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Preservation strategies of lemon (*Citrus aurantifolia*): effects of temperature and storage on fruit quality

Estrategias de conservación del limón (*Citrus aurantifolia*): efectos de la temperatura y el almacenamiento en la calidad de la fruta

Estratégias de preservação do limão (*Citrus aurantifolia*): efeitos da temperatura e do armazenamento na qualidade dos frutos

Fanny Estefanía Cedeño Guaranda[1]
Adriana del Carmen Celi Soto[2]*
Frank Guillermo Intriago Flor[3]
Freddy Eli Zambrano Gavilanes[2]
Dayana Elizabeth Mieles Macías[1]

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University of Zulia, Faculty of Agronomy
olivarian Republic of Venezuela.

[1]Universidad Técnica de Manabí – Facultad de Posgrado, Maestría en Agronomía, Mención Producción Agrícola Sostenible, Portoviejo km 22.3, Manabí, Ecuador.
[2]Universidad Técnica de Manabí – Facultad de Ingenierías Agroambientales, Carrera de Agronomía, Lodana – Santa Ana km 5.6, Manabí, Ecuador.
[3]Universidad Técnica de Manabí – Facultad de Agrociencias, Chone km 92.2, Manabí, Ecuador.

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Abstract

Lemon (*Citrus aurantifolia* Swingle) is an economically and nutritionally important crop whose shelf life is limited by rapid postharvest deterioration. Losses occurring during storage affect key quality attributes such as firmness, moisture retention, and juice content, making it necessary to identify effective conservation strategies. The objective of this study was to evaluate the effect of different storage temperatures and durations on the postharvest quality of lemon fruits produced in Manabí, Ecuador. A randomized block design with a 4 × 3 factorial arrangement was used, including four temperatures (10, 12, 14, and 26 °C) and three storage periods (9, 12, and 15 days), with four replications and a total of 800 fruits per locality. Physical and chemical characteristics such as fruit weight, diameter, juice content, pericarp weight, pH, and total soluble solids were evaluated. The results showed that storage at 12 °C and 14 °C better preserved fruit quality, whereas storage at 10 °C accelerated dehydration and increased pericarp weight loss. It is concluded that storage temperature is a determining factor in maintaining the postharvest quality of lemon fruits, and this study provides essential information to optimize handling practices and reduce losses along the production chain.

*Corresponding author: adriana.celi@utm.edu.ec

Resumen

El limón (*Citrus aurantifolia* Swingle) es un cultivo de importancia económica y nutricional cuya vida útil se ve limitada por su rápida degradación poscosecha. Las pérdidas generadas durante el almacenamiento afectan la firmeza, la retención de humedad y el contenido de jugo, por lo que resulta necesario identificar estrategias de conservación adecuadas. El objetivo de este estudio fue evaluar el efecto de diferentes temperaturas y periodos de almacenamiento sobre la calidad poscosecha del limón sutil producido en Manabí, Ecuador. Se utilizó un diseño en bloques al azar con arreglo factorial 4 × 3, que incluyó cuatro temperaturas (10, 12, 14 y 26 °C) y tres periodos de almacenamiento (9, 12 y 15 días), con cuatro repeticiones y un total de 800 frutos por localidad. Se evaluaron características físicas y químicas como peso, diámetro, contenido de jugo, peso del pericarpio, pH y sólidos solubles totales. Los resultados mostraron que las temperaturas de 12 °C y 14 °C conservaron mejor la calidad del fruto, mientras que 10 °C aceleró la deshidratación y la pérdida de peso de la cáscara. Se concluye que la temperatura de almacenamiento es un factor determinante para mantener la calidad poscosecha del limón, y este estudio aporta información fundamental para optimizar las prácticas de manejo y reducir pérdidas en la cadena productiva.

Palabras clave: deshidratación, poscosecha, vida útil, período, respiración.

