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Kinetics modelling of physicochemical properties and shelf-life assessment of fresh cayenne pepper (*Capsicum frutescens* L.) under modified atmosphere packaging (MAP)

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Abstract

The physicochemical properties of fresh agricultural products must be evaluated to facilitate the design of modified atmosphere packaging (MAP), and to determine product shelf-life. The present work thus aimed to kinetically evaluate the physicochemical properties, and assess the shelf-life of fresh cayenne pepper stored under MAP conditions. Polyethylene (PE) packaging films with thicknesses of 30, 50, and 80 µm, along with storage temperatures of 5, 15, and 28°C, were investigated. Fresh cayenne pepper was used as the sample, and its physicochemical properties—including colour difference (ΔE), weight loss (WL), pH, soluble solid content (SSC), and vitamin C content—were evaluated as quality parameters. The results indicated that changes in ΔE and WL followed zero-order kinetics, while pH, SSC, and vitamin C content followed first-order kinetics. Storage temperature had a more significant impact on the shelf-life of cayenne pepper than the thickness of the plastic packaging. The longest shelf-life was observed with MAP storage using a 50 µm film at 5°C, extending up to 21 days—approximately four times longer than the control.

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Introduction

The demand for cayenne pepper in Indonesia is high, and has steadily increased over the past few years (Munarso *et al*., 2020). According to the Food and Agricultural Organization of the United Nations (FAO, 2020), Indonesia is the world's fourth-largest producer of cayenne pepper. In Indonesia, cayenne pepper is harvested only once a year or seasonally, yet it is consumed daily. This seasonal production significantly affects price fluctuations, and has even been identified as one of the contributing factors to inflation in Indonesia in March 2021. According to the Indonesian National Strategic Food Price Information Center (PIHPSN, 2023), from January 2021 to September 2023, the monthly average price of cayenne pepper ranged from IDR 36,750 to 96,150 ($2.40 - 6.27). The highest prices typically occur in March due to a cayenne pepper shortage, while the lowest prices are recorded in September, when several regions begin their harvest season. To maintain price stability, it is advisable to store cayenne pepper during the harvest season, and release it during the off-season. However, after harvest, cayenne pepper is highly susceptible to rapid quality deterioration and spoilage due to wilting, pathogen invasion, weight loss, and other factors resulting from improper postharvest handling (Hameed *et al*., 2015).

One approach to extend the shelf-life of fresh agricultural products is modified atmosphere packaging (MAP). Several studies have demonstrated that MAP can effectively preserve the quality of fresh produce when the optimal gas composition and film permeability are appropriately designed (Chitravathi *et al*., 2015; Sahoo *et al*., 2015; Belay *et al*., 2016; Mahajan and Lee, 2023). The application of MAP for fruits and vegetables has shown considerable promise due to its low cost, simplicity, and potential benefits. Öztürk and Ağlar (2019) reported that MAP is an effective technique for preventing postharvest quality losses in kiwifruit. Although the MAP industry has expanded its range of packaging film options, most packaging is still produced using four primary polymers, one of which is polyethylene (PE)

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(Mangaraj *et al*., 2009). Various studies on MAP with different focuses have been conducted globally. For instance, Caner *et al*. (2008) used low-density polyethylene (LDPE) film as packaging material for fresh strawberries, and found it to be the most effective in inhibiting the respiration rate. Ding *et al*. (2002) reported that PE with a thickness of 20 µm resulted in the highest chemical quality score for loquat fruit (*Eriobotrya japonica* Lindl. cv. Mogi). Manolopoulou *et al*. (2010) demonstrated that green peppers (*Capsicum annuum* L. cv. Twingo F1) stored in PE packaging maintained ascorbic acid content during storage. Additionally, Tripetch and Borompichaichartkul (2019) found that PE packaging effectively preserved colour, water content, total phenolics, chlorogenic acid, and antioxidant activity in dried green Arabica coffee (*Coffea arabica* L.) beans over 15 months of storage.

In addition, low storage temperatures can effectively maintain the quality of fresh produce. Low-temperature storage is widely recognised as the most effective method for preserving the postharvest quality of horticultural crops, and remains the most commonly used postharvest technology (Endo *et al*., 2019; Imahori *et al*., 2021; Kantakhoo *et al*., 2022). Furthermore, cold temperatures significantly slow the rate of various metabolic processes, thereby extending the shelf-life of horticultural crops (Imahori *et al*., 2008; Li *et al*., 2016). Therefore, to achieve dual benefits, MAP should be combined with low-temperature storage. However, it is crucial to investigate the various changes in the quality parameters of agricultural products during MAP storage at low temperatures to facilitate a comprehensive understanding for optimal MAP packaging design.

Kinetics analysis is widely used to model changes in the quality parameters of agricultural products during storage. Sapei and Hwa (2014) state that quality changes during storage can be analysed using kinetic models. The application of this analysis has been extensively conducted on various agricultural products. For example, Ali *et al*. (2023) applied kinetics analysis to strawberries (*Fragaria* × *ananassa* Duchesne), Mohd Ali *et al*. (2022) to pineapples (*Ananas comosus* (L.) Merr.), Al-Dairi and Pathare (2021) to tomatoes (*Solanum lycopersicum* L.), Anoraga and Bintoro (2022) to fresh snake fruit (*Salacca zalacca* (Gaertn.) Voss), Vicent *et al*. (2018) to apple (*Malus domestica* (Suckow) Borkh.) tissue during frozen storage, and Mai and Huynh (2017) to *Pangasius* fillets. In kinetics analysis, the primary objective is to determine the rate constant (k) for a given quality parameter over time. A higher rate constant indicates a faster rate of change for that parameter, and vice versa. Temperature is one of the key factors influencing the rate constant. Several studies have reported that the rate constant increases with increasing temperatures across various agricultural products (Albarici *et al*., 2012; Buvé *et al*., 2018; Fatharani and Bintoro, 2019; Kim *et al*., 2022). Therefore, by applying kinetics analysis to different quality parameters of agricultural products, it is possible to determine the rate of change for each parameter, and identify which parameters change most rapidly or slowly. This analysis also enables the development of predictive equations to estimate changes in product quality over time, making it highly useful for monitoring and predicting quality degradation during MAP storage.

To evaluate the effect of temperature on the rate constant, the Arrhenius equation is commonly employed. The Arrhenius equation is used to quantify the impact of temperature on the quality changes of agricultural products (Gonçalves *et al*., 2007). Specifically, it helps determine the activation energy (Ea) and the pre-exponential constant (A) for a given quality parameter at varying temperatures. This approach has been widely applied to agricultural products stored under different MAP conditions. For instance, Choi *et al*. (2017) used the Arrhenius equation for semi-dried persimmons, Fatharani and Bintoro (2019) for sugar palm fruit, Ancheta *et al*. (2020) for *batuan* (*Garcinia binucao* (Blanco) Choisy), Darniadi *et al*. (2021) for freeze-dried durian (*Durio zibethinus* L.), Li *et al*. (2022) for shiitake (*Lentinula edodes* (Berk.) Pegler) mushrooms, Kim *et al*. (2022) for rice (*Oryza sativa* L.), and Choosuk *et al*. (2022) for dried coconut (*Cocos nucifera* L.) chips.

