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Postharvest behavior of feijoa fruit (*Acca sellowiana* Berg) subjected to different 1-MCP doses and storage temperatures

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Abstract - Feijoa is a promising crop in Colombia with high export potential. However, its postharvest shelf-life is short since it is a climacteric fruit with high respiration rates and susceptibility to fruit flies. Techniques such as refrigeration and the use of 1-methylcyclopropene (1-MCP) increase the post-harvest period and prolong fruit quality. The objective of this research was to evaluate the effect of different storage temperatures and 1-MCP doses on postharvest feijoa fruits. A completely randomized design with a 2x4 factorial arrangement was used, where the first factor was temperature (4 and 16 °C), and the second factor was the 1-MCP dose (0, 30, 60 and 90 µg L^{-1}), for a total of eight treatments. The treatments at 4 °C presented lower values for mass loss and respiratory rate, while luminosity, chromaticity, soluble solids and antioxidant activity showed the highest values. The lowest 1-MCP doses at 4 °C had the highest values of titratable acidity and endocarp tone; on the contrary, the highest doses at 4 and 16 °C presented the highest values of phenolic compounds. The refrigerated feijoa fruits had a shelf-life between 36 and 42 days, while those stored at 16 °C only had commercial quality for 14 days, highlighting the importance of cold storage.

Keywords: antioxidant activity, firmness, myrtaceae, phenols, respiratory rate.

Comportamento pós-colheita de frutos de feijoa (*Acca sellowiana* Berg) submetidos a diferentes doses de 1-MCP e temperaturas de conservação

Resumo - A feijoa é uma cultura promissora na Colômbia, com alto potencial de exportação. No entanto, sua vida útil pós-colheita é curta, pois é uma fruta climatérica com altas taxas respiratórias e suscetibilidade a moscas-das-frutas. Técnicas como a refrigeração e o uso de 1-metilciclopropeno (1-MCP) aumentam o período pós-colheita e prolongam a qualidade dos frutos. O objetivo desta pesquisa foi avaliar o

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efeito de diferentes temperaturas de armazenamento e de doses de 1-MCP na pós-colheita de feijoas. Foi utilizado um delineamento inteiramente casualizado, com estrutura fatorial 2x4, sendo o primeiro fator a temperatura (4 e 16 °C), e o segundo fator a dose de 1-MCP (0; 30; 60 e 90 μg L^{-1}), totalizando oito tratamentos. Os tratamentos a 4 °C apresentaram menores valores para perda de massa e intensidade respiratória, enquanto luminosidade, cromaticidade, sólidos solúveis e atividade antioxidante apresentaram os maiores valores. As menores doses de 1-MCP a 4 °C apresentaram os maiores valores de acidez titulável e tônus do endocarpo; pelo contrário, as maiores doses a 4 e 16 °C apresentaram os maiores valores de compostos fenólicos. Os frutos de feijoa refrigerados apresentaram vida de prateleira entre 36 e 42 dias, enquanto os armazenados a 16 °C apresentaram qualidade comercial por apenas 14 dias, destacando a importância do armazenamento refrigerado.

Termos para indexação: atividade antioxidante, firmeza, myrtaceae, fenóis, taxa respiratória.

Introduction

The feijoa (*Acca sellowiana* Berg) is a plant native to South America (AMARANTE et al., 2017a) and is an exotic fruit with high antioxidant, immunological, and anticancer properties, among others (MARTIN et al., 2015); this means that the fruit has excellent commercial acceptance worldwide for fresh consumption and in agribusiness (FARIAS et al., 2020). As a result, it is widely cultivated worldwide in countries such as New Zealand, Georgia, Ukraine, Colombia, California, Australia, Turkey, China and Brazil (SACHET et al., 2019). In Colombia, 307 ha are cultivated, and an average production of 2,765 t was recorded in the departments of Boyacá, Cundinamarca, Santander, and Caldas (AGRONET, 2021), where the departments of Boyacá (242 ha; 2,372 t) and Cundinamarca (2,372 t) are the larger producers (55 ha; 360 t) (FISCHER et al., 2020).

Feijoa production in Colombia represents a productive system with great economic potential, especially in cold and moderate cold climate zones where it has greater adaptation (PEREA et al., 2010). However, it is difficult to establish the appropriate maturity point for harvest because of its botanical characteristics, which directly affects the post-harvest shelf-life (PARRA-CORONADO; FISCHER, 2013). During this period, the fruits experience changes that are responsible for determining their final quality. In the case of the feijoa, variations in chemical composition and epidermis color and decreases in firmness have been observed, where over-ripeness is detrimental to quality in terms of flavor and darkening of the pulp and seeds (PARRA-CORONADO et al., 2018). This is mainly due to the fact that it is a fruit with a climacteric behavior, high respiratory rates and ethylene production, which decrease post-harvest duration and require immediate refrigeration to preserve quality (PARRA-CORONADO; FISCHER, 2013).

Storage at low temperatures (RAMÍREZ et al., 2005) and 1-methylcyclopropene (1-MCP) (AMARANTE et al., 2008) increase the post-harvest shelf-life since they delay ripening and allow feijoa fruits to retain their quality and characteristics for much longer (PARRA-CORONADO; FISCHER, 2013).

Cold storage under optimal conditions reduces qualitative and quantitative losses generated by physiological disorders and rot; in addition, it delays maturation and senescence, prolonging commercial shelf life, where the recommended storage conditions for feijoa in Colombia include approximately one month to 4 °C, followed by 5 days on the shelf at 20 °C (PARRA-CORONADO; FISCHER, 2013).

In addition, the use of treatments such as 1-MCP combined with cold storage has greater effectiveness (PARRA-CORONADO; FISCHER, 2013) because ripening in climacteric fruits is genetically regulated by ethylene, which is why treatments seek to control this hormone either by reducing it in the atmosphere or by blocking its synthesis and eliciting action as a post-harvest conservation strategy. 1-MCP inhibits ethylene action, reducing the maturation of various fruit species, such as pears, bananas, apples, and kiwis, among others (RUPAVATHARAM et al., 2015a).

For this reason, the objective of this research was to evaluate the effect of different storage temperatures and 1-MCP doses on the postharvest behavior of feijoa.

Material and Methods

This research was carried out in the plant physiology laboratory of the Pedagogical and Technological University of Colombia (UPTC), Tunja-Boyacá campus, at 5°32'25" N 73°21'41" W and an altitude of 2,691 m a.sl., with an average annual temperature of 12.5 °C and relative humidity of 65%. Feijoa fruits were collected from a commercial crop in the municipality of Jenesano-Boyacá, with a mean annual temperature of 17.1 °C and relative humidity of 70%.

The 'clone 41' cultivar of feijoa fruit were harvested with a homogeneous size and in a similar state of maturity, with good phytosanitary conditions and free of mechanical damage. The fruits were taken to the Plant Physiology Laboratory, where they were classified by size and mass (approximately 100 g): oval-shaped, with a smooth texture and penetrating aroma, according to market demands.

