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Analysis of the Kinetics of Color Change and Weight Loss in Cherry Tomatoes during Hypobaric Storage

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ABSTRACT

Cherry tomatoes are highly susceptible to deterioration due to rapid respiration and metabolic activity. Changes in color and weight loss are key indicators reflecting quality degradation during storage. This study aimed to analyze the effects of ozone pretreatment and variations in hypobaric storage pressure on the dynamics of color changes (L, a*, b*, ΔE, hue, and chroma) and weight loss of cherry tomatoes during storage, as well as to determine the relationships among these quality parameters. Color evaluation was conducted using a computer vision method, while data analysis was performed using a zero-order kinetic approach. The results showed that low storage pressures (26 kPa and 64 kPa) consistently slowed changes in lightness, redness intensity, and overall color stability compared to normal atmospheric conditions (101 kPa). Meanwhile, weight loss increased with storage duration but was lower under hypobaric conditions. Based on principal component analysis (PCA), a total variance of 97.969% was obtained for ozone pretreatment combined with hypobaric storage, indicating strong correlations among the variables in the dataset. Hypobaric storage is effective in maintaining the quality of cherry tomatoes by reducing the rates of color change and weight loss, while the effect of ozone pretreatment was more limited compared to the influence of storage pressure.*

1. INTRODUCTION

Cherry tomatoes (*Solanum lycopersicum* L. var. *cerasiforme*) are one of the increasingly important horticultural commodities in Indonesia due to their economic value and steadily rising consumer demand, particularly in modern markets. Although specific data on cherry tomato production is not yet fully disaggregated in national statistics, total tomato production in Indonesia reached 1.11 million metric tons in 2021 and has shown a trend of increasing domestic consumption demand year over year. At the regional level, provinces such as Lampung recorded tomato production of 206,780 quintals in 2023 (BPS, 2023). However, cherry tomatoes are classified as a highly perishable commodity due to their high respiration rate and metabolic activity after harvest, making them susceptible to quality deterioration during storage (Zhou *et al*., 2021).

Quality deterioration of cherry tomatoes during storage is generally characterized by changes in skin color, softening of the flesh, and increased weight loss. Color change is one of the earliest and most easily observable quality indicators for consumers, and thus plays a crucial role in determining the level of acceptance and purchasing decisions regarding fresh tomatoes (Tsouvaltzis *et al*., 2023). Physiologically, color changes in tomatoes are closely related to chlorophyll degradation and the accumulation of carotenoid pigments, particularly lycopene, during the ripening and storage processes (Panebianco *et al*., 2024). Therefore, monitoring color changes can serve as an effective approach for evaluating the quality and freshness of cherry tomatoes.

Quantitative evaluation of tomato color changes is generally conducted using the CIE $L*$, $a*$, and $b*$ color system, which can objectively represent the brightness, intensity of red color, and yellowness of the fruit's surface. Several studies have reported that the $L*$, $a*$, and $b*$ parameters have a strong correlation with the level of ripeness and carotenoid pigment content in tomatoes, making them reliable indicators of postharvest quality (Saad *et al*., 2016). Furthermore, computer vision-based color analysis offers the advantage of being a non-destructive method that enables continuous quality monitoring during storage (Buitrago *et al*., 2024).

Various postharvest technologies have been developed to slow the metabolic rate and preserve the quality of tomatoes; one of these is hypobaric storage. Hypobaric storage is carried out by lowering the air pressure in the storage chamber to suppress the rate of respiration, ethylene production, and enzymatic activity, which ultimately slows down the ripening process and color degradation of the fruit (Salas-Sanjuan *et al*., 2023; Kou *et al*., 2016). Several studies have reported that storing tomatoes at subatmospheric pressure is effective in preserving color and reducing weight loss compared to normal atmospheric conditions (Muhammad *et al*., 2022; Inestroza-Lizardo *et al*., 2018).

In addition to storage pressure, the application of ozone has also been extensively studied as a supporting technology for maintaining the postharvest quality of fruits and vegetables. Ozone, whether in gaseous form or as ozonated water, is known to act as a powerful oxidizing agent that can suppress microorganisms and influence the stability of color pigments during storage (Pandiselvam *et al*., 2023; Milella *et al*., 2025). For some horticultural commodities, ozone pretreatment has been reported to slow down color changes and maintain visual quality, although its effectiveness is highly influenced by ozone concentration, application methods, and storage conditions (Ulfatimah *et al*., 2023).

However, studies that integrate ozone pretreatment with hypobaric storage and quantitatively analyze the color change dynamics of cherry tomatoes using a kinetic approach remain relatively limited. Most previous studies have focused on descriptive quality assessments, so information regarding the rate of quality changes during storage has not been comprehensively documented. Therefore, research is needed to quantitatively assess color changes and weight loss in cherry tomatoes to gain a deeper understanding of the effectiveness of this combination of technologies.

Based on this background, this study aims to evaluate the effect of a combination of ozone pretreatment and variations in hypobaric storage chamber pressure on the dynamics of color changes ($L*$, $a*$, $b*$, hue, chroma, and ΔE) as well as weight loss in cherry tomatoes during storage, using a zero-order kinetic analysis approach as the basis for assessing the rate of postharvest quality deterioration. Hypobaric storage has been shown to be effective in maintaining the quality of cherry tomatoes by slowing the rate of color change and weight loss, while the effect of ozone pretreatment is more limited compared to the effect of storage pressure.

2. MATERIALS AND METHODS

2.1. Equipment and Materials

The equipment used in this study included an ozone pretreatment unit with a capacity of 1.5 kg and dimensions of 80×70×14 cm. Ozone was generated using a generator (model PX-902), and its concentration was measured using a gas detector (Dienmern DM 509-O3). A hypobaric storage unit was used as a low-pressure storage chamber for cherry tomatoes. The unit was equipped with a storage tank, vacuum pump, vacuum control unit, valves, hoses, and clamps.

The material in this study was Sweet 100 cherry tomatoes at optimal ripeness, free from physical damage (no bruises or cuts), and of uniform size, weighing 10–15 g and measuring 1.5–3 cm in diameter. Samples were stored in a 60×42×37 cm container during the ozone treatment. The samples were placed in 2-liter Hermetico glass jars—22 cm tall, 12 cm in diameter, and with 4 mm thick glass—as treatment vessels. Color analysis was performed using a computer vision setup equipped with a Canon EOS 700D camera. Sample weight was measured using a digital scale (Fujitsu FSR-A320).

2.2. Methods

Ozone gas pretreatment was performed by placing cherry tomatoes in a sealed container and then exposing them to ozone gas generated by an ozonizer until a concentration of 4.99 ppm was reached (±4 minutes). The ozone concentration during treatment was monitored using an ozone gas detector. Ozone water pretreatment was performed by soaking the cherry tomatoes in ozonated water for 15 minutes (0.308 mg/L). After the pretreatment process was complete, the cherry tomatoes were drained and dried at room temperature before being placed in s in the hypobaric storage chamber. The pretreated cherry tomatoes were then placed in glass jars and stored in the hypobaric storage chamber at pressures of 26 kPa, 64 kPa, and 101 kPa. The application of these pressure variations was based on a study by Maharani *et al*. (2022), which reported the effectiveness of hypobaric storage for horticultural commodities (bell peppers). This pressure range was used to represent conditions ranging from low to normal pressure and to re-examine their effects on tomatoes subjected to different pretreatments, namely water and ozone gas. Storage was conducted at an average temperature of 26 ℃ with a relative humidity (RH) of 80% for all treatments throughout the storage period.

The parameters analyzed included color changes ($L*$, $a*$, $b*$, hue, chroma, and ΔE) using a computer vision setup and a Canon EOS 700D camera to capture images for color analysis. The top of the device has special holes for mounting LEDs and UV lights, while the base has a hole with a diameter matching the camera lens to ensure the camera is positioned at the optimal point. Tomato color observations were conducted on the same surface throughout storage. Images were captured using the camera and then analyzed using Python (Google Colab) to obtain the $L*$, $a*$, and $b*$ (CIELAB) values. Weight loss was measured using the gravimetric method, which compared the difference in total sample weight before and after the storage period and expressing it as a percentage of the initial weight.

