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The Effectiveness of Hydrocooling in Maintaining Broccoli Quality During Storage

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ABSTRACT

Broccoli is a vegetable with high economic value, but it is also a highly perishable agricultural product after harvest. One method to extend its shelf life is hydrocooling, which involves cooling the product immediately after harvest to reduce the respiration rate, a key factor in quality degradation during storage. This study aimed to determine the optimal temperature and duration of hydrocooling to maintain the quality of fresh broccoli and to observe quality changes during storage. Hydrocooling was applied by immersing broccoli in cold water for 10 and 20 minutes, followed by storage at room temperature and low temperature. Quality observations were conducted for 7 days at room temperature and 16 days under chilled storage (5°C). The quality parameters observed included respiration rate, moisture content, weight loss, microbial contamination, color, and vitamin C content. Results showed that under room temperature storage, there was no significant difference between broccoli with and without hydrocooling; both maintained their quality only up to 4 days. However, the combination of hydrocooling and chilled storage preserved broccoli quality up to 14 days, while the control (without hydrocooling) only lasted until day 10. Therefore, hydrocooling is effective when combined with low-temperature storage, helping to maintain postharvest freshness and extend the shelf life of broccoli.

1. INTRODUCTION

Broccoli is one of the vegetables with relatively high economic value, as it is a primary source of vitamins, minerals, and fiber. According to Suwarto (2010), broccoli has several advantages over other vegetables because it contains two phytochemical compounds, sulforaphane and indole-3-carbinol, which can induce detoxification enzymes and deactivate carcinogens that cause cancer. Additionally, the chromium content in broccoli can help regulate blood sugar levels, while its high fiber, vitamin, and mineral, including omega-3 fatty acids, contributes to lowering blood pressure and cholesterol level. As a result, broccoli is highly favored by Indonesian people. Per capita broccoli consumption statistics, sourced from the National Socioeconomic Survey (Susenas) shows that broccoli consumption has increased every year (Yolandika *et al*., 2017).

Data from the Ministry of Agriculture (2024) shows that vegetable production in Indonesia decreased by 4.34% in 2023 compared to 2022. As a result, Indonesia has sought to meet market demand by importing various types of vegetables from neighboring countries. According to the Central Statistics Agency (BPS, 2023), China is the largest exporter of vegetables to Indonesia, with a total of 641,132 metric tons of vegetables such as broccoli, cabbage, and carrots. The import of broccoli could become a concern since it negatively impacts the local agricultural activities. It may lead to excessive dependence on foreign supply, harm local farmers, and contribute to a trade deficit in agricultural

sector. Therefore, the solution is to increase domestic broccoli production by applying agricultural technology and improving postharvest handling of the product to maintain its quality and to reduce losses while demand for the product keeps increasing. The demand for broccoli in urban areas continues to increase, both in quantity and quality. This growing demand needs to be considered in broccoli production and postharvest handling. Therefore, support of postharvest technology to increase supply of the product while maintaining its quality from land to consumers.

As mentioned above a lot of benefits of broccoli, it also has a drawback which is short shelf-life, especially in tropical climates like Indonesia. According to Caleb *et al*. (2016), broccoli is highly perishable and prone to postharvest deterioration due to relatively high temperature and humidity. Ahmad (2013) stated that reducing the respiration rate and water loss quickly, as well as limiting ethylene production and preventing bacterial growth, can be achieved through the precooling method. Precooling to remove field heat and low temperature storage are two examples of postharvest temperature control methods for broccoli. One technique within the precooling method is hydrocooling which is relatively easy to apply because no need specific equipment.

To date, information regarding the effect of hydrocooling duration and storage temperature on the quality of broccoli remains limited, particularly for bulk or unpackaged storage. Based on this, the aim of this study is to determine the effectiveness of hydrocooling in slowing the quality deterioration of fresh broccoli and to identify changes in quality parameters during storage. The benefits of this research include providing practical guidance for farmers, distributors, and postharvest handlers in selecting appropriate precooling methods and optimal storage temperatures to maintain the quality of broccoli during storage.

2. MATERIALS AND METHODS

2.1. Research Location and Time

The research was conducted at the Laboratory of Food and Agricultural Product Processing Engineering, Faculty of Agricultural Engineering and Technology, IPB University, from September to November 2024.

2.2. Materials and Equipment

The equipment used in this study includes, a colorimeter analyzer (DS-200), a styrofoam box (70 cm × 49 cm × 40 cm, 2 cm thick), a digital scale, a stopwatch, a thermohygrometer, cool storage (5°C), trays, a burette, Erlenmeyer flasks, measuring cylinders, an analytical balance, as well as various glassware and other supporting laboratory tools.

The main material used in this research was fresh Bejo broccoli of the Green King variety, locally grown, with harvest criteria of 60 days after transplanting or 85 days after sowing, weighing approximately 250–300 g, with a diameter of 10-15 cm and a stem length of 6-8 cm. Hydrocooling was conducted using ice cubes and water sourced from the IPB Campus Water Treatment Facility.

2.3. Research Procedure

The initial step in this study was sorting the broccoli to remove any dirty or rotten stems, followed by the hydrocooling treatment, which involved immersing 20 samples in a styrofoam box. The samples were immered in a Styrofoam box filled with water and ice flakes to reach a temperature of 0–3°C for specific durations: 10 minutes (H10) and 20 minutes (H20). These durations were chosen based on a previous study by (Blongkod *et al*., 2016), which applied hydrocooling for 15 minutes; thus, this study used both shorter and longer durations. As a comparison, samples without hydrocooling were used as the control. During the immersion process, the water temperature was maintained between 0–3°C by adding crushed ice when the temperature approached 3°C.

Water and broccoli temperatures were measured using a thermocouple to detect any temperature changes and to maintain low temperatures throughout the hydrocooling process. After the hydrocooling treatment, the broccoli was drained to remove excess water. Once air-dried, the unpackaged broccoli was placed on labeled trays according to treatment groups and stored under the assigned conditions: room temperature (28°C) and cold temperature (5°C).

