing 85–90% water and providing 200 kJ per 100 g of energy (Prasad & Paul, 2021). However, fresh-cut fruits including papaya is susceptible to microbial attack and abiotic stress because processing disrupts the fruit's physiological functions. As a result, fresh-cut papaya spoils and deteriorates more quickly (Chen *et al*., 2025; Chen *et al*., 2023). Therefore, it is important to ensure the freshness and safety of fresh-cut papaya during storage (Rong *et al*., 2024a). Smart packaging offers a solution to this problem by enabling consumers to detect the freshness of fresh-cut papaya in the packaging during storage (Rong *et al*., 2023).

Smart packaging technology can be used to monitor the freshness of fresh-cut papaya through indicators that detect changes in freshness parameters during storage (Kumar *et al*., 2025; Zhang *et al*., 2025). Smart packaging indicators are generally attached to the packaging material and provide visual information regarding changes in the internal or external conditions of the packaged product (Rong *et al*., 2023). One type of smart packaging indicator is a colorimetric gel label that responds to gases produced by the fruit during storage. These gases can induce color changes in the label, thereby indicating changes in fruit freshness (Rong *et al*., 2024a).

There are two types of colorimetric gel labels commonly used for detecting fruit freshness: ethylene indicators and CO_2 indicators. Although both types can be applied, CO_2 indicators have several advantages for freshness monitoring, including higher sensitivity and more distinct color changes on the indicator label. CO_2 is also a major product of fruit respiration and microbial activity (Choi *et al*., 2023; Mills *et al*., 2023). When CO_2 dissolves in water, it forms carbonic acid and lowers the pH of the surrounding environment, allowing it to be detected by pH-sensitive indicators (Rong *et al*., 2024b).

CO_2-sensitive colorimetric gel labels are suitable for monitoring fresh-cut papaya because papaya produces a large amount of CO_2 during ripening stage (Rong *et al*., 2024b). A colorimetric gel label generally consists of a matrix and a pH-sensitive dye. Biopolymer-based matrices are commonly used because they are considered safer for food packaging applications (Rong *et al*., 2023). Meanwhile, the pH-sensitive dyes used in these labels can be either synthetic or natural (Rong *et al*., 2024b). However, synthetic dyes have raised safety-related concerns, encouraging the development of natural dye-based freshness indicators. Rong *et al*. (2024b) further developed a natural dye-based colorimetric label using alizarin for monitoring fresh-cut papaya freshness.

Natural dyes are generally considered safer and more acceptable to consumers (Rong *et al*., 2024b). In addition to alizarin, anthocyanin is another potential natural dye for freshness indicator labels because of its sensitivity to pH changes (Ge *et al*., 2026; Wu *et al*., 2026a). Anthocyanin extracted from purple sweet potato (Ipomoea batatas L.) is a promising natural pH-sensitive dye because of its high anthocyanin content. These water-soluble pigments possess a relatively stable acylated structure, high stability, and diverse biological activities, making them attractive for use as natural colorants in smart packaging systems (Choi et al., 2017; Sun et al., 2016). Previous studies have demonstrated the potential of colorimetric gel labels for monitoring the freshness of fresh-cut papaya. Rong *et al*. (2023) developed a CO_2-sensitive colorimetric label using bromothymol blue as a synthetic dye, while Rong *et al*. (2024a) further introduced a natural dye-based label using alizarin for non-destructive freshness monitoring of fresh-cut papaya. These studies confirmed that CO_2 accumulation in the package could be used as an indicator of freshness deterioration in fresh-cut papaya. However, the use of anthocyanin extracted from purple sweet potato waste as natural pH-sensitive dye for fresh-cut papaya freshness indicators has not been specifically evaluated, particularly in terms of how different anthocyanin concentrations affect label color response during storage.

Previous studies reported that anthocyanin concentrations may influence the sensitivity and physical characteristics of colorimetric indicators labels (Meng *et al*., 2026; Miao *et al*., 2026). Nevertheless, it remains unclear whether increasing anthocyanin concentration in the label matrix will result in significantly different color responses when the label is applied to an actual fresh-cut papaya packaging system. In addition, the freshness parameters that most strongly influence the performance of anthocyanin-based indicator labels in fresh-cut papaya packaging have not been clearly identified.

Therefore, this study aimed to determine the effect of different anthocyanin concentrations (0.5%, 1.0%, 1.5%, 2.0%, and 2.5%) on the color change of the freshness indicator labels during fresh-cut papaya storage at 4 ± 2 °C. This study also aimed to identify the freshness parameters that influence the performance of the anthocyanin-based indicator labels in fresh-cut papaya packaging.

2. MATERIALS AND METHODS

This study was conducted at the Biomass Production Systems Engineering Lab, Instructional Laboratories 1 and 2, and the Downstream Process Engineering Lab, Labtek IA SITH - ITB Jatinangor Campus, from August 2024 to May 2025.