Resumo

O limão (*Citrus aurantifolia* Swingle) é uma cultura de grande importância econômica e nutricional, cuja vida útil é limitada pela rápida deterioração pós-colheita. As perdas ocorridas durante o armazenamento afetam atributos de qualidade, como firmeza, retenção de umidade e teor de suco, tornando necessário identificar estratégias de conservação eficazes. O objetivo deste estudo foi avaliar o efeito de diferentes temperaturas e períodos de armazenamento na qualidade pós-colheita do limão-sutil produzido em Manabí, Equador. Utilizou-se um delineamento em blocos ao acaso, com arranjo fatorial 4 × 3, incluindo quatro temperaturas (10, 12, 14 e 26 °C) e três períodos de armazenamento (9, 12 e 15 dias), com quatro repetições e um total de 800 frutos por localidade. Foram avaliadas características físicas e químicas, como peso do fruto, diâmetro, teor de suco, peso do pericarpo, pH e sólidos solúveis totais. Os resultados mostraram que as temperaturas de 12 °C e 14 °C conservaram melhor a qualidade do fruto, enquanto 10 °C acelerou a desidratação e aumentou a perda de peso do pericarpo. Conclui-se que a temperatura de armazenamento é um fator determinante para manter a qualidade pós-colheita do limão, e este estudo fornece informações essenciais para otimizar as práticas de manejo e reduzir perdas ao longo da cadeia produtiva.

Palavras-chave: desidratação, qualidade pós-colheita, vida útil, período de armazenamento, taxa de respiração.

Introduction

Citrus crops are cultivated in over 140 countries, primarily in tropical and subtropical regions, and hold significant economic and nutritional importance (Liu *et al.*, 2012). As the most widely produced fruit group worldwide (Zacarías *et al.*, 2020), citrus fruits play a crucial role in both food security and the agricultural economy. In Ecuador, key lime (*Citrus aurantifolia* Swingle) occupies the largest cultivated area among citrus species and is subject to strong national and international demand (Santistevan Méndez *et al.*, 2017). Successful commercialization of key lime largely depends on fruit quality, which is determined by both external traits, such as firmness and appearance, and internal attributes, including juice content and nutritional composition, ultimately influencing consumer acceptance (Serna-Escolano *et al.*, 2022). However, this species is highly susceptible to postharvest losses and storage-related issues, which limit shelf life and commercial value (Yaddanapudi and Kumar, 2020). Storage temperature is a critical factor in postharvest preservation, as it directly affects fruit quality and nutritional value (Cheng *et al.*, 2023; Baltazari *et al.*, 2020). In lemon, low ethylene and CO_2 production slows ripening and decay, allowing a shelf life of one to six months depending on storage conditions (López-Gómez *et al.*, 2023). In Manabí Province-the main key lime production area in Ecuador-the crop faces critical limitations. A substantial proportion of losses results from inadequate postharvest management, which drastically shortens shelf life and restricts market availability. This vulnerability occasionally leads to fruit scarcity, undermining the entire value chain. Therefore, strict control over storage conditions, including temperature management and specialized conditioning, is essential to prolong shelf life and meet international standards (Budiarto *et al.*, 2024; Verreydt *et al.*, 2024; Alhassan *et al.*, 2024). Within this context, the present study represents a pioneering effort in Ecuador, evaluating the effect of different storage temperatures across three storage durations. The results provide essential information to optimize fruit quality, minimize postharvest losses, and enhance the competitiveness of this strategic crop in Manabí.

Materials and methods

Study area description

The lemons were harvested in two locations in the province of Manabí, Ecuador. The first was Ayacucho-Santa Ana (01°09′00″ S, 80°17′00″ W; 400 m.a.s.l.) and the second, Guabal-Calceta (00°51′04″ S, 80°08′58″ W; 29 m.a.s.l.). Both areas have a dry tropical climate, characterized by marked seasonal rainfall and high evaporative demand. In Ayacucho-Santa Ana, annual rainfall varies between 500 and 1200 mm, with temperatures ranging from 19 to 37 °C. The soils are clay loam. In Guabal-Calceta, annual rainfall is 962 mm and temperatures range from 20 to 35 °C. The soils have a texture that varies from clay loam to silty loam. The experimental work was carried out at the Agroindustrial Laboratory of the Faculty of Animal Science, Chone Extension, Technical University of Manabí.

