Kinetic Modeling and Shelf Life Prediction of Lanzones (Lansium domesticum Correa) Based on Packaging and Storage Temperature

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Abstract: *Lanzones (Lansium domesticum Correa) is a highly perishable tropical fruit. This study evaluated the effects of polyethylene (PE) packaging (25, 36, and 64 µm thick) and storage temperature (13, 18, and 31 °C) on fruit quality and shelf life. Key quality properties: Weight loss, color (L*, a*, b*), browning index, and total soluble solids (TSS). The degradation patterns of these parameters were modeled using zero- and first-order reaction kinetics, and temperature dependence was analyzed using the Arrhenius equation. Weight loss followed zero-order kinetics, while color and browning index followed first-order kinetics. The browning index was the most effective shelf life indicator. First-order kinetic models based on the browning index accurately predicted shelf life, with relative errors of less than 12%. Polyethylene bags of 36 µm and 64 µm stored at 13 °C best preserved the fruit quality. These results highlight the critical role of packaging and temperature in optimizing the postharvest handling and marketability of lanzones.*

Keywords: Lanzones (*Lansium domesticum* Correa), kinetic modeling, shelf life, packaging, storage temperature

1. INTRODUCTION

Lanzones (*Lansium domesticum* Correa) is a tropical fruit widely cultivated in Southeast Asia, particularly in the Philippines, Thailand, Malaysia, and Indonesia [1]. It is known by various names across regions, including Langsat and Duku (English), Duku, Longkong, and Langsat (Thai), Langseh, Langsep, and Lansa (Malay), Duku, Kokosan, and Langsat (Indonesian), Duku and Langsak (Burmese), Bòn-bon (Vietnamese), Lan Sa (Chinese), Ransa (Japanese), and Árbol de lanza (Spanish) [2]. The fruit has a pleasant aroma and sweet, slightly sour taste. Its edible portion is composed of fleshy juicy arils, which are typically divided into five uneven white translucent segments [3]. Nutritionally, lanzones is rich in essential nutrients, offering per 100 g: energy (66 kcal), moisture content (82.9%), carbohydrates (15.3 g), protein (0.9 g), fat (0.1 g), fiber (0.3 g), calcium (5 mg), iron (0.7 mg), phosphorus (35 mg), vitamin A (15 IU), vitamin B1 (0.08 mg), vitamin B2 (0.02 mg), niacin (0.1 mg), and vitamin C (46 mg) [1]. These characteristics contribute to its economic value in both the local and international markets.

Despite its market potential, lanzones faces significant postharvest challenges due to its short shelf life and rapid quality deterioration. At ambient temperatures, its shelf life is typically limited to 3–5 days. With high moisture content, rapid respiration, physical damage, and susceptibility to spoilage contribute to this short postharvest period [4]. Common issues include peel browning, texture degradation, and off-flavor development, which are often worsened by moisture loss and mechanical injury during handling and storage [2].

Packaging plays an important role in preserving and extending the fruit quality during storage. Polyethylene (PE) packaging films are widely used because of their cost-effectiveness, durability, and ability to create a modified atmosphere that regulates oxygen and carbon dioxide levels, while reducing moisture loss [5,6]. Temperature management is another essential strategy for slowing the postharvest deterioration of fruits. In climacteric fruits, low temperatures delay ripening by reducing respiration rates and ethylene production, whereas in non-climacteric fruits, cold storage slows down metabolic changes, such as moisture loss, discoloration, and texture degradation [7]. However, cold storage may also cause chilling injuries to fruits below their optimum storage temperature [8,9], highlighting the importance of identifying optimal storage conditions.

Shelf life is the period during which a food product remains safe and of acceptable quality under specified storage conditions [10]. For fresh produce, it is a critical aspect of postharvest management, reflecting how long fruits and vegetables retain their nutritional, chemical, and sensory properties under varying environmental conditions. Shelf life is typically assessed by the gradual decline of these attributes over time [9]. Accurate prediction is essential for ensuring food safety, minimizing postharvest losses, and optimizing storage, packaging, transportation, and distribution practices across the supply chain [11]. Kinetic modeling offers a valuable approach for predicting changes in fruit quality over time to better understand the postharvest behavior of fresh produce. Models based on zero-, first-, or higher-order reaction kinetics are commonly used to describe the degradation of quality parameters, such as color, texture, and nutrient content. Zero-order kinetics indicate a constant rate of change, whereas the first- and higher-order models reflect concentration-dependent processes. The Arrhenius equation is also frequently applied to determine the influence of temperature on reaction rates, enhancing shelf life predictions under different temperature conditions [12,13,17]. These models are instrumental for optimizing storage practices and improving postharvest management strategies.