2.1. Research Design

This research was conducted using a Completely Randomized Design (CRD) due to uniform environmental conditions. The treatments in this study consisted of five anthocyanin concentrations (0.5%, 1.0%, 1.5%, 2.0%, and 2.5%) with five replications (U1, U2, U3, U4, U5) per treatment. The anthocyanin concentration range was selected based on previous literature and practical considerations. Rong *et al.* (2024b) reported that 2% alizarin as a natural dye was effective for freshness monitoring of fresh-cut papaya. Therefore, this study used a narrower 0.5% interval to evaluate the effect of anthocyanin concentration around the previously reported effective range. The samples were stored in a showcase cooler at 4±2 °C for 7 days, with testing points conducted every 24 h from day 0 to day 7.

Several parameters were observed and measured for fresh-cut papaya, including: (a) pH, (b) color change, (c) Total Titratable Acidity (TTA), (d) Total Soluble Solid (TSS), (e) weight loss, (f) moisture content, (g) firmness, (h) hedonic quality, and (k) label color difference. In addition, CO_2 concentration in the packaging headspace was also measured.

2.2. Research Procedure

The researchers started by preparing the tools and materials. First, all equipment used in this study was sterilized. The freshness indicator labels were prepared by mixing 2.5 g of cornstarch with 1 g of soy protein isolate (SPI) in 100 mL of distilled water. The solution was then homogenized using a magnetic stirrer while being heated on a hotplate at 80 °C. Next, 1 mL of technical glycerol was added to the solution, followed by stirring and heating for 1 hour until the solution thickened. The anthocyanin solution used in this study was extracted from purple sweet potato waste (*Ipomoea batatas* L.) using the percolation method. Prior to its application in the freshness indicator label, the extract had been characterized with a total extract yield of 30.27%, total anthocyanin content of 5.39 mg/100 g, extract pH of 4.12, and hue angle of 356.41. After the solution was cooled to room temperature, the anthocyanin solution was added using a micropipette at concentrations of 0.5% (0.5 mL), 1.0% (1.0 mL), 1.5% (1.5 mL), 2.0% (2.0 mL), and 2.5% (2.5 mL). The solutions were then stirred with a magnetic stirrer for 5 minutes, and their pH was measured using a calibrated pH meter. The pH of each solution was adjusted to pH 7 using 1 N HCl and 1 N NaOH. The solutions were then sonicated using a sonicator (Branson, Branson Ultrasonics Corporation, USA) for 5 minutes to remove air bubbles. A total of 60 mL of each solution was poured into a 15 cm diameter Petri dish, and oven-dried for 12 hours at 50 °C. The dried labels were removed from Petri dishes and allowed to stand for 24 hours before use. The freshness indicator labels were cut into 3×1 cm pieces and stored in a dark room.

The next step was preparing the smart packaging for fresh-cut papaya. The fresh-cut papaya was packaged in transparent polypropylene (PP) thinwall containers with dimensions of 17.5×12.2×5.1 cm and a capacity of 650 mL. An access hole was made on each plastic container lid to allow CO_2 concentration measurement in the packaging headspace. The plastic containers were washed with soap and running water, then dried with tissue. The holes in the packaging lids were then covered with cloth tape. Each package was assigned a treatment code, replication number, and testing day.

Papayas (*Carica papaya* var. Calina) were selected based on a uniform ripeness level of 90%, similar size, and a harvest age of approximately six months after planting. The papayas were then washed with running water and dried with tissue. The papayas were cut in an air-conditioned room to minimize fruit damage. The papaya flesh was separated from the skin and seeds, cut into cubes, and temporarily stored in plastic containers. Then, 200±5 g of fruit was weighed for each package. The package lids were equipped with indicator label pieces according to treatment code. After that, the containers were sealed tightly and stored in a showcase cooler at 4±2 °C for 7 days. Storage in the POLYTRON showcase cooler was arranged based on replication groups, with the first replication group placed on the top shelf and the following replication groups placed on the lower shelves.

2.3. Data Collection Techniques

The researchers employed different data-collection techniques depending on the parameters measured.

2.3.1. CO_2 concentration (ppm)

CO_2 concentration in the packaging headspace was measured using a Go-Direct Vernier CO_2 gas meter. The method employed follows the approach of Rong *et al.* (2023), with slight modifications to enable device connection and to fully measure CO_2 in the packaging headspace. The sensor was inserted through the access hole prepared on the packaging lid. The measurement was conducted every 10 seconds for 60 seconds using the Vernier application, and the recorded values were used to determine the CO_2 concentration in ppm.

2.3.2. pH of fresh-cut papaya

The pH of fresh-cut papaya was measured using a calibrated pH meter (Mettler-Toledo International Inc., USA). A total of 100 g of fresh-cut papaya was crushed and filtered through cheesecloth. The filtrate was collected in a 15 mL Falcon tube and measured in duplicate for each sample.