The research method used a 3×3 factorial completely randomized design (CRD) with two factors, as shown in Table 1. Quality observations were conducted periodically according to pressure variations, specifically on days 0, 3, 6, 9, 12, and 15 for pressures of 26 and 64 kPa, and on days 0, 1, 3, 5, 7, and 9 for a pressure of 101 kPa. The difference in the observation periods between 101 kPa and hypobaric pressures (26 and 64 kPa) is due to the fact that at 101 kPa, the respiration rate and ethylene production in cherry tomatoes are higher, accelerating ripening and decay; therefore, observations were limited to day 9. Meanwhile, under hypobaric conditions, low pressure was found to suppress the respiration rate and slow down quality deterioration, allowing observations to be conducted for up to 15 days. Cherry tomatoes were stored in 27 glass jars for 3 replicates, with each jar containing 15 cherry tomatoes for each treatment and replicate.

Table 1. Randomized experimental design

Pretreatment	**Pressure (P)**		
	26 kPa	**64 kPa**	**101 kPa**
Control (K)	KP26	KP64	KP101
Ozone Gas (G)	GP26	GP64	GP101
Ozonated Water (A)	AP26	AP64	AP101

2.3. Test Parameters

2.3.1. Color elements *L**, *a**, *b**

Values on lightness ($L*$), degree of greenness to redness ($a*$), and degree of bluishness to yellowness ($b*$) of the samples were measured periodically during the storage period. Measurements of $L*$, $a*$, and $b*$ were performed using a computer vision method based on a digital camera. Each treatment and replicate used the same tomato throughout the storage period. Images were captured from the same area of the fruit's surface (exocarp) to ensure the accuracy of color measurements.

The data obtained was in RGB format and was then processed using the Google Colab application to generate CIE-Lab data. This method allows for non-destructive monitoring of changes in color values, enabling the quantitative observation of the development of red color intensity in cherry tomatoes during storage.

2.3.2. Hue (h°)

The hue value (which describes the color shift from green toward yellowish red during the ripening and storage processes) is calculated based on the $a*$ and $b*$ color parameters using Equation 1 (Malakar *et al*., 2020).

$$h^\circ = \arctan(b*a*) \times 57.3 \qquad (1)$$

2.3.3. Chroma

The chroma value is calculated based on the L^*, a^*, and b^* values obtained and is then used to calculate chroma using Equation 2 (Souza *et al*., 2018).

$$Chroma = \sqrt{(a^2 + b^2)} \tag{2}$$

2.3.4. Color Change (ΔE)

The average value was calculated to represent the color value of the sample. The obtained L^*, a^*, and b^* values were then used to calculate the color difference (ΔE) using Equation 3 (Li *et al*., 2022).

$$\Delta E = \sqrt{(L_0 - L)^2 + (a_0 - a)^2 + (b_0 - b)^2} \tag{3}$$

where L_0, a_0, and b_0 are the initial values of L^*, a^*, and b^*, while L, a, and b are the corresponding L^*, a^*, and b^* values at the subsequent time point.

2.3.5. Weight Loss

Weight loss in cherry tomatoes was measured using the gravimetric method, which involves comparing the difference in total sample weight before (W_1) and after (W_2) the storage period and expressing it as a percentage of the initial weight. Weight loss can be calculated using Equation 4 (Parambath *et al*., 2016; Maharani *et al*., 2019).

$$Weight\ Loss = \frac{W_1 - W_2}{W_2} \times 100\% \tag{4}$$

2.4. Data Analysis

The research results were analyzed using Principal Component Analysis (PCA) and kinetic analysis. PCA was used to analyze the correlations and variance in cherry tomato quality during storage based on color parameters, including L^*, a^*, b^*, Hue (°), Chroma, ΔE, and weight loss, using SPSS 26. Additionally, kinetic analysis was performed. Changes in cherry tomatoes based on color and weight loss were analyzed using zero-, first-, and second-order reaction rate kinetics in Equations (5), (6), and (7) (Romansyah *et al*., 2025).

$$C_t = C_0 \pm k_0.t \tag{5}$$

$$C_t = C_0.exp(\pm k_1.t) \tag{6}$$

$$C_t = \frac{C_0}{C_0.k_2.t+1} \tag{7}$$

where C_t is parameter at time t, C_0 is initial value of the parameter being tested, t is storage duration (days), k_0 is zero-order reaction rate constant, k_1 is first-order reaction rate constant, and k_2 is second-order kinetic reaction constant.

Kinetic models were used to determine the reaction rate constant (k), the coefficient of determination (R^2), the root mean square error ($RMSE$), and X^2 in equations (8), (9), and (10) as indicators of model fit (Maharani *et al*., 2024).

$$R^2 = \left(\frac{\sum X_{i,exp}.X_{i,pre}}{\sqrt{\left(\sum X_{i,exp^2}\right).\left(\sum X_{i,pre^2}\right)}}\right)^2 \tag{8}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(X_{i,exp} - X_{i,pre})^2\right] \tag{9}$$

$$X^2 = \frac{(X_{i,exp} - X_{i,pre})^2}{X_{i,pre}} \tag{10}$$

where subscript *exp* is for experiment and *pre* is for prediction.

Table 2. Kinetic parameters for the changes of tomatoes' color elements during storage at different pretreatment and pressure

