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RESEARCH ARTICLE

Effect of 1-methylcyclopropene on jackfruit with marketing simulation at 8°C

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ABSTRACT

Jackfruit is a tropical fruit and competes with traditional crops such as mango, banana, and pineapple with regard to the quantity exported from the state of Nayarit, Mexico. Because jackfruit is a climacteric fruit with a high respiration rate and ethylene production, it has a limited market due to its short shelf life. The effect of the application of 1-methylcyclopropene (1-MCP) post-harvest to extend the shelf life of jackfruit was studied. Physiologically mature fruits were used and 1-MCP was applied at concentrations of 300, 600, and 1000 nL·L^{-1}; control fruit without treatment was also evaluated. The fruits were stored for 5 days at 8°C and then were stored at 25°C to simulate the commercialization of the fruit. An absolute control group stored permanently at 25°C was used. The following analyses were carried out: physiologic and physicochemical factors, antioxidant capacity, vitamin C, total carotenoids, total soluble phenols, and sensory evaluation of the fruits when ripe. The climacteric peak for the absolute controls and fruit treated with 1-MCP (300, 600, and 1000 nL·L^{-1}) occurred on days 3, 14, 17, and 17 respectively, prolonging the climacteric peak by an average of 13 days. The maximum rates of ethylene production were reported on days 3, 15, 17, and 17 in the same order, prolonging this by an average of 13 days. The treatment with 1-MCP (600 nL·L^{-1}) extended the shelf life of jackfruit by 9 days compared with the absolute control, preserving the physicochemical, phytochemical, and sensory characteristics for up to 17 days of storage, confirming that the application of 1-MCP post-harvest is effective, providing the opportunity to increase the export destinations of Mexican jackfruit.

Keywords: Jackfruit; 1-Methylcyclopropene; Marketing conditions; Physiologic and physicochemical parameters; Total soluble phenols; Antioxidant capacity

INTRODUCTION

Jackfruit (*Artocarphus heterophyllus* Lam.) is a tropical fruit with a constantly expanding niche market due to a high level of consumption in Asia (Vargas-Torres et al., 2017). Mexico produces and exports jackfruit on the American continent, with more than 90% of the production allocated to North American countries (SIAP, 2017). The state of Nayarit is the main producer in Mexico with just over 93% of annual production (SIAP, 2021). However, the technological development of this crop is still incipient, and despite this situation, jackfruit cultivation represents a valuable income opportunity for Nayarit families and is a material of interest to researchers (Luna-Esquivel et al., 2013). Respiration behavior in jackfruit fruit is climacteric; values of 103.49 mL kg^{-1} h^{-1} have been reported at its maximum peak of CO_2 production and 45.55 µL kg^{-1} h^{-1} in the production of ethylene stored at 25°C. Therefore, jackfruit has a short shelf life (Morelos-Flores et al., 2021).

Ethylene is a plant hormone with an important role in fruit post-harvest (Bapat et al., 2010). It is responsible for regulating the maturation and senescence processes at the physiologic, physicochemical, and molecular levels (Kesari et al., 2007). During the ripening process, various changes are manifested that are interesting with regard to the sensory quality of the fruit (color, total soluble solids, texture, acidity, and volatile compounds, among others) (Bouzayen et al., 2010). According to several studies on the mechanism of action of ethylene, various technologies, and processes have

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been investigated to reduce the unfavorable effects of this hormone, such as refrigeration, modified atmosphere, and chemical retardants. Chemical retardants show the best results in controlling maturity and senescence in climacteric fruit (Balaguera-López et al., 2014). 1-Methylcyclopropene (1-MCP) has been used as a post-harvest treatment (Blankenship and Dole, 2003). The mechanism of action of 1-MCP is based on occupying ethylene receptors through an irreversible bond. Thus, 1-MCP interferes in the signaling cascade responsible for the transduction of signals expressed by genes linked to maturation (In et al., 2013). However, due to the generation of new ethylene receptors, 1-MCP delays but does not inhibit ripening, therefore, the marketed fruit maintains the characteristics desired by consumers (Watkins, 2006). The US Environmental Protection Agency reported that subchronic, chronic, immune, endocrine, or non-dietary exposure to 1-MCP does not have adverse effects on the fruit (US Environmental Protection Agency, 2008). Several studies have reported the use of 1-MCP post-harvest for climacteric fruits such as jackfruit. Mata-Montes de Oca et al. (2007) used a concentration of 300 nL L^{-1} of 1-MCP in jackfruit stored at 25°C, extending its shelf life to 22 days. In this research, the control of respiration and the displacement of the appearance of the climacteric peak were highlighted. On the other hand, Morelos-Flores et al. (2021) worked with jackfruit stored at 13°C and subjected to marketing simulation and 1-MCP, evaluating the concentrations of 300, 600 and 1000 nL L^{-1} on the physicochemical and physiological parameters of the fruit. In this investigation, shelf life was extended to day 21 for 600 and 1000 nL L^{-1}, while at 300 nL L^{-1}, shelf life was extended to 17 days. The characteristics of the fruits treated with 1-MCP were the control of firmness loss, color, and a decrease in respiration rate and ethylene production. Similar results to those obtained in jackfruit were found in other climacteric fruits such as avocado (Osuna-García et al., 2007), kiwi (Chai et al., 2021), and pear (Guo et al., 2020), among others. In this sense, this research aimed to evaluate the effect of different concentrations of 1-MCP in jackfruit fruits subjected to marketing simulation. Since jackfruit has a high economic value for the community of the state of Nayarit and post-harvest handling technology and processes are still under development, the objective of this study was to evaluate the effect of 1-MCP on physicochemical and physiological parameters of jackfruit stored at 8°C and subjected to a marketing simulation.