2.3.3. Label color change

The color of the freshness indicator label was measured using a calibrated colorimeter (CS-10, CHNSpec Technology Co., Ltd., China). Each label was placed on white HVS paper before measurement. The measured values of parameters *a**, *b**, and *L** were averaged and then calculated using the following total color change formula (ΔE):

$$\Delta E = \sqrt{(L^*-L)^2 + (a^*-a)^2 + (b^*-b)^2} \quad (1)$$

where L is 92.61 (white plate standard), a is -0.50 (white plate standard), b is 5.60 (white plate standard), L^*, a^*, b^* are measurement results parameters with a colorimeter

2.3.4. Color change of fresh-cut papaya

The color change of fresh-cut papaya was measured using a calibrated CS-10 colorimeter directly on the surface of the same fresh-cut papaya sample at each testing point. Duplications were performed on each sample. Then, the parameters a^*, b^*, and L^* were averaged and calculated using the total color difference (ΔE) Equation 1.

2.3.5. Total titratable acidity of fresh-cut papaya

The Total Titratable Acidity (TTA) test for fresh-cut papaya was conducted by dissolving 5 g of slurry in distilled water in a 25 mL volumetric flask, then homogenizing it by shaking. The sample was then filtered through Whatman No. 1 filter paper in a funnel. Then, 10 mL of the filtrate was transferred to a 125 mL Erlenmeyer flask, and three drops of 1% phenolphthalein indicator were added. The solution was then homogenized by shaking. Next, the sample was titrated with 0.1 N NaOH solution standardized with 0.1 N oxalic acid solution. The titration was continued until the solution turned reddish-orange. Then, the amount of 0.1 N NaOH solution used to titrate the sample was used in the calculations. Duplications were performed for each sample. The titration results were calculated using the following Equation (2).

$$\text{TTA (\%)} = \frac{\text{Vol. NaOH} \times \text{N NaOH} \times \text{DF} \times \text{MWCA}}{\text{Sample weight} \times 1000} \times 100\% \quad (2)$$

where N NaOH is NaOH normality, DF is dilution factor, and MWCA is molecular weight of citric acid.

2.3.6. Total soluble solids of fresh-cut papaya

The Total Soluble Solids (TSS) of fresh-cut papaya were measured using an handheld refractometer (PAL-1, Atago Co., Ltd., Japan) and expressed as °Brix. The fresh-cut papaya sample was crushed with a mortar and pestle, then filtered through a cheesecloth. The filtrate was then measured with a calibrated refractometer, and the °Brix reading was recorded. Measurements were conducted in duplicate for each sample.

2.3.7. Weight loss of fresh-cut papaya

The weight loss of the fresh-cut papaya samples was measured at each testing point using an Ohaus digital scale. The initial weight before storage (W_i) was recorded. The second weight was measured the day after storage (W_f). Duplicate tests were performed on each sample. The data obtained was then calculated using the following Equation 3:

$$\Delta W(\%) = \frac{W_i - W_f}{W_i} \times 100\% \quad (3)$$

2.3.8. Moisture content of fresh-cut papaya

Moisture content of fresh-cut papaya was determined using the air-oven drying method and expressed as a percentage (%). An empty porcelain dish was oven-dried until a constant weight was obtained and recorded as W_0. Then, 5 g of fresh-cut papaya sample was placed in the porcelain dish and weighed as W_1. The sample was dried in a B-One oven at 105 °C for 6 h, placed in a desiccator for 15 minutes, and weighed until a constant weight was obtained as W_2. Measurements were conducted in duplicate for each sample. Moisture content was calculated using Equation 4:

$$\text{Moisture content } (\%) = [(\frac{W_1 - W_2}{W_1 - W_0})] \times 100\% \quad (4)$$

2.3.9. Firmness of fresh-cut papaya

Fruit firmness was measured in duplicate for each sample using a DFAS 15 fruit sclerometer. The probe was inserted into the flesh of the fresh-cut papaya, and the firmness value was recorded.

2.3.10. Hedonic quality of fresh-cut papaya

The organoleptic testing was conducted using the hedonic quality technique, which measured several parameters, included aroma, color, texture, and overall acceptability of fresh-cut papaya on storage days 5 to 7. This test included 15 semi-trained panelists. They were asked to perform a sensory evaluation of the fresh-cut papaya samples using the hedonic quality rating scale described in Table 1.

Table 1. Hedonic quality score and description of fresh-cut papaya

Parameter	Score and Description				
	1	2	3	4	5
Color	Brownish	Dull orange color	Pale orange color	Bright orange color, but slightly faded	Very bright orange color
Aroma	Bad	Less fresh	Quite fresh	Fragrant and fresh	Very fragrant and very
Firmness	Very soft, easily crumbles when touched	Very soft, but does not crumble immediately	Soft	Quite soft	Hard
Acceptance	Very dislike	Dislike	Neutral	Like	Very like

2.3.11. Label color difference

The color difference of the freshness indicator labels was evaluated using a paired-comparison test by 15 semi-trained panelists. The day-0 label was used as the reference, and the labels from storage days 5 to 7 were compared with the reference label. The criteria used in the paired-comparison test of the freshness indicator labels are 0 (the color is not different) and 1 (the color is different).