Parameter	Order	Pretreatment	Pressure	Model	k (/day)	R^2	RMSE	PE (%)	X^2
ΔE	0	Control	26 kPa	E(t) = 8.61 – 0.265 t	0.265	0.983	1.33	2.61	1.96
			64 kPa	E(t) = 5.06 + 0.308 t	0.308	0.965	1.47	3.44	1.55
			101 kPa	E(t) = 7.14 – 0.703 t	0.703	0.881	1.77	5.27	17.98
		Ozone Gas	26 kPa	E(t) = 6.71 – 0.119 t	0.119	0.956	1.12	3.05	1.42
			64 kPa	E(t) = 5.21 + 0.057 t	0.057	0.971	0.90	2.67	0.84
			101 kPa	E(t) = 5.22 – 0.117 t	0.117	0.979	0.73	1.90	0.72
		Ozonated Water	26 kPa	E(t) = 7.15 + 0.308 t	0.308	0.994	1.67	3.56	1.66
			64 kPa	E(t) = 4.02-0.144 t	0.144	0.953	1.28	4.67	3.76
			101 kPa	E(t) = 6.43 + 0.122 t	0.122	0.998	0.38	0.80	0.12
Hue	0	Control	26 kPa	Hue(t) = 39.54 + 0.097 t	0.097	0.999	0.36	0.11	0.01
			64 kPa	Hue(t) = 39.54 + 0.165 t	0.165	0.999	0.47	0.16	0.03
			101 kPa	Hue(t) = 39.54 – 0.021 t	0.021	0.999	0.50	0.16	0.03
		Ozone Gas	26 kPa	Hue(t) = 39.54 + 0.131 t	0.131	0.999	1.16	0.28	0.20
			64 kPa	Hue(t) = 39.54 + 0.204 t	0.204	0.999	0.42	0.22	0.06
			101 kPa	Hue(t) = 39.54 + 0.119 t	0.119	0.999	0.22	0.07	0.007
		Ozonated Water	26 kPa	Hue(t) = 39.54 + 0.113 t	0.113	0.999	1.05	0.37	0.16
			64 kPa	Hue(t) = 39.54 + 0.129 t	0.129	0.999	0.89	0.29	0.11
			101 kPa	Hue(t) = 39.54 + 0.137 t	0.137	0.999	0.17	0.05	0.004
Chroma	0	Control	26 kPa	Chroma(t) = 63.49 – 0.001 t	0.001	0.999	1.66	0.31	0.26
			64 kPa	Chroma(t) = 63.49 + 0.503 t	0.503	0.999	2.06	0.35	0.37
			101 kPa	Chroma(t) = 63.49 – 0.090 t	0.090	0.998	2.26	0.43	0.48
		Ozone Gas	26 kPa	Chroma(t) = 63.49 + 0.108 t	0.108	0.999	1.70	0.32	0.27
			64 kPa	Chroma(t) = 63.49 + 0.270 t	0.270	0.998	2.51	0.50	0.56
			101 kPa	Chroma(t) = 63.49 + 0.392 t	0.392	0.999	1.23	0.24	0.13
		Ozonated Water	26 kPa	Chroma(t) = 63.49 – 0.098 t	0.098	0.998	2.36	0.54	0.53
			64 kPa	Chroma(t) = 63.49 – 0.044 t	0.044	0.999	1.08	0.21	0.11
			101 kPa	Chroma(t) = 63.49 + 0.524 t	0.524	0.999	1.25	0.26	0.14
L	0	Control	26 kPa	L(t) = 0.19 + 0.675 t	0.675	0.920	3.31	70.38	11.09
			64 kPa	L(t) = 0.31 + 0.739 t	0.739	0.928	3.61	55.68	11.76
			101 kPa	L(t) = 0.96 + 1.860 t	1.860	0.994	5.10	15.77	12.54
		Ozone Gas	26 kPa	L(t) =0.14 + 0.387 t	0.387	0.907	1.94	54.00	6.54
			64 kPa	L(t) = 0.27 + 0.403 t	0.403	0.911	1.39	32.88	4.04
			101 kPa	L(t) = 0.59 + 1.266 t	1.266	0.992	3.52	17.61	9.07
		Ozonated Water	26 kPa	L(t) = 0.15 + 0.568 t	0.568	0.906	2.83	69.59	9.68
			64 kPa	L(t) = 0.29 + 0.643 t	0.643	0.9279	3.14	62.50	10.13
			101 kPa	L(t) = 0.83 + 1.739 t	1.739	0.991	4.88	18.55	12.93
L*	0	Control	26 kPa	L*(t) = 29.52 + 0.055 t	0.055	0.999	0.86	0.41	0.15
			64 kPa	L*(t) = 29.52 + 0.297 t	0.297	0.998	1.25	0.47	0.30
			101 kPa	L*(t) = 29.52 + 0.120 t	0.120	0.998	1.36	0.55	0.37
		Ozone Gas	26 kPa	L*(t) = 29.52 + 0.088 t	0.088	0.997	1.65	0.58	0.55
			64 kPa	L*(t) = 29.52 – 0.241 t	0.241	0.997	1.69	0.71	0.55
			101 kPa	L*(t) = 29.52 + 0.368 t	0.368	0.999	0.94	0.42	0.17
		Ozonated Water	26 kPa	L*(t) = 29.52 + 0.029 t	0.029	0.997	1.63	0.77	0.53
			64 kPa	L*(t) = 29.52 – 0.7694 t	0.079	0.999	1.02	0.39	0.21
			101 kPa	L*(t) = 29.52 + 0.492 t	0.492	0.999	0.92	0.38	0.16
a*	0	Control	26 kPa	a*(t) = 48.97 + 0.057 t	0.057	0.999	0.19	0.05	0.004
			64 kPa	a*(t) = 48.97 + 0.367 t	0.367	0.999	1.03	0.24	0.12
			101 kPa	a*(t) = 48.97 + 0.354 t	0.354	0.999	0.41	0.08	0.02
		Ozone Gas	26 kPa	a*(t) = 48.97 + 0.117 t	0.117	0.999	0.11	0.03	0.001
			64 kPa	a*(t))= 48.97 + 0.169 t	0.169	0.999	0.89	0.25	0.09
			101 kPa	a*(t) = 48.97 + 0.140 t	0.140	0.999	0.76	0.21	0.07
		Ozonated Water	26 kPa	a*(t) = 48.97 + 0.084 t	0.084	0.999	0.12	0.03	0.002
			64 kPa	a*(t) = 48.97 – 0.066 t	0.066	0.999	0.47	0.13	0.03
			101 kPa	a*(t) = 48.97 + 0.226 t	0.226	0.999	0.77	0.22	0.07
b*	0	Control	26 kPa	b*(t) = 40.39 + 0.434 t	0.434	0.998	1.72	0.51	0.41
			64 kPa	b*(t) = 40.39 + 0.496 t	0.496	0.998	1.56	0.46	0.33
			101 kPa	b*(t) = 40.39 + 0.718 t	0.718	0.999	0.82	0.25	0.09
		Ozone Gas	26 kPa	b*(t) = 40.39 + 0.524 t	0.524	0.998	1.81	0.49	0.45
			64 kPa	b*(t) = 40.39 + 0.468 t	0.468	0.998	1.58	0.46	0.35
			101 kPa	b*(t) = 40.39 + 0.574 t	0.574	0.999	0.52	0.16	0.04
		Ozonated Water	26 kPa	b*(t) = 40.39 + 0.357 t	0.357	0.999	1.14	0.32	0.19
			64 kPa	b*(t) = 40.39 + 0.276 t	0.276	0.999	0.97	0.28	0.13
			101 kPa	b*(t) = 40.39 + 0.661 t	0.661	0.999	0.73	0.21	0.07

3. RESULTS AND DISCUSSION

3.1. General Interpretation of Kinetic Data

Table 2 presents the results of the kinetic analysis of quality changes in cherry tomatoes during storage under various combinations of ozone pretreatment and storage chamber pressure. The data on total color change (Δ*E*), *L**, *a**, *b**, hue, chroma, and weight loss obtained exhibit characteristics consistent with a zero-order reaction, resulting in the reaction rate constant (*k*), coefficient of determination (R^2), root mean square error (*RMSE*), and X^2 values shown in Table 2. The zero-order kinetic model was selected based on the relatively high values of the coefficient of determination (R^2), along with low values for the root mean square error (*RMSE*), percentage of error (*PE*), and chi-square (X^2). The higher the R^2 value (close to one) the greater the effect (Maharani *et al*., 2024).

Changes in *L**, *a**, *b**, hue, and chroma are represented by a zero-order relationship because the rate of change in lycopene pigment during ripening is constant and is controlled by physiological activity rather than the pigment concentration itself. Furthermore, weight loss follows a zero-order model because water loss occurs at a constant rate due to transpiration rather than the concentration of components within the fruit, resulting in a linear relationship between weight loss and storage time. Previous research by Li *et al*. (2022) also indicated that Δ*E* and weight loss were modeled as zero-order processes during the storage of shiitake mushrooms. Furthermore, since the initial value of Δ*E* is 0, the zero-order model is most appropriate for describing color changes during storage. The interpretation of the data in the table provides a comprehensive overview of the effects of ozone pretreatment and storage pressure on color changes in cherry tomatoes during the storage period.

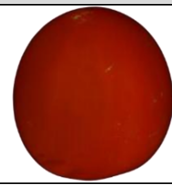
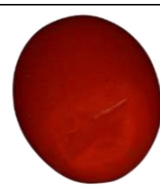
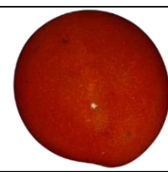
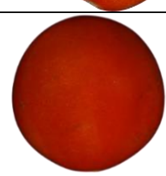
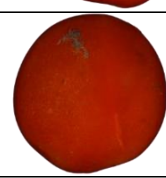
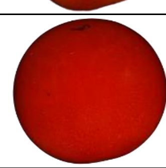
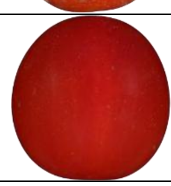
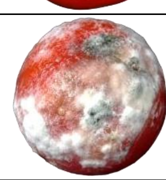
Based on the kinetic data in Table 2, all observed cherry tomato quality parameters—including total color change (Δ*E*), *L**, *a**, *b**, hue (*h*°), chroma, and weight loss—show a good fit to the zero-order kinetic model with high coefficient of determination (R^2) values approaching 1. This indicates that changes in cherry tomato quality during storage occur linearly with time. The relatively small model error, as indicated by low RMSE and PE values, reinforces the model's validity in describing the rate of quality change across various treatment variations.