Plantation conditions

The crops at both sites were planted at a spacing of 8 × 8 m and managed under flood irrigation. Fertilization, pest control, and disease management were carried out by the growers in each area.

Fruit sampling and handling

A total of 1,600 fruits of *Citrus aurantifolia* Swingle (subtle lemon) were collected, with 800 fruits obtained at each site from approximately 15 trees per location. Harvesting was carried out at commercial maturity, defined by local criteria that consider external green coloration, firmness to manual pressure, and sufficient juice content. After collection, the fruits were placed in plastic crates and transported to the laboratory at 21 °C to avoid heat buildup and early dehydration. No precooling was applied upon arrival, as temperature treatments were initiated immediately according to the experimental design. Each fruit was individually wrapped in kraft paper to reduce moisture loss and then allocated to its corresponding storage treatment and storage period.

Evaluation of fruit quality

Fruit quality parameters were evaluated at the end of each storage period, under the four temperature treatments: 10 °C, 12 °C, 14 °C and 26 °C. Measurements were taken at harvest (day 0) and at the defined storage durations of 9 days, 12 days and 15 days, following the methodology described by Nasrin *et al.* (2020). Equatorial diameter (ED) and polar diameter (PD) were measured using a precision caliper (Truper®, CALDI-1488, China). Fruit weight (FW), pulp weight (PW), and pericarp weight (PeW) were determined using a precision balance (CAMRY®, ACS-6ZE14, China). Juice content (JC) was quantified using a graduated cylinder (mL). Titratable acidity (TA) was determined by titration with 0.1 N NaOH using phenolphthalein as an indicator. The results were expressed as citric acid percentage.

The sugar content in the total soluble solids (TSS) (°Brix) was determined by direct measurement of the fruit juice using a digital refractometer (OPTi, Bellingham, Stanley, United Kingdom).

Experimental design and statistical analysis

A randomized complete block design (RCBD) with a 4 × 3 factorial arrangement was employed, considering two factors: temperature levels and storage duration. The evaluation sites, Ayacucho and Calceta, were treated as independent experiments. In each location, 12 treatments were established with four replications. Each replication consisted of 22 fruits, and each set of 22 fruits was considered the experimental unit.

The treatment levels were defined as follows: temperatures of 10 °C (TE1), 12 °C (TE2), 14 °C (TE3), and ambient temperature of 26 °C (TE4); and storage durations of 9 days (D1), 12 days (D2), and 15 days (D3). Data were analyzed through analysis of variance (ANOVA) using InfoStat version 2020. Simple effects analysis was performed to evaluate the independent influence of each factor. Mean comparisons were conducted using Tukey's test ($p<0.05$). In addition, Dunnett's test ($p\leq0.05$) was applied to compare all treatments against the control.

Results and discussion

Effect of time and temperature on Key lime quality

Table 1 shows that both storage time and temperature significantly influenced the characteristics of Key lime fruit, affecting its quality during the storage period. The interaction between these two factors had a direct effect on juice content, total soluble solids (°Brix), and pH, which in turn determined the perception of fruit quality.

Prolonged storage and inadequate temperatures reduced juice content, modified °Brix, total soluble solids, and acidity, and increased peel weight loss. These findings confirmed that optimal postharvest management is essential to preserve fruit quality. Similar results were reported by Badiche-El Hilali *et al.* (2023), who demonstrated that proper postharvest practices, including melatonin application, delayed senescence and maintained fruit quality. Thus, the time-temperature interaction was decisive, as it directly influenced the main quality attributes and consumer perception. These results highlight the importance of controlling lemon storage conditions, as small variations in temperature and duration can accelerate deterioration and compromise market acceptability.

Key lime fruit diameter

Figure 1 shows that equatorial and polar diameters of Key lime fruits responded differently to temperature and location.