A completely randomized design with a 2x4 factorial arrangement was used: the first factor was the storage temperature (4 °C and 16 °C), and the second factor was the different 1-MCP doses (0, 30, 60 and 90 µg L^{-1}), for a total of eight treatments with 4 repetitions and 32 experiment units (EU). Each EU corresponded to 20 fruits, which were placed in 42-ounce commercial Styrofoam boxes during storage, depending on the treatments and storage temperatures. The different 1-MCP doses were prepared with the methodology implemented by Rupavatharam et al. (2015a), with 0.014% soluble powder to achieve the desired doses of 30, 60 and 90 µg L^{-1}, and the fruits were immersed for one hour, then left to dry at room temperature (16 °C) and placed in Styrofoam boxes to be stored at 4 and 16 °C.

For 42 days, the accumulated mass loss (ML) expressed in percentage (%) was evaluated; the mass of six feijoa fruit was established with a 0.001g precision electronic balance, VîBRL AJ220E (Shinko Denshi Co., Ltd, Japan). The value was recorded for each measurement over time and was calculated according to the methodology used by Álvarez-Herrera et al. (2021). For the respiratory rate (RR): three fruits were used for each EU, which were placed in 2L SEE BC-2000 hermetic chambers (Vernier Software & Technology, OR, USA) for 10 min. Then, the amount of CO_2 was determined with a VER CO_2-BTA infrared sensor (Vernier Software & Technology, OR, USA) using the interface system LabQuest2 (Vernier Software & Technology, USA). The measurements are expressed in mg kg^{-1} h^{-1} of CO_2 according to Álvarez-Herrera et al. (2021). For the fruit firmness (N): a similarly sized fruit for each EU was used, whose firmness was measured with a GY-4 penetrometer (Yueqing Handpi Instruments Co., Ltd, China) with a 3.5 mm diameter tip, a pressure depth of 10 mm and an accuracy of 0.01 N.

The color of the endocarp and exocarp was determined with a CHNSpec CS-200 Minolta digital colorimeter (Hangzhou CHNSpec Technology Co., Ltd, China) on the scale of *L**: luminosity, *a**: chromaticity from green to red, and *b**: chromaticity from blue to yellow with the CIELAB model. Six fruits per UE were used, and the chromaticity and hue (hue) were calculated using the method used by Jaime-Guerrero et al. (2021). For the soluble solids (SS): the juice of three feijoa fruits was extracted for each EU, where two drops of the juice were taken from each one, and the SS was measured and expressed in °Brix using a HANNA HI 96803 digital refractometer with a scale of 0% to 85% (Hanna Instruments, Woonsocket, RI). The titratable acidity (TA) was calculated with the volume of sodium hydroxide (NaOH) incorporated in 5 mL of juice from three feijoa fruit added to 50 mL of distilled water with three drops of phenolphthalein as an indicator of the color change, following the method of Jaime-Guerrero (2021), and expressed in percentage of citric acid (0.064 g meq^{-1}).

The total phenolic compounds (TPC) were measured with the Folin-Ciocalteu method (AMARANTE et al., 2017b), where 1.0 g of feijoa pulp and 10 mL of 80% ethanol were macerated. The resulting extract was centrifuged at 4500 rpm for 10 min. 0.5 mL of the extract were taken and mixed with 0.75 mL of Folin-Ciocalteu 1 N, then left to stand at room temperature for 5 min., then 0.75 mL of 20% sodium carbonate were added, followed by mixing and rest for 90 min. at room temperature. Finally, the absorbance at 760 nm was measured for each repetition and expressed in mg 100 g^{-1} of fresh weight. The calibration curve was made with gallic acid as a reference standard, then solutions were prepared at concentrations of 5, 10, 40, 80, 100, 140 and 200 ppm, and the equation of the straight line was established based on the acid standard of gallic acid prepared at different concentrations.

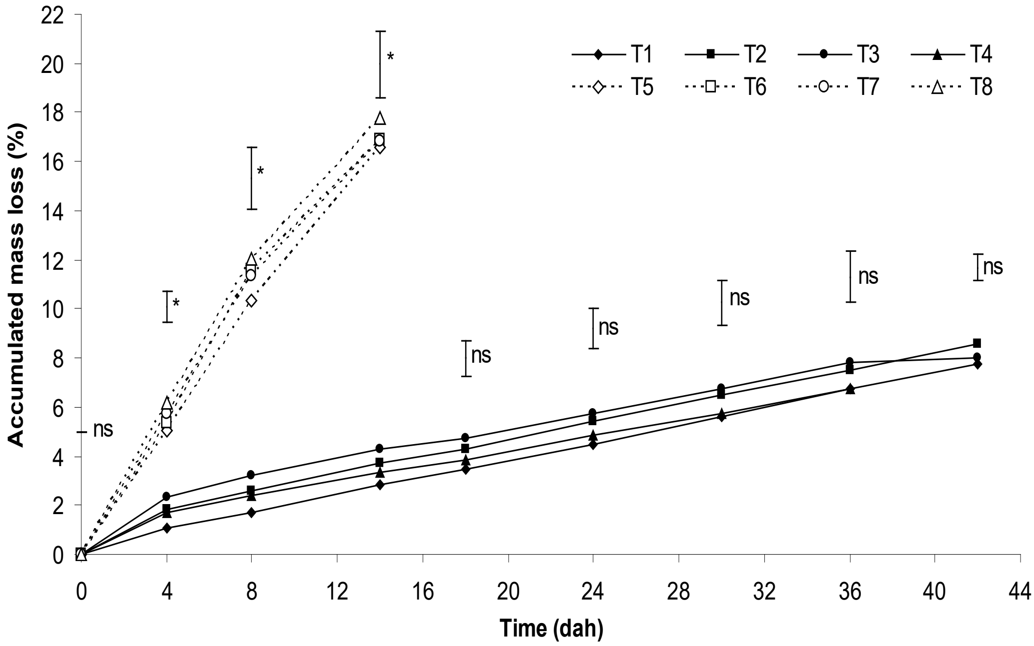
The total antioxidant activity (TAA) was determined with the 2,2'azinobis-3-ethylbenzothiazolin 6 sulfonic acid (ABTS) method (RE et al., 1999). First, a stock solution of ABTS (7 mM) was prepared: 0.0960 g of ABTS was weighed and dissolved in 25 mL of distilled water. A persulfate solution was prepared with potassium ($K_2S_2O_8$) (2.45 mM), and 0.0165 g of $K_2S_2O_8$ was weighed and dissolved in 25 mL of distilled water. For the ABTS radical, 3 mL of the ABTS stock solution and 3 mL of the potassium persulfate solution were placed in an amber bottle, stirred until homogenized and covered with aluminum foil; this solution was incubated for 16 hours at room temperature. Once the ABTS radical was formed, it was diluted in ethanol until an absorbance value of 0.7±1 at 754 nm was obtained. A calibration curve with Trolox was prepared, initially starting with a 200 mM Trolox solution, for which 0.050 g of Trolox reagent was weighed and brought to 100 mL with 96% ethanol. Aliquots of 2.5; 3.75; 5; 6.25; 7.5; 8.75 and calibrated at 25 mL with a concentration for the calibration curve of 200, 300, 400, 500, 600 and 700 µmol, respectively. For the measurement, 200 µL of feijoa extract were taken, and 3.8 mL of ABTS were added and allowed to stand for 45 min. Finally, the mixture was placed in 5 mL plastic cuvettes and measured in the spectrophotometer at 754 nm, and expressed in µmol of Trolox per g of extract (TE g^{-1}).