2.3.12. Data analysis techniques

All data were statistically analyzed using One-Way ANOVA and multiple linear regression at a 95% confidence level. The software used was IBM SPSS Statistics 16.0.

3. RESULTS AND DISCUSSION

3.1. Effect of Anthocyanin Concentration on the Color Change of Indicator Label

The effect of anthocyanin concentration on the color change of the freshness indicator labels was analyzed using one-way ANOVA. In this analysis, label color change (ΔE) was used as the dependent variable, while anthocyanin concentration was used as the independent variable. The analysis was performed separately for each storage day from day 0 to day 7. The complete statistical outputs, including F-values, p-values, and eta-squared (η^2) effect sizes, are presented in Table 3. The results showed that anthocyanin concentration did not significantly affect the color change of the freshness indicator labels during fresh-cut papaya storage ($p > 0.05$).

Based on Table 2, no significant differences were observed among anthocyanin concentration treatments during storage. On day 0, the *F*-value, *p*-value, and effect size were not applicable because all treatments had an initial color change value of zero. Although the η^2 values varied among storage days, the *p*-values were greater than 0.05, indicating that increasing anthocyanin concentration from 0.5% to 2.5% did not produce statistically different label color responses under fresh-cut papaya packaging conditions.

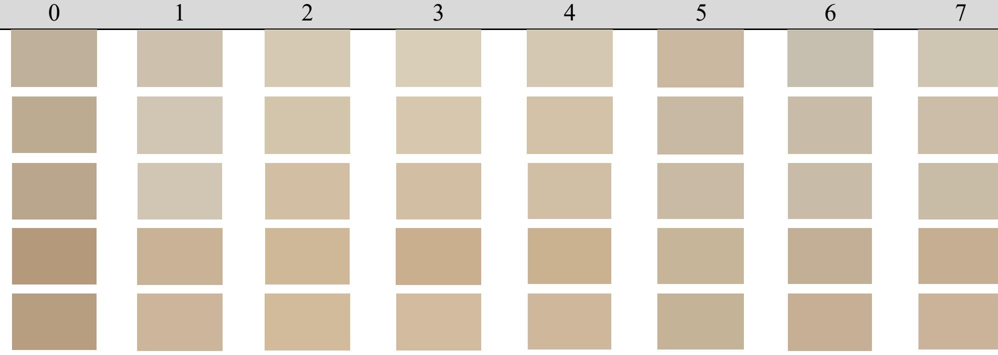
Table 2. One-Way ANOVA results for the effect of anthocyanin concentration on indicator label color change during storage

Storage day	SS between groups	SS within groups	df between	df within	*F*-value	*p*-value	η^2
Day 0	0.000	0.000	4	20	N/A	N/A	N/A
Day 1	44.388	170.617	4	20	1.301	0.303	0.206
Day 2	15.113	56.376	4	20	1.340	0.290	0.211
Day 3	28.758	92.091	4	20	1.561	0.231	0.238
Day 4	6.053	91.271	4	20	0.332	0.853	0.062
Day 5	77.338	287.136	4	20	1.347	0.287	0.212
Day 6	26.596	219.110	4	20	0.607	0.662	0.108
Day 7	11.064	144.379	4	20	0.383	0.818	0.071

Note: η^2 = (SS between groups)/(SS total). N/A = no available value because all label color change values on day 0 were zero.

Table 3. Visual color changes of anthocyanin-based freshness indicator labels during 7 days of fresh-cut papaya storage at 4 ± 2 °C

Anthocyanin concentration in the freshness indicator label	Storage period (days) 0	1	2	3	4	5	6	7
0.5%								
1.0%								
1.5%								
2.0%								
2.5%								



As shown in Table 3, the indicator labels exhibited measurable color changes during storage, with *ΔE* values exceeding the visual perceptibility threshold of 2. However, the color differences among the different anthocyanin concentration treatments were not clearly distinguishable by visual observation.

A paired-comparison test was conducted on the indicator labels from each treatment on storage days 5 to 7 to evaluate whether the label color change could be visually distinguished from the initial condition. In this test, the label on day 0 was used as the reference label. Based on the evaluation by 15 semi-trained panelists at a 95% confidence level, the labels from the 1.0%, 1.5%, and 2.5% anthocyanin treatments showed a perceptible color difference from the reference label on day 5. On day 6, no treatment showed a perceptible color difference from the reference label. Meanwhile, on day 7, only the 1.5% anthocyanin treatment showed a perceptible color difference from the reference label.