Differences in the reaction rate constant (*k*) values among treatments indicate that storage pressure is the most dominant factor in controlling the rate of quality change in cherry tomatoes. In general, storage at low pressures (26 and 64 kPa) resulted in smaller *k* values for nearly all color parameters compared to normal atmospheric pressure (101 kPa), indicating a slower rate of color degradation, accumulation of carotenoid pigments, and color hue stability during storage. These conditions are reflected in the Δ*E*, *L**, *a**, and *b** values, which change more slowly under hypobaric pressure, indicating that reduced pressure is effective in suppressing the rate of respiration and metabolic activity in the fruit.

Meanwhile, the hue value (h°) showed relatively small changes across all treatment variations, as indicated by a low *k* value. This suggests that the hue direction of cherry tomatoes remained within the red ripeness zone throughout storage. This indicates that the color changes that occurred were dominated by changes in color intensity (lightness and darkness) rather than shifts in hue direction. The chroma values show that low pressure is able to maintain color saturation more stably, whereas a pressure of 101 kPa tends to accelerate changes in color intensity. The weight loss of cherry tomatoes during storage follows zero-order kinetics with a high R^2 value, where storage pressure is the most dominant factor, as indicated by the highest rate constant (*k*) value at 101 kPa across all pretreatments, while the combination of hypobaric pressure (particularly 26 kPa) with ozone gas pretreatment resulted in the lowest *k* value, making it the most effective at suppressing the rate of weight loss, consistent with the quality control patterns observed in other color parameters. The results of the study indicate that cherry tomatoes treated with ozone and stored under hypobaric conditions at 26 kPa were able to extend their shelf life to 43 days, whereas cherry tomatoes treated with ozone and stored under hypobaric conditions at 64 kPa lasted for 28 days. Meanwhile, cherry tomatoes treated with ozone and stored at 101 kPa (control) lasted only 9 days in storage. A visual comparison of cherry tomatoes before and after hypobaric storage is shown in Table 3.

The effect of ozone pretreatment, whether in the form of gaseous ozone or ozonated water, is more selective and relatively smaller than the effect of storage pressure. For several parameters, particularly Δ*E*, *L**, and *a**, the combination of ozone pretreatment with hypobaric pressure showed lower *k* values compared to the control. Lower *k* values not only indicate a slower rate of quality change but also a decrease in fruit metabolic activity, such as respiration

Table 3. Visual changes of cherry tomatoes under hypobaric conditions (26 kPa, 64 kPa, and 101 kPa)

Treatment	Duration of Hypobaric Storage (days)			
	0	9	28	43
Ozonated water 26 kPa				
Ozone gas 26 kPa				
Control 26 kPa				
Ozonated water 64 kPa				-
Ozone gas 64 kPa				-
Control 64 kPa				-
Ozonated water 101 kPa			-	-
Ozone gas 101 kPa			-	-
Control 101 kPa			-	-

and ethylene production. These conditions inhibit the enzymatic activities involved in chlorophyll degradation and carotenoid synthesis, thereby slowing down the ripening process and color changes. However, the overall kinetic results indicate that controlling storage pressure is the primary factor in maintaining the visual quality of cherry tomatoes during storage, while ozone pretreatment serves as a supplementary treatment.

3.2. Lightness (L^*)

The L^* value parameter in the CIE-Lab color system is used to represent the brightness of the cherry tomato surface, where a decrease or increase in this value is associated with changes in light reflectance intensity due to color degradation and the accumulation of carotenoid pigments (Peralta-Ruiz *et al*., 2020). Changes in the L^* value can be seen in Figure 1, which shows that the L^* value across all treatments tended to increase during the early storage phase (days 3 through 6), then gradually decreased until the end of storage. At 64 kPa, in both the ozone gas, ozonated water, and control treatments, L^* values were relatively higher and more stable compared to 101 kPa, particularly during the middle to late stages of storage. Conversely, at 101 kPa, the faster decline in L^* values in some treatments indicated accelerated color changes leading to ripening. This is consistent with the concept that color changes during the ripening and storage of tomatoes affect color parameters, including the L^* value. Previous studies have shown that color changes in tomatoes during storage involve both chlorophyll degradation and the accumulation of carotenoid pigments such as lycopene and β-carotene, which affect the L^* value and overall color hue (Loayza *et al*., 2021).

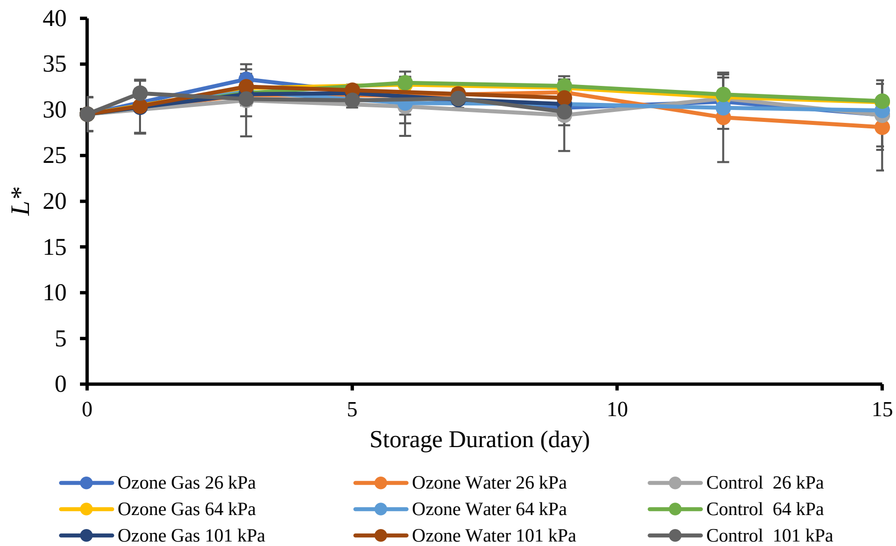


Figure 1. Effect of treatment on the changes of L^* values of cherry tomatoes during storage

Based on the kinetic results in Table 2, changes in the L^* value of cherry tomatoes during storage followed a zero-order reaction model with a relatively high coefficient of determination (R^2) across all pressure treatments, including the control and those treated with ozone gas and ozonated water. The reaction rate constant (k) values showed clear differences among the pressure treatments, with the 101 kPa ozone gas treatment generally exhibiting a higher k value compared to the 26 kPa and 64 kPa treatments (specifically 0.4929) indicating a faster rate of brightness change. This finding is consistent with the L^* graph, which shows an earlier change at 101 kPa, while at lower pressures, changes in L^* values occur more slowly and tend to remain stable until the end of storage. This indicates that low pressure can slow down changes in the structure and composition of the surface pigments of cherry tomatoes, thereby allowing visual brightness to be maintained longer during storage.

3.3. Redness (a^*)

Figure 2 shows a graph of the a^* values, which indicates that the a^* values for all treatment variations increased from an initial value of 49–50 to a peak value in the range of 51–53 on days 4–8 of storage, particularly in the 64 kPa pressure control treatment, which showed the most significant increase compared to the other treatments. The increase in a^* values indicates a shift in fruit color from green to red, which is a characteristic indicator of cherry tomato ripening. This supports the literature indicating that a^* increases significantly as tomatoes undergo color degradation and lycopene pigment synthesis during the ripening process (Panebianco *et al*., 2024). Changes in the a^* value were relatively stable or decreased slightly after reaching a peak in the middle of the storage period, indicating that most of the red color development had concluded by that phase. Previous studies have also shown that the a^* value increases during tomato ripening and storage, indicating the development of red color, which is an important parameter for assessing fruit ripeness and visual appeal (Park *et al*., 2018).