Despite the known benefits of packaging and cold storage, there is a lack of integrated studies evaluating the combined effects of packaging and storage temperatures on the quality and shelf life of lanzones. Moreover, although kinetic and Arrhenius-based models have been applied to different fruits, their application to lanzones remains limited. Given their high perishability and sensitivity to storage conditions, there is a need to develop predictive models that incorporate both packaging and temperature variables.

Therefore, this study aimed to evaluate the effects of polyethylene packaging and storage temperature on the postharvest quality of lanzones and develop kinetic models for shelf life prediction. These findings are expected to provide valuable insights into improving storage practices and extending the marketability of this economically important tropical fruit.

2. MATERIALS AND METHODS

2.1 Preparation of Samples

Lanzones (*Lansium domesticum* Correa) fruits at commercial maturity were harvested from a backyard garden in Nagcarlan, Laguna, Philippines. The fruits were carefully handled and promptly transported to the Agricultural, Food, and Bioprocess Engineering Division Laboratory (UPLB). The fruits were sorted and only those without visible physical imperfections, such as discoloration, spoilage, or decay, were selected for the experiment. Before packaging and storage, the selected lanzones fruits were gently washed with distilled water to remove surface contaminants and allowed to air dry to eliminate any residual moisture on the peel.

In this study, polyethylene bags measuring 24 cm × 17 cm with three bag thicknesses (25 µm, 36 µm, and 64 µm) were tested. These bags were procured from a commercial supplier in Divisoria, Manila, Philippines. To ensure precise and consistent thickness measurements, six bags of each thickness were selected, with five readings taken at random points on each bag using a digital micrometer (Mitutoyo 293-831-30).

2.2 Packaging and Storage Setup

Approximately 20 lanzones fruits were packed into polyethylene (PE) bags (25, 36, and 64 µm thickness) and the control (no packaging) and stored at three different temperatures (13°C, 18°C, and 31°C). Four replicates were prepared for each packaging and temperature.

The packaged fruits were stored in a controlled environment with a relative humidity (RH) of 85%. Before starting the storage test, the bags were checked to ensure proper sealing. Storage conditions were closely monitored using a Temperature and Humidity Data Logger (Tinytag TGP-4500). The experiment was terminated when a mold was observed on the fruit peel surface, marking the point when the fruit was no longer in a good condition.

2.3 Quality Analysis

2.3.1 Weight Loss

The weight of each sample replicate was recorded using a digital weighing scale (PRACTUM224-15) every three days throughout the storage period. Weight loss was calculated as a percentage of the initial weight (day zero) using the following formula [5]:

$$Weight\ Loss\ (\%) = \frac{W_i - W_f}{W_i} \times 100$$

Where W_i is the initial weight of the sample at day zero, and W_f is the weight of the sample at each observation period.

2.3.2 Color (L*, a*, b*)

The color of lanzones peel (pericarp) was measured using a colorimeter (Konica Minolta CR-10). Color was recorded using three parameters, lightness (L*), redness (a*), and yellowness (b*), which were used to monitor changes in peel color. Two readings were taken from opposite sides at the midsection of each fruit. Color measurements were conducted every three days throughout the storage period [14].

2.3.3 Browning Index

The Browning Index (BI), an indicator of browning intensity, was calculated using the values of L*, a*, and b* color parameters [15]. Browning Index was computed using the following formula:

$$Browning\ Index\ (BI) = \frac{[100\ (x\ -\ 0.31)]}{0.17}$$

where,

$$x = \frac{(a*\ + 1.75L*)}{(5.645L*\ + a* - 0.3012b*)}$$

2.3.4 Total Soluble Solids

Total soluble solids (TSS) in the fruit juice were measured using a digital refractometer (ATAGO 3810), following the method described by [16]. The pulp was blended with distilled water and then filtered. A drop of the filtered juice was placed on the prism of a digital handheld refractometer. TSS was expressed in degrees Brix.

2.4 Kinetics Modeling of Quality Changes

2.4.1 Reaction Kinetics Modeling

The general rate equation used to describe the degradation of quality attributes in fruits is given by the following expression [9]:

$$\frac{dCt}{dt} = \pm kC_t^n$$

where *Ct* represents the quality parameter at time t, k is the reaction rate constant, and *n* denotes the reaction order. The positive and negative sign indicates that the quality parameter (*Ct*) increases or decreases over time.