2.4. Research Design

This study used a two-factor factorial completely randomized design (CRD). The duration of hydrocooling was divided into three levels: no hydrocooling (H0), 10 min (H10), and 20 min (H20), which served as the first factor. The second factor was storage temperature: room temperature at 28°C (TR) and low temperature at 5°C (T5). A total of 18 experimental units were generated from 6 treatment combinations, with each combination replicated three times.

To determine the effect of the treatments, analysis of variance (ANOVA) was conducted at a 5% significance level. If significant differences were found, the analysis was followed by Tukey's post-hoc test using R Studio software.

2.5. Quality Observation

2.5.1. Moisture Content

Moisture content was measured using the oven-drying method (AOAC, 2012). The moisture content of the sample was calculated using the following formula:

$$Moisture\ content\ (\%\ wet\ basis) = \frac{\text{Weight loss (g)}}{\text{Sampel weight (g)}} \times 100\% \quad (1)$$

2.5.2. Weight Loss

Weight loss can be expressed as the percentage change from the initial weight to the final weight after storage. Before storing the broccoli, the initial weight was measured. The samples were weighed before (*A*) and after (*B*) storage, and the weight loss (*W*) was calculated using the following formula:

$$W = \frac{\text{A}-B}{\text{A}} \times 100\% \quad (2)$$

2.5.3. Microbial Contamination

The general steps for total plate count (TPC) observation in broccoli include sampling broccoli that has undergone hydrocooling for 10 and 20 min to obtain data variation. This is followed by sample dilution, which involves grinding or homogenizing the selected broccoli sample. A serial dilution is then performed to obtain a suitable microbial concentration for counting. The diluted samples are then plated onto microbial growth media such as PCA (plate count agar), and the solution was evenly spread over the surface of the agar using a spreader.

Afterward, the agar plates are placed in an incubator set at the appropriate temperature (35–37°C) for one to two days. Microbial colonies that grow on each plate are then counted. The standard unit used is colony-forming units (CFU) per gram of broccoli. The results are compared with the maximum allowable microbial contamination limit as specified by the Indonesian National Standard (SNI) 7388:2009.

2.5.4. Color

Color measurement was carried out using a chromameter (CR 200). Color was measured based on L^*, a^*, and b^* values at three different points to objectively evaluate the broccoli's color. The L^* value indicates lightness (range = 0–100; higher values mean lighter color), the a^* value represents green to red tones (range = -128 to 127; positive values indicate more red, negative values indicate more green), and the b^* value represents blue to yellow tones (range = -128 to 127; positive values indicate more yellow, negative values indicate more blue) (Utama, 2001).

After collecting L^*, a^*, and b^* data, the values were calculated using the formulas shown in Equation (3) and (4). Equation (3) was used to calculate chroma, which indicates color purity, and Equation (4) was used to determine the hue or color tone. The equations used are as follows:

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

$$h* = arctan\frac{b^*}{a^*} \quad (4)$$

2.5.5. Vitamin C

Vitamin C content was measured using the iodometric titration method (Cresna *et al*., 2014). 5-gram sample was crushed, then dissolved and diluted to the mark in a 100 mL volumetric flask. From the filtered solution, 25 mL of filtrate was pipetted. A rapid titration was performed using 0.01 N iodine solution until a blue color appeared after adding a few drops of starch indicator. The vitamin C content was calculated using the following formula:

$$Vit.C\ \left(\frac{mg}{100g}\right) = \frac{(VI_2 \times 0.88 \times Fp\ )}{Ws\ (gram)} \times 100 \quad (5)$$

where VI_2 is volume of iodine solution (mL), 0.88 is mg of ascorbic acid equivalent to 1 mL of 0.01 N I_2 solution, *Fp* is dilution factor, and *Ws* is sample weight (g).

3. RESULTS AND DISCUSSION

3.1. Effect of Hydrocooling Duration on Broccoli Temperature

The results showed that 20 min of hydrocooling more effectively reduced broccoli temperature and maintained it at a stable level throughout the 20 min period. In contrast, the 10 min hydrocooling treatment was less effective in sustaining the temperature drop, as the broccoli's temperature began to rise again, indicating that 10 minutes was not sufficient to effectively lower the field heat of the broccoli. Figure 1 shows that the broccoli temperature stabilized around 5°C. The 20 min treatment was more effective in reducing the broccoli's temperature closer to that of the cooling water (0°C). A longer hydrocooling duration allowed for more even and thorough cooling, although a slight temperature increase occurred at the end. This increase indicates thermal equilibrium between the broccoli and the cooling medium, suggesting that the optimal immersion time should not exceed 20 min.

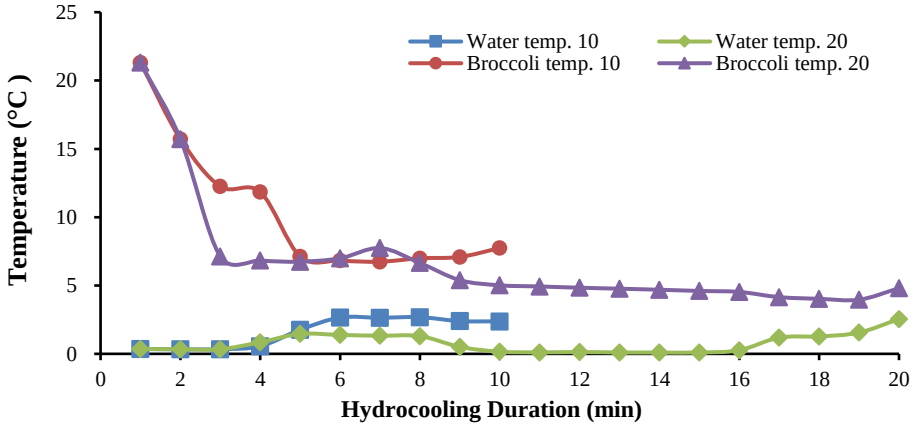

Figure 1. Changes in water and broccoli temperature during hydrocooling

Based on the graph above, a significant temperature drop occurred during the initial 0–5 minutes, especially for broccoli treated with 10 minutes (orange line) and 20 minutes (yellow line) of hydrocooling. This indicates that during the early phase of the hydrocooling process, heat transfer from the broccoli to the cooling water was highly effective. After about 5–10 minutes, the broccoli temperature began to stabilize. The temperatures of broccoli treated for 10 and 20 minutes tended to approach the cooling water temperature, around 0–3°C.