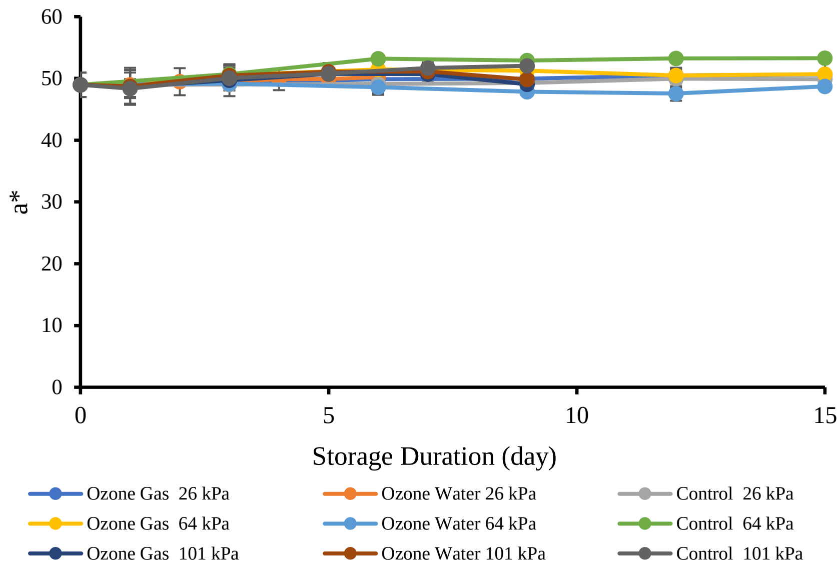


Figure 2. Effect of treatment on the changes of a^* values of cherry tomatoes during storage

Based on the kinetic results in Table 2, the a^* parameter, which represents the intensity of the red color, also shows a good fit to the zero-order kinetic model. The value of the rate constant (k) for a^* was relatively higher in the 64 kPa control treatment, at 0.3674, indicating accelerated red color formation compared to the 26 kPa control treatment, which had a k value of 0.0579. These results indicate that ozone pretreatment did not have a significant effect on changes in the a^* value (Kou *et al*., 2016).

3.4. Yellowness (b^*)

The b^* value in the CIE-Lab color system represents a shift in color from blue toward yellow. Figure 3 shows a graph of b^* values over the storage period, revealing an upward trend from the initial values in all treatments through days 4 to 6, followed by stabilization or a slight decrease toward the end of the observation period. An increase in the b^* value indicates a tendency for the yellow color component to increase during the early stages of storage. In the context of ozonation, this change may be caused by ozone-induced oxidation of green pigments (chlorophyll), resulting in a yellow color (positive b^* component), which has frequently been reported in some fruits and vegetables during storage (Milella *et al*., 2025).

Based on the kinetic results in Table 2, the change in the b^* value indicates that this parameter also follows a zero-order reaction, with high R^2 values across all pressure and pretreatment variations. The reaction rate constant b^* tended to increase in the control treatments at 64 kPa and 101 kPa, reaching 0.4962 and 0.7184, respectively, indicating an increase in yellow color intensity during storage. This pattern is consistent with the b^* graph, where the b^* value increased during the middle phase of storage before fluctuating. Changes in the b^* value are related to the transformation of non-lycopene carotenoid pigments and a shift in hue from pure red to yellowish red, which is common in cherry tomatoes during further ripening and storage (Panebianco *et al*., 2024).

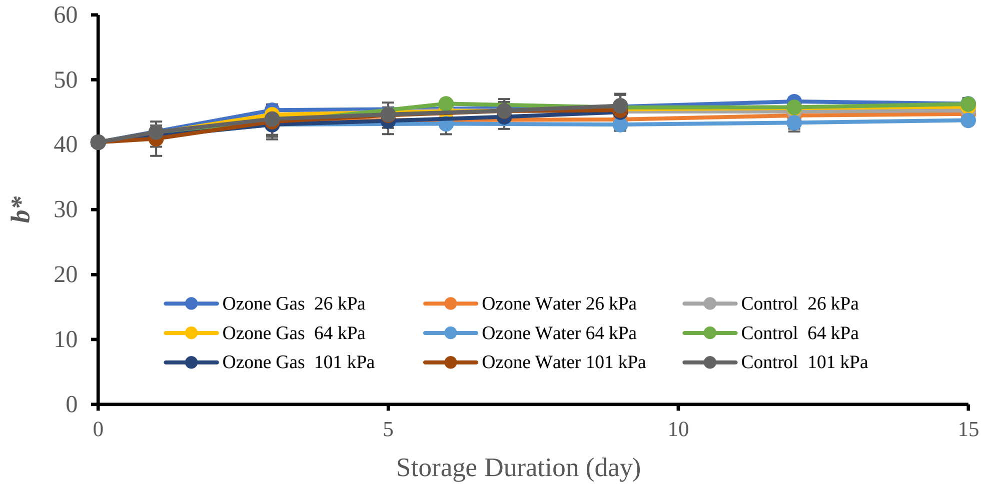


Figure 3. Effect of treatment on the changes of *b** values of cherry tomatoes during storage

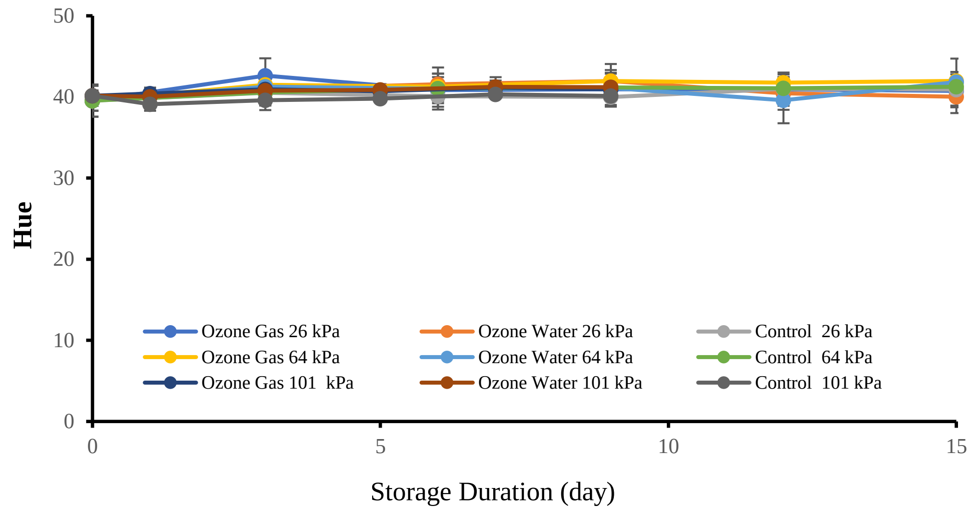


Figure 4. Effect of treatment on the changes of hue (*h*°) values of cherry tomatoes during storage

3.5. Hue angle (*h*°)

The hue angle value graph shown in Figure 4 reveals that ozone treatment at a pressure of 101 kPa exhibited a more stable trend of increasing hue values compared to the control group over the period from day 0 to day 15. This suggests that ozone treatment can moderate changes in hue during storage. In contrast, the control at 26 kPa showed a more pronounced decrease in hue values, which may reflect the degradation of natural green pigments due to oxidative processes and tissue metabolism not controlled by additional oxidizing agents. This is consistent with previous research indicating that ozone possesses high oxidative activity capable of affecting color pigments such as carotenoids; in some cases, this can slow color changes or even maintain visual brightness during storage, depending on the concentration and duration of ozone exposure (Pandiselvam *et al*., 2023).

Based on the kinetic results in Table 2, the hue angle (°) value showed relative stability during storage, as evidenced by the low kinetic rate value of 0.113 for the 26 kPa ozone water pretreatment treatment and a high R^2 value of 0.9999, indicating that the hue of the cherry tomatoes remained within the red ripeness zone throughout the entire period. The relatively stable hue graph supports this finding, showing that although the *L**, *a**, and *b** values changed, the direction of the fruit's hue shift remained constant in line with the progression of ripening. This is consistent with the findings of

Nakashima *et al*. (2023), who stated that in the late ripening phase of tomatoes, color changes are more reflected in intensity ($L*$ and $a*$) than in hue shifts.