MATERIALS AND METHODS

The study was carried out in the May-June 2019 season, when jackfruit (*Artocarphus heterophyllus* Lam.), known locally as "agüitada", was harvested at physiologic maturity. The fruits were obtained from an orchard located in Estacion Nanchi, a locality in Santiago Ixcuintla, Nayarit, México. The fruits were transferred to the Laboratorio Integral en Investigación en Alimentos del Tecnológico Nacional de México. They were washed by immersion, and antifungal treatment with thiabendazole (800 ppm) was applied for 3 min. Subsequently, they were left to dry at room temperature and the peduncle was sealed with copper oxychloride. The 1-MCP treatments were applied in hermetic containers (512 L) at concentrations of 300, 600, and 1000 $nL \cdot L^{-1}$ exposing the fruit to the gas for 12 h. Control fruit and fruits treated with 1-MCP were stored at 8°C for 5 days, and the fruits were transferred to a temperature of 25°C to simulate the marketing conditions. Absolute control fruit was also stored at 25°C throughout their shelf life. The data analysis carried out in this research was divided into 2 stages: physiologic and physicochemical analysis; and determination of total soluble phenols, antioxidant capacity, total carotenoids, vitamin C, and sensory analysis.

Physiologic analysis

The physiologic analyses were carried out on a daily basis until the end of the shelf life of the fruit. The method proposed by Tovar et al. (2001) was used to determine the respiration rate (RR) and the ethylene production rate (EPR). A digital scale (Torrey L-PCR; Mexico) with a capacity of 20 *kg* and 0.5 *g* precision was used to determine the physiologic weight loss (PWL) reporting the difference in weight with respect to the original as a percentage weight loss (López-Mora et al., 2013).

Physicochemical analysis

Physicochemical analyses were carried out every 48 hours until 21 days of storage. Total soluble solids (TSS) (method 932.14), titratable acidity (TA) (method 942.15), and pH (method 981.12) of jackfruit bulbs were analyzed as established by the Association of Analytical Communities (AOAC, 2005). The firmness was evaluated following the method proposed by Morelos-Flores et al. (2021) using a texturometer (TA.TXplus; Stable Micro Systems, UK). A colorimeter (CR300; Minolta, Japan) was used to determine the color of the peel (PC) and bulbs (BC), reporting the angle (°hue), chroma (C), and luminosity (L) (Morelos-Flores et al., 2021).

In the second stage, the fruits with the concentration of 1-MCP that showed the best results in physicochemical and physiological analyses were evaluated. An organic aqueous extraction (OAE) of freeze-dried bulbs was prepared for the spectrophotometric analyses, following the method proposed by Pérez-Jiménez et al. (2008).

Total soluble phenols (TSP) were quantified using the Folin-Ciocalteu reagent and the method described by Montreau (1972) with some modifications. A microplate reader (Biotek, BT800TS, Germany) was used and read at 750 nm. The

calculations were carried out with a standard curve of gallic acid and the results were expressed as milligram gallic acid equivalents per 100 grams dry weight (mg GAE/100 g DW).

The evaluation of the *in vitro* antioxidant capacity of OAE was determined by DPPH and FRAP methods following the methodologies of Prior and Cao (1999) and Benzie and Strain (1996) respectively. A microplate reader (Biotek, BT800TS, Germany) was used and read at 517 nm (DPPH) and 595 nm (FRAP). For both determinations, the data were compared with a Trolox calibration curve and reported as millimoles Trolox equivalent per 100 grams dry weight (mmol TE/100g DW).

Quantification of total carotenoids and vitamin C

For the quantification of total carotenoids (TC), the method proposed by Philip and Chen (1988) was used with some modifications. The absorbance was measured at 448 nm (Cintra 10e; GBC Scientific Equipment, Australia) using ether-acetone as a blank, and the values were expressed as microgram of β- carotene equivalents per 100 grams dry weight (μg βCE/100g DW).

The quantification of vitamin C was carried out using the technique proposed by Barbosa et al. (2017). the filtered OAE was injected into an HPLC-DAD (Agilent Technologies®, 1260 Infinity, Germany) with a Poroshell 120 EC-C18 reversed-phase column (2.7μ, 4.6 mm x 100 mm; Agilent Technologies, USA). Ascorbic acid was detected at 250 nm with a UV-vis photodiode array detector, and the concentration was calculated using an ascorbic acid standard curve; the results were expressed as milligram of ascorbic acid equivalents per gram dry weight (mg AAE/g DW).

Sensory analysis

Sensory analysis was applied as recommended by Pedrero and Pangborn (1989) using an evaluation format with an unstructured scale. Thirty untrained judges evaluated the color, odor, flavor, and texture.

Statistical analysis

A bifactorial design was carried out considering the concentrations of 1-MCP and days of storage as factors. The results were evaluated using a bidirectional analysis of variance (ANOVA) and LSD test of comparison of means of all samples (two fruits) analyzed in triplicate with $\alpha = 0.05$ and a confidence level of 95%, using Prism 8 software (GraphPad, USA).

RESULTS

Physiologic analysis

Analysis of the RR showed that the absolute control fruit stored at 25°C (Fig. 1A) presented a climacteric peak on day 3 of storage with 103.49 mL of CO_2 kg^{-1} h^{-1}, with only 8 days of shelf life. Control fruit stored at 8°C (Fig. 1B) maintained low levels of RR during refrigeration; however, the climacteric peak appeared on day 8 with 115.85 mL of CO_2 kg^{-1} h^{-1}. After the treatments with 1-MCP (Fig. 1B), a delay was observed in the appearance of the climacteric peak and therefore the shelf life increased. A concentration of 300 nL L^{-1} showed the climacteric peak on day 14, with 127.87 mL of CO_2 kg^{-1} h^{-1}, reaching a shelf life of 17 days. At 600 and 1000 nL L^{-1}, the climacteric peak appeared on day 17 with 154.02 and 168.45 mL of CO_2 kg^{-1} h^{-1}, respectively, however, 17 days of storage was achieved with a concentration of 600 nL L^{-1} and 18 days with 1000 nL L^{-1}.