The changes in the quality parameters of the fruit during storage were analyzed using zero- and first-order degradation reaction kinetics, as described by [15]. The use of reaction order kinetics in postharvest studies has been well documented for different fruits, including pineapple [9], kiwifruit [17], and sweet cherry [18]. The equations used were as follows:

Zero-Order Kinetics

$$A_t - A_0 = -kt$$

First-Order Kinetics

$$lnA_t - lnA_0 = -kt$$

Where k is the degradation rate constant (day^{-1}), A_o is the initial value of the quality parameter, A_t is the measured value at storage time t.

After identifying the best-fit kinetic model (zero- or first-order) for each packaging and temperature combination, the temperature dependence of the rate constant was analyzed using the Arrhenius equation. The Arrhenius model has been widely applied in food quality studies, including those of pineapple [19], banana, guava, mango [20], and papaya [21]. The temperature dependence of the degradation rate constant (k) was modeled using the Arrhenius equation:

Arrhenius Equation

$$lnk = lnk_o - \frac{E_a}{RT}$$

Where k is the reaction rate constant, k_o is the Arrhenius constant, E_a is the activation energy (kcal/mol), R is the universal gas constant (8.314 J/mol·K), T is the absolute temperature (K).

The parameter with the lowest activation energy (E_a) was considered the most sensitive to temperature and thus most influential in shelf-life determination.

2.4.2 Shelf Life Prediction of Lanzones

Based on the identified key quality parameter, the shelf life of lanzones fruit was predicted using a corresponding kinetic model, as described by [15]:

Zero-Order Reaction Model

$$ts = \frac{N_t - N_o}{k_T}$$

First-Order Reaction Model

$$ts = \frac{\ln\left(\frac{N_o}{N_t}\right)}{k_T}$$

Where t_s is the predicted shelf life, N_o is the initial acceptable value of the quality parameter, N_t is the limiting value (threshold) at the end of shelf life, k_t is the degradation rate constant at temperature T.

2.5 Model Evaluation

The performance of the kinetic models was evaluated using the coefficient of determination (R^2) and root mean square error (RMSE). The model that provided the best fit was selected to represent the changes in lanzones quality over time under different storage conditions [5].

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(M_i - P_i)^2}{\sum_{i=1}^{n}(M_i - \bar{M})^2}$$

where Mi is the observed values, Pi is the model predictions, and $\bar{M}$ is the mean of observed values. An R^2 close to 1 indicates a strong fit, while lower values suggest poor model explanation.

$$RSME = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(M_i - P_i)^2}$$

where n is the number of observations. RMSE measures prediction error in the same units as the response variable, with lower values indicating better accuracy.

2.6 Statistical Analysis

Analysis of variance (ANOVA) was conducted to assess the significance of packaging and temperature on the physicochemical properties of lanzones fruit during storage. Regression analysis was used to evaluate the goodness of fit of reaction order kinetic models and the Arrhenius equation. Statistical analyses were performed using OriginPro 2025 software (OriginLab Corporation, Northampton, Massachusetts, USA).

3 RESULTS AND DISCUSSION

3.1 Quality Changes of Lanzones

3.1.1 Weight Loss

Weight loss during postharvest storage is an important determinant of the quality, marketability, and shelf life of fruit. A significant interaction was observed between packaging and temperature ($P<0.05$), indicating that the effect of packaging on weight loss varied with temperature. Figure 1 shows the effect of the treatments on the weight loss of lanzones. The control (no packaging) consistently exhibited the highest weight loss, increasing from 11.86% on day 3 to 21.35% on day 6 at 31°C. In contrast, packaging treatments significantly reduced weight loss, with thicknesses of 25, 36, and 64 µm maintaining weight loss below 1% at 13°C and 18°C, while even the control at these temperatures remained below 3%. This result supports the findings of [22], who emphasized the role of polyethylene packaging in reducing water vapor transmission and slowing weight loss during cold storage. Temperature played a critical role, as storage at 31°C led to the highest weight loss, followed by storage at 13 °C, while storage at 18°C resulted in the least weight loss. This trend aligns with the observations of [23], who demonstrated that cold storage combined with moisture-barrier packaging minimized shrinkage and extended the storage life of tropical fruits. These results underscore the treatments in minimizing moisture loss during storage.

3.1.2 Color Changes

Color is one of the most closely monitored quality attributes in postharvest handling, as it serves as a vital indicator of fruit condition and plays a crucial role in influencing consumer preferences and buying decisions [24]. The color of the lanzones, lightness (L*), redness (a*), and yellowness (b*) were significantly affected by packaging and storage temperature (P<0.05). The lightness (initially 67.2) decreased over time, with thicker polyethylene (64 µm) and lower temperatures (13 and 18°C) best preserving it. In contrast, the control at 31 °C led to faster discoloration. Redness (initially 7.3) increased during storage, especially at 31°C and in the control, while polyethylene packaging and cooler temperatures slowed this increase. Yellowness (initially 35.3) also declined but was better maintained with thicker (36 and 64µm) packaging at 13°C. Overall, combining thicker polyethylene with cooler storage effectively preserved fruit color, supporting previous findings. Similarly, [23] reported that longkong lightness decreases over time across different packaging and temperature conditions, along with an increase in redness and decrease in yellowness, reflecting comparable color dynamics during storage.