3.2. Moisture Content

Moisture content is one of the parameters that determines the quality of food during storage. In general, the moisture content of broccoli tends to decrease compared to its initial condition before storage. A previous study by Blongkod *et al*. (2016) reported that weight loss and moisture loss were higher in treatments without hydrocooling. Figure 2 and 3 reveal moisture content of broccoli during storage at room temperature and 5 °C.

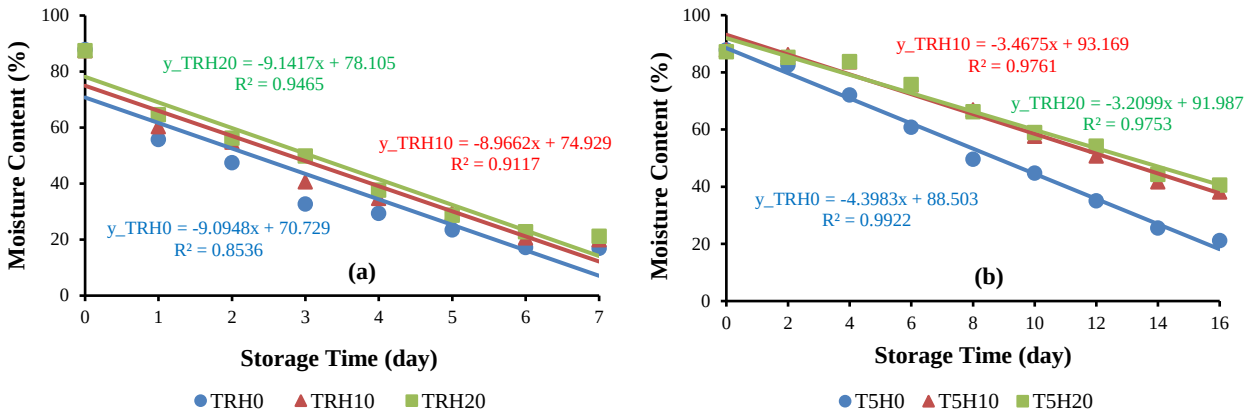

Figure 2. Decrease of broccoli's moisture content during storage: (a) at room temperature, and (b) at 5°C.

As shown in Figures 2a and 2b, the decrease in moisture content during storage exhibited a consistent linear trend at room temperature, with coefficients of determination (R^2) ranging from 0.85 to 0.95, indicating a strong correlation between moisture loss and storage duration. Moisture loss occurred rapidly, with a daily reduction rate of approximately ±9.00% (TRH0 = –9.09%, TRH10 = –8.97%, TRH20 = –9.14%). According to Asgar (2017), a 10% moisture loss not only affects product quality but also impacts visual appearance and structural components of the broccoli.

After day 7, the broccoli samples showed a significant decline in quality, both visually and physically, making them unsuitable for further measurement and analysis. Therefore, observation data were only available up to day 7. This indicates that the optimal shelf life of broccoli lies within this range, especially in the absence of precooling treatment or low storage temperatures.

In contrast, broccoli stored at 5°C (Figure 2b) experienced a slower and more controlled rate of moisture loss compared to those stored at room temperature (Figure 2a), with daily reduction rates ranging from 3.21% to 4.40% (T5H0 = –4.40%; T5H10 = –3.47%; T5H20 = –3.21%) and very high R^2 values (>0.97), indicating that under cold storage, moisture loss is strongly influenced by storage duration. These findings reinforce the importance of cold storage in maintaining moisture content and extending the postharvest quality of broccoli.

Statistical analysis results shown in Table 1 indicate that hydrocooling treatment and storage temperature significantly affect the product's moisture content during storage. On day-2, the highest moisture content was found in H20 (70.78%) and H10 (70.54%), while H0 (no hydrocooling) had a lower moisture content of 65.02%. Although not statistically significant (all labeled with the letter 'a'), these values suggest that hydrocooling tends to help retain the initial moisture content.

Table 1. Broccoli moisture content (%) from various hydrocooling treatments and storage temperatures on days 2, 4, and 6. Initial moisture content on day 0 = 87.70%

Treatment	Mean (Water Content)			
	Day 0	Day 2	Day 4	Day 6
Hydrocooling:				
H0	87.70	65.02[a]	50.78[a]	39.06[a]
H10	87.48	70.54[a]	59.24[a]	48.19[a]
H20	87.52	70.78[a]	60.79[a]	49.34[a]
HSD 5%		41.44	25.32	32.55
Storage Temperature:				
Room Temperature		52.87[b]	33.98[b]	20.28[b]
Temperature 5°C		84.69[a]	79.89[a]	70.78[a]
HSD 5%		27.66	16.88	21.70

Note: Different letters in the same column indicate significant differences based on Tukey's post-hoc test at the 5% level ($p< 0.05$).

Meanwhile, the effect of storage temperature was much more pronounced. Broccoli stored at room temperature experienced a rapid decrease in moisture content, from 52.87% on day 2 to only 20.28% on day 6. In contrast, storage at 5°C was able to retain significantly higher moisture levels, from 84.69% to 70.78%. The difference between the two temperatures was significant (letters a ≠ b across all observation days), indicating that cold storage significantly slows down the rate of moisture loss. Low temperatures reduce moisture loss because the respiration rate is lower, which in turn decreases water evaporation.