The combination of kinetics and Arrhenius analysis is widely used to determine the storage time or shelf-life of a product through the accelerated shelf-life test (ASLT). The ASLT method has been extensively applied to estimate the shelf-life of various agricultural products during storage. Calligaris *et al*. (2019) used ASLT to estimate the shelf-life of extra virgin olive oil, Indra Purnama *et al*. (2023) for black and *cahyo* garlic chili sauce, Hayati *et al*. (2022) for *kawista* fruit salad, Bilbie (2022) for a new dry snack food product, Brilian *et* *al*. (2023) for *beluntas* leaves and seaweed, and Rahmadani *et al*. (2023) for snakehead fish dispersion products. Thus, by applying kinetics analysis and the Arrhenius equation, it is possible to determine the rate of change in product quality parameters and estimate the product's shelf-life. The availability of mathematical models allows for the prediction of quality changes and shelf-life without the need for direct measurements. Herregods (1995) states that mathematical modelling of MAP can help determine the optimal storage duration, minimise losses, and achieve a balance between cost and benefit. Therefore, the objective of the present work was to analyse physicochemical changes kinetically, and determine the shelf-life of fresh cayenne pepper during MAP storage under varying storage temperatures and plastic film thicknesses.

Materials and methods

Materials

The present work utilised fresh cayenne peppers of the CRC 212 variety at the mature stage as the sample. Visually, the peppers were orange at this stage, and turned red upon full ripening. The peppers were purchased directly from local farmers in Kalasan, Yogyakarta, Indonesia. Upon arrival at the laboratory, they were washed under running water to remove impurities, and then air-dried. The peppers were subsequently sorted and cleaned, ensuring that only fresh, uniform peppers—free from blemishes and consistent in colour and size—were used in the present work. Polyethylene (PE) plastic films measuring 20 × 30 cm with three different thicknesses—30, 50, and 80 µm—were used as packaging materials. The permeability coefficients of the plastic films to oxygen and carbon dioxide were 1.67769E-15 and 3.59327E-15, 2.39902E-15 and 4.55851E-15, and 2.86979E-15 and 5.17129E-15 mol/m.s.Pa for thicknesses of 30, 50, and 80 µm, respectively. Under MAP at ambient temperature, these films produced constant oxygen and carbon dioxide concentrations within the packages of 3.00 and 6.03%, 2.05 and 7.58%, and 0.58 and 12.65% for film thicknesses of 30, 50, and 80 µm, respectively. Additional materials used in the present work included distilled water and ascorbic acid, which were required for the analysis of vitamin C content in the samples. All materials were obtained from suppliers in Yogyakarta, Indonesia.

Methods

Each PE plastic film was filled with 200 g of fresh cayenne peppers. The packages were then stored at three different temperatures: 5°C, 15°C, and ambient tropical room temperature, which averaged at 28°C. As a control, a conventional unpackaged storage method at ambient room temperature was also prepared. The physicochemical properties of the samples, including colour difference (ΔE), weight loss (WL), pH, soluble solid content (SSC), and vitamin C content, were measured daily over a 15-d storage period. However, for samples stored at 28°C, observations were conducted only until d 7, as the cayenne peppers deteriorated beyond usability after this period.

ΔE measurement

Colour measurements were expressed as CIE L*, a*, and b* values. Measurements were conducted using a portable colorimeter (SU, 3NH SC-10) under consistent lighting conditions. The colour of the same cayenne pepper sample was measured at the same point throughout the storage period by marking a location near the measurement area. Each treatment was measured three times using different cayenne pepper samples, and the results were averaged to obtain a representative colour value. This approach ensured that the measurement results objectively and accurately reflected the colour condition of the cayenne peppers. The L*, a*, and b* values represented lightness, redness, and yellowness, respectively (Malakar *et al*., 2020). The colour difference (ΔE) was calculated from these values using Eq. 1. ΔE was selected as the colour parameter because it exhibited the most consistent changes during the storage period.

$$\Delta E = \sqrt{(L_0 - L)^2 + (a_o - a)^2 + (b_0 - b)^2} \quad \text{(Eq. 1)}$$

where, L_o, a_o, and b_o = initial values of L^*, a^*, and b^*, respectively, while L, a, and b = corresponding values at subsequent time points.

Weight loss measurement

The weight of fresh cayenne pepper samples from each package was recorded daily to monitor weight changes. A digital scale (Fujitsu FS-AR210, accuracy 0.1 mg) was used for this measurement. Measurements were conducted daily for 15 d, with three replications for each treatment, and means were obtained and reported. The percentage of weight loss (WL) was determined using Eq. 2 (Caleb *et al*., 2013; Devgan *et al*., 2019):

$$WL(\%) = \left(\frac{W_0 - W_t}{W_0}\right) x\ 100\% \quad \text{(Eq. 2)}$$

where, W_0 and W_t = initial sample weight and sample weight on subsequent days, respectively, in gram (g).

pH measurement

The pH of the samples was determined following the method proposed by Ali *et al*. (2014). A total of 10 g of cayenne pepper was homogenised with 90 mL of distilled water using an electric blender (Miyako BL-152 PF-AP). The mixture was then filtered using Whatman No. 40 filter paper. The pH of the filtrate was then measured using a digital pH meter (Toledo FP 20). Measurements were conducted daily for 15 d, with three replications for each treatment, and means were obtained and reported.

Soluble solid content measurement

The soluble solid content (SSC) was expressed as degrees Brix (°Brix), and measured using a digital refractometer (ATAGO, PAL-α). For this measurement, 10 g of cayenne pepper was compressed using a clamp to extract the liquid, which was then homogenised. A single drop of the extracted liquid was placed onto the refractometer's sensor glass for measurement (Ali *et al*., 2014; Han *et al*., 2017). Measurements were conducted daily for 15 d, with three replications for each treatment, and means were obtained and reported.

Vitamin C measurement

The vitamin C content of the sample was quantified using the spectrophotometric method, following the procedures described by Desai and Desai (2019) and Riscahyani *et al*. (2019). The measurement process began with the preparation of a 100 ppm vitamin C solution. A standard calibration curve was created using 4, 8, 12, 16, and 20 ppm ascorbic acid solutions prepared from the 100 ppm stock solution. For sample preparation, 2.5 g of crushed cayenne pepper was placed into a 50-mL volumetric flask, and distilled water was added up to the mark. The mixture was then homogenised and filtered. Subsequently, 35 mL of the filtrate was transferred into another 50-mL volumetric flask, and distilled water was added up to the mark. Absorption measurements were taken at the maximum wavelength using a spectrophotometer (GENESYS 10 UV-Vis). The absorbance was recorded at 265 nm, and the measurement was performed daily for 15 d, with three replications for each treatment, and means were obtained and reported. The vitamin C content was estimated using the calibration curve equation (Eq. 3):

$$Y = 0.0557x + 0.114 \quad R^2 = 0.9797 \quad \text{(Eq. 3)}$$

The total vitamin C content, expressed as a percentage (w/w), was calculated using Eq. 4:

$$Total\ Vitamin\ C = \frac{Y - 0.114}{0.0557}\ x\ FP \quad \text{(Eq. 4)}$$

The percentage of vitamin C was then calculated using Eq. 5, as described by Vikram *et al*. (2005).

$$Vitamin\ C\ (\%) = \frac{m\ Vitamin\ C}{m\ sample}\ x\ 100\% \quad \text{(Eq. 5)}$$

where, *Y* = absorbance value, *FP* = dilution factor, and *m* = mass of the sample in grams (g).