The maximum ethylene production of the absolute control fruit (25°C) coincided with the climacteric peak on the third day of storage (Fig. 1C) with 45.55 μL kg^{-1} h^{-1}. The fruit stored at 8°C showed a control effect on the production of ethylene. In the case of the control (Fig. 1D), the maximum EPR occurred on day 11 with 33.39 μL kg^{-1} h^{-1}. A concentration of 300 nL L^{-1} (Fig. 1D) prolonged the ethylene peak until day 15 of storage with 29.20 μL kg^{-1} h^{-1}. With 600 and 1000 nL L^{-1} (Fig. 2B), the climacteric peak days coincide with the maximum increases in EPR with 52.71 and 56.50 μL kg^{-1} h^{-1}, respectively.

Analysis of the data showed an increase in weight loss in all fruit. For the absolute control (Fig. 1E), the weight loss was greater than 1% each day, reaching 9.96% on day 8. The control fruit in the marketing simulation (Fig. 1F) had a loss of 14.45% on the last day of shelf life. In the case of the fruit treated with 1-MCP (Fig. 1F), higher percentages of PWL were obtained; however, it should be taken into account that the shelf life increased from 8 to 9 days similar to the absolute control. The results obtained from the lowest to the highest concentration of 1-MCP were 25.61%, 26.64%, and 27.27%; the statistical analysis did not show significant differences ($p < 0.05$) between these values. In the research carried out by Osuna-García et al. (2011), different concentrations of 1-MCP (100, 200, and 300 nL L^{-1}) were applied to Mexican plum fruits (*Spondias purpurea* L.) without showing effects until day 7 of storage. After day 7, the fruits maintained values of 18.6% PWL for 100 nL L^{-1}, 16.5% for 200 nL L^{-1}, and 16.6% for 300 nL L^{-1}.

Physicochemical analysis

The TSS in the absolute control fruit showed a final value of 29.55% (Table 1), establishing the value at the consumption stage. The control bulbs with simulation showed a decrease in the generation of TSS, reaching 26.63% on day 14. The application of 1-MCP to the fruit (Table 1) showed control over the TSS parameter until

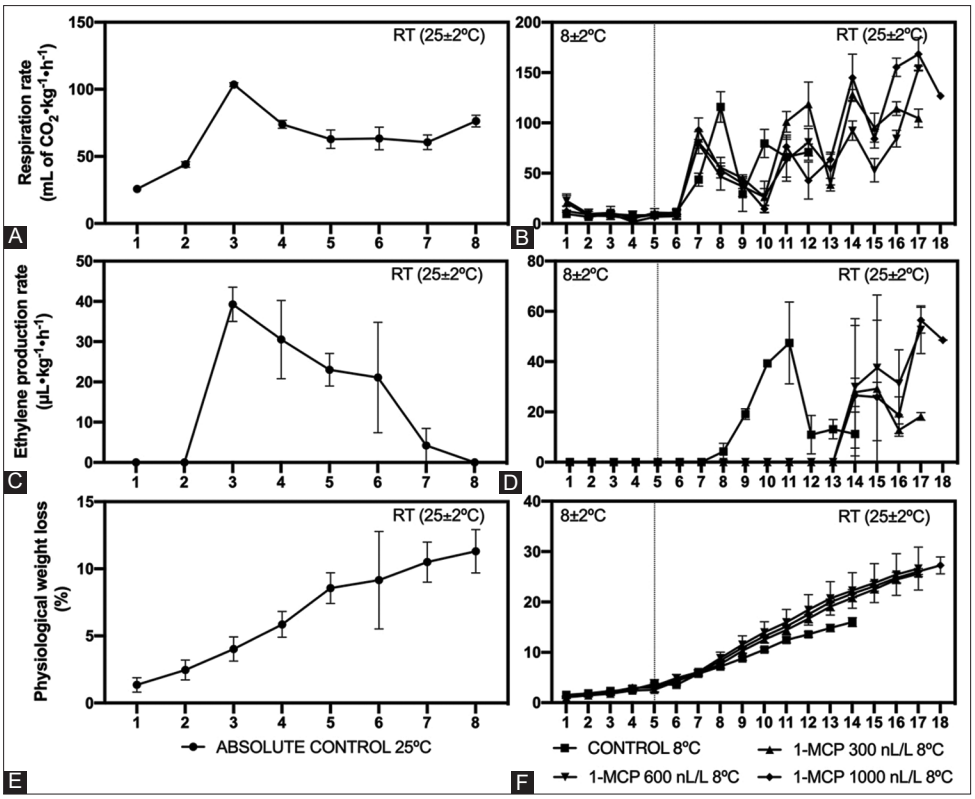

Fig 1. The physiology of jackfruit in the absolute control fruit (left) and in the control fruit and the 1-MCP-treated fruit (right): (A-B) respiratory rate; (C-D) ethylene production rate; (E-F) physiologic weight loss. The dotted line indicates the day of the change from refrigeration temperature to 25°C.

Fig 2. Color analysis of jackfruit peel: (A) absolute control stored for 8 days; (B) control stored at 8°C for 14 days; (C) treatment with 1-MCP 1000 nL L–1 stored for 18 days.

days 17 and 18; when the values were close to those of the absolute control fruit (28.48%, 27.50%, and 26.33%, respectively).