The data were subjected to normality and homoscedasticity tests, and an analysis of variance (Anova) was performed to determine the statistical differences between treatments and between measurements over time. Subsequently, Tukey's average comparison tests were applied ($P<0.05$). Statistical program R version 3.6.3 was used for these steps (RStudio Connect 1.8.).

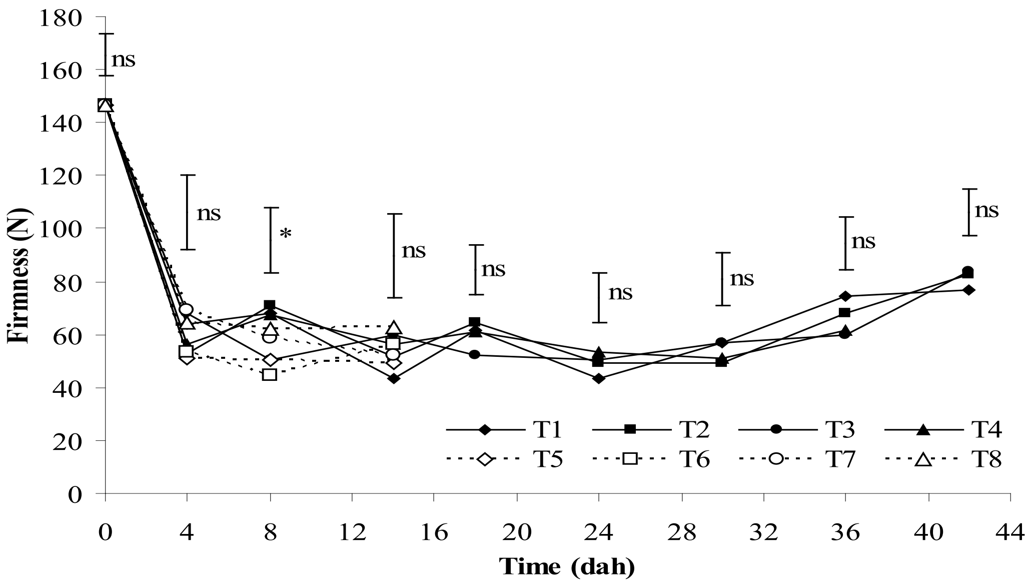
Results and Discussion

Accumulated mass loss (ML)

The loss of mass (ML) showed significant differences between treatments ($P\leq0.05$) at 4, 8 and 14 days after harvest (dah), where the refrigerated fruits presented a lower ML (2.57%±0.10) than the fruits that remained at room temperature (11.3%±0.22) (Figure 1A). Over time, the fruits stored at 16 °C had a postharvest shelf-life of only 14 days, while the refrigerated treatments lasted between 36 and 42 days, that is, statistically significant differences were observed for all measurements (4 °C: 4.67%±0.16 and 16 °C: 11.3%±0.22).



A



B

Figure 1 - A) Accumulated mass loss (%) and B) firmness (N) in feijoa fruits subjected to different 1-MCP doses and storage temperatures. T1: 4°C and 0 μg L^{-1}; T2: 4°C and 30 μg L^{-1}; T3: 4°C and 60 μg L^{-1}; T4: 4°C and 90 μg L^{-1}; T5: 16°C and 0 μg L^{-1}; T6: 16°C and 30 μg L^{-1}; T7: 16°C and 60 μg L^{-1}; T8: 16°C and 90 μg L^{-1} of 1-MCP. dah: days after harvest. Vertical bars indicate the minimum significant difference at each sampling point according to Tukey ($P \leq 0.05$), ns: not significant, *: significant differences.

This observation was attributed to water loss from transpiration in the fruits, which increases the rate of disintegration of the cell membrane and the loss of solutes, inducing water stress in the tissues and accelerating senescence (DÍAZ-PÉREZ, 2019), as observed by Parra-Coronado et al. (2018), where fruits stored at 18 °C showed a higher ML (13.01±1.98%) and therefore less postharvest durability, while refrigerated fruits had a lower ML (5.94±0.75%) and a longer useful life because of high respiratory rates that decrease fruit quality when the ML is greater than 5% (DÍAZ-PÉREZ, 2019).

Firmness

Firmness did not present significant differences between treatments, except for day 8, where the fruits stored at 4 °C with 30 μg L^{-1} of 1-MCP showed greater resistance to penetration (70.79 N±2.32) than those stored at 16 °C with 30 μg L^{-1} (44.45 N±1.19). Significant differences were obtained between all measurement times at 4 and 16 °C, with average values of 70 and 80 N (Figure 1B).

The activity of polygalacturonase (PG), the enzyme responsible for pectin solubilization and fruit softening, is greater inside the mesocarp; therefore, the loss of firmness starts inside and moves outward, that is, resistance is greater in the external epidermis than in the pulp (PARRA-CORONADO et al., 2018). This was observed by Amarante et al. (2017a), where higher 1-MCP doses delay changes in firmness because the activity of the enzymes that degrade the cell wall is reduced in response to the inhibition of ethylene action by 1-MCP. In addition, low storage temperatures (6 °C probably maintain firmness) in feijoa fruits because of a decrease in PG activity and the speed of most metabolic processes (RAMÍREZ et al., 2005).

Respiratory rate (RR)

Significant statistical differences were observed between treatments for RR on days 4, 8, 14, 30 and 36, where the fruits at 16 °C presented a higher RR during the first 3 measurements (76.02 mg CO_2 kg^{-1}h^{-1}±1.58) than those stored at 4 °C (8.54 mg CO_2 kg^{-1}h^{-1}±0.96). The fruits subjected to 90 μg L^{-1} and 4 °C had a respiratory peak in the last two measurements (28.8 mg of CO_2 kg^{-1}h^{-1}±0.42) at 36 days, which coincided with senescence and loss of commercial quality (Figure 2). Statistical differences were observed for all treatments with averages of 17.99 and 73 mg kg^{-1} h^{-1} of CO_2 at 4 and 16 °C.