Data analysis

The collected data from this experiment were analysed using kinetics equations to determine the rate of quality change in cayenne pepper. The shelf-life of the cayenne pepper samples was assessed using the ASLT method based on the Arrhenius equation.

Kinetics analysis and modelling

The changes in ΔE, WL, pH, SSC, and vitamin C content of the cayenne pepper samples under MAP were analysed by applying zero-, first-, and second-order kinetic models, as expressed in Eqs. (6), (7), and (8), respectively (Vikram *et al*., 2005; Gonçalves *et al*., 2007; Ansari *et al*., 2014):

Zero-order kinetics:

$$C_t = C_0 \pm k_0 . t \quad \text{(Eq. 6)}$$

First-order kinetics:

$$C_t = C_0 . exp^{(\pm k_1 . t)} \quad \text{(Eq. 7)}$$

Second-order kinetics:

$$C_t = \frac{C_0}{C_0 . k_2 . t + 1} \quad \text{(Eq. 8)}$$

where, Co and Ct = quality parameter of the sample at the initial time and at any time t during storage, respectively (expressed in C units); t = storage time (days), while k_0, k_1, and k_2 = rate constants of quality change for zero-, first-, and second-order kinetics, respectively (expressed in C unit.day^{-1}, day^{-1}, and C unit^{-1}.day^{-1}).

The accuracy of the kinetics models was validated against the experimental data by calculating the coefficient of determination (R^2), root mean squared error (RMSE), and chi-squared (χ^2) as shown in Eqs. (9), (10), and (11), respectively (Gomez and Gomez, 1983; Doymaz, 2013; Ansari *et al.*, 2015; Park *et al.*, 2023):

$$R^2 = \left(\frac{\sum X_{i,exp} . X_{i,pre}}{\sqrt{(\sum X_{i,exp}{}^2)(\sum X_{i,pre}{}^2)}} \right)^2 \quad \text{(Eq. 9)}$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} \left(X_{i,exp} - X_{i,pre} \right)^2 \right] \quad \text{(Eq. 10)}$$

$$\chi^2 = \frac{\left(X_{i,exp} - X_{i,pre} \right)^2}{X_{i,pre}} \quad \text{(Eq. 11)}$$

where, $X_{i,exp}$ and $X_{i,pre}$ = experimental and predicted values, respectively, and N = number of observations.

Shelf-life assessment

The shelf-life of fresh cayenne pepper was assessed using the Arrhenius equation (Eq. 12). By rearranging this equation and substituting it into Eqs. (6), (7), and (8), the shelf-life (t) was determined using Eqs. (13), (14), and (15) for zero-, first-, and second-order kinetics, respectively:

$$k = A \ x \ exp^{\left(-\frac{E_a}{RT} \right)} \quad \text{(Eq. 12)}$$

Shelf-life for zero-order kinetics:

$$t = \frac{C_t - C_0}{\left(\text{A}.e^{-\frac{Ea}{R} \cdot \frac{1}{T}} \right)} \quad \text{(Eq. 13)}$$

Shelf-life for first-order kinetics:

$$t = \frac{Ln \ (C_t / C_0)}{\left(\text{A}.e^{-\frac{Ea}{R} \cdot \frac{1}{T}} \right)} \quad \text{(Eq. 14)}$$

Shelf-life for second-order kinetics:

$$t = \frac{(C_0 - C_t)}{C_t . C_0 . \left(\text{A}.e^{-\frac{Ea}{R} \cdot \frac{1}{T}} \right)} \quad \text{(Eq. 15)}$$

where, A = pre-exponential factor (expressed in C unit.day^{-1}, day^{-1}, and C unit^{-1}.day^{-1} for zero-, first-, and second-order kinetics, respectively), Ea = activation energy (cal.mol^{-1}), R = gas constant (1.987 cal.mol^{-1}.K^{-1}), and T = storage temperature (K).

Results and discussion

Kinetics analysis and modelling

In the present work, kinetics analysis was conducted on the values of ΔE, WL, pH, SSC, and vitamin C of cayenne pepper samples during storage. Zero-, first-, and second-order kinetics equations were applied to these five parameters. The most appropriate kinetics model was selected based on the values of R^2, RMSE, and χ^2. The optimal kinetics order was determined as the model with the highest R^2 value and the lowest RMSE and χ^2 values (Roberts *et al.*, 2008; Yalçınöz and Erçelebi, 2017).

Colour difference (ΔE)

Figure 1 presents the ΔE values of cayenne pepper samples at the three studied storage temperatures. It was observed that ΔE consistently increased over time, indicating that the difference between the initial surface colour of the cayenne pepper and its subsequent colour became more pronounced. Al-Dairi and Pathare (2021) found a significant increase in the ΔE of stored tomatoes, while Bhanushree *et al.* (2018) reported a similar trend in papaya fruit, both coated and uncoated with chitosan. This colour change was attributed to alterations in various pigments, primarily due to chlorophyll degradation, which occurs simultaneously with the induction of carotenoid synthesis (Solovchenko *et al.*, 2006).

The ΔE value at a storage temperature of 5°C was lower than those at 15 and 28°C. However, at 15 and 28°C, the ΔE values were approximately the same. In general, an increase in storage temperature resulted in a higher ΔE value, indicating that cayenne pepper colour changed more rapidly at higher temperatures. A similar phenomenon was observed in lettuce and broccoli (Manolopoulou and Varzakas, 2016). Vicent *et al.* (2018) also stated that the colour change in apple tissue accelerated with increasing storage temperature. Regarding the effect of plastic film thickness, it was found that at storage temperatures of 5 and 15°C, polyethylene (PE) film with a thickness of 50 µm resulted in the lowest ΔE