The difficulty in visually distinguishing the label color among treatments may be associated with the anthocyanins in the indicator label dissolving along with the water molecules produced from the respiration and transpiration processes of the fresh-cut papaya. The cold storage temperature also contributes to increased accumulation of water molecules on the low-permeability packaging lid's surface, leading to condensation. While the internal water content of the fruit decreases or remains stable, moisture can sometimes escape the fruit tissues and accumulate as liquid condensation inside the package due to temperature shifts (Mahajan *et al*., 2016). Therefore, the water molecules in the packaging have wetted the label surface, leading to the dissolution of anthocyanin compounds from the label matrix, reducing the clarity of color differences among treatments. Anthocyanin compounds, which are hydrophilic toward water, are readily released from the label matrix when the matrix is less hydrophobic. According to Koosha *et al.,* 2019 and Huang *et al.,* 2025 anthocyanins possess hydroxyl groups that form attractive interactions with water molecules via hydrogen bonds, thereby affecting the mechanical properties of the label. Additionally, the higher the concentration of anthocyanins added to the matrix, the lower the matrix elasticity and the weaker the binding of the anthocyanin compounds to the matrix polymer.

3.2. Effect of Fruit Freshness on the Performance of Freshness Indicator Labels

The results showed that the freshness of fresh-cut papaya decreased during 7 days of low-temperature storage at 4 ± 2 °C, as indicated by changes in the measured freshness parameters, including CO_2 concentration in the packaging headspace, pH, moisture content, weight loss, firmness, Total Titratable Acidity (TTA), Total Soluble Solids (TSS), fruit color change, and sensory evaluation. Changes in the physicochemical freshness parameters, excluding sensory evaluation, are presented in Figure 1. The CO_2 concentration in the packaging headspace increased sharply on the first day of storage and then remained relatively stable. Several parameters, such as pH, Total Titratable Acidity (TTA), and Total Soluble Solids (TSS), showed relatively stable trends with only slight changes during storage. In contrast, fruit firmness decreased as weight loss increased. Fruit color change also increased during storage, indicating a gradual difference from the initial fruit color.

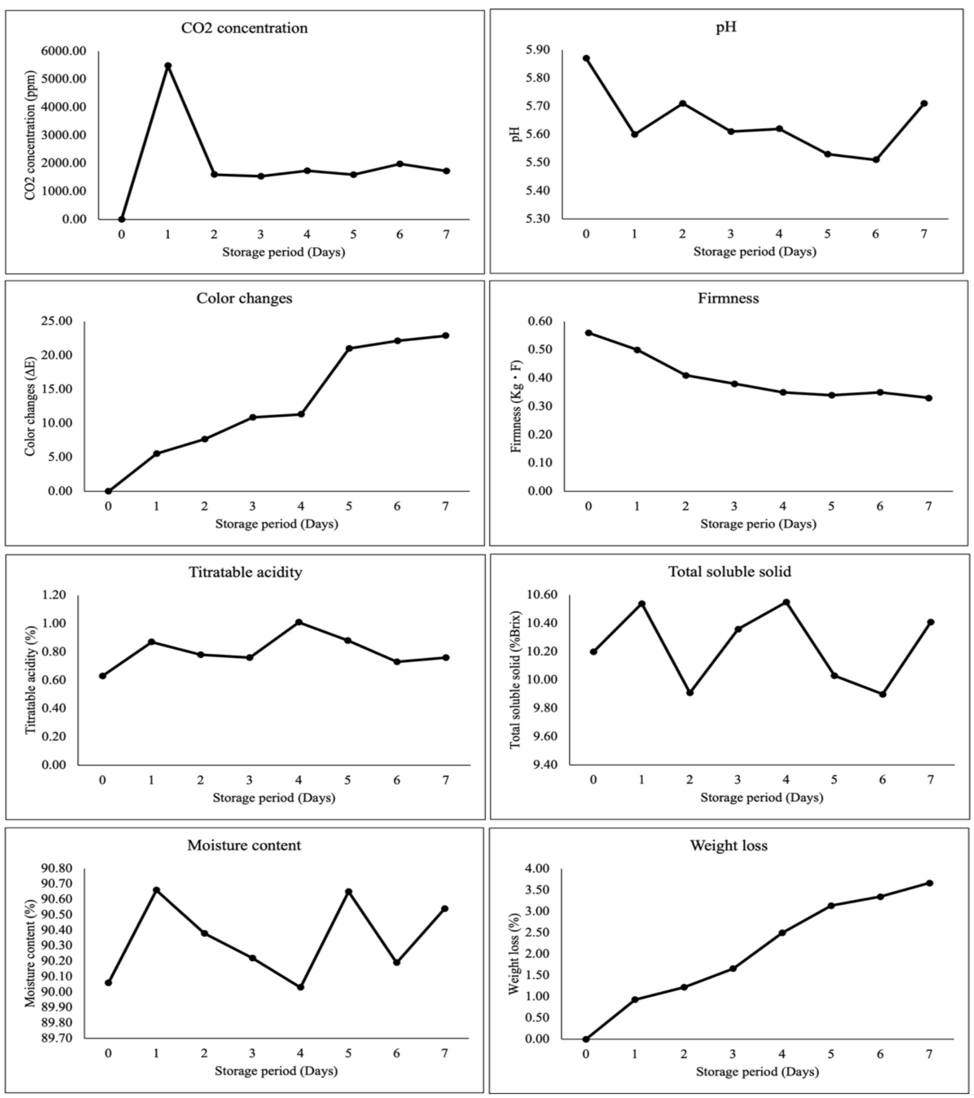


Figure 1. Changes in physicochemical freshness parameters of fresh-cut papaya during 7 days of storage at 4±2 °C: CO_2 concentration, pH, moisture content, weight loss, firmness, Total Titratable Acidity (TTA), Total Soluble Solids (TSS), and fruit color change