3.6. Chroma

Chroma describes the intensity of a food product's color. As the chroma value increases, the color becomes brighter; conversely, a decrease in chroma indicates a faded color (Song *et al*., 2024). Changes in chroma values are shown in Figure 5. The chroma values of cherry tomatoes during 9 and 15 days of storage showed a decrease on days 3.5 and 6, particularly in the 101 kPa and 64 kPa control treatments (black and gray lines). Subsequently, the values increased on days 9 and 12 for low-pressure treatments such as 26 kPa gas (yellow) and 26 kPa water (light blue), while the control values remained below 65. This indicates that hypobaric storage at 26 kPa and 64 kPa stabilizes color saturation by slowing chlorophyll degradation and maximizing lycopene biosynthesis, resulting in higher chroma values compared to normal atmospheric conditions at the end of storage (Maryam *et al*., 2022).

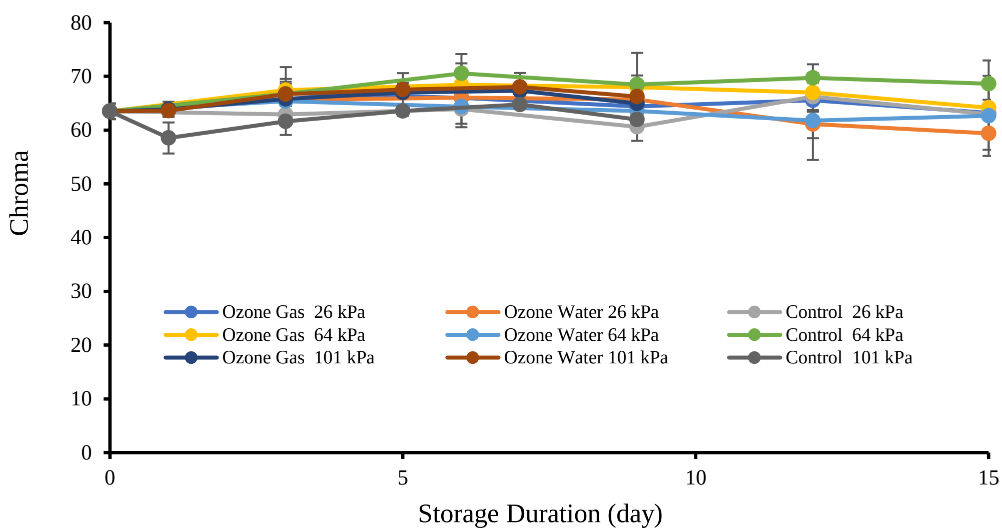


Figure 4. Effect of treatment on the changes of chroma values of cherry tomatoes during storage

Based on the kinetic data in Table 2, it can be seen that cherry tomatoes stored at pressures of 26 kPa (control) and 64 kPa (ozonated water) exhibited slower changes in chroma, with k values of 0.0012 and 0.0445, respectively. Furthermore, cherry tomatoes pretreated with ozonated water and stored at a pressure of 101 kPa exhibited the fastest change in chroma, with a k value of 0.246. These kinetic results indicate that ozone pretreatment does not have a significant effect on changes in chroma compared to pressure treatment. According to a study (Kou *et al*., 2016), hypobaric conditions can slow down the activity of enzymes involved in chlorophyll degradation and lycopene synthesis, so that the color change from green to red occurs more slowly and the chroma value remains relatively stable during storage.

3.7. Color Change (Δ*E*)

Figure 6 shows the changes in ΔE values for cherry tomatoes from day 0 to day 15 across several treatment variations and ripeness levels. On day 0, all lines start at 0, indicating that the color of the cherry tomatoes on the first day of storage had not yet changed, so this was used as a reference point. In general, almost all ΔE curves increased sharply from day 0 to day 3 or day 6, indicating a fairly clear color change due to the ripening process. Cherry tomatoes stored at pressures of 26 and 64 kPa exhibited lower average color changes, with values ranging from 2.6 to 6.85, compared to cherry tomatoes stored at a pressure of 101 kPa. These color change values indicate that storing cherry tomatoes at low pressures (26 and 64 kPa) slows down pigment degradation and the ripening process, preventing rapid changes in the color of the cherry tomato skin. Based on the study by Muhammad *et al*. (2022), hypobaric storage at pressures of 40 and 50 kPa for tomatoes was able to produce a synergistic effect in maintaining quality compared to the control treatment, particularly in preserving color quality.

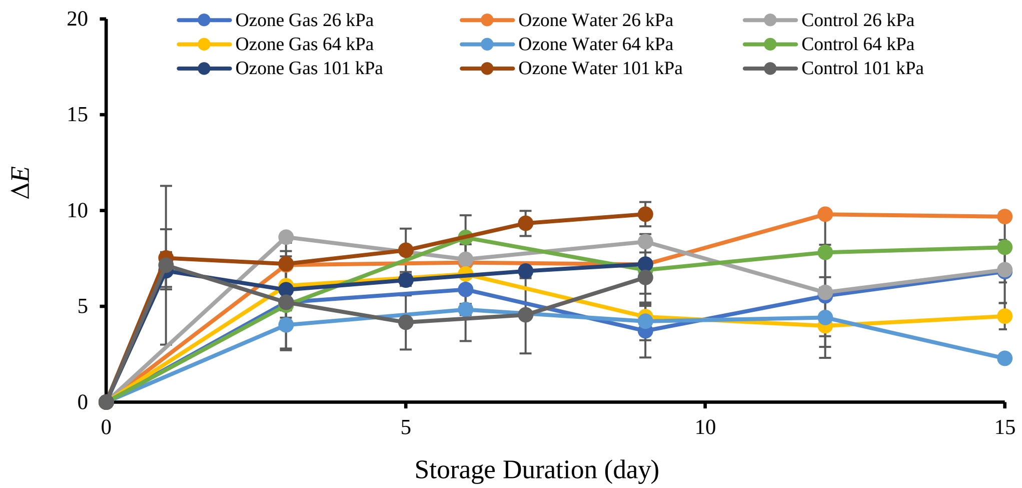


Figure 6. Effect of treatment on the color change (Δ*E*) of cherry tomatoes during storage

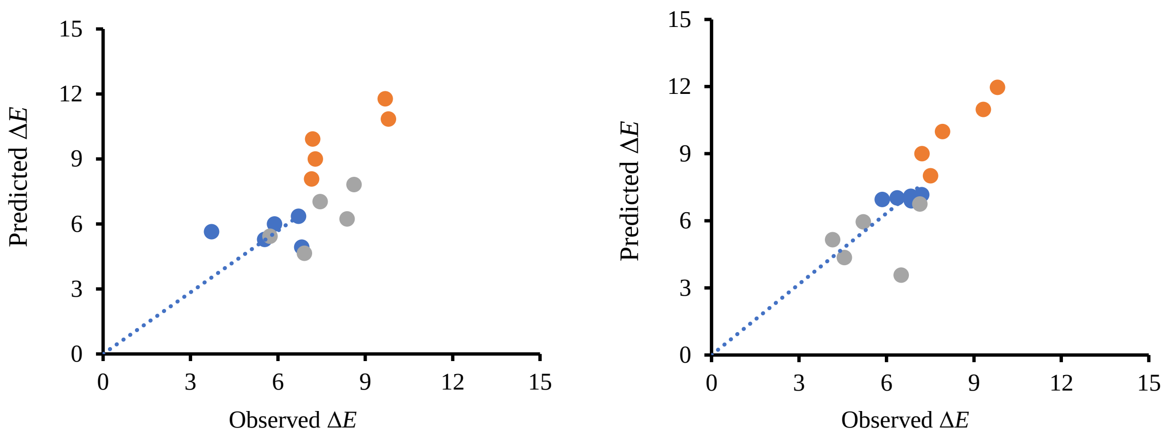


Figure 7. Validation plots of Δ*E* for cherry tomatoes during hypobaric storage at: (a) 26 kPa, and (b) 101 kPa

Based on the results of the kinetic analysis in Table 2, it can be seen that cherry tomatoes stored at a pressure of 101 kPa exhibited a faster change in the Δ*E* value compared to cherry tomatoes stored at pressures of 26 and 64 kPa. Furthermore, cherry tomatoes pretreated with ozone and stored at a pressure of 64 kPa exhibited the slowest change in Δ*E* with the lowest *k* value of 0.057. These results demonstrate that the application of 64 kPa hypobaric pressure combined with ozone creates optimal storage conditions for minimizing ethylene metabolism, thereby slowing the kinetic parameters of color change and minimizing color changes. These results are consistent with those of Pristijono *et al*. (2017), who reported that low-pressure storage of tomatoes reduced calyx browning by 12.5%. To evaluate the equations presented in Table 1, a test was conducted using observed data via R^2 validation.