In Ayacucho (Figure 1A and 1C), the equatorial diameter was more sensitive at 14 °C, with a significant reduction after 15 days, consistent with the findings of Latocha *et al.* (2014). In contrast, the polar diameter remained stable until the end of storage, in agreement with Cao *et al.* (2019). In Calceta (Figure 1B and 1D), storage at 10 °C reduced the equatorial diameter from day 9, whereas the polar diameter decreased initially but stabilized between days 12 and 15, as reported by Lufu *et al.* (2020). At 14 °C, the polar diameter showed significant reductions, which could be attributed to limited antioxidant capacity against oxidative stress, as suggested by Rastgoo *et al.* (2024).

Table 1. Analysis of variance for the experiment evaluating the effect of temperature levels and storage periods on the quality of Key lime fruit (*Citrus aurantifolia* Swingle) in Ayacucho-Santa and Ana Guabal-Calceta, Manabí Province, Ecuador.

Location	Variables	Block	Time	Temperature	Time × Temp	Ad. con vs com tre	CV
	DP	0.7325	0.0064	0.0677	0.0327*	0.0184*	2.9
	DE	0.4589	0.0058**	0.0000***	0.0007***	0.0049**	2.6
	PI	0.4345	0.0029**	0.0115*	0.0094**	0.8322	10.7
Ayacucho	CJ	0.0858	0.1993	0.0137*	0.0002***	0.0000***	6.8
	PC	0.2576	0.0000***	0.0003***	0.0101**	0.0000***	6.4
	GB	0.1159	0.0245*	0.0159*	0.0003***	0.0769	4.3
	pH	0.0019**	0.0000***	0.0301*	0.0001***	0.0000***	3.3
	DP	0.5717	0.0616	0.0001***	0.0000***	0.0000***	5.4
	DE	0.7019	0.0013**	0.0000***	0.0061**	0.0002***	3.4
	PI	0.6986	0.1693	0.0001***	0.0027**	0.0000***	9.0
Calceta	CJ	0.9257	0.0008***	0.1905	0.0079**	0.3911	11.9
	PC	0.8444	0.0235*	0.0001***	0.0000***	0.0000***	13.8
	GB	0.8706	0.0030**	0.5203	0.0000***	0.0038**	3.7
	pH	0.3546	0.1910	0.3938	0.4938**	0.7263	34.5

Variables: DP: Polar diameter (mm). DE: Equatorial diameter(mm). PI: Initial weight (g). CJ: Juice content (mL). PC: Peel weight (g). GB: °Brix (%). *: $p\leq0.05$; **: $p\leq0.01$; ***: $p\leq0.001$; CV: Coefficient of variation (%).