The effect of freshness parameter changes on the performance of the freshness indicator label was evaluated using multiple linear regression analysis. In this model, the color change of the indicator label (*ΔE*) was used as the dependent variable, while storage period, anthocyanin concentration, CO_2 concentration in the packaging headspace, fruit pH, weight loss, moisture content, fruit firmness, TTA, TSS, and fruit color change were used as independent variables.

The multiple linear regression model showed a strong relationship between the dependent variable and the predictors, with a correlation coefficient of R = 0.880. The model had an R^2 value of 0.775, indicating that 77.5% of the variation in label color change could be explained by the predictors included in the model. After adjustment for the number of predictors, the adjusted R^2 value was 0.697, indicating that approximately 69.7% of the variation in label color change could still be explained by the model. The standard error of the estimate was 1.857, indicating the average prediction error of the model in ΔE units.

Based on ANOVA results, the multiple linear regression model was statistically significant, as indicated by $F = 9.978$ and $p = 0.000$. This result indicates that the predictors included in the model collectively explained the variation in indicator label color change. Therefore, at least one independent variable significantly contributed to the prediction of label color change. The regression coefficient results showed that three predictors significantly influenced the color change of the indicator label, namely storage period, fruit firmness, and CO_2 concentration in the packaging headspace. These predictors had p-values below 0.05 and were therefore considered significant in the regression model. The significant regression coefficients are presented in Table 4.

Table 4. Significant regression coefficients for indicator label color change

Model	Unstandardized Coefficients		Sig.
	B	Std. Error	
Storage period	-0.796	0.363	0.036
Fruit firmness	-43.733	9.629	0.000
CO_2 concentration in the packaging headspace	0.001	0.000	0.000

Notes: Only independent variables (predictors) with $p < 0.05$ are presented; dependent variable is color change (ΔE) of indicator label.

3.2.1. Interpretation of Significant Regression Coefficients

The regression coefficients were interpreted based on the direction and significance of the unstandardized coefficient (B) for each significant predictor. Storage period and fruit firmness showed negative coefficients, whereas CO_2 concentration in the packaging headspace showed a positive coefficient. Since multiple linear regression evaluates each predictor while accounting for the other variables included in the model, the negative coefficient of storage period (B = -0.796) should be interpreted as a partial effect and does not necessarily represent the simple visual trend of label color change over storage time.

The negative coefficient of storage period indicates that after the effects of other freshness parameters were considered, storage period had a negative partial association with indicator label color change. This may be related to the early response of the label to rapid CO_2 accumulation at the beginning of storage, followed by reduced clarity of color changes at later storage stages due to moisture accumulation and condensation on the packaging lid. Condensation may moisten the label surface and promote anthocyanin migration from the matrix, thereby reducing the visual distinction of label color changes over time. The negative coefficient of fruit firmness indicates that lower firmness, which reflects fruit softening during storage, was associated with greater indicator label color change. Meanwhile, the positive coefficient of CO_2 concentration indicates that CO_2 accumulation in the packaging headspace was associated with the color response of the anthocyanin-based freshness indicator label.

In this study, fresh-cut papaya was stored for 7 days under cold storage conditions at 4±2 °C. During storage, fresh-cut fruit continues to undergo physiological processes, such as respiration and transpiration, as long as substrates and energy remain available. These processes contribute to fruit deterioration, although cold storage can slow down the rates of respiration and transpiration rather than completely stop them (Gardjito & Swasti, 2014; Yang *et al.,* 2025; Wu *et al.,* 2026b). Adiletta *et al.,* (2020) reported that physiological processes continue in fresh-cut papaya during cold storage. As storage time increased, the freshness of fresh-cut papaya gradually decreased, leading to physical and chemical changes. However, because low-temperature storage slows the deterioration process, the changes in freshness parameters may occur more gradually. In addition, moisture accumulation and condensation inside the package may affect the clarity of the label color response by wetting the label surface and promoting anthocyanin migration from the matrix. Therefore, the color response of the freshness indicator label became less pronounced during cold storage. Figure 2 shows a decreasing trend in the color change of the indicator labels as storage time increased.

