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Storability of 'SCS417 Monalisa' apple as affected by harvest maturity, 1-methylcyclopropene treatment, and storage atmosphere

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Abstract – The objective of this work was to determine the storability of 'SCS417 Monalisa' apple fruit in response to harvest maturity, 1-methylcyclopropene (1-MCP) treatment, and storage atmospheres. Fruit quality was evaluated after two, four, six, and eight months plus one day or seven days in shelf life at 22°C. The controlled atmosphere (CA) and 1-MCP (1.0 μL L^{-1}) treatments reduce fruit ethylene production and respiration, prevent rapid softening, and inhibit the incidence of scald-like symptoms, flesh browning, cracking, and fungal decay, in comparison with air storage . The combination of 1-MCP and CA provides additive benefits in firmness retention and in the reduction of the incidence of physiological disorders. CA and/or 1-MCP increase the risk of fruit developing wrinkly skin disorder. The loss of flesh firmness and acidity and the development of all physiological disorders and decay are higher in late-harvested fruit. The storage life of 'SCS417 Monalisa' apple is about two months in cold air and from six to eight months in cold CA, considering the time necessary to reach a flesh firmness of 53 N. The limiting factor for the long-term storage of 'SCS417 Monalisa' apple fruit under CA without 1-MCP is the development of physiological disorders and fungal decay.

Index terms: *Malus* × *domestica*, decay, flesh firmness, physiological disorders.

Armazenabilidade de maçã 'SCS417 Monalisa' conforme maturação na colheita, tratamento com 1-metilciclopropeno e atmosfera de armazenagem

Resumo – O objetivo deste trabalho foi determinar a armazenabilidade de maçãs 'SCS417 Monalisa' em resposta à maturação na colheita, ao tratamento com 1-metilciclopropeno (1-MCP) e às atmosferas de armazenamento. A qualidade dos frutos foi avaliada após dois, quatro, seis e oito meses mais um dia ou sete dias de vida de prateleira a 22°C. Os tratamentos atmosfera controlada (AC) e 1-MCP (1,0 μL L^{-1}) reduzem a produção de etileno e a respiração dos frutos, previnem o amolecimento rápido da polpa, e inibem a incidência de escaldadura, escurecimento da polpa, rachaduras e podridões fúngicas, em comparação ao armazenamento ao ar. A combinação de 1-MCP e AC proporciona benefícios aditivos na retenção da firmeza da polpa e na redução da incidência de distúrbios fisiológicos. A AC e/ou 1-MCP aumentam o risco de os frutos desenvolverem o distúrbio superfície rugosa. A perda de firmeza e acidez dos frutos e o desenvolvimento de todos os distúrbios fisiológicos e a podridão são maiores em frutos colhidos tardiamente. O potencial de armazenamento das maçãs 'SCS417 Monalisa' é de cerca de dois meses em ar refrigerado e de seis a oito meses em AC refrigerada, considerando o tempo necessário para atingir a firmeza de polpa de 53 N. O fator limitante para o armazenamento a longo prazo da maçã 'SCS417 Monalisa' sob AC sem 1-MCP é o desenvolvimento de distúrbios fisiológicos e podridões fúngicas.

Termos para indexação: *Malus* × *domestica*, apodrecimento, firmeza da polpa, distúrbios fisiológicos.

Introduction

Apple production in Brazil focuses in just two cultivars (Gala and Fuji) that have been accounting for about 95% of the total production, for many decades (Anuário..., 2019).

The new apple cultivar SCS417 Monalisa originated from a cross between 'Gala' and 'Malus 4' and has been attracting the attention of apple growers because it is resistant to main apple diseases, such as apple scab and *Glomerella* leaf spot, as well as because the cultivar produces high-quality fruit, regarding appearance and sensorial attributes (Denardi et al., 2013). Currently, there is an expansion of 'SCS417 Monalisa' commercial orchards, especially for the organic production in southern Brazil. However, there is still no information available regarding the storage potential of 'SCS417 Monalisa' apple fruit. In that case, studies should determine the 'SCS417 Monalisa' apple responses to storage conditions and inhibition of ethylene by 1-methylcyclopropene (1-MCP).

As a competitive ethylene action inhibitor, 1-MCP delays fruit ripening and senescence, maintaining a higher flesh firmness and increasing storage life (Watkins et al., 2015). However, 1-MCP effects vary among cultivars, which can also increase the incidence of physiological disorders and decay in some apple cultivars, such as Gala (Thewes et al., 2017) and Empire (Lee et al., 2012).