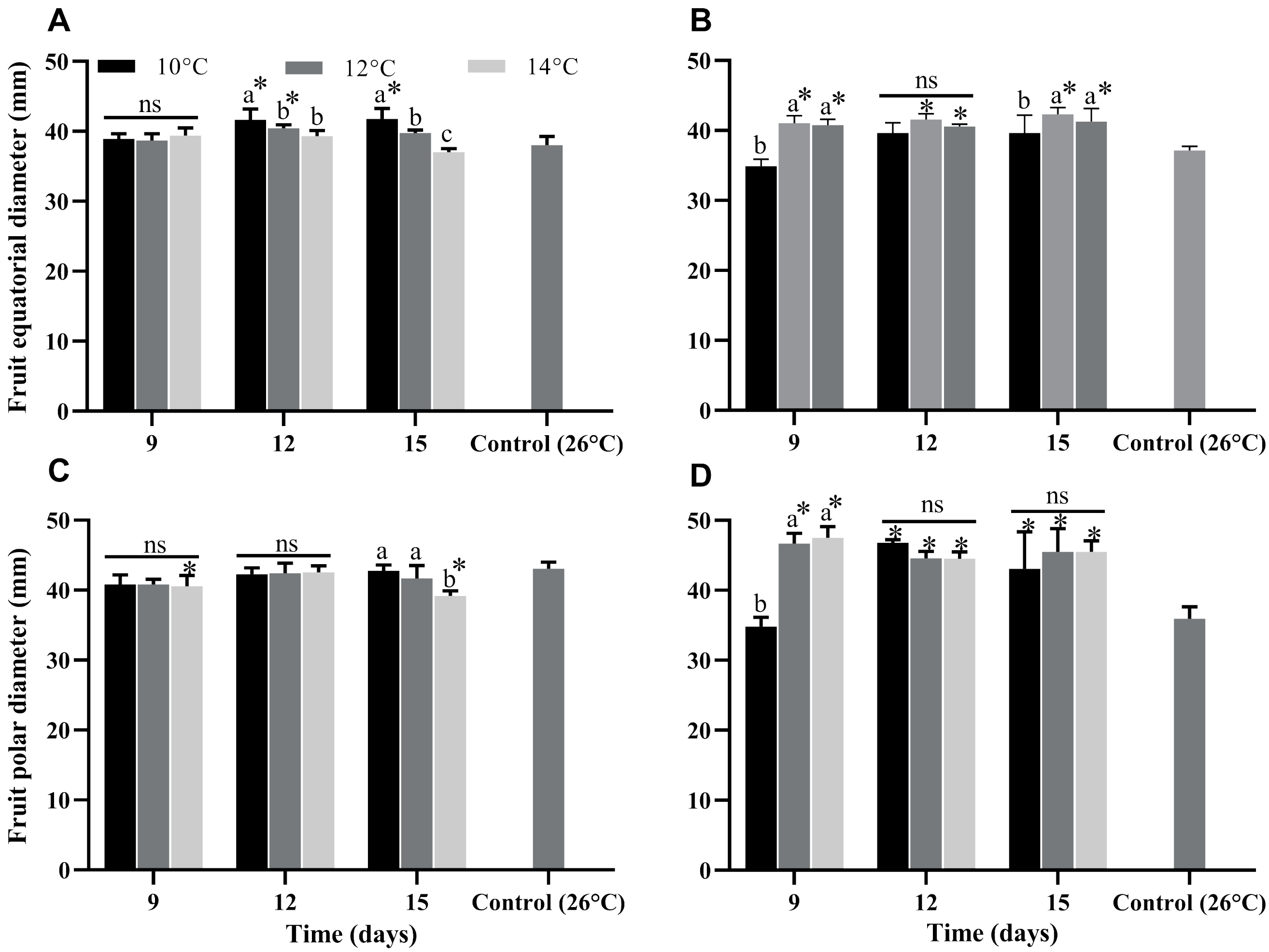

Figure 1. Equatorial (A, B) and polar (C, D) diameters of Key lime (*Citrus aurantifolia*) fruits from two locations in Manabí (Ayacucho: A, C; Calceta: B, D) under different storage times and temperatures. Columns with the same letter do not differ statistically according to the Scott-Knott test (p≤0.05).

Fruit weight

The analysis of the effect of different temperatures and storage times on the weight of Ayacucho and Calceta subtle lemon fruits (table 2), shows significant differences ($p \leq 0.05$) between locations and storage conditions. In Ayacucho, it was observed that 10 °C was the optimum temperature for maintaining fruit weight during storage periods of 9, 12, and 15 days, compared to temperatures of 12°C and 14 °C, which induced great er weight loss.

These results indicate that low storage temperatures favor the conservation of fruit weight, mainly due to a reduction in transpiration and water loss. Temperature plays a key role in this response, as higher temperatures accelerate dehydration and increase physiological weight loss in citrus fruits (Sun *et al.*, 2022). Strengthening postharvest handling practices for subtle lemon is essential, since storage at ambient temperature is still commonly used by retailers in producing areas, which can compromise fruit quality throughout the supply chain (Lerslerwong *et al.*, 2023). In this regard, recent studies show that both storage conditions and storage duration significantly affect the physical and nutritional properties of citrus fruits (Baltazari *et al.*, 2020).

Juice content

The relationship between juice content and storage time at different temperatures of lemon fruits from two locations in Manabí (Ayacucho and Calceta) is shown in the figure 2.