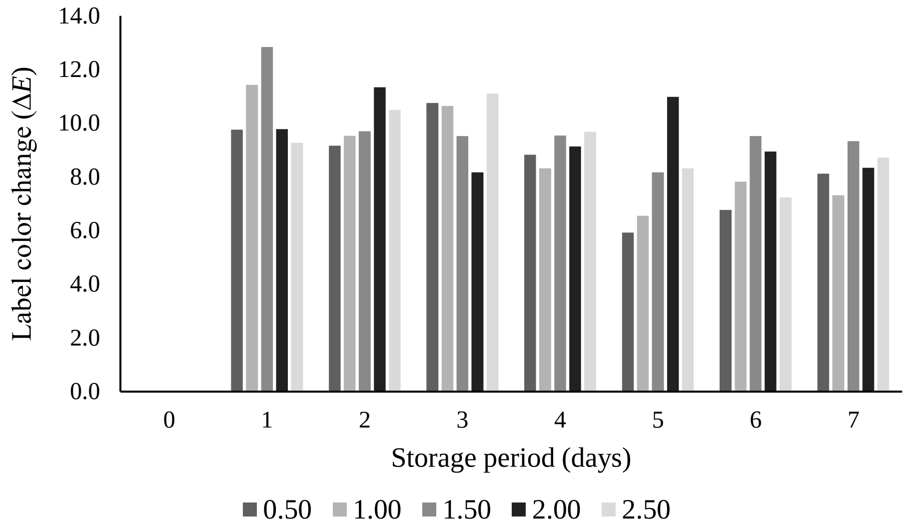


Figure 2. Color change of freshness indicator labels (Δ*E*) for all treatments during 7 days of storage at 4±2 °C

On day 0, no color change was detected on the freshness indicator labels because the anthocyanins had not yet responded to changes in the packaging environment. On day 1, a visible color change was observed. According to Rong *et al.* (2024a), the color change of an indicator label, expressed as ΔE, can be visually observed when $\Delta E > 2$. The early color response on day 1 may be associated with physiological changes in fresh-cut papaya after peeling and cutting. These processing steps cause tissue injury and increase the exposed surface area, which can accelerate respiration at the beginning of storage. Tabassum *et al.* (2023) reported that fresh-cut papaya generally has a higher respiration rate than whole fruit due to increased metabolic activity in exposed cells and tissue surfaces.

The increase in respiration can promote CO_2 accumulation in the packaging headspace. When CO_2 dissolves in water, it forms carbonic acid, which can release H^+ ions and lower the pH of the surrounding environment. This acidic condition can interact with anthocyanins in the label matrix and induce a color response (Rong *et al*., 2024). Therefore, in this study, the color change observed on the first day of storage was interpreted as being more directly associated with wound-induced respiration and CO_2-related pH changes rather than ethylene as the direct mechanism of label color response.

However, the color response of the indicator labels did not continue to increase consistently during the following storage days. Although physiological processes continued during cold storage, the low storage temperature slowed the rates of respiration and transpiration. In addition, moisture accumulation and condensation inside the package may have moistened the label surface and promoted anthocyanin migration or dissolution from the matrix. This condition could reduce the clarity of the label color response at later storage stages and may explain the decreasing trend in label color change shown in Figure 2.

Next, this study found that CO_2 concentration in the packaging headspace had a positive relationship with the color change of the freshness indicator label. The increase in CO_2 concentration was associated with the respiration process of fresh-cut papaya during cold storage. CO_2 accumulated in the packaging headspace can dissolve in water and form carbonic acid, which releases H^+ ions and lowers the pH of the surrounding environment. This acidic condition can be detected by pH-sensitive indicators and may induce a color response in the anthocyanin-based indicator label (Rong *et al*., 2024; Cao *et al*., 2026). Therefore, the increase in CO_2 concentration in the packaging headspace was associated with a greater magnitude of color change in the freshness indicator label.

Visually, no obvious change was observed in the appearance of fresh-cut papaya during storage. However, changes in freshness still occurred, as indicated by changes in its physical and chemical properties. The visual appearance of fresh-cut papaya during 7 days of cold storage at 4±2 °C is shown in Figure 3.

Furthermore, panelists assessed the color, aroma, texture, and overall acceptability of fresh-cut papaya during the last three days of storage using a hedonic quality test. The evaluation was conducted on days 5 to 7 because previous research reported that quality deterioration in fresh-cut papaya became more apparent during this storage period (Rong *et al*., 2024a). The results of the hedonic quality test are shown in Figure 4.

The results showed a decrease in color, texture, and overall acceptability from day 5 to day 7 of storage. However, the aroma attribute showed a slower decline compared with the other attributes. Most sensory attributes received scores around or below 3, indicating that the fresh-cut papaya tended to have a pale to dull orange color, a soft to very soft texture, and neutral to low acceptability. These results suggest that the sensory quality of fresh-cut papaya decreased during the last three days of storage, leading to reduced consumer acceptability. However, microbiological analysis is required to confirm product safety and consumption suitability.