3.3. Weight Loss

Weight loss data show a significant increase in broccoli weight loss during storage at room temperature up to day 7, as seen in Figure 3a and 3b. Based on the regression graph (Figure 3a), the weight loss rate of broccoli at room temperature increased sharply from day 0 to day 7. The linear regression equation shows that the TRH0 treatment had a weight loss rate of 9.47% per day (R^2 = 0.9415), TRH10 had 9.71% per day (R^2 = 0.9632), and TRH20 had 9.05% per day (R^2 = 0.9798). The high coefficients of determination indicate a strong linear relationship between weight loss and storage duration.

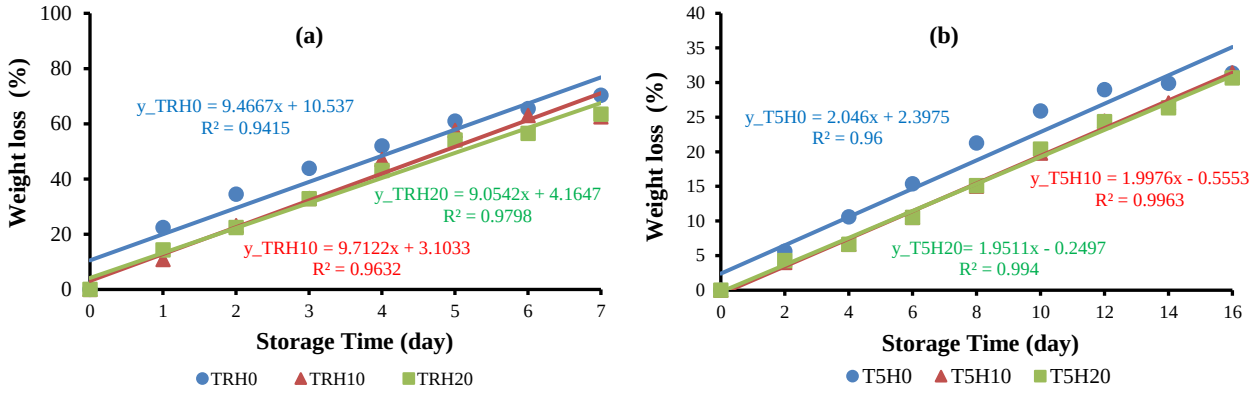

Figure 3. Weight loss of broccoli during storage: (a) at room temperature, (b) at 5°C

Storage of broccoli without hydrocooling treatment (TRH0) consistently showed the highest weight loss at each observation point, while the 20-minute hydrocooling treatment (TRH20) generally had the lowest weight loss. In contrast, broccoli stored at 5°C experienced a much lower weight loss compared to storage at room temperature, as shown in Figure 3b. The regression graph shows a slower and more controlled increase in weight loss over the 16-day storage period. T5H0 (without hydrocooling) always exhibited the highest weight loss at each time point, while T5H20 showed the lowest weight loss at nearly every time point. This supports Dadhich *et al*. (2008), who stated that weight loss in fruits and vegetables stored in cold rooms is lower compared to those stored at ambient temperature.

Statistical analysis in Table 2 shows that the treatment without hydrocooling (TRH0) and stored at 5°C had the highest weight loss, reaching 40.42% on day 6, whereas TRH20 had only 33.52%. However, statistical tests indicated that differences between treatments were not significant until day 4 and only began to show trends of difference by day 6. By that time, the broccoli may already have become unsuitable for consumption due to significant weight loss.

The hydrocooling treatment (H10 and H20) samples stored at 5°C showed lower weight loss compared to samples without hydrocooling (H0), especially up to day 10, where the H0 treatment resulted in a weight loss of 25.86%, while H10 and H20 had 19.81% and 20.37%, respectively. This indicates that storing broccoli at a low temperature effectively slows down the rate of weight loss. Based on the data (Tables 2 and 3), from day 2 to day 16, broccoli experienced much lower weight loss under cold storage than at room temperature. Lowering the storage temperature significantly slows down the rate of water loss, thereby reducing weight loss and helping to maintain the freshness of broccoli. In addition, although not always statistically significant, hydrocooling treatment shows potential in suppressing the rate of weight loss especially when combined with low-temperature storage.

Table 2. Weight loss (%) of broccoli from various hydrocooling treatments and storage temperatures on Days 2, 4, and 6.

Treatment	Mean (Weight loss)		
	Day 2	Day 4	Day 6
Hydrocooling			
H0	20.03[a]	31.26[a]	40.42[a]
H10	13.52[a]	26.83[a]	37.73[ab]
H20	13.36[a]	24.87[a]	33.52[b]
HSD 5%	3.42	7.02	5.55
Storage Temperature:			
Room Temperature	26.64[a]	47.37[a]	61.65[a]
Temperature 5°C	4.63[b]	7.94[b]	12.12[b]
HSD 5%	2.28	4.68	3.70

Note: Different letters in the same column indicate significant differences based on Tukey's post-hoc test at the 5% level ($p < 0.05$). Identical letters indicate no significant difference.

Table 3. Effect of hydrocooling on weight loss on days 8, 10, 12, 14, and 16 under cold storage (5°C)

Hydrocooling Treatment	Mean (Weight loss)				
	Day 8	Day 10	Day 12	Day 14	Day 16
Temperature 5°C:					
H0	21.26[a]	25.86[a]	28.96[a]	29.88[a]	31.36[a]
H10	15.00[b]	19.81[b]	24.42[a]	27.04[a]	31.41[a]
H20	15.08[b]	20.37[b]	24.33[a]	26.35[a]	30.67[b]
HSD 5%	4.49	4.05	5.84	4.58	6.86

Note:Different letters in the same row indicate significant differences based on Tukey's post-hoc test at the 5% level ($p < 0.05$). Identical letters indicate no significant difference.