The values for TA and pH showed fluctuations in the control fruit and those treated with 1-MCP (Table 1), with a slight increase in TA and a slight decrease in pH; however, no statistically significant differences were found ($p < 0.05$). The absolute control fruit presented TA values of 0.17 g/100 g and pH values of 5.88, which were taken as reference values for the treated fruits. The TA and pH values for the control at 8°C were 0.24 g/100 g and 5.21, respectively. The TA values after treatment with 1-MCP are shown in Table 1.

The results obtained in the PF and BF analysis (Table 1) showed how these parameters began to decrease with the days of storage, as well as the effectiveness of 1-MCP by delaying the loss of firmness. The reference values used to allow us to assess the changes in the fruit were those on the initial day of the analysis. A different behavior was obtained with the treatments with 1-MCP in the PF because the firmness of the fruit was maintained until the last day its shelf life. Because firmness was determined by puncturing the fruit, it was not possible to use the same fruit for each day in this experiment, which explains the variability in the data. However, the efficacy of 1-MCP with regard to this parameter is demonstrated. Unlike PF, the BF values showed a loss of firmness (Table 1).

The degradation of chlorophyll in the peel and the production of carotenoids in the bulbs of control and treated fruit were manifested naturally, however, the control effect of post-harvest technology was evident (Table 1).

Table 1: Physicochemical analysis of jackfruit

Storage days	Control		1-MCP 8°C		
	25°C	8°C	300 nL·L^{-1}	600 nL·L^{-1}	1000 nL·L^{-1}
Total soluble solids (%)					
1	8.33±1.53^{a}	8.33±1.53^{a}	8.33±1.53^{a}	8.33±1.53^{a}	8.33±1.53^{a}
3	20.98±0.95^{a}	11.50±0.36^{b}	10.43±1.48^{b}	10.10±0.08^{b}	11.90±3.12^{b}
5	27.05±0.95^{a}	13.38±0.25^{b}	10.04±0.03^{b}	18.08±7.42^{c}	11.26±0.26^{b}
8	29.55±3.52^{a}	17.85±2.48^{b}	14.85±0.10^{b}	15.35±0.83^{b}	15.73±1.89^{b}
11		28.95±0.52^{b}	15.48±1.02^{c}	15.18±1.82^{c}	16.88±0.32^{c}
14		26.63±0.90^{b}	24.88±2.51^{bc}	21.45±1.21^{c}	22.73±1.36^{c}
17			28.48±0.68^{b}	27.50±3.07^{b}	
18					26.33±2.06^{b}
Titratable acidity (%)					
1	0.17±0.05^{a}	0.17±0.05^{a}	0.17±0.05^{a}	0.17±0.05^{a}	0.17±0.05^{a}
3	0.45±0.13^{a}	0.29±0.03^{b}	0.29±0.06^{b}	0.21±0.04^{b}	0.33±0.07^{b}
5	0.32±0.06^{a}	0.26±0.07^{a}	0.32±0.14^{a}	0.43±0.12^{a}	0.27±0.04^{a}
8	0.25±0.06^{a}	0.19±0.02^{a}	0.24±0.03^{a}	0.22±0.06^{a}	0.21±0.02^{a}
11		0.36±0.06^{b}	0.24±0.06^{bc}	0.19±0.01^{c}	0.19±0.03^{c}
14		0.24±0.02^{b}	0.41±0.06^{c}	0.21±0.01^{b}	0.26±0.07^{b}
17			0.37±0.04^{b}	0.46±0.05^{b}	
18					0.46±0.15^{b}
pH					
1	5.88±0.15^{a}	5.88±0.15^{a}	5.88±0.15^{a}	5.88±0.15^{a}	5.88±0.15^{a}
3	4.73±0.07^{a}	5.25±0.19^{b}	5.36±0.16^{b}	5.33±0.11^{b}	5.21±0.08^{b}
5	4.83±0.05^{a}	4.89±0.09^{a}	5.17±0.09^{bc}	4.74±0.46^{ac}	5.12±0.06^{bc}
8	5.46±0.29^{a}	5.53±0.18^{a}	5.24±0.07^{ab}	5.2±0.00^{ab}	5.26±0.08^{ab}
11		5.01±0.11^{b}	5.29±0.07^{c}	5.32±0.09^{c}	5.23±0.13^{bc}
14		5.21±0.01^{b}	4.80±0.16^{c}	4.95±0.28^{c}	5.02±0.01^{bc}
17			5.15±0.02^{b}	5.07±0.07^{b}	
18					5.14±0.03^{b}
Peel firmness (N)					
1	300.68±34.36^{a}	300.68±34.36^{a}	300.68±34.36^{a}	300.68±34.36^{a}	300.68±34.36^{a}
3	298.96±32.06^{a}	330.68±43.31^{a}	314.83±32.43^{a}	324.10±22.61^{a}	364.77±55.19^{a}
5	266.49±35.68^{a}	315.56±57.68^{ab}	304.33±40.27^{ab}	351.29±71.34^{b}	325.79±44.63^{ab}
8	238.68±23.80^{a}	295.81±33.85^{ab}	322.45±27.39^{b}	354.80±48.99^{b}	293.49±46.87^{b}
11		252.17±34.17^{b}	366.78±53.36^{c}	362.15±52.07^{c}	372.32±56.67^{c}
14		156.60±94.19^{b}	352.78±79.96^{c}	420.97±51.50^{c}	327.33±32.55^{c}
17			299.58±79.71^{b}	330.81±45.36^{b}	
18					338.16±62.43^{b}
Bulb firmness (N)					
1	16.91±4.16^{a}	16.91±4.16^{a}	16.91±4.16^{a}	16.91±4.16^{a}	16.91±4.16^{a}
3	11.92±1.77^{a}	33.07±6.04^{b}	32.90±5.10^{b}	36.68±8.63^{b}	35.75±9.83^{b}
5	7.22±2.51^{a}	32.63±7.97^{b}	23.46±5.56^{b}	26.82±10.30^{b}	22.36±6.49^{b}
8	6±2.60^{a}	15.63±2.34^{b}	21.87±4.52^{b}	21.14±3.75^{b}	21.93±3.87^{b}

(Contd...)