The ripening behavior of 'SCS417 Monalisa' under cold air and controlled atmosphere (CA) storage conditions have not been described yet. 'Gala' apple, a parental of 'SCS417 Monalisa' (Denardi et al., 2013), has been shown to have a rapid postharvest ripening, with a storage life of approximately four months in the air, and from six to seven months under controlled atmosphere conditions (Bai et al., 2005). Apple maturity at harvest plays an important role in determining fruit storability and postharvest life (DeLong et al., 2014; Doerflinger et al., 2015; Thewes et al., 2017). Therefore, the evaluation of 'SCS417 Monalisa' apple fruit response to 1-MCP at different harvest maturities and to the combination of 1-MCP and storage conditions is required to determine the best postharvest practices for fruit quality maintenance and reduction of production losses.

The objective of this work was to determine the storability of 'SCS417 Monalisa' apple fruit in response to harvest maturity, 1-methylcyclopropene (1-MCP) treatment, and storage atmospheres.

Materials and Methods

'SCS417 Monalisa' fruit were produced in an orchard located at the experimental station of Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina (Epagri), in the municipality of Caçador (26°46'19.9"S, 50°55'12.7"W, at 960 m altitude), in Santa Catarina state, southern Brazil. The climate of the region is subtropical with warm summers and rainfall spread evenly throughout the year (Cfb, Köppen-Geiger's classification system). The mean temperature, relative humidity, and the sum of rain precipitation, during the growing season were 20.5°C, 80%, and 600 mm, respectively (Argenta et al., 2022a). The orchard soil is a typical Oxisol.

The apple trees of 'SCS417 Monalisa' were grafted on 'Marubakaido' rootstock with an M9 interstock, and they were planted in 1.0×4.0 m, in 2012. Trees were trained to a central leader. Orchard practices, such as mineral fertilization, weed, insect and disease controls, pruning, and growth regulator treatments for dormancy release, followed the recommendations for apple production in southern Brazil (Sezerino, 2018).

Fruit with similar size that were representative of the orchard were harvested at the mid-canopy height in the inner and outer canopy on both tree-row sides. In the laboratory, visually unblemished fruit were randomly selected to prepare homogeneous samples of 25 fruit held on fiberboard trays.

Two experiments were carried out over three growing seasons (2019, 2020, and 2021). The experiments followed a completely randomized design. In both experiments, fruit were treated or not with 1-MCP and stored in the air (~21 kPa O_2) or controlled atmosphere (CA) with low O_2 and CO_2 partial pressures (CA, 1.5 kPa O_2 and <0.5 kPa CO_2). Assessments of fruit ripening and quality were performed both at harvest and after 2, 4, 6, and 8 months of storage plus 1 or 7 days of shelf life at 22°C.

Fruit were harvested on February 6th, 2019, and February 3rd, 2021, in experiment 1, and they were subjected to four postharvest treatments, as follows: regular air atmosphere (air); 1-MCP exposure and then air atmosphere (air+MCP); CA (1.5 kPa O_2 and <0.5 kPa CO_2); and 1-MCP exposure and then CA (CA+MCP). The CA with low pCO_2 was chosen based on preliminary studies, showing fruit susceptibility to CO_2 injury.

Fruit were harvested on February 6th and 17th, 2020, in the experiment 2. These two harvest dates represented early (harvest 1) and late (harvest 2) harvest maturities. Following harvests, fruit were subjected to two postharvest treatments, as follows: regular air atmosphere (air); and 1-MCP exposure and then air atmosphere (air+MCP).

Within 24 hours after harvest, fruit were exposed to ≈ 1.0 $\mu L\ L^{-1}$ 1-MCP, in a sealed steel container (1 m^3), for 12 hours at ambient temperature. 1-MCP gas was generated by mixing cyclodextrin-1-MCP powder EthylBloc (AgroFresh Inc., Spring-house, USA) and water, and its concentration inside the container was checked as previously described by Mattheis et al. (2005). Untreated fruit remained in the air at the same temperature as 1-MCP-treated fruit.