3.4. Microbial Contamination

Total Plate Count (TPC) testing is a basic microbiological analysis used to determine the total number of viable cells in food, including both pathogenic and non-harmful saprophytic bacteria (Ramadhani 2016 in Paluseri, 2023). The purpose of measuring bacterial count in broccoli is to assess food safety, cleanliness, and the potential for spoilage during storage. Based on Table 4, at day 0 under room temperature storage, TRH0 and TRH20 had the same initial microbial count (1.88×10^4), while TRH10 was lower (1.10×10^4). On day 3, all treatments showed a significant increase, especially TRH10 (5.60×10^5) and TRH20 (1.71×10^5), indicating rapid microbial growth. By day 6, TRH20 still had the highest microbial count (1.90×10^5), followed by TRH10 (1.20×10^5), while TRH0 remained much lower (6.80×10^4). This shows that hydrocooling does not kill microbes and is not intended for microbial inactivation. Meanwhile, the control treatment (TRH0/T5H0) still showed microbial growth, although at a slower rate, likely due to the absence of added water contact that could introduce new microbes. Room temperature storage accelerates microbial growth, as this temperature supports bacterial metabolism and reproduction. Therefore, hydrocooling slightly increases the number of microbes during storage at room temperature.

Table 4. Total plate count in broccoli during storage at room temperature (colonies/ml)

Storage Temperature	Treatment	Days			ΔTPC
		0	3	6	
Room Temperature	TRH0	1.88×10^4	6.50×10^4	6.80×10^4	4.92×10^4
	TRH10	1.10×10^4	5.60×10^5	1.20×10^5	1.09×10^5
	TRH20	1.88×10^4	1.71×10^5	1.90×10^5	1.71×10^5

Table 5 shows that at 5°C storage, on day 3, the highest microbial count was in T5H10 (4.45×10^5) and the lowest in T5H0 (1.32×10^5). On day 6, microbial growth increased in all treatments, but remained within safe limits (except T5H10, which stayed high at 5.55×10^5. By day 16, microbial counts in T5H10 dropped significantly (9.50×10^3), while T5H0 and T5H20 remained in the 10^4 range. The largest change in microbial count occurred in T5H10 (4.355×10^5), followed by T5H20 (1.632×10^5) and T5H0 (8.67×10^4). Storage at 5°C was effective in slowing microbial growth compared to

room temperature, as it reduces enzymatic and metabolic activity. At 5°C, TPC even decreased, showing that cold storage is highly effective in suppressing microbial growth. This is in line with (Ashari, 2006), who stated that to prevent microbial spoilage in broccoli, it is recommended to store it at low temperatures (below 10°C). For both room and cold storage, TPC values ranged from 10^4 to 10^5 CFU/g, which are generally still safe for raw vegetables. According to SNI 7388: 2009, food is considered safe if the total number of colony-forming units (CFU) for TPC does not exceed 1×10^6 CFU/g.

Table 5. Total plate count in broccoli during storage at 5°C (colonies/ml)

Storage Temperature	Treatment	Day			ΔTPC
		3	6	16	
Temp. 5°C	T5H0	1.32×10^5	5.95×10^4	4.53×10^4	8.67×10^4
	T5H10	4.45×10^5	5.55×10^5	9.50×10^3	4.35×10^5
	T5H20	1.98×10^5	6.85×10^4	3.48×10^4	1.63×10^5

3.5. Color Analysis

Figure 4 and 5 portray visual appearance of fresh broccoli and after storage, both at room temperature and at 5 °C. Broccoli stored at room temperature rapidly damaged. After 4 days of storage, the color of broccoli visually changed from green to yellowish (Figure 4). In contrast, broccoli stored at 5 °C stand longer. After 16 days, the color of broccoli remain green (Figure 5). In this study, the CIE Hunter $L^*a^*b^*$ color system was used to measure the color of broccoli. The observed parameters included brightness (L^*) to assess how light or dark the broccoli was, green color (a^*) to measure the intensity of the green hue, and yellow color (b^*) to evaluate the yellow coloration of the broccoli.

(a) (b) (c) (d) (e) (f)

Figure 4. Visual appearance of brokoli: (a) TRH0 day 0, (b) TRH10 day 0, (c) TRH20 day 0, (d) TRH0 day 4, (e) TRH10 day 4, and (f) TRH20 day 4.

(a) (b) (c) (d) (e) (f)

Figure 5. Visual appearance of brokoli: (a) T5H0 day 0, (b) T5H10 day 0, (c) T5H20 day 0, (d) T5H0 day 16, (e) T5H10 day 16, and (f) T5H20 day 16.

3.5.1. L^* Value

Based on the L^* value on day 6, there was a significant decline from the initial value of around 38 to approximately 30 (Table 6). However, no significant difference was found among the hydrocooling treatments. In contrast, a significant difference was observed between storage temperatures. The L^* value of broccoli stored at room temperature dropped sharply (Figure 6a), while at 5°C it remained stable or even increased, and on days 4 and 6, the L^* value is statistically difference. These results indicate that the hydrocooling treatment alone was not effective in maintaining broccoli brightness when stored at room temperature or beyond 4 days. However, a different trend was observed under cold storage conditions, as shown in the Figure 6b.

Table 6. *L** Values of broccoli from various hydrocooling treatments and storage temperatures on days 2, 4, and 6.

Treatment	Mean (*L** Value)		
	Day 2	Day 4	Day 6
Hydrocooling:			
H0	37,61[a]	31,59[a]	30,22[a]
H10	38,03[a]	31,79[a]	29,93[a]
H20	38,05[a]	31,86[a]	29,91[a]
HSD 5%	6,57	4,63	6,34
Storage Temperature:			
Room Temperature	37,17[a]	24,34[b]	20,36[b]
Temperature 5°C	38,63[a]	39,14[a]	39,68[a]
HSD 5%	4,38	3,08	4,23

Note: Different letters in the same column indicate significant differences based on Tukey's post-hoc test at the 5% level ($p < 0.05$). Identical letters indicate no significant difference.