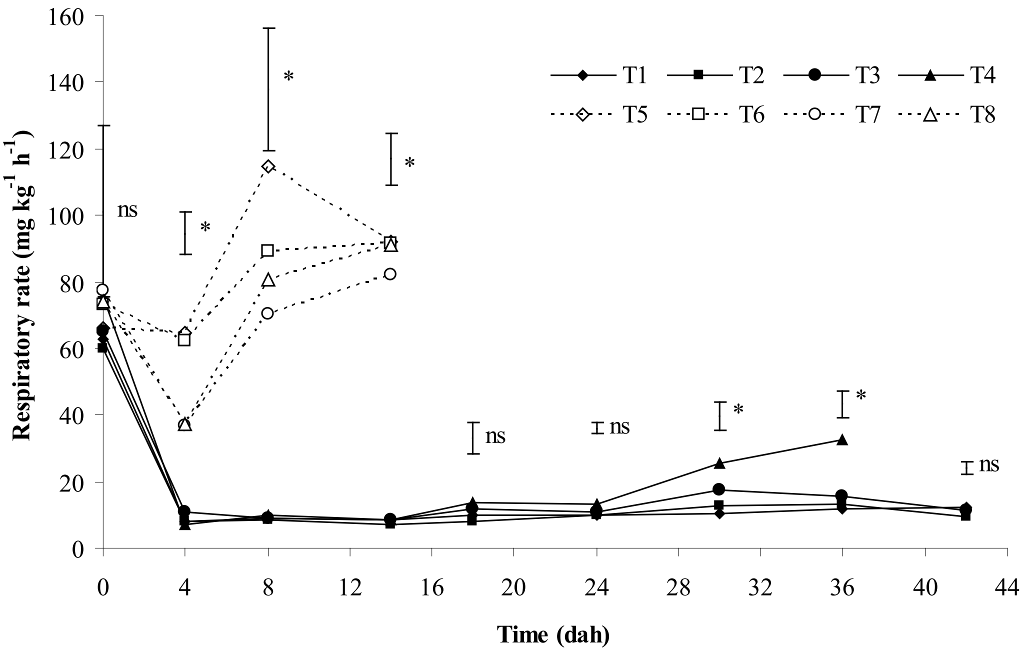
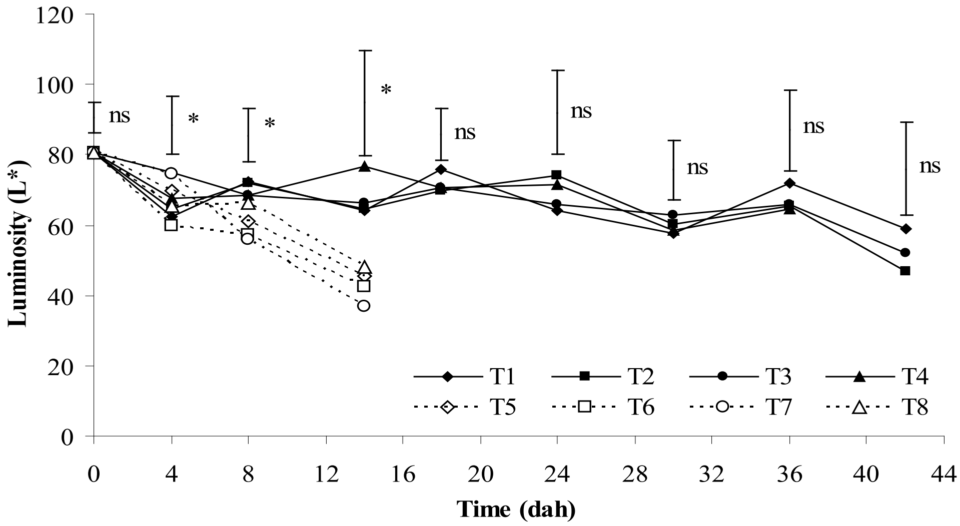


Figure 2 - Respiration rate (mg kg^{-1} h^{-1}) in feijoa fruits subjected to different 1-MCP doses and storage temperatures. T1: 4°C and 0 μg L^{-1}; T2: 4°C and 30 μg L^{-1}; T3: 4°C and 60 μg L^{-1}; T4: 4°C and 90 μg L^{-1}; T5: 16°C and 0 μg L^{-1}; T6: 16°C and 30 μg L^{-1}; T7: 16°C and 60 μg L^{-1}; T8: 16°C and 90 μg L^{-1} of 1-MCP. dah: days after harvest. Vertical bars indicate the minimum significant difference at each sampling point according to Tukey ($P \leq 0.05$), ns: not significant, *: significant differences.

This behavior is due to the fact that the feijoa is a climacteric fruit (PARRA-CORONADO; FISCHER, 2013); therefore, it increases the production of ethylene and respiration to carry out the metabolic processes during maturation, such as tissue softening and synthesis of pigments and volatile compounds. However, low storage temperatures help reduce RR and extend shelf-life (SALTVEIT, 2019). This is why feijoa fruits stored at 4 °C showed a RR between 60 and 200 nmol kg^{-1} s^{-1} of CO_2, while fruits at 20 °C had a RR between 315 and 701 nmol kg^{-1} s^{-1} of CO_2. Furthermore, in both cases, 1-MCP did not affect the treatments (RUPAVATHARAM et al., 2015b; RUPAVATHARAM et al., 2015a).

On the other hand, during the first four days, the preclimacteric period was observed (Figure 2), characterized by a decrease in RR, as stated by Rodríguez et al. (2006) who observed a similar behavior in the first two dah for clones 'Quimba' and '8-4'.



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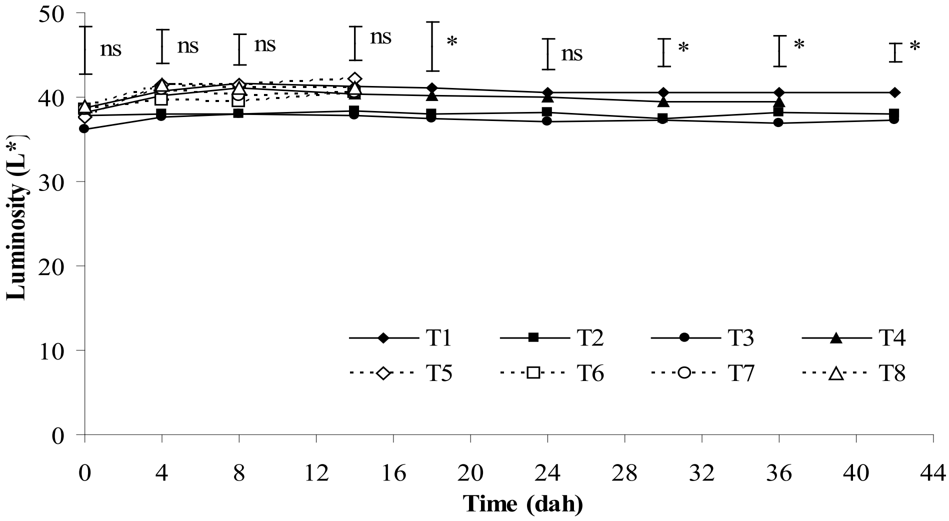


B)

Figure 3 - Luminosity (*L**) of A) endocarp and B) exocarp in feijoa fruits subjected to different 1-MCP doses and storage temperatures. T1: 4°C and 0 μg L^{-1}; T2: 4°C and 30 μg L^{-1}; T3: 4°C and 60 μg L^{-1}; T4: 4°C and 90 μg L^{-1}; T5: 16°C and 0 μg L^{-1}; T6: 16°C and 30 μg L^{-1}; T7: 16°C and 60 μg L^{-1}; T8: 16°C and 90 μg L^{-1} of 1-MCP. dah: days after harvest. Vertical bars indicate the minimum significant difference at each sampling point according to Tukey ($P \leq 0.05$), ns: not significant, *: significant differences.