Table 1: ***(Continued)***

Storage days	Control		1-MCP 8°C		
	25°C	8°C	300 nL·L^{-1}	600 nL·L^{-1}	1000 nL·L^{-1}
11		6.00±1.27^{a}	18.23±2.42^{b}	16.45±4.20^{b}	22.10±1.96^{b}
14		3.17±1.06^{a}	17.37±3.38^{b}	18.15±2.44^{b}	28.76±11.46^{c}
17			8.76±4.44^{b}	8.61±4.49^{b}	
18					9.18±3.36^{b}
Peel color (° hue)					
1	106.25±1.52^{a}	106.25±1.52^{a}	106.25±1.52^{a}	106.25±1.52^{a}	106.25±1.52^{a}
3	103.47±2.44^{a}	104.16±0.93^{a}	102.88±4.49^{a}	105.47±2.25^{a}	105.20±2.31^{a}
5	98.68±5.91^{a}	102.14±2.09^{a}	102.13±5.48^{a}	104.67±1.97^{a}	105.13±3.95^{a}
8	84.45±8.33^{a}	96.75±7.34^{b}	102.22±4.59^{bc}	103.86±3.27^{c}	104.55±2.46^{c}
11		92.11±4.57^{b}	101.29±6.40^{c}	102.99±3.92^{c}	104.36±3.20^{c}
14		82.51±6.44^{b}	98.58±7.46^{c}	99.75±6.23^{c}	99.29±5.90^{c}
17			85.74±9.06^{b}	87.19±6.25^{b}	
18					79.45±6.92^{b}
Bulb color (° hue)					
1	80.5±10.73^{a}	80.5±10.73^{a}	80.50±10.73^{a}	80.50±10.73^{a}	80.50±10.73^{a}
3	73.00±7.71^{a}	73.94±2.15^{a}	67.79±1.45^{a}	73.31±2.68^{a}	68.72±2.13^{a}
5	64.86±2.62^{a}	71.17±2.12^{b}	71.94±1.63^{b}	72.90±8.65^{b}	72.54±2.07^{b}
8	64.06±4.48^{a}	73.75±3.81^{b}	72.61±1.31^{b}	72.55±1.23^{b}	77.87±7.76^{b}
11		63.94±9.54^{b}	73.69±1.91^{c}	73.68±1.99^{c}	73.02±2.78^{c}
14		69.96±5.61^{a}	71.27±2.49^{b}	74.65±1.77^{b}	74.47±1.69^{b}
17			72.70±1.43^{b}	72.53±3.05^{b}	
18					67.12±4.50^{b}

The temperature change from 8°C to 25°C was done on day 5. Values are presented as the mean ± standard deviation (n = 3). Lowercase letters represent the effect of days stored. Different letters indicate a significant difference ($\alpha = 0.05$)

The initial value for the absolute control fruit was 106.25° hue (lemon green) and the value on the last day of storage was 84.45° hue (olive green) (Fig. 2A). For the BC, the initial value was 80.5° hue (light yellow) and the value after 8 days of storage was 64.06° hue (saffron yellow) corresponding to the edible material used (Fig. 3A). On the other hand, a delay in the degradation of chlorophyll and in the synthesis of carotenoids was achieved in control fruit stored at 8°C; on day 14, 87.54° hue was found for PC (Fig. 2B) and 69.96° hue for BC (Fig. 3B), similar to the values for the absolute control. As mentioned earlier, the effect of 1-MCP on the loss of peel color (Fig. 2C) and the generation of color in the bulbs (Fig. 3C) is evident; values similar to the control values were obtained after an extra 8–9 days.

The remaining determinations were analyzed for the treatment that presented the best results in the physiologic and physicochemical analyses. The 600 nL L^{-1} treatment was chosen because shelf life was prolonged with characteristics attractive to the consumer as a consequence of the application of 1-MCP during storage.

Total soluble phenols and determination of antioxidant capacity

The content of TSP was determined (Table 2) on day 1. There were no statistically significant differences ($p < 0.05$) between the control fruit and those treated with 1-MCP. The absolute control showed a gradual increase in the content of TSP until day 5, however, it decreased markedly on the last day of storage. In the case of the control at 8°C, fluctuations were observed throughout storage, however, the TSP content between days 1 and 14 was not affected. Treatment at 600 nL L^{-1} showed a similar pattern, however, at the end of the shelf life, the content of TSP was decreased compared with day 1.

Antioxidant capacity FRAP and DPPH

The values reported in this trial (Table 2) did not present statistically significant differences ($p < 0.05$) on day 1 with respect to the absolute control fruit and the fruit treated with 600 nL L^{-1} 1-MCP. However, the control at 8°C differed from the rest. The absolute control presented a decrease in FRAP on the last day of storage. The control