3.1.3 Browning Index

Peel browning is a critical indicator of postharvest quality, and the internal flesh often remains edible and of high quality as browning intensifies and visual appeal decreases. This significantly reduces consumer acceptance and market value because appearance strongly influences purchasing decisions. A significant interaction was observed between packaging and temperature (P<0.05). Figure 2 shows the effect of the treatments on the browning index of lanzones. Packaging treatments reduced browning, particularly at a thickness of 64 µm, and the control had the highest browning. Lower temperatures reduced browning at 18°C and 13°C, whereas 31°C had the highest browning. There was an increase in browning from day 3 to 6. In combination, 31°C and the control showed the highest increase in browning. This interaction underscores the synergistic role of packaging and temperature. Polyethylene packaging, especially at medium thickness, limits gas exchange and moisture loss, thereby maintaining internal humidity and suppressing the enzymatic oxidation processes responsible for browning. The lowered temperature further slowed transpiration and oxidative reactions, consistent with previous findings that combined packaging and low temperatures are effective in reducing enzymatic browning [8].

3.1.3 Total Soluble Solids (TSS)

Total soluble solids represent the concentration of dissolved substances in a solution and are widely used as an indicator of fruit sweetness and overall ripeness. [25]. Measuring the TSS provides a reliable estimate of the sugar content of fruits [26]. The interaction between packaging and temperature had a significant effect on TSS (P<0.05). Figure 3 shows the TSS levels of lanzones under different packaging and temperatures. The initial TSS value was 15.4 °Brix. Among the packaging treatments, the 25 µm polyethylene and control treatments recorded the highest TSS, while the other treatments exhibited relatively similar values. The polyethylene packaging bags at 13°C had the lowest moisture content. Additionally, TSS increased from day 3 to day 6 for most treatments. These observed trends are consistent with those of previous tropical fruit studies. [27] reported an increase in TSS during early storage due to enzymatic starch breakdown into simple sugars, driven by α-amylase and β-amylase activities.

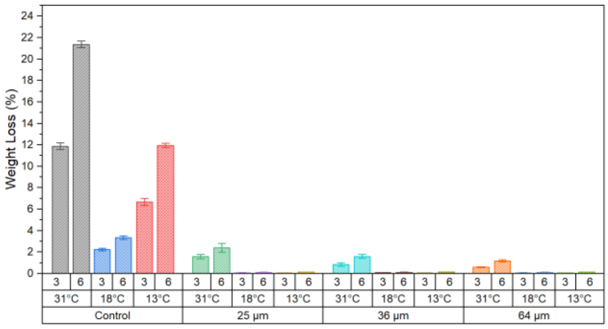

Fig 1. Mean weight loss (%) of lanzones fruit under different packaging and temperatures at storage periods of days 3 and 6. Error bars represent standard deviation.

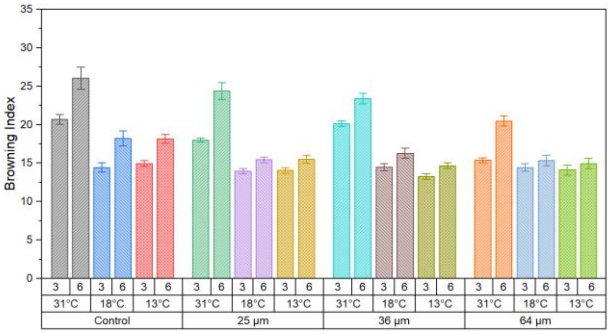

Fig 2. Mean browning index of lanzones fruit under different packaging and temperatures at storage periods of days 3 and 6. Error bars represent standard deviation.

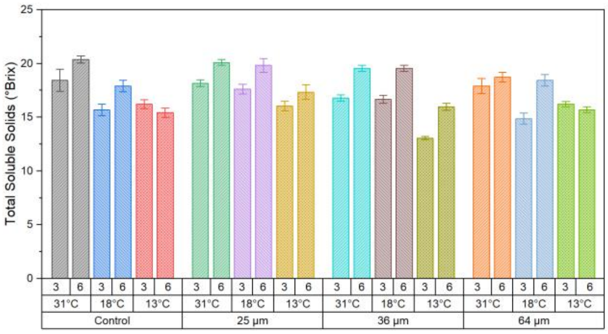

Fig 3. Mean total soluble solids (°brix) of lanzones fruit under different packaging and temperatures at storage periods of days 3 and 6. Error bars represent standard deviation.