The novelty of this research lies in the development of a sustainable colorimetric freshness indicator using anthocyanins extracted from purple sweet potato waste as a natural pH-sensitive dye for fresh-cut papaya packaging. While previous studies have demonstrated the feasibility of freshness indicators using synthetic dyes or other natural pigments, the effect of waste-derived purple sweet potato anthocyanin concentration on indicator performance in a real fresh-cut fruit packaging system has not been systematically investigated. This study further advances the field by elucidating the relationship between anthocyanin concentration, label color response, and physicochemical changes in fresh-cut papaya during refrigerated storage. The findings reveal that indicator performance is governed primarily by changes in package headspace CO_2 concentration and fruit firmness rather than by anthocyanin concentration alone, providing new insights into the sensing mechanism of anthocyanin-based freshness indicators. Consequently, this research contributes to the development of low-cost, environmentally friendly smart packaging by promoting agricultural waste valorization while offering scientific guidance for designing reliable freshness indicators for minimally processed fruits.

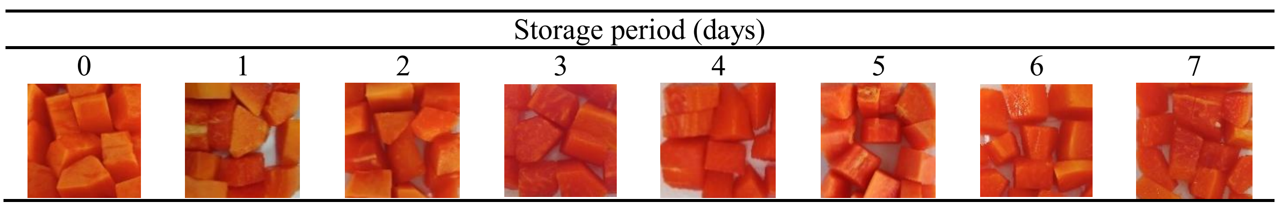


Figure 1. Appearance of fresh-cut papaya during 7 days of cold storage (4 ± 2 °C)

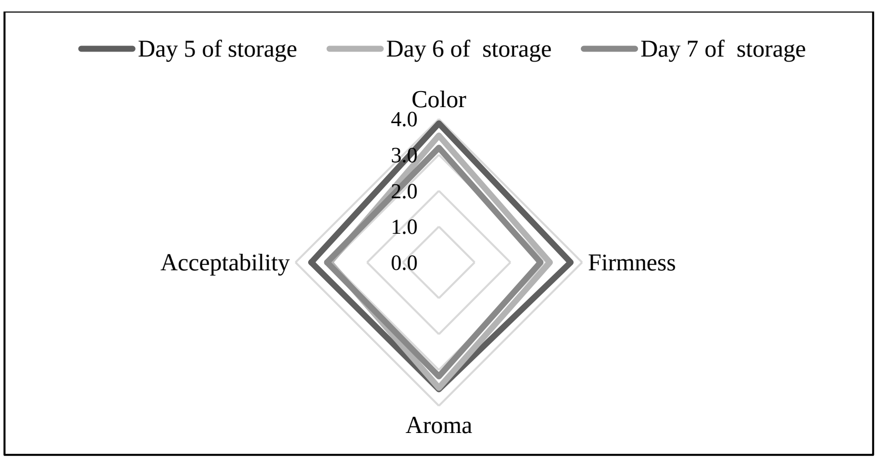


Figure 2. Average hedonic quality scores of fresh-cut papaya from all treatments on storage days 5 to 7 at 4±2 °C

3. CONCLUSIONS

This study found that variations in anthocyanin concentration (0.5%, 1.0%, 1.5%, 2.0%, and 2.5%) did not significantly affect the color change of the freshness indicator labels during fresh-cut papaya (*Carica papaya* L. var. Calina) storage. The performance of the freshness indicator labels was more closely associated with changes in freshness parameters, particularly CO_2 concentration in the packaging headspace and fruit firmness. These findings indicate that the color response of anthocyanin-based freshness indicator labels is influenced not only by dye concentration but also by the physicochemical changes occurring in fresh-cut papaya during storage. The results suggest that anthocyanin-based freshness indicator labels have potential for monitoring quality changes in fresh-cut papaya under cold storage conditions. However, the label response may be affected by moisture accumulation and condensation inside the package, which can reduce the clarity of color changes. Therefore, future studies should improve the moisture resistance and stability of the label matrix and include microbiological validation to confirm the relationship between label color response, freshness deterioration, and product safety. Further characterization of the anthocyanin extract using UV–Vis spectroscopy is also recommended to confirm the spectral properties of the natural dye used in the indicator label.

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DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE MANUSCRIPT PREPARATION

Not applicable. The authors did not use any generative AI tools or services in the preparation of this manuscript. All content is entirely the intellectual work of the authors.

AUTHOR CONTRIBUTION

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
ICA	✓			✓				✓	✓	✓	✓		✓	✓
RRM	✓	✓		✓			✓	✓		✓		✓		✓
PSJ	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓			
RA	✓	✓		✓			✓	✓				✓		
LPW				✓					✓	✓	✓			

C: Conceptualization	Fo: Formal Analysis	O: Writing - Original Draft	Fu: Funding Acquisition
M: Methodology	I: Investigation	E: Writing - Review & Editing	P: Project Administration
So: Software	D: Data Curation	Vi: Visualization	
Va: Validation	R: Resources	Su: Supervision	

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