Two hours after 1-MCP treatment, all treated and nontreated fruit were moved into cold storage rooms and cooled at 0.8°C within 48 hours of harvest. Fruit samples for air storage were packed in cardboard boxes lined with perforated low-density polyethylene bags (20 µm = 10 µm per wall). Fruit samples for CA storage were enclosed in 0.150 m^3 stainless steel chambers with a plexiglass lid.

The storage temperature was 0.8±0.8°C, and relative humidity (RH) ranged between 92 to 95% for 90% of the recorded data, based on box plot analysis. Temperature and RH were monitored as described by Argenta et al. (2022b). The CA with low pO_2 and pCO_2 was established within 54 hours after fruit cooling. Concentrations of O_2 and CO_2 were maintained and monitored as described by Argenta et al. (2022b).

Maturity of 25 individual apples was determined for each one 24 hours after harvest, by the analyses of respiration, ethylene production, firmness, starch index (SI), soluble solids content (SSC), and titratable acidity (TA). For the post-storage assessment of fruit firmness, physiological disorders, and fungal decay, evaluations were performed for 50 fruit from each harvest date, postharvest treatment, storage duration, and length of shelf life combination. For ethylene production, respiration, TA, and SSC measurements, four replicates of eight fruit were evaluated. Flesh firmness, starch index (1–9 scale), SSC, and TA were assessed as described by Argenta et al. (2020), while ethylene and CO_2 production were assessed as described by Mattheis et al. (2005). External and internal disorders were visually assessed using subjective scales of severity, where a score of one is indicative of the absence of disorders (Argenta et al., 2020). Internal disorders were assessed from four transverse slices across the fruit. The severity of disorders was recorded according to the area of fruit surface or cortex cross-section affected or the number of lesions per fruit. The assessments of fungal decay, skin browning ('scald-like'), shriveling, bitter pit, flesh browning, and fruit cracking were accomplished as previously described by Argenta et al. (2020) and Argenta et al. (2022a). Fruit affected by wrinkly skin was scored as follows: 1, 1–30% of the fruit surface with light wrinkles; 2, 31–60% of the fruit surface with light to deep wrinkles; or 3, > 60% of the cortex with light to deep wrinkles.

Each experiment was analyzed separately. Data from both years in experiment 1 were pooled, as the fruit response to storage treatments was similar for most variables (for instance, firmness, TA, fungal decay, and physiological disorders). Physiological and physicochemical data were subjected to a regression analysis using the equation dynamic fit Wizard of SigmaPlot software, Version 14 (Systat Software Inc., San Jose, USA). Statistical models for each variable and treatment were initially selected by examining the Akaike information criterion (AIC) and its validation by analyses of the determination coefficient and regression residuals. Additionally, treatment means for these variables were compared by the Fisher's least significant difference LSD test, at 5% probability at each storage duration.

Severity of physiological disorders and fungal decay data did not fit the normal distribution by Shapiro-Wilk's test. In that case, the nonparametric Kruskal-Wallis' test for multiple comparisons of treatments and storage time was performed using R (R Core Team, 2020) and the add-on package 'Agricolae' for the severity of disorders. An index of incidence (percentage) weighted by severity was calculated for each disorder and treatment, as previously described by Argenta et al. (2020).

Results and Discussion

At harvest, the starch index ranged between 4.1 to 6.2, and the flesh firmness between 80.6 and 87.5 N (Table 1), which are adequate for mid- and long-term storage, based on the recommendations for other apple cultivars, such as the parental Gala (Argenta & Mondardo, 1994; Thewes et al., 2017). In 2020, fruit from the second harvest were at more advanced maturity than fruit from the first harvest, mainly considering the flesh firmness, starch index, and soluble solids differences observed between harvests (Table 1).

Air-stored fruit without the 1-MCP treatment had the earliest increase and the highest rate of ethylene production over the storage period, reaching the maximum production rate after four months (Figure 1). The treatment with 1-MCP delayed the ethylene rise by two months in the air-stored fruit. 1-MCP had no effect on the ethylene production in CA fruit held one day at 22°C. However, after seven-day shelf life at 22°C, the ethylene production was lower in CA fruit treated with 1-MCP. Ethylene production in CA-stored fruit was lower, in comparison to that on air-stored fruit after 4-8 months followed by one day at 22°C, regardless of the 1-MCP treatment. These responses to CA and 1-MCP treatment throughout the storage period are similar to those observed for other apple cultivars, such as Gala (Mattheis et al., 2005) and Luiza (Argenta et al., 2022b). However, the ethylene production rate by CA control fruit was similar to that of fruit subjected to air storage and 1-MCP treatment after seven days of shelf life. This rise of the ethylene production in 'SCS417 Monalisa' apples during their shelf life does not correspond to that observed for other early season cultivars, such as Gala and Luiza (Mattheis et al., 2005; Argenta et al., 2022b).