3.2 Kinetic Modeling of Quality Degradation

The degradation kinetics of different quality parameters in lanzones fruit were modeled under different packaging conditions and storage temperatures using zero- and first-order reaction models. Table 1 summarizes the estimated kinetic parameters for weight loss, color (L*, a*, b*), browning index, and total soluble solids (TSS) under different packaging conditions: control, polyethylene (PE) bags (25, 36, and 64 µm thickness), stored at 13°C, 18°C, and 31°C.

Weight loss followed the zero-order kinetic model best across most treatments, with exceptionally high R^2 = 0.818-1.000 and low RMSE= 0.008-0.963, especially observed in the control and 36 µm PE bags. These findings are consistent with earlier studies that reported zero-order kinetics for weight loss in postharvest produce, including shiitake mushrooms [28], fresh-cut pineapple [17], sweet cherry [18], and kiwifruit [11].

Table 1. Estimated reaction order kinetics for physical parameter of lanzones under different packaging and storage temperatures.

PARAMETER	PACKAGING	TEMPERATURE	Zero Order			First Order		
			k	R^2	RMSE	k	R^2	RMSE
Weight Loss	Control	31°C	3.557	0.996	0.963	1.278	0.807	2.650
		18°C	0.555	0.960	0.478	0.969	0.800	2.053
		13°C	1.987	0.995	0.572	1.181	0.811	2.417
	25 µm	31°C	0.397	0.964	0.327	0.913	0.805	1.908
		18°C	0.022	0.953	0.020	0.440	0.984	0.237
		13°C	0.020	0.964	0.016	0.428	0.979	0.267
	36 µm	31°C	0.268	1.000	0.004	0.848	0.848	1.521
		18°C	0.022	0.998	0.004	0.440	0.930	0.511
		13°C	0.020	0.923	0.024	0.428	0.998	0.085
	64 µm	31°C	0.193	1.000	0.008	0.794	0.858	1.371
		18°C	0.022	0.983	0.012	0.440	0.959	0.386
		13°C	0.018	0.818	0.037	0.414	0.939	0.449
Lightness (L*)	Control	31°C	4.412	0.990	1.907	0.084	0.999	0.011
		18°C	2.050	0.923	2.515	0.034	0.912	0.044
		13°C	2.325	0.926	2.780	0.039	0.914	0.050
	25 µm	31°C	4.253	0.993	1.560	0.080	0.978	0.051
		18°C	1.570	0.877	2.498	0.025	0.870	0.041
		13°C	0.717	0.999	0.106	0.011	0.998	0.002
	36 µm	31°C	3.542	0.981	2.102	0.063	0.992	0.023
		18°C	0.925	0.983	0.510	0.014	0.986	0.007
		13°C	0.895	0.921	1.115	0.014	0.916	0.018
	64 µm	31°C	3.425	0.846	6.209	0.061	0.832	0.116
		18°C	0.903	0.974	0.621	0.014	0.971	0.010
		13°C	0.833	0.999	0.082	0.013	1.000	0.001
Redness (a*)	Control	31°C	0.767	0.906	1.045	0.081	0.882	0.126
		18°C	0.508	0.996	0.143	0.058	1.000	0.004
		13°C	0.413	1.000	0.008	0.049	0.999	0.008
	25 µm	31°C	0.558	0.883	0.861	0.063	0.866	0.105
		18°C	0.130	0.912	0.171	0.017	0.907	0.023
		13°C	0.305	0.989	0.135	0.037	0.995	0.011
	36 µm	31°C	0.763	0.908	1.029	0.081	0.884	0.125
		18°C	0.405	0.971	0.298	0.048	0.982	0.027
		13°C	0.092	0.818	0.184	0.012	0.820	0.024
	64 µm	31°C	0.383	0.789	0.841	0.046	0.784	0.102
		18°C	0.267	0.961	0.229	0.033	0.951	0.032
		13°C	0.167	0.987	0.082	0.021	0.983	0.012
Yellowness (b*)	Control	31°C	1.987	0.996	0.523	0.069	0.986	0.035
		18°C	1.392	0.998	0.241	0.045	1.000	0.000
		13°C	1.303	0.830	2.498	0.042	0.822	0.082
	25 µm	31°C	1.417	0.991	0.572	0.046	0.997	0.011
		18°C	0.650	0.862	1.102	0.020	0.857	0.034
		13°C	0.478	1.000	0.029	0.014	0.999	0.002
	36 µm	31°C	1.783	0.960	1.551	0.060	0.942	0.063
		18°C	0.678	0.928	0.804	0.020	0.921	0.025
		13°C	0.158	0.999	0.020	0.005	0.999	0.001
	64 µm	31°C	1.287	0.998	0.253	0.041	0.993	0.014
		18°C	0.687	0.939	0.743	0.021	0.932	0.024
		13°C	0.317	0.999	0.041	0.009	0.999	0.002
Browning Index	Control	31°C	2.170	0.990	0.939	0.116	0.964	0.095
		18°C	0.863	0.934	0.972	0.056	0.952	0.053
		13°C	0.853	0.983	0.474	0.055	0.993	0.020
	25 µm	31°C	1.892	0.995	0.567	0.105	1.000	0.009
		18°C	0.400	0.981	0.237	0.028	0.987	0.014
		13°C	0.412	0.989	0.184	0.029	0.994	0.010
	36 µm	31°C	1.730	0.957	1.551	0.098	0.928	0.116
		18°C	0.542	0.998	0.110	0.037	1.000	0.003
		13°C	0.272	0.874	0.437	0.020	0.880	0.031
	64 µm	31°C	1.240	0.957	1.119	0.075	0.977	0.049
		18°C	0.382	0.985	0.200	0.027	0.979	0.017
		13°C	0.317	0.995	0.098	0.023	0.992	0.009
TSS	Control	31°C	0.825	0.984	0.449	0.047	0.973	0.033
		18°C	0.413	0.832	0.786	0.025	0.838	0.046
		13°C	15.667	0.000	0.653	0.000	0.000	0.041
	25 µm	31°C	0.779	0.990	0.337	0.044	0.981	0.026
		18°C	0.733	1.000	0.000	0.042	0.999	0.006
		13°C	0.321	0.966	0.255	0.020	0.971	0.014
	36 µm	31°C	0.688	0.964	0.561	0.040	0.975	0.027
		18°C	0.688	0.951	0.663	0.040	0.962	0.033
		13°C	0.092	0.032	2.143	0.006	0.027	0.150
	64 µm	31°C	0.550	0.923	0.674	0.032	0.913	0.042
		18°C	0.504	0.617	1.684	0.030	0.603	0.103
		13°C	0.046	0.114	0.541	0.003	0.119	0.034