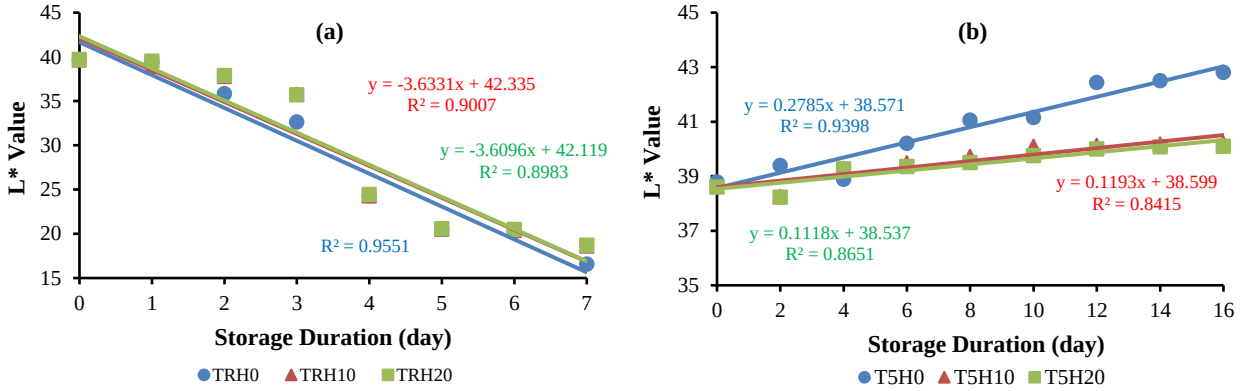

Figure 6. *L** value of broccoli during storage: (a) at room temperature, (b) at 5°C

Unlike storage at room temperature, storage at 5°C showed an increase in *L** values over time. The T5H0 treatment showed the highest increase, from an initial value of approximately 38 to 42.80 on day 16. This suggests that the non-hydrocooling treatment showed some bright spots or signs of broccoli turning from green to yellow by day 10, with a regression equation of y = 0.2785x + 38.571 (R^2 = 0.9398). Meanwhile, the T5H10 and T5H20 treatments showed more moderate increases, with rates of around 0.11–0.12 per day. The R^2 values remained high (0.8415–0.8651), indicating that the *L** values of broccoli in these treatments remained lower than the control, suggesting they stayed fresh until day 14. This is in line with Marlina *et al*. (2014) as cited in Khoerunnisa *et al*. (2023), who stated that longer shelf life is generally associated with a decline in brightness.

Based on statistical analysis, no significant differences were found among the hydrocooling treatments. However, there were significant differences between storage temperatures. Storage at 5°C was able to maintain broccoli brightness for up to 14 days, whereas storage at room temperature only maintained brightness until day 3.

3.5.2. Greenness Value *a**

The *a** color at room temperature storage shows color values that tend to increase from negative to positive, indicating a shift from green towards red. The following is a color graph of *a** in broccoli stored at room temperature and temperature 5°C. The *a** value measurements showed that the *a** values increased linearly during 7 days of storage at room temperature. Based on the regression graph (Figure 7a), the highest rate of increase in *a** value occurred in the TRH10 treatment (y = 3.0461x – 10.433; R^2 = 0.8246), followed by TRH20 and TRH0 with nearly similar rates. From day 0 to day 2, a decrease in green color was observed. At the beginning of storage (day 0), all treatments had negative *a** values ranging from –10.08 to –10.10, indicating a dominant fresh green color. However, from day 1 to day 3, the *a** value increased progressively (approaching zero and even becoming positive), indicating that the green color began to fade and shift toward the red or brown spectrum, reflecting a decline in visual quality. This may be caused by

chlorophyll degradation, the main green pigment in broccoli, due to exposure to room temperature and enzymatic activity (such as chlorophyllase and peroxidase), which accelerate the loss of green pigment.

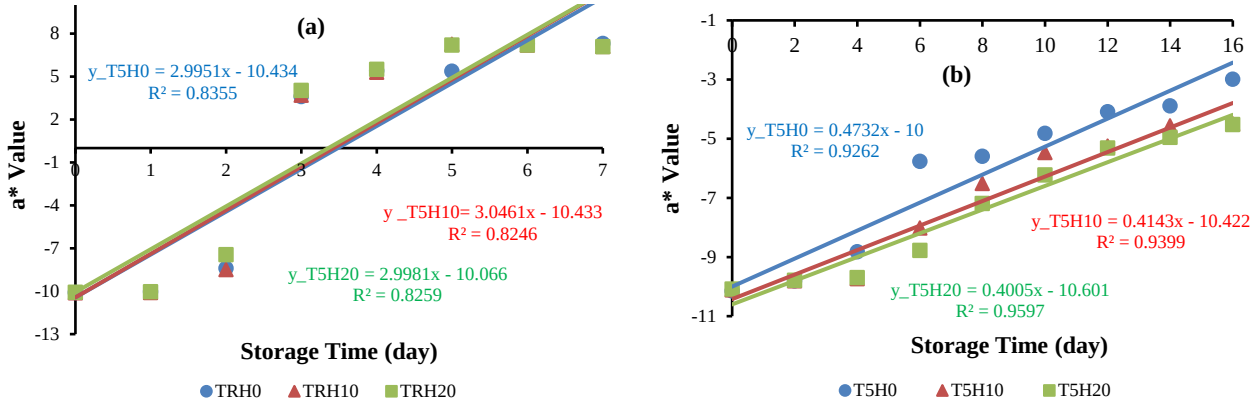

Figure 7. Greenness value (*a**) of broccoli during storage: (a) at room temperature, (b) at 5°C

In cold storage, the *a** value of broccoli remained stable in the negative range, indicating that the broccoli retained its green color. The graph of changes in *a** value during cold storage is shown in Figure 7b. The *a** value graph shows that the treatment without hydrocooling (T5H0) experienced the highest increase, with the *a** value reaching around –3 on day 15. Meanwhile, T5H10 showed a slower increase than T5H0, but faster than T5H20. T5H20 had the slowest and lowest increase in *a** value, remaining close to –6 on day 15. The differences among the three treatments had a noticeable effect, maintaining a more negative green color, which indicates a better ability to preserve chlorophyll. This is supported by the statistical test results in Table 7. Statistically, hydrocooling treatment did not show a significant effect on *a** value until day 10. However, on day 12, a difference was observed between H10 and H20, indicating a significant difference between treatments, which became noticeable in the color change by day 10. Never-

Table 7. *a** Value of broccoli from various hydrocooling treatments and storage temperatures on days 2, 4, and 6.