A higher ethylene production is generally associated with a higher respiration rate in climacteric fruit (Saltveit, 2019), such as those observed for 'SCS417 Monalisa' control fruit stored in the air (Figure 1). Similarly, the lowest respiration in fruit subjected to CA and 1-MCP, after 6- and 8-month storage followed by seven days in shelf life, was associated to the lowest ethylene production.

The respiration of the fruit under CA conditions after one day at 22°C remained below or similar to that at harvest, regardless of the 1-MCP treatment. However, after seven days in shelf life at 22°C, following 2 and 4 months of storage, the respiration of CA control fruit increased to higher rates than those of fruit subjected to air storage and treated with 1-MCP.

In contrast, respiration in air-stored fruit treated with 1-MCP was higher than CA control fruit, after seven days in shelf life, following 6 and 8 months of storage. This result shows that the relative effectiveness of CA vs 1-MCP to regulate 'SCS417 Monalisa' apple fruit respiration depends on the length of cold storage and shelf life.

The respiration rate was maintained low over the whole storage period, when fruit were stored under CA, either with or without 1-MCP treatment (Figure 1). Under CA conditions, the fruit respiration rate was maintained in a similar level to that of fruit stored in the air and treated with 1-MCP, which shows that the storage under CA reduced the fruit metabolism to a similar level of that caused by 1-MCP in air-stored fruit. Previous studies have reported an additive effect of 1-MCP and CA on the respiration reduction in 'Gala' (Thewes et al., 2015;

Table 1. Mean and standard deviation of 25 fruit of 'SCS417 Monalisa' apple (*Malus domestica*) one day after harvest, from the experiments 1 and 2. Caçador, Santa Catarina state, Brazil.

Experiment	Year	Harvest time	Starch index (SI) (1-9)	Flesh firmness (N)	SSC (%)	TA (%)
1	2019	Feb. 06 (H1)	5.8±2.0	81.5±5.2	14.1±0.6	0.538±0.06
1	2021	Feb. 03 (H1)	6.2±1.7	80.6±6.6	13.6±0.5	0.489±0.04
2	2020	Feb. 06 (H1)	4.1±1.9	87.5±5.8	13.9±0.3	0.574±0.02
2	2020	Feb. 17 (H2)	6.1±1.8	83.4±6.0	15.6±0.5	0.544±0.04

SSC, soluble solid contents; and TA, titratable acidity.

Anese et al., 2020; Thewes et al., 2015), 'Fuji' (Weber et al., 2017), and 'Luiza' apples (Argenta et al., 2022b); however, this behavior was observed in 'SCS417 Monalisa' apples only after seven days of shelf life at 22°C.

Flesh firmness is one of the main eating quality attributes in apples (Bonany et al., 2013) and a critical measure to define storage life in response to storage conditions. 'SCS417 Monalisa' apple not treated with 1-MCP and stored in the air had a fast firmness loss over storage, regardless of the harvest maturity and growing season (Table 2), reaching firmness below 53 N after two months of storage. Hence, based on the rate of flesh firmness loss, the storage life of 'SCS417 Monalisa' apples is less than two months when fruit are subjected to air storage without the 1-MCP treatment. The fast firmness loss under air storage conditions is possibly due to the increased ethylene production (Figure 1), which is known to trigger the expression and/or activity of cell-wall degrading enzymes (Gwanpua et al., 2016). In fruit treated with 1-MCP, the rate of flesh firmness loss was reduced, regardless of the harvest maturity and growing season (Figure 2 A and B). Fruit harvested at advanced maturity and exposed to 1-MCP retained a higher firmness after 2-8 month storage than early harvested fruit not exposed to 1-MCP (Figure 2 B). These results further corroborate the hypothesis that the fast firmness loss in air-stored fruit is due to the ethylene production and action in the fruit. The firmness loss rate of 'SCS417 Monalisa' apples was greater than that observed in other early season cultivars, such as Gala (Mattheis et al., 2005) and Luiza apples (Argenta et al., 2022b) stored in the air and under CA.