Changes in the color parameters lightness (L*), redness (a*), and yellowness (b*) were best described by first-order kinetic models across most packaging and temperature conditions. Lightness showed strong first-order fits, R^2 = 0.832-0.999 and low RMSE= 0.001-0.116, particularly in 25 µm and 36 µm PE bags stored, with high R^2 values and lower RMSE compared to zero-order models, indicating a consistent logarithmic degradation in visual brightness over time. Redness (a*) and yellowness (b*) also exhibited first-order behavior, especially a lower RMSE than the zero order. Higher rate constants were observed in thinner packaging and controls at elevated temperatures, indicating more rapid color loss under less protective conditions. These results align with findings from fresh-cut fruits such as pineapple and kiwifruit [17, 11], but differ from zero-order trends observed in dried products such as coconut chips, which may be due to their processed attributes [15]. Overall, thicker PE films and cooler storage effectively delayed color changes in the lanzones during storage.

The browning index exhibited strong fits for both zero and first-order models. However, the first-order model generally provided slightly better predictive accuracy (R2 = 0.88-1.000 and RMSE = 0.003-0.116), particularly in the 25 µm PE packaging treatments. This supports findings from studies on fresh fruit, where enzymatic browning progresses nonlinearly over time [29]. While [15] modeled browning in coconut chips using zero-order kinetics, the more dynamic enzymatic activity in fresh fruit under a modified atmosphere likely explains the better fit with first-order models in this study.

The modeling of Total Soluble Solids (TSS) exhibited greater variability, indicated by a low coefficient of determination (R^2). Despite this, the Root Mean Square Error (RMSE) remained low, suggesting that the model's predictions were consistently close to the actual values, even though the data showed considerable variation. This highlights how differences in fruit structure and biochemical makeup can significantly affect the behavior and predictability of TSS changes during storage or processing. Further support for these trends comes from [18], who developed predictive models for sweet cherry storage in which TSS did not align clearly with either model. This variability reinforces the fact that TSS has different degradation patterns.

In general, the choice between zero- and first-order models should be based on the specific behavior of each quality parameter. As emphasized by [11], zero-order models are best suited when a quality attribute declines linearly over time, whereas first-order models are more appropriate when degradation follows a logarithmic trend. The variability observed across commodities highlights the complexity of postharvest kinetics and the importance of tailoring models to both product and treatment variables.