The graphs in Figures 7 show that the average regression coefficient (R^2) exceeds 0.8811. This indicates that the obtained model equation is highly capable of predicting the decline in cherry tomato quality during storage. The results of this study indicate that storage using the ozone pretreatment method and hypobaric conditions is effective in maintaining cherry tomato quality.

3.8. Weight Loss

Weight loss during storage decreased to 9.43% on the last day of storage. The increase in weight loss was largely due to high transpiration rates. In each treatment, there was a corresponding increase in weight loss, as tomatoes are fruits with a climacteric respiration pattern. Climacteric fruits are those that experience a sharp increase in respiration and ethylene production after harvest (Ghasemi & Chayjan, 2019). The highest weight loss was observed in the 101 kPa control treatment, suggesting that high pressure can mitigate weight loss more effectively than low pressure (Maharani *et al*., 2019). This can be seen in Figure 7, which shows that weight loss increases with storage time across all treatments, though at different rates and magnitudes depending on the type of pretreatment and pressure used. From day 0 to day 3, weight loss remained relatively low in all treatments, indicating that water loss and respiratory activity were still limited. From day 6 to day 9, the increase in weight loss became more pronounced, particularly in the control treatment, regardless of the pressure (26, 64, or 101 kPa). This indicates that without pretreatment, the material loses water more rapidly due to uninhibited transpiration and respiratory activity (Ulfatimah *et al*., 2023). The gas treatment at 26 kPa showed the lowest weight loss compared to the water treatment and the control group at the same pressure until the end of storage. This suggests that the gas treatment at 26 kPa effectively suppressed the rate of respiration and water evaporation from the material's tissue, thereby minimizing weight loss. The control treatment, on the other hand, showed the highest weight loss, particularly at a pressure of 101 kPa, indicating that high pressure can accelerate physiological degradation and water loss.

Based on the kinetic data in Table 2, it can be seen that cherry tomatoes stored with ozone gas pretreatment at a pressure of 26 kPa experienced a slower rate of weight loss, with a k value of 0.3873. Conversely, cherry tomatoes without ozone pretreatment, and at a pressure of 101 kPa experienced the fastest rate of weight loss, with a k value of 1.860. The low pressure of 26 kPa inhibits the rates of respiration and transpiration by reducing the oxygen concentration around the product, while ozone gas pretreatment can reduce water vapor permeability (Kan *et al*., 2025). Conversely, at 101 kPa without ozone, high oxygen availability enhances respiratory activity, resulting in water loss with a k value nearly five times higher. These results indicate that combining ozone pretreatment with hypobaric storage can minimize weight loss in cherry tomatoes during storage. To evaluate the equations presented in Table 1, tests were conducted using observed data via R^2 validation. The closer the R^2value is to 1, the stronger the effect (Maharani *et al*., 2024).

Based on the validation graph in Figure 9, the average regression coefficient (R^2) exceeds 0.9072. This indicates that the obtained model equation is capable of predicting the decline in cherry tomato quality during storage with maximum accuracy. The results of this study show that storage using the ozone pretreatment method and hypobaric conditions can maintain the quality of cherry tomatoes.

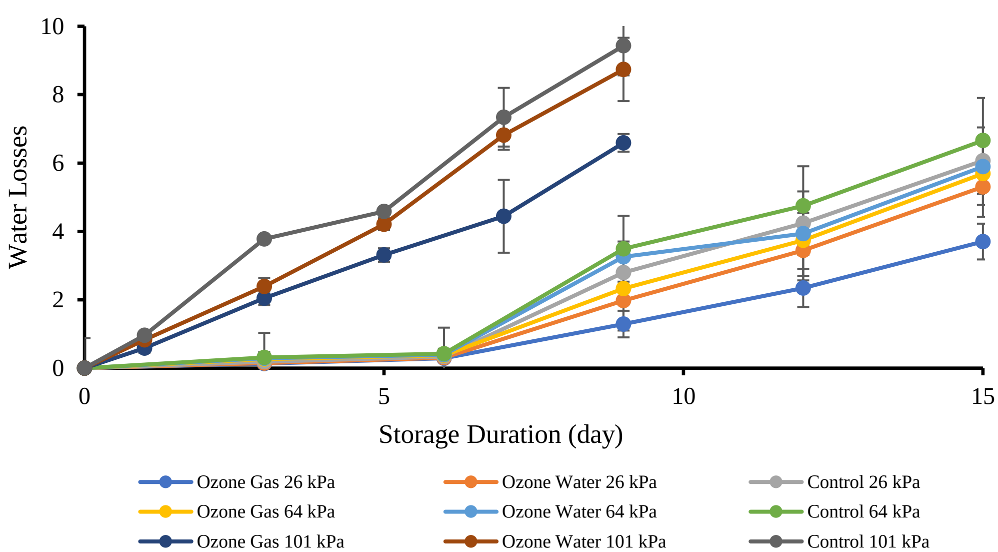


Figure 8. Effect of ozone treatment and pressure on the weight loss of cherry tomatoes during storage

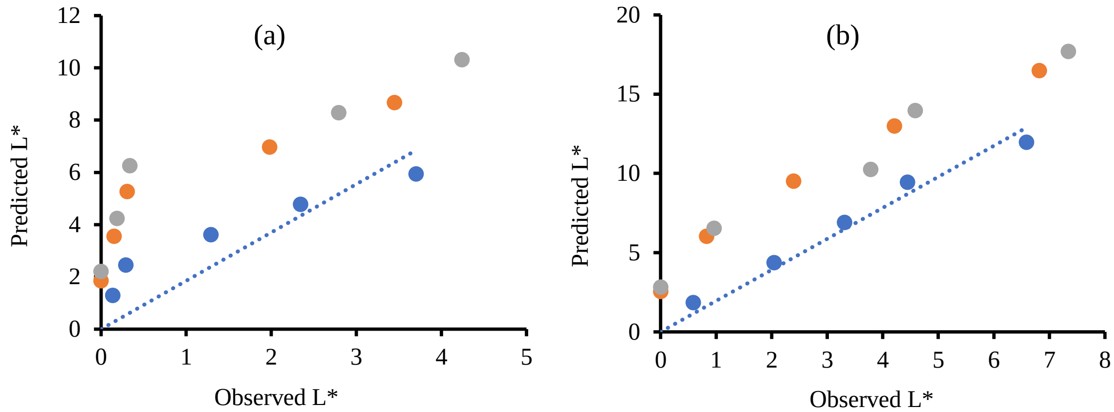


Figure 9. Validation graph of cherry tomato weight loss during hypobaric storage at: (a) 26 kPa pressure, (b) 101 kPa pressure

3.9. Interpretation and Visualization of PCA Analysis

Principal Component Analysis (PCA) is a multivariate statistical method for simplifying complex variable structures by transforming a set of strongly correlated variables into independent principal components (Rodrigues *et al*., 2021). The parameters analyzed include *L*, *a**, *b**, hue, chroma, color difference (ΔE), and weight loss. Based on the results of the Anti-image Matrices test, the parameters *L**, *a**, *b**, hue, and chroma meet the requirements for use in PCA factor analysis. The requirement that must be met in factor analysis is a Measure of Sampling Adequacy (MSA) value > 0.50. Therefore, the PCA loading plot shown in Figure 10 and the PCA score plot shown in Figure 9 were obtained.