Results showed that low temperatures favored fruit weight conservation by reducing transpiration and water loss. In Calceta, storage at 12 °C proved more effective in maintaining fruit weight throughout the storage period. These observations were consistent with Castellano *et al.* (2016), who reported greater weight losses at 30 °C than at 10 °C due to higher transpiration rates. Similarly, Serna-Escolano *et al.* (2022) observed 24 % weight loss at low temperatures after 21 days, which they attributed to reduced peel transpiration. Comparable trends were observed in Ayacucho, where temperatures between 7 and 10 °C better preserved fruit weight. Juice content in Key lime was strongly influenced by storage temperature. In Ayacucho, storage at 12 and 14 °C caused significant reductions, whereas in Calceta, 10 °C maintained stability and high juice content throughout the storage period, reflecting more efficient preservation. These results were supported by previous studies (Cheng *et al.*, 2023).

Table 2. Effect of different temperature levels and storage times on the initial weight of lemon fruits from Ayacucho and Calceta, in the province of Manabí, Ecuador.

	Province of Manabí, Ecuador					
	Ayacucho			Calceta		
	Temperature (°C)					
Days	**10**	**12**	**14**	**10**	**12**	**14**
9	36.76 ± 0.75 a	27.96 ± 4.80 b*	38.03 ± 1.29 a	32.81 ± 1.41 c	46.56 ± 1.91 a*	44.63 ± 1.17 a*
12	40.75 ± 1.46 a	40.77 ± 1.10 a	39.73 ± 0.83 a	44.94 ± 0.79 a*	44.13 ± 2.72 a*	42.69 ± 0.57 a*
15	44.72 ± 2.47 a	37.65 ± 1.22 a	35.27 ± 0.82 a	38.69 ± 3.30 b*	49.38 ± 1.96 a*	43.75 ± 1.33 a*
Control		37.40 ± 1.73			28.95 ± 1.31	

Values followed by equal letters in the same column do not differ statistically according to the Scott-Knott test (p≤0.05). Values followed by * differ from the control treatment according to Dunnett's test (p≤0.05).

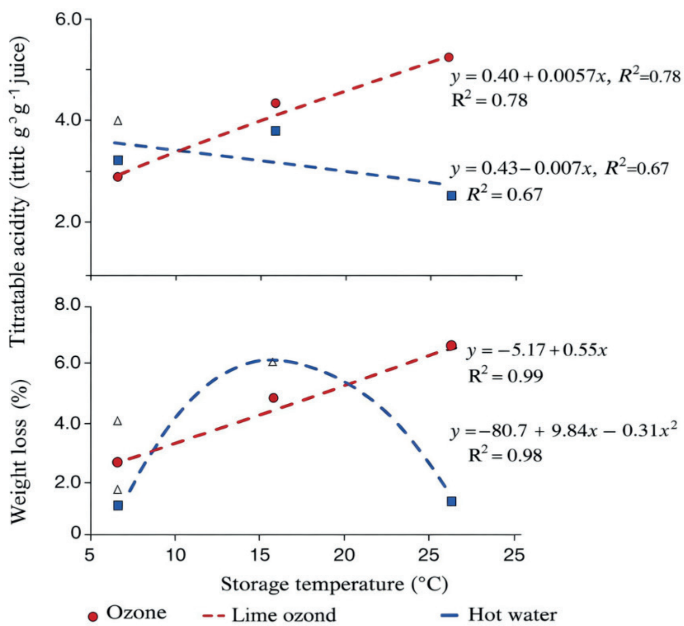

Figure 2. Relationship between juice content and storage time at different temperatures of lemon fruits from two locations in Manabí: Ayacucho (A) and Calceta (B). R^2 = coefficient of determination.

Soluble solids content (°Brix)

Table 3 showed that total soluble solids (°Brix) in lime fruits varied significantly (p≤0.05) according to storage temperature and time, with notable differences between locations. At 10 °C, °Brix values remained stable, reaching a maximum in Calceta (8.20 at 9 days), indicating that this temperature favored sugar retention. At 12 °C, a significant increase in °Brix was observed in both locations, reaching a maximum at 12 days (8.88 in Ayacucho).