3.3 Arrhenius Modeling

The best-fitting kinetic model for each quality parameter was incorporated into the Arrhenius equation to evaluate the temperature sensitivity of the quality degradation in the lanzones during storage. This modeling approach allowed for a quantitative description of the degradation behavior as a function of temperature and enabled the identification of key indicators that could support shelf-life prediction. Table 2 summarizes the Arrhenius derived activation energies (Ea) for key quality attributes of lanzones stored under different packaging conditions: control and polyethylene (PE) bags (25, 36, and 64 µm thickness). Activation energy (Ea) analysis revealed that PE packaging markedly enhanced the thermal stability of key quality parameters in lanzones, with higher Ea values indicating a reduced sensitivity to temperature-induced degradation. For weight loss, the control showed the lowest Ea (38.75 kJ/mol), while 25 µm and 36 µm PE bags increased Ea to 128.44 and 111.51 kJ/mol, respectively, reflecting improved moisture retention through modified atmospheres comparable to values reported for fresh-cut potatoes and sweet cherries [18, 28].

Table 2. Kinetic parameters of quality parameters of lanzones under different packaging conditions during storage obtained by the Arrhenius equation.

Packaging	Parameter	Arrhenius Equation	Ea (kj/mol)	R^2	RMSE
Control	Weight Loss	lnk = 16.33 - 4661.1 (1/T)	38.75	0.273	1.146
	L*	lnk = 11.161 - 4170 (1/T)	34.67	0.826	0.288
	a*	lnk = 5.541 - 2446.6 (1/T)	20.34	0.996	0.023
	b*	lnk = 5.535 - 2501.7 (1/T)	20.8	0.979	0.055
	Browning Index	lnk = 10.381 - 3824.8 (1/T)	31.8	0.927	0.161
	TSS	lnk = -35.811 + 10679 (1/T)	-	0.346	2.208
25 µm	Weight Loss	lnk = 49.723 - 15448 (1/T)	128.44	0.933	0.623
	L*	lnk = 27.909 - 9244 (1/T)	76.86	0.979	0.202
	a*	lnk = 9.331 - 3731.9 (1/T)	31.03	0.360	0.749
	b*	lnk = 15.755 - 5730.2 (1/T)	47.64	1.000	0.014
	Browning Index	lnk = 19.727 - 6709.1 (1/T)	55.78	0.910	0.317
	TSS	lnk = 11.571 - 3563.7 (1/T)	29.63	0.585	0.452
36 µm	Weight Loss	lnk = 42.659 - 13412 (1/T)	111.51	0.935	0.533
	L*	lnk = 22.994 - 7855.2 (1/T)	65.31	0.931	0.321
	a*	lnk = 24.444 - 8152.5 (1/T)	67.78	0.779	0.653
	b*	lnk = 35.372 - 11571 (1/T)	96.2	0.893	0.602
	Browning Index	lnk = 22.461 - 7529.2 (1/T)	62.6	0.986	0.135
	TSS	lnk = 25.905 - 7913.6 (1/T)	65.79	0.524	1.135
64 µm	Weight Loss	lnk = 37.896 - 12054 (1/T)	100.22	0.952	0.408
	L*	lnk = 23.325 - 7966.5 (1/T)	66.23	0.944	0.292
	a*	lnk = 8.08 - 3385 (1/T)	28.14	0.900	0.169
	b*	lnk = 19.09 - 6756.1 (1/T)	56.17	0.920	0.299
	Browning Index	lnk = 17.201 - 6027.2 (1/T)	50.11	0.977	0.139
	TSS	lnk = 32.177 - 9875.2 (1/T)	82.1	0.555	1.331

Color attributes also showed packaging-related improvements. The lightness (L*) increased from 34.67 kJ/mol in the control to 76.86 kJ/mol under 25 µm PE, indicating reduced surface discoloration; redness (a*) showed more variability, with values ranging from 20.34 to 67.78 kJ/mol depending on treatment, likely influenced by oxygen availability and phenolic activity; and yellowness (b*) showed a strong thickness-dependent increase from 20.80 kJ/mol (control) to 96.20 kJ/mol (36 µm PE), indicating delayed pigment degradation. These values surpassed those reported for dried coconut chips, suggesting better thermal protection in the fresh fruit matrices [15]. Similarly, the browning index improved with thicker packaging, rising from 31.80 kJ/mol in the control to 62.60 kJ/mol under 36 µm PE, aligning with literature values for enzymatic browning in fresh and dried fruits. Overall, the increasing Ea trends across weight loss, color, and browning parameters underscore the effectiveness of PE packaging, especially at medium to high thicknesses, in mitigating temperature-driven deterioration in fruits, such as lanzones.