Figure 10 shows the contributions of the five color parameter variables analyzed to the principal components PC1 (59.759%) and PC2 (38.210%). These two principal components explain 97.969% of the total data variability, indicating that this two-dimensional representation is highly effective in describing the variation in color characteristics of tomato samples treated with ozone pretreatment and hypobaric pressure. The component plot in Figure 10 shows the positions of the main color parameters, namely Hue, Chroma, and the *L**, *a**, and *b** parameters. The Hue parameter is located in the upper right quadrant with high coordinates on both PC1 and PC2, indicating that this parameter has a strong positive correlation with both principal components. This suggests that ozone and hypobaric pressure pretreatment significantly influence changes in the product's base color.

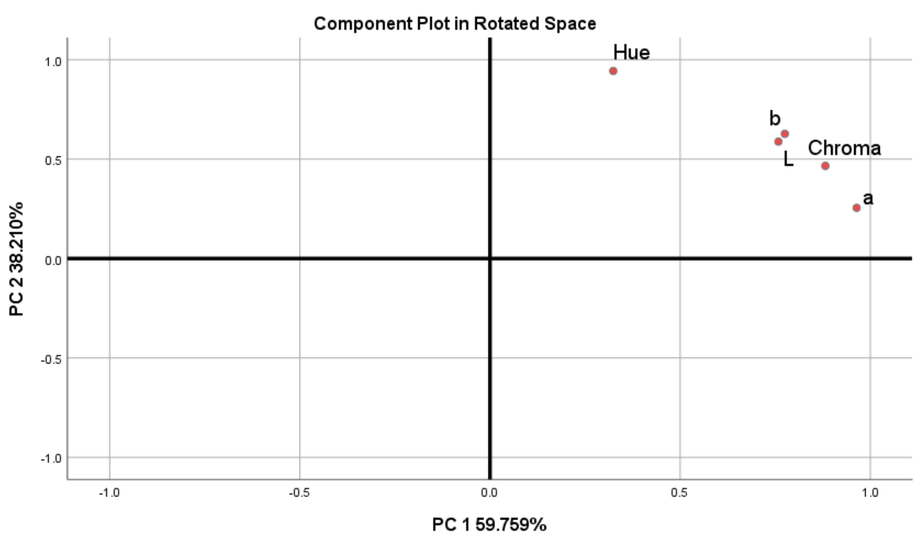


Figure 10. PCA loading plot

The Chroma and $b*$ parameters are located close together in the right quadrant with high PC1 values but relatively moderate PC2 values, indicating that these two parameters share similar characteristics. Meanwhile, the $L*$ (lightness) parameter is positioned separately from the other color parameters, suggesting that changes in luminance are governed by a different mechanism in response to the combination of ozone pretreatment and hypobaric pressure. The distance between parameters on this biplot reflects the relationships among them; parameters that are close together tend to exhibit similar patterns of change. The $a*$ parameter is located in the right quadrant with very high PC1 coordinates, indicating that color shifts toward red-green are highly sensitive to variations in the applied treatments.

The PCA score plot in Figure 11 represents the distribution of tomato samples with various combinations of ozone pretreatment and hypobaric pressure treatments. The distribution pattern of the samples shows clustering based on pressure levels, indicating that the hypobaric pressure parameter has a significant effect on the color characteristics of the samples. Samples at 26 kPa (A1P26, A2P26, A3P26, G1P26, G2P26, G3P26, K1P26, K2P26, K3P26) are distributed from the upper-left to the middle quadrant, with some samples exhibiting high factor scores on the vertical axis. Meanwhile, samples subjected to pressures of 64 kPa and 101 kPa are located lower on the vertical axis, indicating distinct color characteristics compared to the low-pressure group.

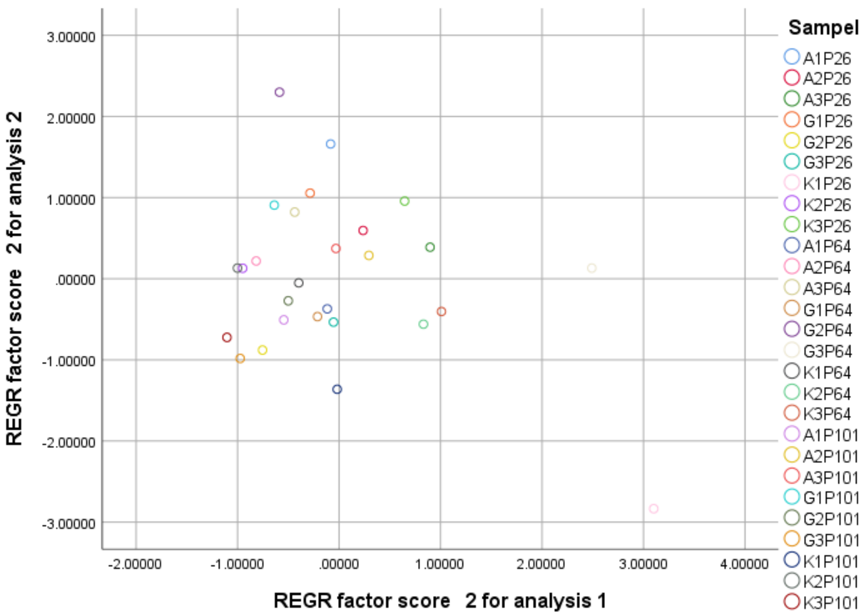


Figure 11. PCA score plot

The horizontal axis (REGR factor score 1) shows differences related to the degree of pigment degradation and overall color intensity, while the vertical axis (REGR factor score 2) indicates changes in brightness and yellowness. Sample A1P26, located at the top of the plot, exhibits the highest brightness value, indicating that the combination of ozone water pretreatment at 26 kPa produces the brightest-colored product. In contrast, several samples treated at 101 kPa, such as A2P10, are located in the lower quadrant, indicating lower brightness and greater color changes.

These results suggest that lower hypobaric pressure tends to be more effective in maintaining tomato color quality during ozone pretreatment. These findings are consistent with those of Maharani *et al*. (2022), who found that ozone pretreatment combined with low pressure can better preserve the color difference values of the samples. A storage pressure of 26 kPa was found to be most effective in slowing down changes in color difference compared to 64 kPa and 101 kPa.

The novelty of this research lies in the integration of ozone pretreatment and hypobaric storage for cherry tomatoes, which was quantitatively analyzed using a quality change kinetics approach. Unlike previous studies that generally evaluated quality descriptively, this study provides insight into the rate of quality degradation through kinetic parameters and integrates Principal Component Analysis to identify the interrelationships between parameters and storage conditions. The findings contribute to identifying a hypobaric pressure of 26 kPa as the most effective condition for delaying quality deterioration and extending the shelf life of cherry tomatoes up to 43 days, thereby establishing a scientific foundation for developing hypobaric storage strategies combined with ozone pretreatment.

4. CONCLUSIONS AND RECOMMENDATIONS

Pretreatment and hypobaric storage affect changes in the quality of cherry tomatoes during storage. Hypobaric storage, particularly at a pressure of 26 kPa, is effective in slowing down quality deterioration. Cherry tomatoes treated with ozone and stored under hypobaric conditions at 26 kPa can extend their shelf life up to 43 days, whereas cherry tomatoes treated with ozone and stored under hypobaric conditions at 64 kPa last for 28 days. Meanwhile, cherry tomatoes treated with ozone and stored under hypobaric conditions at 101 kPa (control) lasted only 9 days in storage. The combination of low pressure and ozone pretreatment showed the best performance in maintaining quality and has the potential to extend shelf life. Additionally, PCA analysis results showed a total variation of 97.969%, indicating a strong relationship among quality parameters.

AUTHOR CONTRIBUTION

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
DMM	✓	✓		✓	✓	✓		✓		✓		✓		✓
AR			✓		✓		✓		✓		✓		✓	
KRP									✓				✓	
DS						✓		✓						
LCH						✓		✓						

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

During the preparation of this work, the authors used Claude AI to assist in identifying relevant journal articles and improving sentences that were not appropriately worded. After using this tool/service, the authors reviewed and edited the content as necessary and take full responsibility for the content of the publication.

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