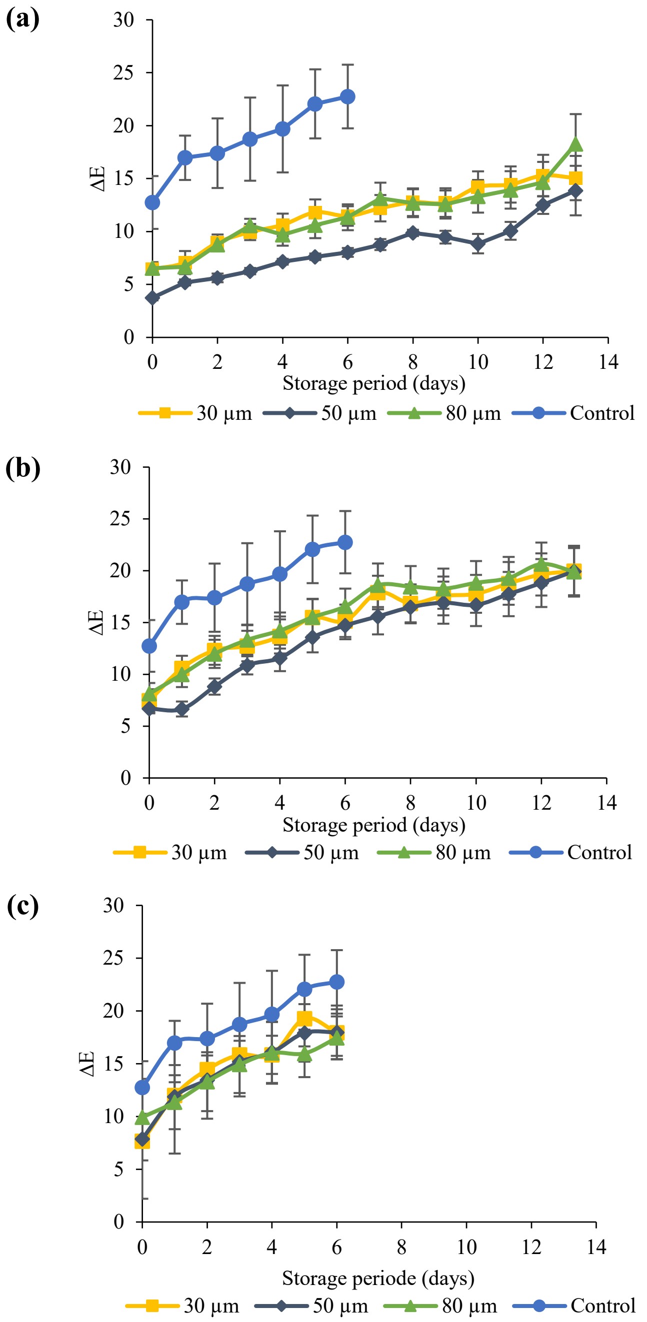

Figure 1. Colour changes in fresh cayenne pepper samples during storage at **(a)** 5°C, **(b)** 15°C, and **(c)** 28°C.

value compared to films of 30 and 80 µm. This suggests that 50-µm PE film provided the optimal O_2 and CO_2 exchange rate between the packaging and the external environment, best supporting the respiration process of cayenne pepper. Conversely, films with thicknesses of 30 and 80 µm resulted in exchange rates that were too high and too low, respectively, for the respiration needs of the cayenne pepper. Cia *et al.* (2006) reported that LDPE film with a thickness of 50 µm was suitable for packaging 'Fuyu' persimmon fruit. Similarly, Panda *et al.*, (2016) found that 50-µm LDPE packaging film was the most effective in preserving the organoleptic properties of strawberries. The control treatment consistently produced the highest ΔE values across all storage temperatures, indicating that plastic film packaging was effective in preserving the colour of cayenne pepper. Devgan *et al.* (2019) reported that MAP was beneficial in maintaining the quality attributes of yellow bell peppers, including colour stability. Additionally, Malakar *et al.* (2020) found that changes in the total colour difference of king chilies were slower under MAP conditions compared to unpackaged samples.

The observed ΔE values were analysed using zero-, first-, and second-order kinetics models. The results indicated that the colour change in cayenne pepper was best described by a zero-order kinetic model (Table 1). Similar findings have been reported for mushrooms (Li *et al.*, 2022), mangoes (Corzo and Álvarez, 2014), honey (Bulut and Kilic, 2009), dried basil (Demirhan and Özbek, 2009), and celery leaves (Demirhan and Özbek, 2011). Additionally, the rate constant (k) consistently increased with increasing storage temperature, indicating that the rate of ΔE change accelerated at higher temperatures. Regarding the relationship between k values and plastic film thickness, the results generally showed that thicker plastic packaging led to lower k values, further supporting its role in preserving cayenne pepper colour.

Weight loss (WL)

Figure 2 presents the weight loss of cayenne pepper samples at the three studied storage temperatures. It was observed that weight loss increased with storage time across all treatments. This indicates that the decrease in sample weight during storage was due to water evaporation from the cayenne pepper samples. At the same storage temperature, the control consistently exhibited the greatest weight loss compared to storage under MAP. This suggests that plastic packaging effectively reduced weight loss in cayenne pepper samples. The lower weight loss in MAP was likely due to the reduced difference in water vapour pressure between the product and the surrounding air, leading to lower water evaporation (Öztürk and Ağlar, 2019). The thickness of the plastic packaging also influenced weight loss; however, the effect was not substantial.

Table 1. Order and *k* values of cayenne pepper samples' quality parameters.

Parameter	Order	Plastic film thickness (µm)	Storage temperature (°C)	k	Kinetics model	R^2	RMSE	χ^2
ΔE	Zero	30	5	0.8437 ± 0.2849	$C_{\Delta E} = 0.8437t + 6.44$	0.9942	0.9946	1.0761
			15	1.2374 ± 0.3089	$C_{\Delta E} = 1.2374t + 7.45$	0.9868	1.8381	3.1842
			28	2.6503 ± 0.3951	$C_{\Delta E} = 2.6503t + 7.65$	0.9810	1.7310	2.2302
		50	5	0.7684 ± 0.1130	$C_{\Delta E} = 0.7684t + 3.75$	0.9911	0.9598	1.2787
			15	1.215 ± 0.3200	$C_{\Delta E} = 1.2150t + 6.69$	0.9947	1.3212	1.4429
			28	2.4606 ± 0.5472	$C_{\Delta E} = 2.4606t + 7.88$	0.9881	1.4716	1.6321
		80	5	0.8557 ± 0.2876	$C_{\Delta E} = 0.8557t + 6.54$	0.9931	1.1259	1.3789
			15	1.2423 ± 0.3461	$C_{\Delta E} = 1.2423t + 8.13$	0.9892	1.7588	2.3688
			28	1.6985 ± 0.2449	$C_{\Delta E} = 1.6985t + 9.93$	0.9960	0.9560	0.7165
		Control	28	2.2686 ± 0.4171	$C_{\Delta E} = 2.2689t + 12.75$	0.9940	1.3194	1.1595
WL	Zero	30	5	0.3784 ± 0.0228	$C_{WL} = 0.3784t + 1.02$	0.9981	0.3374	0.4303
			15	0.4400 ± 0.0409	$C_{WL} = 0.4401t + 0.92$	0.9990	0.3794	0.5244
			28	0.5840 ± 0.0539	$C_{WL} = 0.584t + 1.17$	0.9986	0.3153	0.4082
		50	5	0.4135 ± 0.0280	$C_{WL} = 0.4135t + 0.92$	0.9973	0.3893	0.6032
			15	0.3264 ± 0.0206	$C_{WL} = 0.3264t + 0.94$	0.9980	0.2760	0.2651
			28	0.3504 ± 0,0115	$C_{WL} = 0.3504t + 1.05$	0.9978	0.1972	0.2342
		80	5	0.3473 ± 0.0110	$C_{WL} = 0.3473t + 0.87$	0.9985	0.3100	0.4401
			15	0.3426 ± 0.0179	$C_{WL} = 0.3426t + 0.96$	0.9953	0.3663	0.6581
			28	0.3909 ± 0.0506	$C_{WL} = 0.3909t + 0.95$	0.9983	0.2201	0.2940
		Control	28	7.2929 ± 0.5029	$C_{WL} = 7.293t + 9.16$	0.9987	3.8447	5.2012
pH	First	30	5	-0.0026 ± 0.0163	$C_{pH} = 4.33exp^{(-0.0026t)}$	0.9976	0.2281	0.1906
			15	-0.0014 ± 0.0163	$C_{pH} = 4.33exp^{(-0.0014t)}$	0.9677	0.2252	0.1841
			28	0.0208 ± 0.0269	$C_{pH} = 4.33exp^{(0.0208t)}$	0.9995	0.1022	0.0188
		50	5	-0.0026 ± 0.0162	$C_{pH} = 4.33exp^{(-0.0026t)}$	0.9978	0.2213	0.1790
			15	-0.0016 ± 0.0156	$C_{pH} = 4.33exp^{(-0.0016t)}$	0.9977	0.2257	0.1840
			28	0.0231 ± 0.0270	$C_{pH} = 4.33exp^{(0.0231t)}$	0.9996	0.1012	0.0183
		80	5	-0.0018 ± 0.0164	$C_{pH} = 4.33exp^{(-0.0018t)}$	0.9974	0.2422	0.2136
			15	-0.0002 ± 0.0161	$C_{pH} = 4.33exp^{(-0.0002t)}$	0.9975	0.2354	0.1989
			28	0.0214 ± 0.0271	$C_{pH} = 4.33exp^{(0.0214t)}$	0.9990	0.1125	0.0226
		Control	28	0.0215 ± 0.0254	$C_{pH} = 4.33exp^{(0.0215t)}$	0.9990	0.0109	0.0213
SSC	First	30	5	0.0175 ± 0.0072	$C_{SSC} = 5.56exp^{(0.0175t)}$	0.9928	0.5553	0.7624
			15	0.0163 ± 0.0055	$C_{SSC} = 5.56exp^{(0.0163t)}$	0.9928	0.5449	0.7177
			28	0.0268 ± 0.0119	$C_{SSC} = 5.56exp^{(0.0268t)}$	0.9981	0.2723	0.0956
		50	5	0.0224 ± 0.0102	$C_{SSC} = 5.56exp^{(0.0224t)}$	0.9921	0.6323	0.9285
			15	0.0196 ± 0.0090	$C_{SSC} = 5.56exp^{(0.0196t)}$	0.9933	0.5635	0.7593
			28	0.0225 ± 0.0143	$C_{SSC} = 5.56exp^{(0.0225t)}$	0.9909	0.5938	0.4873
		80	5	0.0253 ± 0.0103	$C_{SSC} = 5.56exp^{(0.0253t)}$	0.9916	0.6391	0.8947
			15	0.0197 ± 0.0096	$C_{SSC} = 5.56exp^{(0.0197t)}$	0.9947	0.4713	0.5384
			28	0.0286 ± 0.0127	$C_{SSC} = 5.56exp^{(0.0286t)}$	0.9950	0.4665	0.2927
		Control	28	0.0587 ± 0.0132	$C_{SSC} = 5.56exp^{(0.0587t)}$	0.9930	0.6155	0.4401