Treatment	Mean (*L** Value)		
	Day 2	Day 4	Day 6
Hydrocooling:			
H0	-9.10[a]	-1.71[a]	0.76[a]
H10	-9.14[a]	-2.21[a]	-0.40[a]
H20	-8.62[a]	-2.09[a]	-0.79[a]
HSD 5%	2.04	1.13	2.72
Storage Temperature:			
Room Temperature	-8.12[a]	-5.40[a]	7.22[a]
Temperature 5°C	-9.80[b]	-9.41[b]	-7.52[b]
HSD 5%	1.36	0.75	1.81

Table 8. Effect of hydrocooling on *a** value on days 8, 10, 12, 14, and 16 during cold storage.

Hydrocooling Treatment	Mean (*a** value)				
	Day 8	Day 10	Day 12	Day 14	Day 16
Temperature 5°C:					
H0	-5.59[a]	-4.82[a]	-4.08[a]	-3.89[a]	-2.99[a]
H10	-6.51[a]	-5.46[a]	-5.25[b]	-4.57[a]	-4.49[a]
H20	-7.19[a]	-6.22[a]	-5.31[b]	-4.95 [a]	-4.52[a]
HSD 5%	5.52	5.15	1.07	3.08	2.22

Note: Different letters in the same column indicate significant differences based on Tukey's post-hoc test at the 5% level ($p < 0,05$). Identical letters indicate no significant difference.

theless, in general, the effect of hydrocooling on *a** value tends to be less significant than the effect of storage temperature. This is in line with Aminudin (2010), who stated that lower storage temperatures help maintain the green color of broccoli florets, while higher temperatures cause a faster color change from green to yellow or brown.

3.5.3. *b** Value

The *b** value in the CIE *L*a*b** color system represents the intensity of yellow (positive) and blue (negative) coloration. Figure 8 portrays changes of *b** values of broccoli during storage at room and 5 C temperatures. At low temperature (5°C), the increase in *b** value occurred more slowly and within a much narrower range. The R^2 values indicates a very strong linear relationship, but the rate of increase was much slower compared to room temperature. This suggests that cold storage is effective in slowing down the surface color change of broccoli toward yellow, as also shown in Table 9.

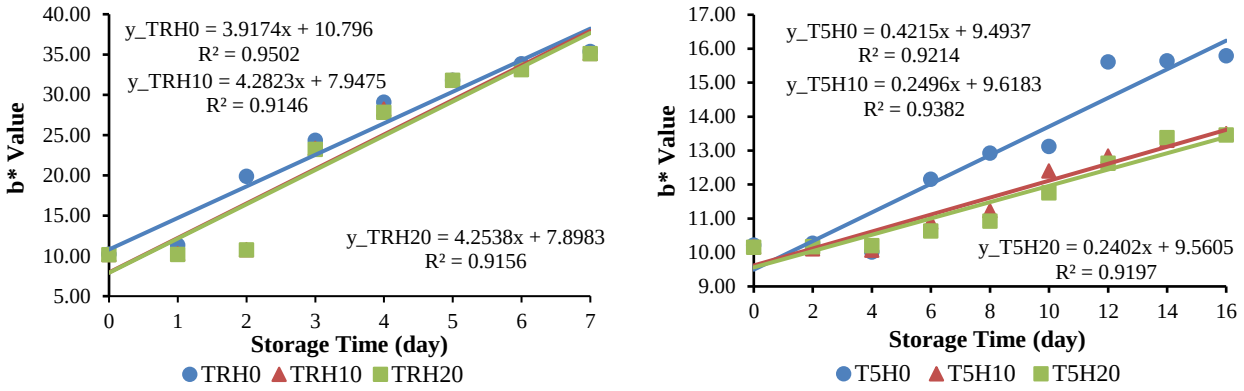

Figure 8. Yellowness value (*b**) of broccoli during storage: (a) at room temperature, (b) at 5°C

Table 9. *b** Value of broccoli from various hydrocooling treatments and storage temperatures on days 2, 4, and 6.

Treatment	Mean (*b** Value)		
	Day 2	Day 4	Day 6
Hydrocooling:			
H0	15.08[a]	19.56[a]	23.01[a]
H10	10.44[b]	19.14[a]	22.29[a]
H20	10.46[b]	19.03[a]	21.88[a]
HSD 5%	2.71	1.76	6.04
Storage Temp:			
Room Temp.	13.80[a]	28.39[a]	33.56[a]
Temp. 5°C	10.18[b]	10.09[b]	11.23[b]
HSD 5%	1.81	1.17	4.03

*Note: Different letters in the same column indicate significant differences based on Tukey's post-hoc test at the 5% level ($p < 0,05$). Identical letters indicate no significant difference.

The post-hoc test results for the hydrocooling treatments stored for 16 days showed no significant difference in *b** values, despite an increase over time. This indicates that although the *b** value increased up to day 16, the final value at 5°C (around 13–15) was still much lower compared to room temperature storage on day 6 (33.56), suggesting that the effect of hydrocooling alone on *b** value was not significant. However, when combined with cold storage, hydrocooling was effective in delaying color change during the storage period.

Storage temperature had a highly significant effect on the *b** value of broccoli. Room temperature storage caused a drastic increase in *b** value, indicating undesirable surface color changes. According to Asgar (2017), the greenest broccoli had a *b** value of 15.21 on day 5 when stored at 5°C using packaging. In this study, however, a *b** value of 15.21 was observed on day 12 (15.62) without hydrocooling and without packaging. The value remained stable at 13.50 and 13.46 in the T5H10 and T5H20 treatments, respectively, on day 16.