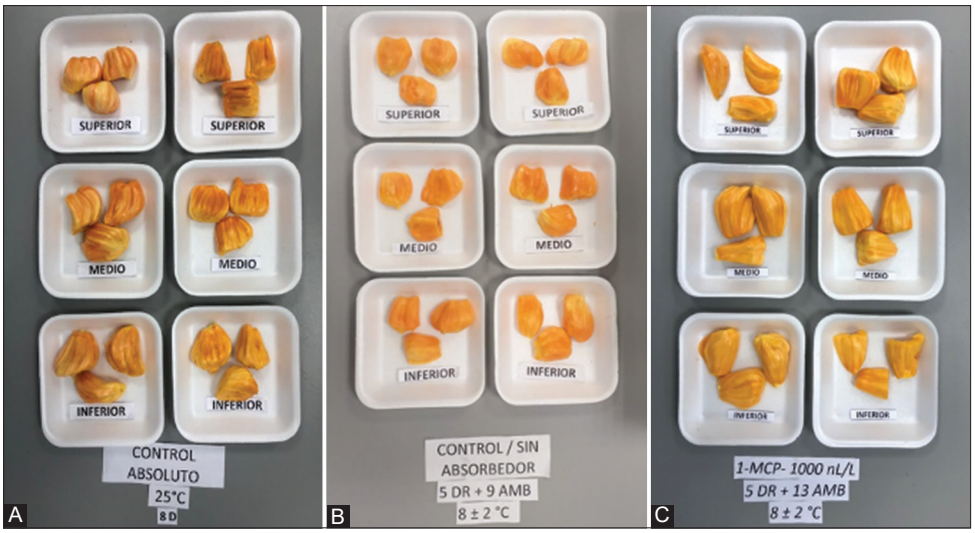

Fig 3. Color analysis of jackfruit bulbs: (A) absolute control stored for 8 days; (B) control stored at 8°C for 14 days; (C) treatment with 1-MCP 1000 nL L–1 stored for 18 days.

Table 2: Antioxidant capacity in jackfruit bulbs.

Storage days	Control		1-MCP 8°C
	25°C	8°C	600 nL·L^{-1}
Total soluble phenols (mg GAE/100 g DW)			
1	90.86±3.27^{a}	98.55±2.47^{b}	113.58±3.12^{c}
3	111.95±4.62^{a}	114.04±1.96^{a}	88.11±1.41^{b}
5	139.01±4.59^{a}	100.29±7.58^{b}	100.10±4.15^{b}
8	96.84±0.31^{a}	89.72±0.78^{b}	104.36±0.48^{c}
11		115.22±4.42^{b}	95.41±2.78^{a}
14		104.68±0.27^{b}	87.32±3.89^{c}
17			93.14±3.21^{a}
FRAP (mmol TE/100 g DW)			
1	331.04±23.04^{a}	231.31±1.54^{b}	337.79±40.40^{a}
3	284.18±58.54^{a}	319.48±7.78^{a}	273.31±10.85^{b}
5	413.79±4.77^{a}	290.29±11.34^{b}	308.85±13.92^{b}
8	186.85±9.50^{a}	237.95±9.71^{b}	263.87±18.05^{b}
11		415.34±6.80^{b}	301.95±7.34^{c}
14		269.32±18.83^{b}	260.24±1.14^{a}
17			299.57±39.50^{b}
DPPH (mmol TE/100 g DW)			
1	392.13±11.34^{a}	948.22±18.42^{b}	392.13±11.34^{a}
3	281.15±10.88^{a}	527.04±6.91^{b}	398.18±11.09^{c}
5	383.44±0.82^{a}	892.51±41.28^{b}	352.72±9.86^{a}
8	255.93±16.93^{a}	892.98±40.43^{b}	353.36±21.94^{c}
11		339.72±24.76^{b}	288.20±14.39^{c}
14		986.39±5.64^{b}	321.25±17.69^{c}
17			291.64±6.27^{c}

The temperature change from 8° to 25°C was done on day 5. Values are presented as the mean ± standard deviation (n = 3). Lowercase letters represent the effect of days stored. Different letters indicate a significant difference ($\alpha = 0.05$).
DW: dry weigth

at 8°C and the fruit treated with 600 nL L^{-1} showed fluctuations in FRAP, however, on the last day of storage, the results were similar to those on day 1.

Statistically significant differences ($p < 0.05$) are reported (Table 2) for all treatments during the storage period. In the absolute control, a decrease in DPPH was observed between day 1 and its senescence. The control at 8°C showed fluctuations in DPPH, however, on day 14, the values were close to those on day 1. Moreover, treatment with 1-MCP at 600 nL L^{-1} was found to decrease DPPH activity on the last day of storage.

Quantification of total carotenoids and vitamin C

Quantification of TC revealed statistically significant differences ($p > 0.05$), fluctuations, and increases with respect to the first day of storage were found in all fruit (Table 3). TC in the absolute controls decreased with storage. The control at 8°C showed a decrease in the TC content on the day of the marketing simulation, however, senescence decreased considerably by day 14. In the fruit treated with 1-MCP, TC content had decreased by day 5 of the marketing simulation and continued to decrease by day 17. The statistical analysis of the values obtained (Table 3) for the content of ascorbic acid showed significant differences ($p > 0.05$) between the control fruit and those treated with 1-MCP. In the absolute control bulbs, vitamin C content decreased considerably from day 1 to 8 and the same tendency was seen in the control bulbs at 8°C. The treatment with 1-MCP prolonged the useful life of the bulbs up to 17 days and although the vitamin C content also decreased, the decrease was less compared with the control fruit.

Sensory analysis

In the color analysis, a higher preference could be observed for the bulbs treated with 1-MCP, with a mean acceptance of 8.36; the mean acceptance for absolute controls was 8.06. In the odor evaluation, the highest degree of acceptance was found for the fruit treated with 1-MCP, with an average of 7.23 compared with 6.9 for the controls. Moreover, the taste acceptance levels favored the absolute control fruit with a value of 7.26 compared with 7.1 for the treated bulbs ($p < 0.05$). Finally, in the evaluation of texture, the acceptance value was 8.40 for the control fruit and 7.26 for the treated fruit.