		30	5	0.1597 ± 0.1226	$C_{Vit\ C} = 1.05exp^{(0.1597t)}$	0.9040	3.5001	15.954
			15	0.1682 ± 0.1213	$C_{Vit\ C} = 1.05exp^{(0.1682t)}$	0.8844	4.0830	22.0451
			28	0.2443 ± 0.2821	$C_{Vit\ C} = 1.05exp^{(0.2443t)}$	0.9533	2.0123	3.1532
		50	5	0.1614 ± 0.1149	$C_{Vit\ C} = 1.05exp^{(0.1614t)}$	0.8601	4.5471	19.2047
Vitamin C	First		15	0.1821 ± 0.1200	$C_{Vit\ C} = 1.05exp^{(0.1821t)}$	0.8769	4.9315	14.6496
			28	0.2982 ± 0.2449	$C_{Vit\ C} = 1.05exp^{(0.2982t)}$	0.9253	2.7932	7.1197
		80	5	0.1682 ± 0.1213	$C_{Vit\ C} = 1.05exp^{(0.1682t)}$	0.8865	4.1135	15.7495
			15	0.1703 ± 0.1195	$C_{Vit\ C} = 1.05exp^{(0.1703t)}$	0.8623	4.8402	26.6136
			28	0.1900 ± 0.2866	$C_{Vit\ C} = 1.05exp^{(0.1900t)}$	0.8355	3.7149	15.6028
		Control	28	0.3082 ± 0.2190	$C_{Vit\ C} = 1.05exp^{(0.3082t)}$	0.9545	2.1124	5.1715

Unit of A is C unit.day^{-1} and day^{-1} for zero and first order kinetics, respectively.

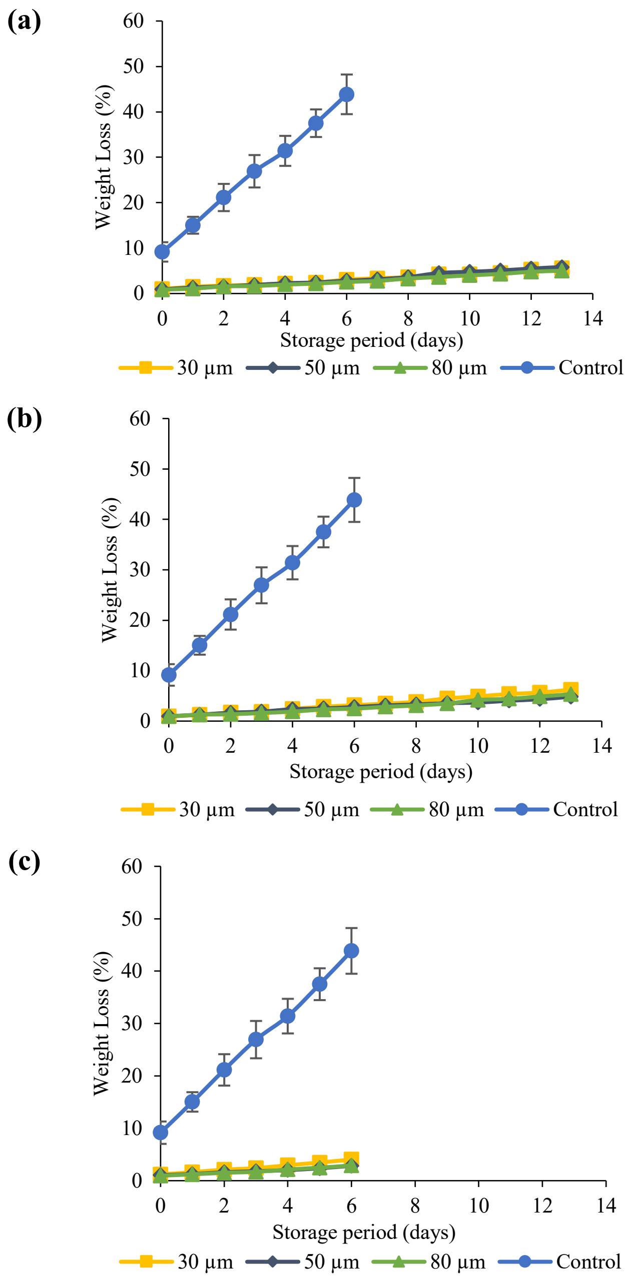

Figure 2. Weight loss changes in fresh cayenne pepper samples during storage at **(a)** 5°C, **(b)** 15°C, and **(c)** 28°C.