Results showed that soluble solids (TSS) accumulation depended on both temperature and locality. In Ayacucho, TSS increased at 14 °C (8.36), whereas in Calceta they decreased (7.34). These trends align with recent findings reporting that temperature modulates sugar metabolism and TSS concentration during citrus storage (Strano *et al.*, 2022; Hasbullah and Ismail, 2022; Rastgoo *et al.*, 2024).

Furthermore, increases in TSS have been associated with physiological water loss and metabolic catabolism during storage, as described by Liao *et al.* (2022).

pH

Values followed by equal letters in the same column do not differ statistically according to the Scott-Knott test (p≤0.05). Values followed by * differ from the control treatment according to Dunnett's test (p≤0.05).

The results show that the pH of lemons is influenced by temperature and storage time, as well as the place of origin, highlighting the impact of climatic and agronomic conditions on fruit physiology. Similarly, Reyna-Gonzáles *et al.* (2024) observed that as titratable acidity decreases during storage, pH tends to increase at different temperatures. This behavior is associated with the progressive reduction of organic acids, particularly citric acid, the main contributor to acidity in citrus fruits, whose content is affected by post-harvest metabolic processes (Garganese *et al.*, 2019).

Peel weight

Figure 3 shows pericarp weight of lemon fruits from Ayacucho and Calceta, in the province of Manabí, Ecuador, under different storage times and temperatures.

Figure 3 showed a significant reduction in peel weight, particularly after 15 days, with fruits stored at 14 °C retaining weight more effectively. This behavior is associated with moisture loss and cellular dehydration, processes strongly influenced by storage temperature. Cold storage is widely recognized as one of the most effective strategies to preserve citrus quality (Quintieri *et al.*, 2024), as it maintains firmness and reduces postharvest losses (Deng *et al.*, 2020). Lower temperatures also slow respiration rates, contributing to longer shelf life (Jain *et al.*, 2023), whereas ambient storage accelerates deterioration (Habibi and Susila, 2024). These effects highlight the need for temperature protocols suited to fruit origin and handling conditions (Onwude *et al.*, 2024). Strengthening storage practices is especially important because ambient conditions compromise peel quality and water retention (Lerslerwong *et al.*, 2023), and both storage temperature and duration markedly influence the physical properties of citrus fruits (Baltazari *et al.*, 2020; Liao *et al.*, 2022).

Table 4 shows the effect of different temperature levels and storage periods on the pH of lemons from Ayacucho and Calceta, in the province of Manabí, Ecuador.

Table 3. Effect of different temperature levels and storage times on the soluble solids content (°Brix) of lemon fruits from Ayacucho and Calceta, in the province of Manabí, Ecuador.

Province of Manabí, Ecuador						
	Ayacucho			Calceta		
	Temperature (°C)					
Days	10	12	14	10	12	14
9	7.22 ± 0.25 b	7.37 ± 0.24 b	8.21 ± 0.23 a*	8.20 ± 0.01 a	8.04 ± 0.13 b	7.77 ± 0.18 b*
12	7.92 ± 0.23 a	8.28 ± 0.25 a*	7.52 ± 0.25 b	7.43 ± 0.12 b*	8.67 ± 0.12 a	8.76 ± 0.16 a
15	7.66 ± 0.23 a	7.92 ± 0.25 a	8.36 ± 0.31 a*	8.59 ± 0.11 a	7.54 ± 0.19 c*	7.34 ± 0.23 b*
Control		7.50 ± 0.31			8.54 ± 0.07	

Values followed by letters in the same column do not differ statistically according to the Scott-Knott test (p≤0.05). Values followed by * differ from the control treatment according to Dunnett's test (p≤0.05).

Table 4. Effect of different temperature levels and storage periods on the pH of lemon fruits from Ayacucho and Calceta, in the province of Manabí, Ecuador.