Among all the quality attributes evaluated, the browning index was identified as the most effective parameter for shelf-life modeling. Its relatively low activation energies, consistently high R^2 values, and good model accuracy (RMSE) across packaging treatments indicate high sensitivity to temperature and strong reliability as an early indicator of quality degradation. These findings support its inclusion in shelf-life prediction models and reinforce the importance of packaging and temperature control in preserving lanzones fruit quality.

3.4 Shelf Life Prediction

Shelf life prediction for lanzones under different packaging and temperature conditions was conducted using browning index as the primary indicator. A first-order kinetic model was applied to describe the browning progression, and the rate constants (k values) were estimated using the Arrhenius equation for different packaging treatments and storage temperatures. A browning index threshold of 18 was used to indicate non-marketability, beyond which the fruit was considered unsuitable for sale.

Table 3 presents the predicted shelf life of lanzones based on browning index kinetics under different packaging conditions and storage temperatures, along with the observed shelf life and the corresponding relative error percentages.

In general, the shelf life predictions aligned well with the observed values, particularly at higher temperatures. Under control conditions, the predicted shelf life ranged from 2.91 days at 31°C to 6.43 days at 13°C. The relative error was within 12%, with the lowest error observed at 31°C (4.06%). This suggests that the kinetic model based on the browning index effectively estimated shelf life at high temperatures.

For fruits stored in 25 µm PE packaging, the predicted shelf life increased substantially with decreasing temperature from 3.34 days at 31°C to 13.38 days at 13°C. However, relative errors were higher under this treatment, particularly at 18°C (22.26%) and 13°C (19.61%), indicating that the model tended to overpredict shelf life under moderate to low-temperature conditions, possibly due to interactions between the packaging atmosphere and enzymatic browning that were not fully captured by the model.

In the 36 µm PE treatment, the predictions were more accurate overall. The relative errors remained below 12%, with the lowest error at 31°C (2.77%) and the highest at 18°C (11.34%). The high accuracy of the model under this condition suggests that 36 µm PE packaging created a relatively stable environment, enabling browning kinetics to closely reflect actual shelf life patterns.

The 64 µm PE packaging also showed good agreement between the predicted and observed shelf life. The errors were below 11%, with the lowest at 31°C (3.24%) and the highest at 18°C (10.53%). Shelf life predictions were the longest in this treatment, reaching 15.44 days at 13°C, highlighting the efficacy of thicker packaging in extending fruit quality.

Overall, shelf life prediction based on the browning index using first-order kinetics provided reliable estimates, particularly at high temperatures and with thicker packaging. The relative errors were generally acceptable (<12%), thereby supporting the utility of the model in practical storage applications. In addition, the developed kinetic models allow shelf life prediction at any desired storage temperature. The corresponding rate constant (k) was calculated by substituting a specific temperature into the Arrhenius equation, which can then be applied to the shelf-life formula derived from the first-order kinetic model based on the browning index to estimate the time required for lanzones to reach the threshold of non-marketability. This predictive capability provided a practical and flexible tool.

Table 3. Shelf life prediction of lanzones at different storage temperatures in relation to the changes browning index.

PACKAGING	TEMPERATURE	PREDICTED SHELF LIFE (Days)	OBSERVED SHELF LIFE (Days)	RELATIVE ERROR (%)
Control	31°C	2.91	2.80	4.06
	18°C	5.11	5.80	11.93
	13°C	6.43	5.87	9.48
25 µm	31°C	3.34	3.11	7.46
	18°C	8.95	11.51	22.26
	13°C	13.38	11.19	19.61
36 µm	31°C	3.22	3.31	2.77
	18°C	9.72	8.73	11.34
	13°C	15.27	16.48	7.32
64 µm	31°C	4.44	4.30	3.24
	18°C	10.75	12.02	10.53
	13°C	15.44	14.30	7.99

4 CONCLUSIONS

This study established the critical influence of polyethylene packaging and storage temperature on the postharvest quality and shelf life of lanzones fruit. The use of medium-to-thick PE films (particularly 36 and 64 μm) significantly reduced weight loss, color degradation, and enzymatic browning, especially under cold storage conditions (13 and 18°C). Kinetic analysis revealed that weight loss followed zero-order degradation, whereas color parameters and browning index adhered to first-order kinetics. The Arrhenius equation was used to measure the effect of temperature on degradation, with the activation energy values showing that the packaged samples had better thermal stability. The browning index emerged as the most effective quality attribute for shelf life prediction, providing accurate and reliable estimates when used with first-order kinetic and Arrhenius models. Overall, this study demonstrates that integrating packaging with temperature control, guided by kinetic modeling, can enhance postharvest management and extend the shelf life of lanzones.

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