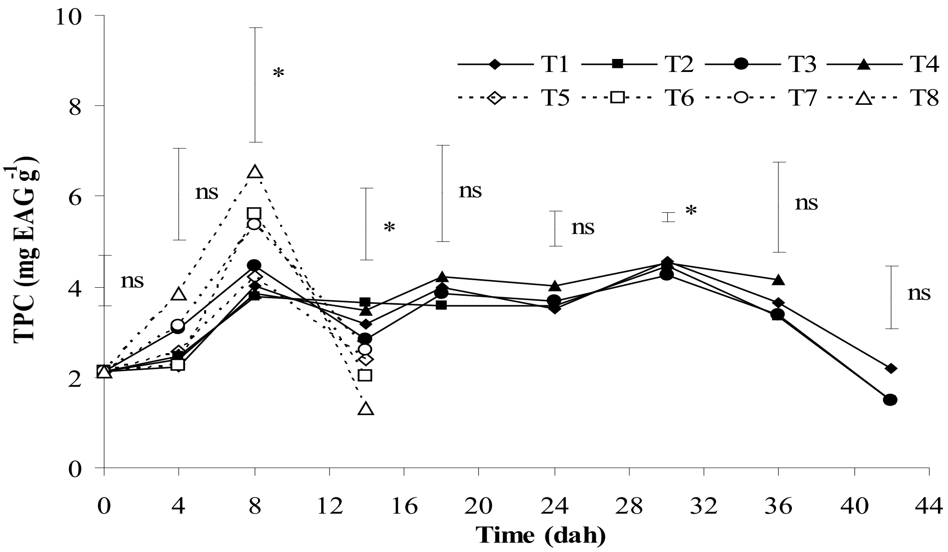
Endocarp color

There were significant statistical differences between the treatments for luminosity (*L**) of the pulp on days 4, 8 and 14, where the treatments at 4 °C presented higher values of *L** (68.52±1.49) than those stored at 16 °C (56.28±1.56) (Figure 3A). Chromaticity or saturation (*C**) did not show significant differences during the 42 days of storage (14.92±0.56), while hue (°*h*) only had significant differences on day 42 with the 60 µg L^{-1} dose (107.46± 0.77) and 0 µg L^{-1} (98.59±2.67) at 4 °C (Table 1). The pulp of the fruits at 4 °C maintained a lighter *L** (values close to 100) than those stored at 16 °C, which showed a greater darkening of the tissues. For saturation, a similar loss of color was seen in the treatments at 4 °C (14.64±0.57) and 16 °C (15.2±0.55) since values close to 0 reflect little saturation, and values close to 100 are more defined. The color intensity was lower in feijoas stored at 16 °C (102.25°±1.27).

Table 1 - Chroma (*C**) and hue (°*h*) of the endocarp in feijoa fruits subjected to different doses and storage temperatures under controlled conditions.

Color attributes	Temperature (°C)	dah	1-MCP doses (µg L^{-1})			
			0	30	60	90
C*	4	0	12.64±0.65^{a,A}	12.64±0.65^{a,A}	12.64±0.65^{a,A}	12.64±0.65^{a,A}
		4	17.12±0.59^{a,A}	14.58±0.38^{a,A}	15.95±0.62^{a,A}	16.82±0.02^{a,A}
		8	16.41±0.95^{a,A}	13.58±0.07^{a,A}	14.43±0.64^{a,A}	16.15±0.73^{a,A}
		14	13.69±0.64^{a,A}	13.26±0.57^{a,A}	15.33±0.45^{a,A}	15.51±0.46^{a,A}
		18	14.69±0.84^{a,A}	15.92±0.77^{a,A}	14.27±1.01^{a,A}	13.55±0.56^{a,A}
		24	14.67±0.51^{a,A}	16.11±0.57^{a,A}	14.17±0.29^{a,A}	15.12±0.33^{a,A}
		30	16.06±0.76^{a,A}	15.16±0.55^{a,A}	15.10±0.81^{a,A}	15.05±0.28^{a,A}
		36	15.23±0.90^{a,A}	13.92±0.36^{a,A}	13.14±0.72^{a,A}	15.84±0.81^{a,A}
		42	12.85±1.01^{a,A}	12.91±0.23^{a,A}	14.95±0.23^{a,A}	---
	16	0	12.64±0.65^{a,A}	12.64±0.65^{a,B}	12.64±0.65^{a,B}	12.64±0.65^{a,A}
		4	15.23±0.66^{a,A}	16.37±0.87^{a,AB}	14.03±0.23^{a,AB}	17.17±0.96^{a,A}
		8	16.42±0.56^{a,A}	19.59±0.72^{a,A}	17.29±0.45^{a,A}	16.21±0.24^{a,A}
		14	15.55±0.50^{a,A}	14.37±0.19^{a,AB}	14.51±0.52^{a,AB}	15.77±0.49^{a,A}
		18	---	---	---	---
		24	---	---	---	---
		30	---	---	---	---
		36	---	---	---	---
		42	---	---	---	---
°h	4	0	100.05±0.88^{a,A}	100.05±0.88^{a,B}	100.05±0.88^{a,A}	100.05±0.88^{a,A}
		4	108.81±0.37^{a,A}	107.48±1.25^{a,AB}	108.02±0.35^{a,A}	108.72±1.14^{a,A}
		8	107.78±0.96^{a,A}	106.83±1.41^{a,AB}	108.55±0.86^{a,A}	104.73±1.22^{a,A}
		14	105.25±2.10^{a,A}	109.641±1.7^{a,AB}	107.44±1.76^{a,A}	107.69±0.69^{a,A}
		18	105.42±0.56^{a,A}	107.95±0.83^{a,AB}	105.12±1.72^{a,A}	108.68±1.91^{a,A}
		24	104.35±0.21^{a,A}	105.77±1.16^{a,AB}	100.83±2.05^{a,A}	99.578±1.08^{a,A}
		30	115.14±3.48^{a,A}	120.69±2.92^{a,A}	109.82±1.85^{a,A}	106.01±0.67^{a,A}
		36	103.88±0.80^{a,A}	105.82±1.39^{a,AB}	109.62±2.11^{a,A}	106.06±1.40^{a,A}
		42	98.59±2.67^{a,A}	81.771±2.43^{b,AB}	107.46±0.77^{a,A}	---
	16	0	100.05±0.88^{a,A}	100.05±0.88^{a,A}	100.05±0.88^{a,A}	100.05±0.88^{a,A}
		4	104.79±0.49^{a,A}	113.95±0.62^{a,A}	104.79±1.15^{a,A}	105.78±1.77^{a,A}
		8	108.65±0.37^{a,A}	105.78±2.43^{a,A}	101.98±1.45^{a,A}	105.21±0.64^{a,A}
		14	103.33±1.67^{a,A}	93.46±3.18^{a,A}	90.04±1.61^{a,A}	97.95±0.82^{a,A}
		18	---	---	---	---
		24	---	---	---	---
		30	---	---	---	---
		36	---	---	---	---
		42	---	---	---	---

dah: days after harvest. Values followed by different lowercase letters in the same row indicate statistically significant differences between treatments (*P*≤0.05). Values followed by different uppercase letters in the same column indicate statistically significant differences in postharvest time. (---) Loss of consumption quality. Means of 4 replicates ± standard error.