Flesh firmness of 'SCS417 Monalisa' apples remained highest over eight months of storage under CA + 1-MCP treatment, being the response to 1-MCP more pronounced after longer storage periods (Figure 2 A), as also reported for 'Gala' and 'Delicious' apples (Bai et al., 2005; Mattheis et al., 2005; Thewes et al., 2017; Anese et al., 2020). However, this response of 'SCS417 Monalisa' apples to 1-MCP under CA regarding flesh firmness is

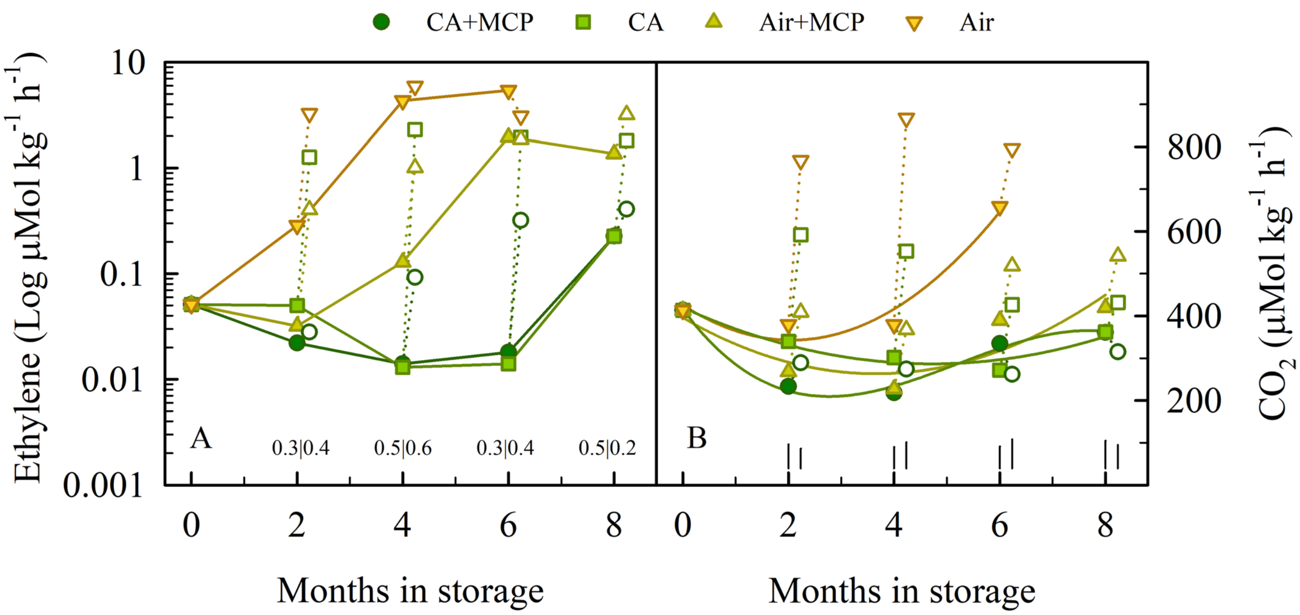

Figure 1. Ethylene production and respiration rate of 'SCS417 Monalisa' apple (*Malus domestica*) at harvest and after storage (experiment 1). Fruit were treated (+MCP, 1 µL L^{-1}) or not treated with 1-MCP and stored at 0.8°C in the air or under controlled atmosphere conditions (CA, 1.5 kPa O_2 and <0.5 kPa CO_2), from two to eight months. Fruit were held at 22°C, for one day (filled symbols) or seven days (open symbols) after the removal from storage. Inserted numbers or vertical lines are Fishers' LSD values at 5% probability. Lines of statistical models (Table 2) are presented when fitted (at 5% probability) to ethylene and CO_2 production data by a regression analysis. Caçador, Santa Catarina state, Brazil.

greater than those of 'Luiza' (Argenta et al., 2022b) and 'Fuji' (Bai et al., 2005) fruit. These results evidence that 'SCS417 Monalisa' apples soften faster under CA storage than 'Luiza' and 'Fuji' apples, and that 1-MCP treatment is a key factor to manage 'SCS417 Monalisa' apples softening, even under CA.