DISCUSSION

Physiologic analysis

Bolívar-Fernández et al. (2011) mention that 1-MCP influences the ethylene biosynthetic pathway, participating as an antagonist by occupying ethylene receptors. Thus, the expression of genes for the enzymes 1-aminocyclopropane-1-carboxylate synthase (ACC synthase) and the enzyme 1-aminocyclopropane-1-carboxylate oxidase (ACC oxidase) can be controlled; ACC oxidase depends on oxygen, which decreases its expression and O_2 levels, therefore, CO_2 production remains stable. Similar effects were found in Mexican plum fruit (Osuna-García et al., 2011), Ataulfo mango (Ortiz-Franco et al., 2016), Keitt mango (Osuna-García et al., 2007), and jackfruit edible material "Agüitada" (Morelos-Flores et al., 2021).

The effect of 1-MCP on the production of ethylene is the same as the effect on the RR; because 1-MCP reduces the expression of genes that code for ACC synthase and ACC oxidase enzymes (Balaguera-López et al., 2014). Mata-Montes de Oca et al. (2007) mention that a decrease in temperature generates control over the production of ethylene; because it decreases the enzymatic activity, including ACC synthase and ACC oxidase. Moreover, the fruit treated with 1-MCP also showed control over the EPR parameter. Similar behaviors to those obtained in this research were found in kiwi fruit (Salazar et al., 2019), mangosteen (Piriyavinit et al., 2011), and jackfruit "agüitada" stored at 13ºC (Morelos-Flores et al., 2021), among others.

Jeong et al. (2002) mention that when 1-MCP reduces the RR and the EPR, the transpiration of the fruit decreases and this is reflected in control over the PWL. However, there were no differences between the concentrations of 1-MCP in relation to the PWL. On the other hand, the United Nations Food and Agriculture Organization in the post-harvest handling manual for tropical fruit mentions, that water loss above 5% is the maximum allowable value in fruits. However, only papaya, pineapple, banana, and citrus are considered in this manual (FAO, 2007). The same

Table 3: Quantification of total carotenoids and vitamin C in jackfruit bulbs

Storage days	Control		1-MCP 8°C
	25°C	8°C	600 nL·L^{-1}
Total carotenoids (μg EβC/g DW)			
1	11401.58±874.76^{a}	11401.58±874.76^{a}	11401.58±874.76^{a}
5	14195.56±350.04^{a}	5082.35±142.58^{b}	4006.05±1.08^{c}
8	2618.51±112.82^{a}		
14		1808.78±15.98^{b}	
17			3902.29±93.55^{c}
Vitamin C (mg AAE/g DW)			
1	275.37±115.88^{a}		
5		197.84±38.81^{b}	283.06±27.24^{a}
8	27.09±5.69^{a}		
14		42.92±1.88^{b}	
17			145.96±3.02^{c}

The temperature change was done on day 5, at a temperature of 25°C. Values are presented as the mean ± standard deviation (n = 3). Lowercase letters represent the effect of days stored. Different letters indicate a significant difference ($\alpha = 0.05$)
DW: dry weigth

behavior has been reported in jackfruit agüitada treated with 1-MCP (300, 600, and 1000 nL L^{-1}) stored at 13°C (Morelos-Flores et al., 2021).

Physicochemical analysis

Research on banana fruit (Do Nascimento et al., 2006) showed that β-amylase is regulated by the action of 1-MCP. However, Mainardi et al. (2006) reported that 1-MCP does not inhibit the generation of TSS; they suggest that there are important enzymes in starch degradation that are not regulated by this treatment (Mata-Montes de Oca et al., 2007).

Various investigations have shown that the synthesis and consumption of organic acids during the fruit ripening process depends on the metabolic characteristics of each species. Quintero et al. (2013) reported that TA and pH vary considerably because organic acids in the immature fruit begin to transform or degrade as the fruit breathes. Although the mechanism by which 1-MCP affects these two parameters is not well defined and is different with respect to each fruit, it may be related to the control of RR and EPR. The results of our research are similar to those found by Morelos-Flores et al. (2021) in jackfruit agüitada treated with 1-MCP (300, 600, and 1000 nL L^{-1}) stored at 13°C; no difference was found between the control fruit and treated fruit.

Fruit peel and bulbs can be affected by the coordinated activity of enzymes such as polygalacturonase (EC 3.2.1.15), pectin methyl esterase (EC 3.1.1.11), β-galactosidase (EC 3.2.1.23), xyloglucan endotransglycosylase (EC 2.4.1.207), and expansions. Mata-Montes de Oca et al. (2007) reported that ethylene has an important role in the firmness of the peel of fruit and pulp; because this hormone stimulates the production of enzymes that degrade the mobility of the wall.

The controlling effect of 1-MCP on the enzymes that degrade chlorophyll or on the synthesis of pigments is closely related to blocking the effect of ethylene, delaying the expression of genes that encode the enzymes responsible for these processes (Balaguera-López et al., 2014; Fabi et al., 2007). Osuna et al. (2005), in a study on avocado 'Hass' treated with 1-MCP at 200 nL L^{-1} at 22°C for 12 days and 6°C for 6 days, reported a delay in the formation of the characteristic black color of an avocado when ripe. Marty et al. (2005) reported that the phytoene synthase and phytoene desaturase genes, which are involved in the accumulation of phytoene and phytofluene, were clearly regulated by ethylene, whereas β-carotene and ξ-carotene desaturase were independent. For this reason, coloration could be present in pulps treated with 1-MCP. An effect similar to that found in this research was reported by Morelos-Flores et al. (2021) applying 1-MCP at 300, 600, and 1000 nL L^{-1} to jackfruit (at 13° C). Control over carotenoid production was observed and coloration was similar to that of the absolute control fruit on the last day of storage.