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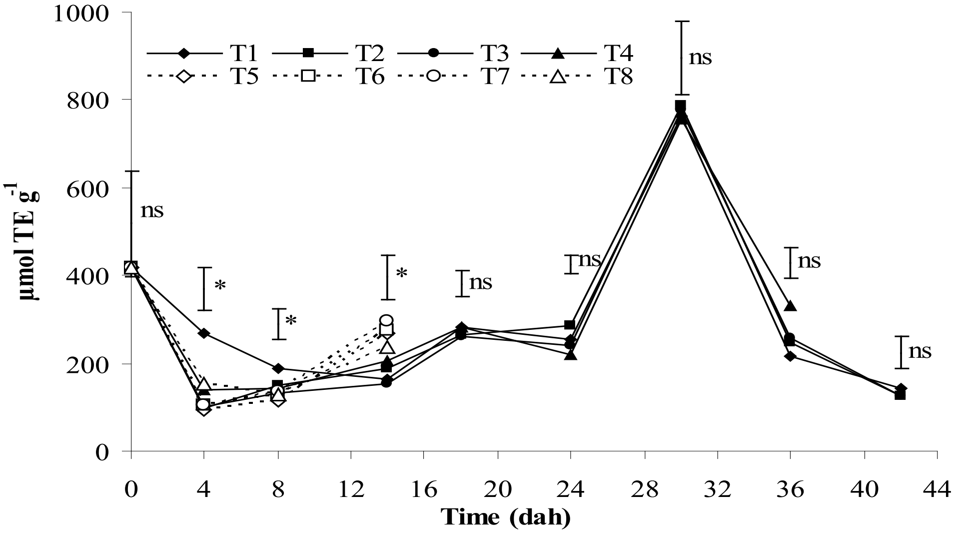

B)

Figure 4 - A) Total phenolic compounds (TPC) (mg EAG g^{-1}) and B) antioxidant capacity in in Trolox per g of extract (TE) in feijoa fruits. T1: 4°C and 0 µg L^{-1}; T2: 4°C and 30 µg L^{-1}; T3: 4°C and 60 µg L^{-1}; T4: 4°C and 90 µg L^{-1}; T5: 16°C and 0 µg L^{-1}; T6: 16°C and 30 µg L^{-1}; T7: 16°C and 60 µg L^{-1}; T8: 16°C and 90 µg L^{-1} of 1-MCP. dah: days after harvest. Vertical bars indicate the minimum significant difference at each sampling point according to Tukey (P≤0.05), ns: not significant, *: significant differences.

Rupavatharam et al. (2015a), who stored feijoa fruits at 4 °C for 6 weeks and left them for 5 days at 20 °C, observed that the fruits presented lower *L** (darker) and °*h* values, as reported by Amarante et al. (2017a), where the fruits at 23 °C presented darkening of the pulp, that is, the *L** value was lower. This is due to the fact that low temperatures decrease the degradation of chlorophylls and promote the accumulation or synthesis of secondary carotenoids and/or an increase in phenolic compounds, such as anthocyanins and flavonols (SOLOVCHENKO et al., 2019).

Similarly, statistical differences were observed for *L** between the measurement times for all doses, with averages of 62.6 and 68.1 at 16 °C and 4 °C, respectively. The *C** values had no statistical differences except for 30 and 60 µg L^{-1} at 16°C (15.2±0.53), and °*h* had not statistical differences with average of 105.11°±1.37 at 4 °C (Table 1). These results are similar to those obtained by Rupavatharam et al. (2015a), where the increase in the dose of 1-MCP preserved the color of the fruits for a longer time under refrigeration conditions at 4 °C.

Exocarp color

Significant differences were obtained between the treatments for the *L** of the skin on days 18, 30, 36 and 42, where the treatment at 4 °C with 0 µg L^{-1} presented the highest values (Figure 3B). In the case of *C**, there were significant differences for all days, except for days 0, 8 and 18, where the fruits stored at 4 °C showed the highest values, meaning these treatments had less loss of saturation or definition. Finally, for *°h*, significant differences were observed for days 4, 24, 30 and 42, where a greater loss of color intensity was observed for fruits stored at 16 °C (Table 2).

Table 2 - Chroma (*C**) and hue (*°h*) of the exocarp in feijoa fruits subjected to different doses and storage temperatures under controlled conditions.

Color attributes	Temperature (°C)	dah	1-MCP doses (µg L^{-1})			
			0	30	60	90
C*	4	0	28.94±0.03$^{a, A}$	27.39±0.19^{a,A}	26.83±0.09^{a,A}	30.18±0.55^{a,A}
		4	34.38±0.35$^{ab, A}$	29.53±0.16^{c,A}	29.17±0.12^{c,A}	35.41±0.37^{a,A}
		8	34.79±0.63$^{a, A}$	30.46±0.12^{a,A}	30.04±0.27^{a,A}	33.92±0.42^{a,A}
		14	33.95±0.51$^{a, A}$	30.54±0.11^{ab,A}	28.28±0.35^{b,A}	33.33±0.61^{ab,A}
		18	33.67±2.41$^{a, A}$	30.61±1.56^{a,A}	66.18±1.41^{a,A}	70.08±2.37^{a,A}
		24	32.45±0.29$^{a, A}$	30.16±0.28^{ab,A}	29.04±0.37^{b,A}	32.49±0.43^{a,A}
		30	34.45±0.69$^{a, A}$	30.19±0.14^{b,A}	28.63±0.33^{b,A}	32.36±0.62^{ab,A}
		36	33.53±0.50$^{a, A}$	29.88±0.36^{ab,A}	28.33±0.53^{b,A}	31.12±0.87^{ab,A}
		42	34.04±0.69$^{a, A}$	29.75±0.27^{b,A}	28.33±0.38^{b,A}	---
	16	0	29.15±0.52^{a,A}	28.16±0.21^{a,C}	29.76±0.34^{a,A}	30.79±0.68^{a,A}
		4	32.56±0.33^{abc,A}	30.24±0.14^{bc,B}	31.36±0.42^{abc,A}	32.58±0.45^{abc,A}
		8	32.38±0.28^{a,A}	31.36±0.08^{a,AB}	30.34±0.79^{a,A}	32.58±0.51^{a,A}
		14	33.74±0.43^{ab,A}	33.06±0.17^{ab,A}	31.85±0.54^{ab,A}	31.01±0.37^{ab,A}
		18	---	---	---	---
		24	---	---	---	---
		30	---	---	---	---
		36	---	---	---	---
		42	---	---	---	---
°h	4	0	127.76±1.52$^{a, A}$	127.96±0.26^{a,A}	129.23±0.21^{a,A}	126.26±0.32^{a,A}
		4	123.7±0.30^{ab,A}	125.08±0.27^{ab,AB}	125.21±0.19^{ab,B}	122.27±0.17^{b,B}
		8	123.98±0.44^{a,A}	125.23±0.12^{a,AB}	125.46±0.13^{a,B}	124.66±0.07^{a,B}
		14	124.36±0.34^{a,A}	125.33±0.15^{a,AB}	126.07±0.07^{a,AB}	124.58±0.12^{a,AB}
		18	124.55±0.62^{a,A}	128.13±0.92^{a,A}	111.34±0.96^{a,AB}	111.31±0.52^{a,AB}
		24	124.9±0.26^{ab,A}	125.43±0.21^{ab,AB}	125.93±0.12^{a,AB}	124.05±0.21^{a,AB}
		30	122.67±0.42^{b,A}	123.89±0.18^{ab,B}	125.28±0.26^{a,B}	123.70±0.03^{a,B}
		36	123.57±0.44^{a,A}	125.52±0.16^{a,AB}	125.83±0.07^{a,AB}	124.57±0.33^{a,AB}
		42	123.58±0.39^{b,A}	125.29±0.33^{ab,A}	126.36±0.09^{a,AB}	---
	16	0	127.54±0.41^{a,A}	128.18±0.20^{a,A}	127.35±0.14^{a,A}	125.95±0.61^{a,A}
		4	125.2±0.2^{ab,AB}	125.81±0.13^{a,B}	126.34±0.15^{a,A}	124.37±0.41^{ab,A}
		8	125.2±0.15^{a,AB}	125.60±016^{a,B}	127.31±0.31^{a,A}	124.32±0.58^{a,A}
		14	123.43±0.15^{a,B}	123.74±0.19^{a,B}	125.68±0.21^{a,A}	126.01±0.32^{a,A}
		18	---	---	---	---
		24	---	---	---	---
		30	---	---	---	---
		36	---	---	---	---
		42	---	---	---	---