In general, it was observed that thicker plastic packaging resulted in lower weight loss, and this effect was more pronounced under high storage temperature conditions. Fonseca *et al.* (2002) reported that MAP effectively reduced weight loss in fruit during cold storage. Differences in storage temperature did not significantly affect weight loss in cayenne pepper samples stored under MAP conditions. The lower WL values observed at room temperature compared to those at 5 and 15°C were due to the shorter observation period at room temperature (only seven days), as previously explained. The WL values of MAP-stored samples generally remained below 5%, whereas those of the control exceeded 40%, approximately eight times higher than in MAP storage. Aglar (2018) reported that MAP treatment played a significant role in reducing weight loss in sweet cherries.

The results of the kinetics analysis showed that the rate of weight loss in cayenne pepper followed a zero-order kinetic model (Table 1). The same kinetic order was also reported by Zhang *et al*. (2021) for kiwi fruit and Li *et al*. (2022) for shiitake mushrooms. In general, it was observed that higher storage temperatures and thinner packaging resulted in greater k values. This indicates that an increase in storage temperature and a decrease in packaging thickness led to an accelerated rate of weight loss in cayenne pepper samples.

pH

Figure 3 presents the changes in the pH value of cayenne pepper at the three studied storage temperatures. It was observed that the pH value increased until the seventh day of storage, after which it consistently decreased for the remainder of the storage period. At storage temperatures of 5 and

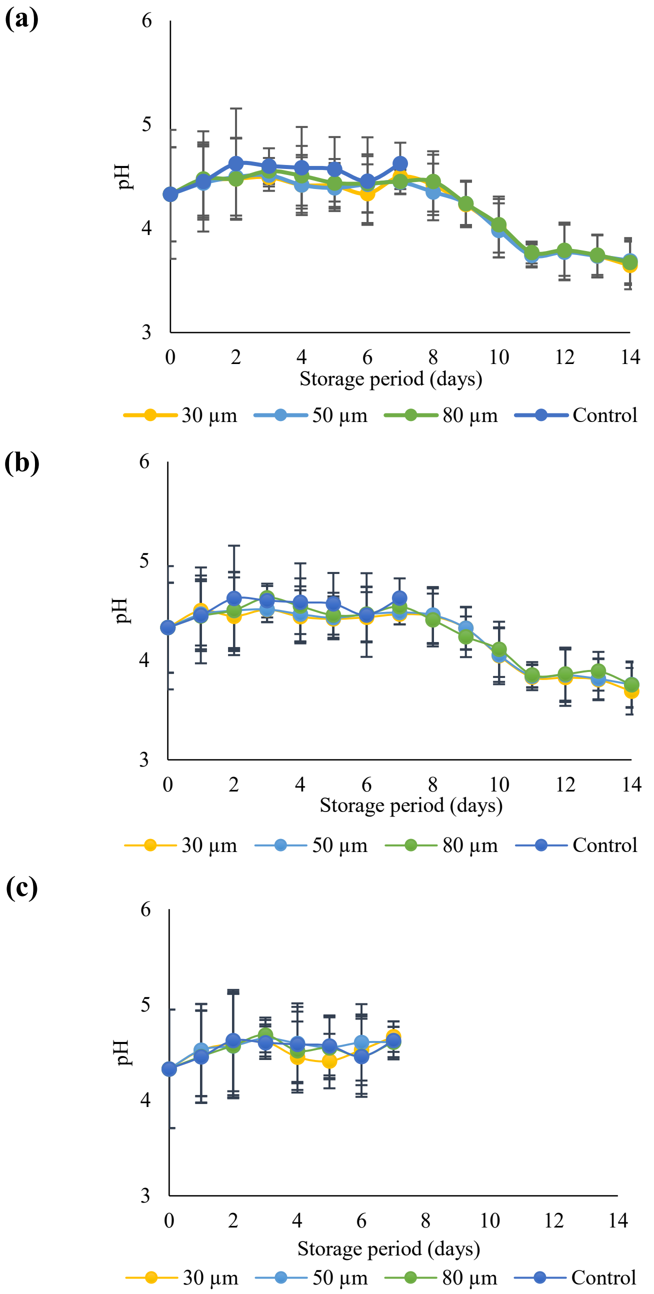

Figure 3. pH changes in fresh cayenne pepper samples during storage at **(a)** 5°C, **(b)** 15°C, and **(c)** 28°C.

15°C, the control consistently exhibited the highest pH values compared to samples stored under MAP until the seventh day. This suggests that plastic packaging effectively reduced pH changes in the cayenne pepper samples. However, under room temperature storage, this difference became less apparent. The effect of different plastic packaging thicknesses on pH was negligible, as the pH values and their patterns of change remained similar across the three packaging thicknesses. This indicates that packaging thickness did not influence the pH value of cayenne pepper. Paulus *et al*. (2021) similarly found that variations in the thickness of LDPE plastic packaging did not affect pH changes in okra during 14 days of storage. Yang (2024) also reported no significant differences in pH between unpackaged cucumbers and those stored in plastic packaging. Storage temperature differences did not have a major influence on pH changes in the cayenne pepper samples. Over the observed storage period, pH values for both the control and MAP samples ranged from approximately 4.5 on the seventh day of storage to around 3.75 on the fourteenth day.

The results of the kinetics analysis indicated that the rate of pH change in cayenne pepper was best described using a first-order kinetic model (Table 1). García-García *et al*. (2008) found that the first-order kinetic model provided a better fit for pH changes in ripe olives. Thakur *et al*. (2019) also stated that pH changes in hydrogels, used as effective drug delivery systems, followed zero- or first-order kinetics. Additionally, it was observed that higher storage temperatures corresponded with larger k values. However, no clear pattern was observed regarding the relationship between k values and the thickness of the plastic packaging. This suggests that while higher storage temperatures increased the rate of pH change in cayenne pepper, there was no consistent correlation between k values and MAP plastic film thickness.

Soluble solid content

Figure 4 presents the changes in the SSC value of cayenne pepper at the three studied storage temperatures. It was observed that the SSC values of all samples tended to increase over time. This increase was likely due to the accumulation of various metabolic products, such as sugars, salts, and other chemical compounds during the ripening process, as well as water evaporation from the samples. Iwanami *et al*. (2024) stated that the increase in SSC is primarily caused by the hydrolysis of starch into sugars during ripening, and the dehydration of fruit after maturity and during storage. Similarly, Ali *et al*. (2014) reported that the SSC values of papaya fruit tended to increase as the fruit ripened. The control samples exhibited the highest SSC values at the same storage temperatures compared to those stored in MAP conditions. This suggests that by slowing down the ripening process, plastic packaging was able to minimise the increase in SSC in cayenne pepper. This agreed with previous studies by Öztürk and Ağlar (2019) and Zhang *et al*. (2021) on kiwi fruits, and Díaz-Mula *et al*. (2012) on sweet cherries. In general,