Total soluble phenols and determination of antioxidant capacity

In a comparison with other studies, it was found that the TSP content of the absolute control was lower than in our study. Shafiq et al. (2017) reported a TSP content of 239.87 mg/100 g DW in mature jackfruit from Lahore, Pakistan. Factors that can affect the content of TSP include the type of vegetative material used, nutritional conditions during growth, and availability of atmospheric carbon dioxide (Anjos et al., 2020). Vargas-Torres et al. (2017) applied a 1-MCP concentration of 1000 nL L^{-1} in jackfruit bulbs, reporting an increase (from 850 to 900 mg/100 g WW) in the content of TSP after 12 days of storage. During ripening, the fruit promotes the synthesis of polyphenols, which is related to its defense mechanism; however, a decrease in the production of phenols may be a consequence of the application of 1-MCP, because it inhibits respiration and the production of ethylene, in addition to the enzymatic activity of polyphenol oxidase, which catalyzes the oxidation of polyphenols (Liu et al., 2018; Vargas-Torres et al., 2017).

FRAP and DPPH antioxidant capacity

Measurement of FRAP antioxidant capacity can indicate the reducing potential of an antioxidant that reacts with a ferric complex, reducing it to a ferrous complex in an acid medium (Liu et al., 2018). The stable free radical elimination analysis using DPPH determines the AC of a sample based on the degree of inhibition it achieves against this radical (Liu et al., 2018).

Saxena et al. (2009) reported that the use of a controlled atmosphere as a post-harvest treatment decreases FRAP or DPPH radical scavenging activity, and this can be attributed to a decrease in the concentration of phenols, ascorbic acid, and flavonoids during fruit storage; because AC is correlated with the presence of these compounds (Thaipong et al., 2006). Jagtap et al. (2010) reported that the antioxidant mechanisms of jackfruit pulp are attributed to its free radical chelating activity, assigning these activities to phenolic compounds and flavonoids. Post-harvest treatments such as storage at low temperatures can increase the activity of antioxidant enzymes such as phenylalanine ammonium lyase (PAL), which is key between the primary (shikimate pathway) and secondary (phenylpropanoid pathway) metabolism and can be induced by stress by cooling (Liu et al., 2018). PAL activity and the phenylpropanoid pathway are considered to be defense mechanisms of the fruit, which suggests that at a minimum

temperature of tolerance to cold, the fruit can maintain or increase its AC due to the enzymatic activity of PAL (Siboza et al., 2014). In addition, Jiang et al. (2001) reported that 1-MCP inhibits the PAL enzyme; thus, the effects of this coupled with refrigeration can be detrimental to the defense system of the fruit.

Quantification of total carotenoids and vitamin C

Barreto et al. (2011) reported that in some climacteric fruit such as papaya, 1-MCP generates an interesting accumulation of lycopene, which can be attributed to the complex regulation system of these pigments. In this investigation, although the content of carotenoids decreased, the loss of this compound was less compared with the control fruit. It is well known that jackfruit contains various carotenoids (all-*trans*-lutein, all-*trans*-β-carotene, all-*trans*-neoxanthin, 9-*cis*-neoxanthin), which are related the prevention of diseases; hence the importance of the conservation of these compounds (Swami et al., 2012). The importance of these results is the recognition that jackfruit is a rich source of vitamin C with important antioxidant properties (Swami et al., 2012). Wang et al. (2009) reported that 1-MCP protects the elimination system of reactive oxygen species (ROS), which is related to the metabolism of ascorbic acid; because it can interact enzymatically and non-enzymatically with ROS. Xu et al. (2019) reported a different behavior with the content of ascorbic acid in kiwis treated with 1-MCP (0.9 μL/L). Higher values were obtained on the last day of storage compared with the untreated control (from 102 to 146 mg/100 g wet weight).

Sensory analysis

In jackfruit bulbs, coloration is provided by β-carotene, and the application of 1-MCP controls the generation of these compounds by blocking ethylene receptors; but this process is not inhibited (Fabi et al., 2007), thus color did develop. Argenta et al. (2003) reported that the production of volatile compounds depends on the concentration of 1-MCP. The flavor is a combination of TSS, TA, and pH (Mattheis and Fellman, 1999), therefore the perception of flavor depends on the levels reported for each of these parameters. Thus, bulbs treated with 1-MCP were able to retain firmness until the day of consumption with a satisfactory modification in the sensory experience, resulting in a longer shelf life. Morelos-Flores et al. (2021) reported general acceptance of all sensory parameters in a sensory analysis of bulbs treated with 1-MCP stored at 13°C, similar to the results in this research.

CONCLUSIONS

The physiologic and physicochemical parameters showed significant differences ($p < 0.05$) between the control fruit and the treated fruit. A delay in ripening was observed in the fruit treated with 1-MCP. A concentration of 600 nL L^{-1} presented the most convenient results for the commercialization chain, increasing the shelf life of the fruit to 17 days. The use of 1-MCP demonstrated an increase in the AC in the FRAP analysis and the content of TC; and managed to preserve the content of TSP. The AC in the analyses for DPPH and vitamin C was slightly decreased. The sensory evaluation showed that the application of 1-MCP at 600 nL L^{-1} improved the perceptions of color and odor perceptions, and the judges showed a slight preference for the control fruit with regard to flavor and firmness. The fact that the development of the odor, color, and flavor characteristics of the fruit is achieved over a longer period of time is promising for greater use of the fruit.

CRediT roles authorship contribution statement

David Antonio Morelos-Flores.: Investigation, Formal analysis, Writing – original draft. Yolanda Nolasco-González.: Conceptualization, review & editing. Héctor González-Hernández.: Conceptualization, – review & editing. Martina Alejandra Chacón-López.: Conceptualization, – review & editing. Luis Martín Hernández-Fuentes.: Conceptualization, – review & editing. Efigenia Montalvo-González.: Conceptualization, – review & editing. María de Lourdes García-Magaña: Conceptualization, Supervision, Project administration, Writing – review & editing.

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