dah: days after harvest. Values followed by different lowercase letters in the same row indicate statistically significant differences between treatments ($P \leq 0.05$). Values followed by different uppercase letters in the same column indicate statistically significant differences in postharvest time. (---) Loss of consumption quality. Means of 4 replicates ± standard error.

Color changes are related to the evolution of the texture, flavor and aroma of the fruits and are closely related to resistance to penetration, as reported by Amarante et al. (2017a), who found reductions in *C** values after storage in feijoa fruits, while Al-Harthy et al. (2008) observed a minimal reduction in hue that generated a slight yellowish coloration.

When analyzing the measurements over time, significant differences are observed for *L** at 0 and 30 µg L^{-1} at 16 °C, while for *C**, there were no significant differences, except for the treatment of 30 µg L^{-1} at 16 °C. For °*h*, differences were obtained between treatments at 4 and 16 °C, that is, the dose between 0 and 30 µg L^{-1} at 16 °C showed an increase in *L** (lighter fruits) and a decrease in *C** (loss of saturation), while the fruits at 4 °C with higher 1-MCP doses obtained a slight decrease in hue when compared to those stored at 16 °C (Table 2). This was observed by Rupavatharam et al. (2015b) with a decrease in the hue angle from 112.8 to 110.5 in fruits stored at 4 °C; however, the color change was not influenced by the doses of 1-MCP. In contrast, Amarante et al. (2017a) stated that fruits had a less green color because of a decrease in °*h* and increase in *L**.

On the other hand, brown-color damage was observed on the skin of the fruits stored at 16 °C, accompanied by damage caused by fruit flies (*Anastrepha fraterculus*), while the refrigerated fruits were not affected because low temperatures kill larvae, which do not pass to the pupal state, as corroborated by Valderrama et al. (2005), who subjected fruit fly larvae to a cold quarantine treatment (1.1 °C) and others to room temperature (19 °C) and observed that, on the third day, the larvae exposed to low temperatures began to die.

Soluble Solids (SS)

No significant differences were obtained between the treatments for SS, except for days 4, 36 and 42 (Table 3), where the fruits at 4 °C with 0 µg L^{-1} showed the highest SS values (9.85°± 0.36), as compared to the same treatments at 16 °C (9.12°±0.27). The fruits stored at 16 °C increased the SS between days 4 and 14, consistent with the increase in IR, while the refrigerated fruits only showed an increase in SS between 14 and 24 dah.

Table 3 - Soluble Solids (SS) (°Brix) and Titratable Acidity (TA) (%) in feijoa fruits subjected to different doses and storage temperatures under controlled conditions.

Chemical properties	Temperature (°C)	dah	1-MCP doses (µg L^{-1})			
			0	30	60	90
SS	4	0	10.07±0.32^{a,A}	10.07±0.32^{a,AB}	10.07±0.32^{a,A}	10.07±0.32^{a,AB}
		4	12.03±0.31^{a,A}	9.60±0.14^{ab,ABC}	8.92±0.25^{ab,AB}	8.55±0.21^{ab,AB}
		8	9.25±0.11^{a,A}	8.70±0.21^{a,ABC}	9.86±0.09^{a,A}	9.82±0.27^{a,AB}
		14	8.67±0.47^{a,A}	8.97±0.32^{a,ABC}	9.62±0.18^{a,A}	8.57±0.28^{a,AB}
		18	10.60±0.32^{a,A}	10.40±0.46^{a,A}	10.55±0.16^{a,A}	9.50±0.40^{a,AB}
		24	11.05±0.66^{a,A}	9.37±0.33^{a,ABC}	11.22±0.34^{a,A}	10.95±0.47^{a,A}
		30	9.65±0.76^{a,A}	8.00±0.23^{a,ABC}	9.17±0.43^{a,AB}	9.05±0.19^{a,B}
		36	7.82±0.09^{a,A}	6.62±0.20^{ab,C}	6.02±0.11^{b,C}	7.27±0.17^{ab,AB}
		42	9.57±0.24^{a,A}	7.02±0.21^{b,C}	6.52±0.26^{b,C}	---
	16	0	10.07±0.32^{a,A}	10.07±0.32^{a,A}	10.07±0.32^{a,A}	10.07±0.32^{a,A}
		4	9.22±0.20^{ab,A}	10.67±0.39^{ab,A}	8.20±0.28^{b,A}	8.70±0.27^{ab,A}
		8	9.62±0.29^{a,A}	9.37±0.17^{a,A}	8.55±0.17^{a,A}	8.75±0.21^{a,A}
		14	7.60±0.29^{a,A}	10.32±0.42^{a,A}	10.65±0.21^{a,A}	10.17±0.05^{a,A}
		18	---	---	---	---
		24	---	---	---	---
		30	---	---	---	---
		36	---	---	---	---
		42	---	---	---	---

(to be continued)

Table 3 - Soluble Solids (SS) (°Brix) and Titratable Acidity (TA) (%) in feijoa fruits subjected to different doses and storage temperatures under controlled conditions. (continuation)

Chemical properties	Temperature (°C)	dah	1-MCP doses (µg L^{-1})			
			0	30	60	90
TA	4	0	$3.05\pm0.09^{a, A}$	$3.05\pm0.09^{a,AB}$	$3.05\pm0.09^{a,AB}$	$3.05\pm0.09^{a,A}$
		4	$2.48\pm0.21^{a, AB}$	$3.19\pm0.06^{a,A}$	$3.22\pm0.05^{a,A}$	$2.61\pm0.06^{a,A}$
		8	$3.15\pm0.11^{ab, A}$	$3.21\pm0.11^{a,A}$	$2.99\pm0.13^{abc,AB}$	$2.47\pm0.11^{abc,A}$
		14	$1.31\pm0.11^{a, B}$	2.43 ± 0.04^{aABC}	$2.18\pm0.18^{a,AB}$	$1.97\pm0.02^{a,A}$
		18	$2.47\pm0.14^{a, AB}$	$1.87\pm0.14^{a,BC}$	$2.43\pm0.13^{a,AB}$	$2.55\pm0.12^{a,A}$
		24	$2.84\pm0.08^{a, A}$	$2.68\pm0.17^{a,ABC}$	$2.88\pm0.16^{a,AB}$	$2.78\pm0.18^{a,A}$
		30	$2.83\pm0.01^{a, A}$	$2.76\pm0.05^{a,ABC}$	$2.47\pm0.04^{ab,AB}$	$2.29\pm0.06^{b,A}$
		36	$2.93\pm0.14^{a, A}$	$1.71\pm0.17^{ab,C}$	$1.61\pm0.13^{b,B}$	$2.16\pm0.12^{ab,A}$
		42	$2.47\pm0.08^{a, AB}$	$2.23\pm0.05^{a,ABC}$	$2.02\pm0.12^{a,AB}$	---
	16	0	$3.05\pm0.09^{a,A}$	$3.05\pm0.09^{a,A}$	$3.05\pm0.09^{a,A}$	$3.05\pm0.09^{a,A}$
		4	$3.01\pm0.06^{a,A}$	$2.37\pm0.11^{a,AB}$	$2.66\pm0.17^{a,A}$	$2.73\pm0.12^{a,A}$
		8	$1.57\pm0.05^{c, B}$	$1.64\pm0.09^{bc,BC}$	$1.89\pm0.17^{abc,A}$	$2.63\pm0.04^{abc,A}$
		14	$1.23\pm0.15^{a,B}$	$1.08\pm0.09^{a,C}$	$1.07\pm0.14^{a,A}$	$1.45\pm0.06^{a,B}$
		18	---	---	---	---
		24	---	---	---	---
		30	---	---	---	---
		36	---	---	---	---
		42	---	---	---	---