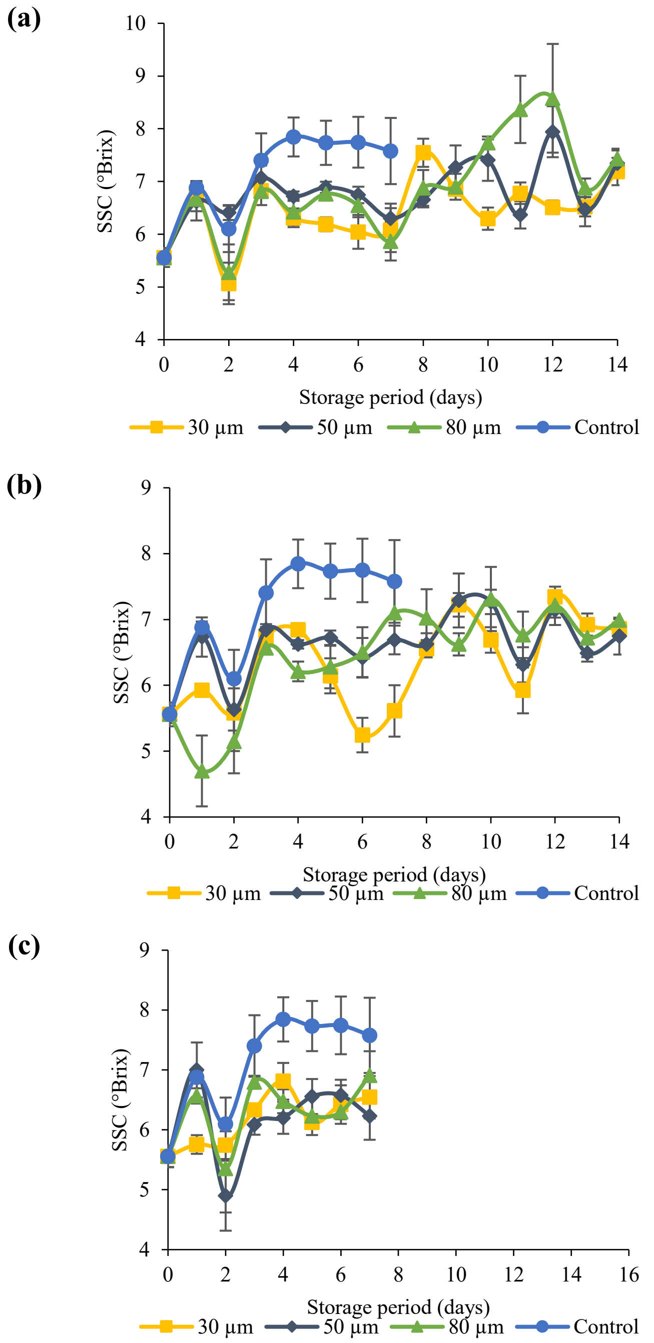

Figure 4. SSC changes in fresh cayenne pepper samples during storage at **(a)** 5°C, **(b)** 15°C, and **(c)** 28°C.

the thickness of the plastic packaging did not significantly affect changes in SSC values, as no consistent pattern was observed among the three packaging thicknesses studied. This indicates that packaging thickness had no notable influence on SSC changes in cayenne pepper samples. Additionally, storage temperature did not have a significant effect on SSC variations, with values for both the control and MAP-stored samples ranging from 6 to 8 during the storage period.

The results of the kinetics analysis revealed that changes in SSC in cayenne pepper followed first-order kinetics (Table 1). Zhang *et al*. (2021) found that SSC followed first-order kinetics in kiwi fruits, and similar findings were reported by Anoraga and Bintoro (2022) for fresh snake fruits. In general, higher storage temperatures and thinner packaging films were associated with increased k values. This suggests that both higher storage temperatures and thinner plastic packaging accelerated the rate of SSC change in cayenne pepper samples.

Vitamin C

Figure 5 presents changes in the vitamin C content of cayenne pepper at the three studied storage temperatures. It was observed that the vitamin C content in all samples tended to increase over time. In the present work, an extended storage period corresponded to increased ripeness, as the colour of the cayenne pepper changed from orange to red when fully ripe. Rahman *et al*. (2016) found that the vitamin C content in strawberries was highest at the fully ripe stage. Similarly, Valšíková-Frey *et al*. (2017) reported that the vitamin C content in tomatoes increased as the fruit gradually ripened. Ernest *et al*. (2017) also observed that vitamin C levels in partially and fully ripe fruits were higher than in unripe fruits, including oranges, lemons, grapes, cashews, and pawpaws. There was no correlation between the increase in vitamin C content and the thickness of the plastic packaging at the same storage temperature. This finding suggests that packaging thickness had no significant effect on the vitamin C levels of cayenne pepper samples. Likewise, no substantial differences in vitamin C content were observed between the control and MAP storage treatments. The relationship between storage temperature and vitamin C levels did not follow a specific pattern. Throughout the storage period, vitamin C values for both the control and MAP-stored samples ranged from 5 to 15 mg/100 mL.

The results of the kinetic analysis indicated that the rate of change in vitamin C content in cayenne pepper was best represented by a first-order kinetic model (Table 1). Al Fata *et al*. (2017) reported that during aerobic degradation, vitamin C degradation follows first-order kinetics. Giannakourou and Taoukis (2021) similarly stated that the loss of vitamin C in fruits and vegetables generally follows first-order kinetics. It was also observed that,

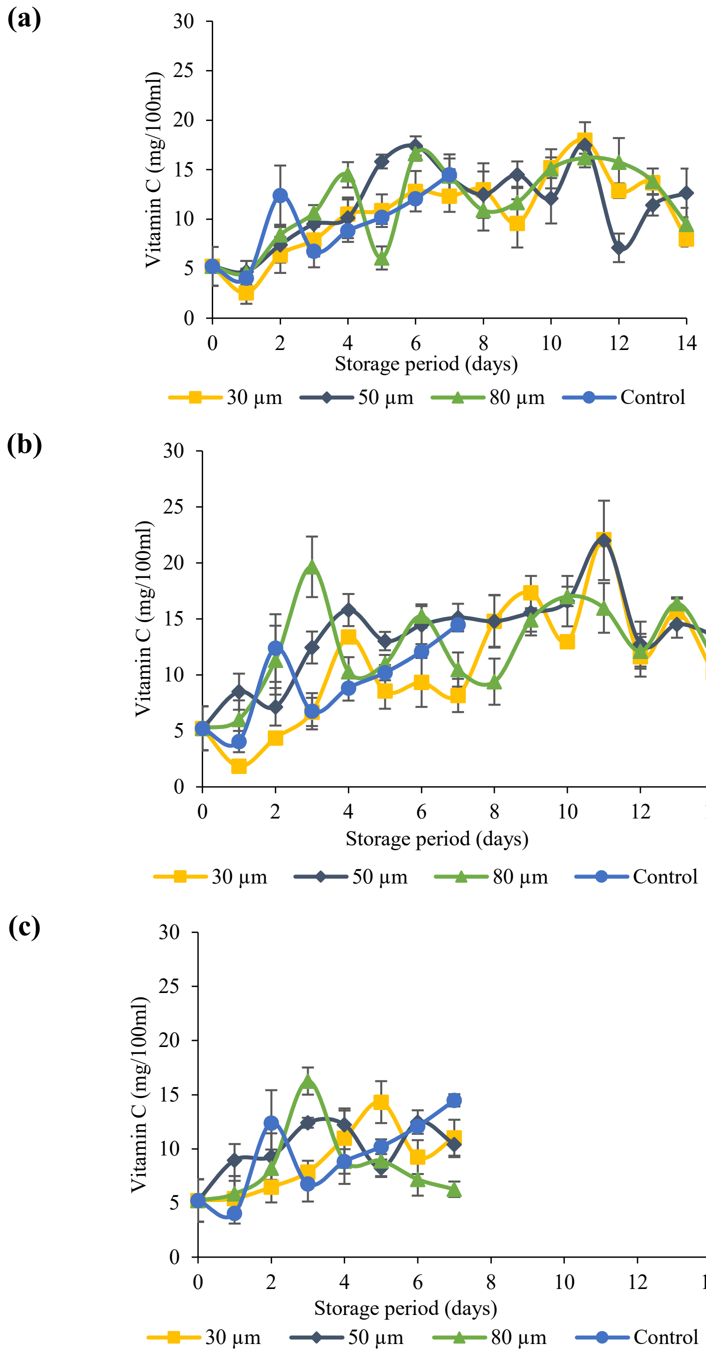

Figure 5. Vitamin C changes in fresh cayenne pepper samples during storage at **(a)** 5°C, **(b)** 15°C, and **(c)** 28°C.