3.6. Vitamin C

According to Asiah *et al*. (2020), the loss of vitamin C is caused by the oxidation of ascorbic acid. In fruits and vegetables that contain chlorophyll pigments, the loss of vitamin C occurs alongside the degradation of those pigments. The following is a graph showing the decline of vitamin C at room temperature.

The average daily reduction in vitamin C across the three treatments (Figure 9a), (TRH0, TRH10, TRH20) ranged from 12.75% to 12.87% per day. This indicates that room temperature storage significantly accelerates the degradation of vitamin C, making the applied hydrocooling method less effective in preserving vitamin C under such conditions. This is also reflected in the visible color change of the broccoli by day 4, where yellowing occurred and the product was no longer suitable for consumption. This is caused by rapid respiration at room temperature, leading to an increase in organic acids and a drop in broccoli pH (Safaryani *et al*., 2007). On the other hand, vitamin C degradation occurred more slowly during cold storage. The following graph shows vitamin C levels at 5°C.

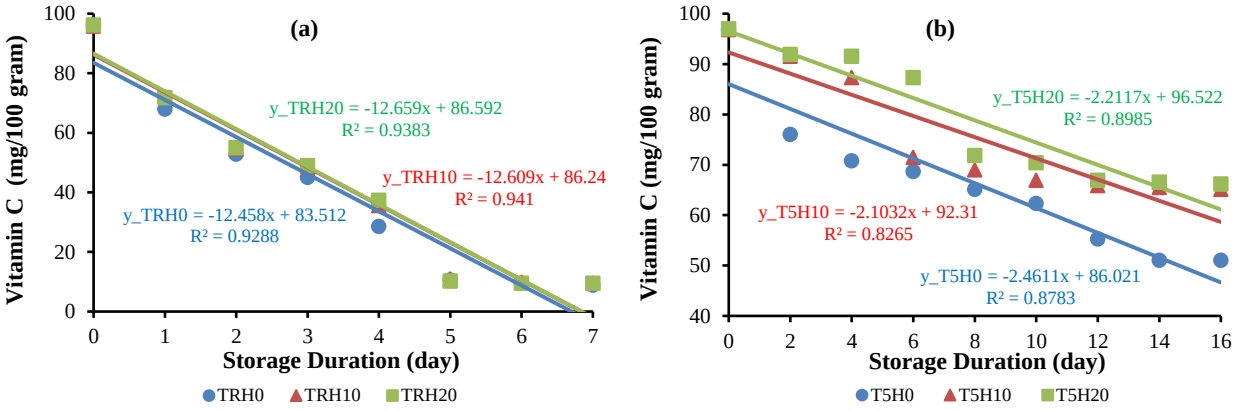

Figure 9. Vitamin C content of broccoli during storage: (a) at room temperature, (b) at 5°C

Storage at 5°C (Figure 9b) showed that the decline in vitamin C occurred more slowly and gradually over the 16-day period. At 5°C, the rate of vitamin C degradation was slower compared to room temperature. The average daily decrease in vitamin C for the T5H0 treatment was around 2.81 mg/day (2.93% per day), while the decreases for T5H10 and T5H20 were lower, approximately 1.97 mg/day (2.03% per day) and 2.06 mg/day (2.10% per day), respectively. This indicates that the T5H10 and T5H20 treatments were more effective in preserving vitamin C content during low-temperature storage. In contrast, under room temperature conditions, vitamin C degradation occurred much more rapidly, with an average decrease of about 12.4–12.5 mg/day or approximately 12.7–12.9% per day across all treatments. The differences among treatments at room temperature were not statistically significant.

Table 10. Vitamin C content of broccoli from various hydrocooling treatments and storage temperatures on Days 2, 4, and 6

Treatment	Mean (Vitamin C Content. mg/100g)		
	Day 2	Day 4	Day 6
Hydrocooling			
H0	64.41[a]	36.72[a]	34.77[a]
H10	73.04[a]	61.42[a]	40.65[a]
H20	73.39[a]	64.41[a]	48.39[a]
HSD 5%	22.77	30.54	28.83
Storage Temp:			
Room Temp	54.09[b]	25.18[b]	6.75[a]
Temp. 5°C	86.47[a]	83.19[a]	75.79[b]
HSD 5%	15.18	20.37	19.22

Note: Different letters in the same column indicate significant differences based on Tukey's post-hoc test at the 5% significance level ($p < 0,05$). Identical letters indicate no significant difference.

Statistical test results also support this finding, where no significant differences were observed among the hydrocooling treatments on days 2, 4, and 6, although numerically, the H20 treatment tended to retain a higher vitamin C content compared to H0. On the other hand, storage temperature had a significant effect. Broccoli stored at room temperature dropped from an average of 54.09 mg/100g on day 2 to only 6.75 mg/100g on day 6, indicating a significant difference due to temperature treatment.

This finding aligns with research by Ashari (2006), which states that to maintain freshness and prevent vitamin C loss, vegetables should be stored at low temperatures. Storage temperature affects the vitamin C content of broccoli, as noted by Safaryani *et al*. (2007), who stated that vitamin C stability generally increases with decreasing storage temperature.

4. CONCLUSIONS

A 20-minute hydrocooling treatment reduced the broccoli temperature closer to that of the cooling water (0–3°C) compared to the 10-minute treatment and effective in maintaining quality of fresh broccoli during storage. This had a direct impact on slowing down quality deterioration, particularly in terms of color, moisture content, and vitamin C levels. Storage at a low temperature was significantly effective in preserving broccoli quality and freshness. The combination of hydrocooling and low-temperature storage showed the best quality retention over 16 days of storage. The 20-minute hydrocooling followed by storage at 5 °C was the most effective in maintaining broccoli quality, as indicated by vitamin C content, color change, moisture level, and reduced weight loss.

This research is recommended to be continued with testing of the best treatment at a commercial scale (pilot plant), economic analysis related to operational costs and energy consumption, as well as improvement of the hydrocooling system using circulating cold water to reduce water usage.

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