dah: days after harvest. Values followed by different lowercase letters in the same row indicate statistically significant differences between treatments (P≤0.05). Values followed by different uppercase letters in the same column indicate statistically significant differences in postharvest time. (---) Loss of consumption quality. Means of 4 replicates ± standard error.

This behavior is similar to that reported by Rodríguez et al. (2006), who observed increases in SS in clone '8-4' feijoa fruits from the first to the sixth dah at room temperature, while the 'Quimba' clone had the maximum SS at 11 dah, as seen in climacteric fruits. Feijoa fruits have a high amount of starch at harvest, which hydrolyzes with maturation, producing an increase in SS; in addition, the most abundant sugars in feijoa are, in order, fructose, sucrose and glucose (PARRA-CORONADO; FISHER, 2013).

When analyzing the measurements over time, significant differences could be seen for the treatments with doses of 30, 60 and 90 µg L^{-1} at 4 °C (Table 3), where a higher 1-MCP dose meant a lower amount of SS in the fruits, as reported by Singh and Pal (2008) in guava fruits.

Titratable Acidity (TA)

No significant differences were obtained between treatments for TA, except for days 8, 30 and 36. The fruits at 4 °C with doses of 0 µg L^{-1} (2.88%) and 30 µg L^{-1} (2.98%) presented the highest TA values, as compared to the same treatments at 16 °C (1.57 and 1.64, respectively). When analyzing this behavior over time, the TA decreased both for the refrigerated fruits and for those stored at room temperature (16 °C), going from 3.05% to 2.22% and from 3.05% to 1.21%, respectively; as TA decreases, SS increases (Table 3), as reported by Rodríguez et al. (2006), who found decreases in TA during postharvest in clone '8-4' and 'Quimba' feijoa fruits stored at room temperature. This decrease occurs because organic acids are either degraded by the activation of the gluconeogenesis pathway to produce glucose or used in the respiration process as maturation occurs. It should be noted that this conversion of acids into sugars is essential for quality (flavor and aroma) and nutritional value in fruits (VALLARINO; OSORIO, 2019).

The TA presented significant differences between 1-MCP doses at 4 °C (2.57) and 16 °C (2.24), as reported by Álvarez-Herrera et al. (2022), who stated that 1-MCP influences the metabolism of carbohydrates and organic acids. This confirmed that, when feijoa fruits are refrigerated, organic acids degrade at a lower rate than when fruits are stored in the environment.

Total Phenolic Compounds (TPC)

There were significant differences between the treatments for days 8, 14 and 30, where the fruits with 0, 30 and 90 µg L^{-1} at 4 °C and 90 µg L^{-1} at 16 °C obtained higher TPC values (mg EAG g^{-1}) (Figure 4A). The feijoa fruits stored at 4 and 16 °C recorded values of 2.95 and 3.15 mg g^{-1}, respectively, which were lower than the ranges found between 4.1 and 11.4 mg g^{-1} by Oliveira et al. (2020), who also identified 30 phenolic compounds. In addition, Amarante et al. (2017b) obtained values between 0.76 to 0.96 mg EAG g^{-1} for TPC in five feijoa accessions and González-García et al. (2018) found 13.72±6.70 mg EAG g^{-1} for fruits stored at room temperature. It should be noted that the application of different treatments before and/or after harvest can induce TPC synthesis (MORENO-ESCAMILLA et al., 2019).

The myrtaceae family is characterized by a high content of phenolic compounds. Feijoa fruit extracts have a large amount of polyphenols, including phenolic acids (gallic acid, acid syringic acid, etc.) and flavonoids (quercetin, flavone, catechin, etc.) (AOYAMA et al., 2018). When evaluating the measurements over time, significant variations in the TPC were found at 8 and 30 dah, where higher values were reached; however, no trend was observed, and the TPC values remained relatively constant during the postharvest measurements (Figure 4). It should be noted that feijoa fruits have a high antimicrobial, anti-inflammatory and antioxidant capacity (MARTIN et al., 2015) probably because they have the ability to chelate metals, inhibit lipoxygenase and capture free radicals (GONZÁLEZ-GARCÍA et al., 2018).

Total antioxidant activity (TAA)

The TAA showed significant differences between the treatments at 4, 8, 14, 24 and 36 dah (Figure 4B), where the fruits at 0, 30, 60 and 90 µg L^{-1} at 4 °C and 60 µg L^{-1} at 16 °C presented higher values. The storage temperature affected the TAA since on average there were values of 277.6 and 231.9 µmol of Trolox per g of extract (TE g^{-1}) for 4 and 16 °C, respectively. This is lower than the values of 320 µmol TE g^{-1} found by Contreras-Calderón et al. (2011) in feijoa fruits, who stated that antioxidants react with free radicals and give them an electron, which generates a weak free radical with no or few toxic effects (AMARANTE et al., 2017b). Likewise, feijoa is characterized by a high amount of antioxidants, as confirmed by Tuncel and Yilmaz (2015), who obtained values from 63.4 to 125.5 µmol TE L^{-1} of dry weight in feijoa fruits.

In the analysis of measurements over time, the TAA showed significant differences for all treatments (Figure 4B). At 30 dah, higher values were seen with 765.7 µmol TE g^{-1}, a possible indicator of stress and the beginning of senescence and loss of consumption quality.

Conclusions

Feijoa fruit subject at 4 °C presented lower values for mass loss and respiratory rate, while luminosity, chromaticity, soluble solids and antioxidant activity showed the highest values. The lowest 1-MCP doses at 4 °C had the highest values of titratable acidity and endocarp tone; on the contrary, the highest doses at 4 and 16 °C presented the highest values of phenolic compounds. The refrigerated feijoa fruits had a shelf-life between 36 and 42 days, while those stored at 16 °C only had commercial quality for 14 days, highlighting the importance of cold storage. The best dose of 1-MCP was 90 µg L^{-1}, since it promoted the highest firmness values in fruits stored at 16 °C.

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