in general, higher storage temperatures and thinner plastic packaging resulted in increased *k* values. This suggests that both higher storage temperatures and thinner plastic packaging accelerated the rate of vitamin C changes in cayenne pepper samples. A summary of the kinetic analysis showed that the order and *k* values of the quality parameters of cayenne pepper varied. This indicates that the rate of change in the quality parameters of cayenne pepper was inconsistent, and did not follow a single trend. In other words, the rate of deterioration of cayenne pepper quality parameters occurred at different speeds. This agreed with studies conducted by Choosuk *et al*. (2022) on dried coconut chips, Cefola *et al*. (2016) on zucchini flowers, Zhang *et al*. (2021) on kiwi fruits, and Zhao *et al*. (2023) on cherry tomatoes. The *k* values obtained in the present work were within the range of those reported in various studies. For instance, Choosuk *et al*. (2022) found *k* values ranging from 0.0489 - 3.9983 day^{-1} for dried coconut chips, while Darniadi *et al*. (2021) reported *k* values ranging from 0.014 - 1.455 day^{-1} for freeze-dried durian.

Shelf-life assessment

Each quality parameter of cayenne pepper at the three storage temperatures was analysed using the Arrhenius equation. This analysis yielded the pre-exponential factor (*A*) and activation energy (*Ea*) for the quality parameters. The results of this analysis are presented in Table 2.

It was found that the values of *A* and *Ea* varied among the quality parameters of cayenne pepper and across different plastic thicknesses. The values of *A* ranged from 1.88 to 666 × 10^{9}, while the values of *Ea* ranged from 885.09 to 1,9156.27 cal.mol^{-1}. These values were within the range of *A* and *Ea* reported in previous studies. Choosuk *et al*. (2022) reported *A* values ranging from 154.315 to 141.21 × 10^{15} for dried coconut chips, Fatharani and Bintoro (2019) found *A* values ranging from 231.019 to 226.348 × 10^{5} for sugar palm fruit, while Cruz-Tirado *et al*. (2021) reported *A* values for chia seeds ranging from 0.37 to 121.9. Regarding *Ea* values, Choosuk *et al*. (2022) reported a range of 2,830 to 25,940 cal.mol^{-1} for dried coconut chips, Fatharani and Bintoro (2019) found *Ea* values between 2,038.029 to 8,762.774 for palm sugar fruit, and Pinheiro *et al*. (2013) observed *Ea* values between 16,350 and 20,650 cal.mol^{-1} for fresh tomato fruits. According to Bickelhaupt and Houk (2017), higher *Ea* values correspond to slower reaction rates.

To determine the shelf-life, a key quality parameter was needed as the primary criterion for evaluating cayenne pepper quality. In practice, consumers primarily assess cayenne peppers based on their colour appearance. Therefore, in the present work, the parameter ΔE, which represents colour changes, was used to estimate the shelf-life of

Table 2. Values of *A* and *Ea* of cayenne pepper samples' quality parameters following Arrhenius analysis.

Quality parameter	30 µm		50 µm		80 µm	
	A	***Ea* (cal.mol^{-1})**	***A***	***Ea* (cal.mol^{-1})**	***A***	***Ea* (cal.mol^{-1})**
ΔE	2864773.94 ± 901366.28	8334.47 ± 954.85	3262485.87 ± 277668.04	8444.55 ± 675.88	6567.58 ± 13.66	4929.35 ± 156.14
WL	18.76 ± 7.13	3158.34 ± 1043.16	19.70 ± 11.37	1126.37 ± 987.76	29.99 ± 21.20	885.09 ± 581.12
pH	4037937989.57 ±1180.18	15830.43 ± 724.85	15040313505.03 ± 1998.12	16530.25 ± 1181.83	666296097815.55 ± 1006.80	19156.27 ± 1038.80
SSC	21.76 ± 12.24	3508.45 ± 448.73	51.40 ± 2.64	2669.93 ± 1106.74	7.88 ± 5.51	2831.08 ±502.58
Vitamin C	3087.99 ± 138.52	5480.64 ± 292.59	2635.72 ± 1520.03	3644.46 ± 921.48	694.35 ± 224.39	4521.82 ± 103.82

Unit of *A* is C unit.day^{-1} and day^{-1} for zero and first order kinetics, respectively.

cayenne pepper. Direct observations were conducted on unpackaged cayenne pepper samples stored at room temperature. Based on these observations, the cayenne pepper changed from orange to fully red on day 5, with a ΔE value of 19.694, and began to rot on day 6. These values were used as acceptance limits to determine the suitability of cayenne pepper for consumption, and served as the basis for ASLT. Subsequently, the shelf-life of cayenne pepper was estimated using Eq. 13, as the ΔE values followed a zero-order kinetic model. Table 3 presents the estimated shelf-life values obtained in the present work.

Table 3. Estimated shelf-life of cayenne pepper samples for each PE thickness at three storage temperatures.

Temperature (°C)	Thickness (μm)	Shelf-life (days)
5	30	17
	50	21
	80	15
15	30	9
	50	10
	80	10
28	30	5
	50	5
	80	6

The results indicated that storage temperature had a more significant effect on the shelf-life of cayenne pepper compared to polyethylene (PE) film thickness. As storage temperature decreased, the shelf-life of cayenne pepper consistently increased. At a storage temperature of 5°C, the shelf-life ranged from two to three weeks. At 15°C, the shelf-life was approximately one and a half weeks, whereas at 28°C, it was comparable to storage without packaging (control), lasting less than one week.

With regard to plastic packaging thickness, no significant effect on shelf-life was observed. At storage temperatures of 15 and 28°C, the three plastic thicknesses resulted in nearly identical shelf-life durations. However, at 5°C, a slight variation in shelf-life was observed, though no consistent relationship was identified between plastic thickness and shelf-life. The longest shelf-life, 21 days, was achieved using MAP with a film thickness of 50 μm at 5°C. This shelf-life was approximately four times longer than that of the control. As previously mentioned, the 50 μm PE film likely provided an optimal balance of O_2 and CO_2 exchange between the packaging and the surrounding environment, supporting the respiration process necessary for maintaining cayenne pepper quality.

Conclusion

The changes in the quality parameters of cayenne pepper followed zero-order kinetics for ΔE and WL, while pH, SSC, and vitamin C exhibited first-order kinetics. Storage temperature had a more significant impact on the shelf-life of cayenne pepper compared to the thickness of the plastic packaging. The longest shelf-life in MAP was 21 days, achieved with a plastic film thickness of 50 μm at a storage temperature of 5°C, which was approximately four times longer than that of the control.

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