Province of Manabí, Ecuador						
	Ayacucho			Calceta		
	Temperatura (°C)					
Days	**10**	**12**	**14**	**10**	**12**	**14**
9	2.06 ± 0.04 a	1.94 ± 0.03 b*	2.04 ± 0.09 a	1.85 ± 0.03 b	1.99 ± 0.03 a	2.10 ± 0.02 a
12	1.90 ± 0.03 b*	1.76 ± 0.01 c*	2.04 ± 0.02 a	2.07 ± 0.03 b	1.79 ± 0.03 a	1.81 ± 0.01 a
15	2.06 ± 0.01 a	2.19 ± 0.05 a	2.06 ± 0.06 a	3.04 ± 1.13 a	2.03 ± 0.03 a	2.14 ± 0.02 a
Control		2.14 ± 0.01			1.96 ± 0.01	

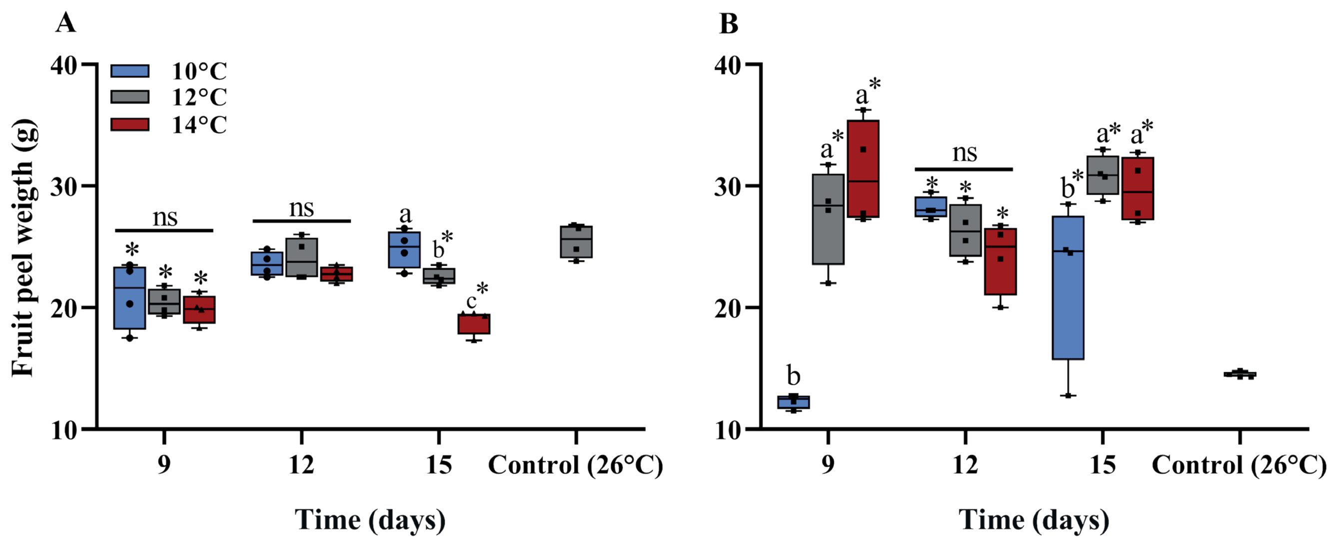

Figure 3. Pericarp weight of lemon fruits from Ayacucho (A) and Calceta (B), in the province of Manabí, Ecuador, under different storage times and temperatures. Boxes with the same letters do not differ statistically according to the Scott–Knott test (p ≤ 0.05). Treatments marked with * differ from the control treatment according to the Dunnett test (p ≤ 0.05). "ns" indicates no significant differences.

Conclusions

Storage temperature is a decisive factor in the postharvest quality of key lime (subtle lemon), directly influencing juice content and peel weight loss. The results demonstrate that temperatures of 12 °C and 14 °C preserve fruit quality more effectively than 10 °C, where dehydration is notably accelerated. Further research is recommended on the implementation of temperature-controlled storage, along with other strategies such as natural coatings, modified atmospheres and good agricultural practices, to delay the ripening and decomposition process and strengthen the value chain, ensuring the competitiveness and sustainability of the crop in global markets.

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