Table 2. Statistical models of variables change as a function of storage time of 'SCS417 Monalisa' apple (*Malus domestica*) fitted by regression analysis from the experiment 1 performed in 2019 and 2021 and experiment 2 performed in 2020, in the municipality of Caçador, in the state of Santa Catarina, Brazil.

Variable	Year	Treatment	Equation	R^2
Ethylene	2019	Air	$f = 0.5+1.1x$	0.89*
		CA	$f = 1.6/(1+\exp(-(x-4.1)/0.5))$	0.94*
		Air+MCP	$f = 0.05+0.04x-0.02x^2+0.003x^3$	0.99*
		CA+MCP	$f = 0.07-0.05x+0.009x^2$	0.89*
Respiration	2019	Air	$f = 422.8-80.5x+19.5x^2$	0.94*
		CA	$f = 395.9-72.6x+9.9x^2$	0.74*
		Air+MCP	$f = 420.1-56.6x+6.0x^2$	0.91**
		CA+MCP	$f = 416.2-169.6x+41.6x^2-2.75x^3$	0.98*
Firmness (N)	2019-2021	Air	$f = 33.2+47.2\exp(-0.37x)$	0.98**
		CA	$f = 63.3+17.8\exp(-0.24x)$	0.99***
		Air+MCP	$f = 82.2-3.14x-0.10x^2$	0.98***
		CA+MCP	$f = 80.9-1.4x$	0.98***
	2020	H1, Air	$f = 30+53.1\exp(-0.57x)$	0.98**
		H2, Air	$f = 36.3+50.7\exp(-0.40x)$	0.99**
		H1, Air +MCP	$f = 88.1-1.3x$	0.93***
		H2, Air +MCP	$f = 83-3.3x$	0.98***
Acidity (%)	2019-2021	Air	$f = 88.1-1.3x$	0.98***
		CA	$f = 0.52-0.02x$	0.96***
		Air+MCP	$f = 0.52-0.03x$	0.95***
		CA+MCP	$f = 0.34+0.19\exp(-0.18x)$	0.87**
	2020	H1, Air	$f = 0.03+0.52\exp(-0.18x)$	0.98**
		H2, Air	$f = 0.02+0.55\exp(-0.15x)$	0.99***
		H1, Air+MCP	$f = 0.57-0.04x$	0.92**
		H2, Air+MCP	$f = 0.04+0.55\exp(-0.09x)$	0.91***
SST (%)	2019-2021	Air	$f = 13.4+0.25x-0.05x^2$	0.96***
		CA	$f = 13.4+0.32x-0.04x^2$	0.92***
		Air+MCP	$f = 13.4+0.54x-0.07x^2$	0.98***
		CA+MCP	$f = 13.3+0.5x-0.06x^2$	0.98***
	2020	H1, Air	$f = 15.05-0.11x$	0.72***
		H2, Air	$f = 13.5+0.4x-0.05x^2$	0.79***
		H1, Air+MCP	$f = 15.15-0.07x$	0.89***
		H2, Air+MCP	$f = 13.7+0.6x-0.07x^2$	0.82***
SST/TA	2019-2021	Air	$f = 26.3+3.9x$	0.92***
		CA	$f = 26.2+1.45x$	0.89***
		Air+MCP	$f = 26.6+1.9x$	0.84***
		CA+MCP	$f = 24.2+3.5x-0.3x2$	0.86**
	2020	H1, Air	$f = 22.9+8.6x$	0.95***
		H2, Air	$f = 21.03+6.7x$	0.95***
		H1, Air+MCP	$f = 24.3+3.7x$	0.93***
		H2, Air+MCP	$f = 24.1+2.6x$	0.93***

***, **, and *Significant models at 0.1%, 1%, and 5% probability, respectively. Air, atmosphere of air (21 kPa O_2); CA, controlled atmosphere; MCP (1-methylcyclopropene); H1, early harvest; H2, late harvest.

The titratable acidity (TA) decreased over the eight months of storage, regardless of storage atmosphere, 1-MCP treatment, and harvest maturity (Figure 3 A and B). Fruit stored in the air, without the 1-MCP treatment, had a more pronounced TA loss, regardless of their maturity at harvest (Figure 3 A and B), as shown for other cultivars, such as Gala (Bai et al., 2005; Brackmann et al., 2008; Thewes et al., 2017). The higher respiration rate might have contributed to the greater TA loss in control fruit stored in the air (Figure 1). Fruit treated with 1-MCP retained higher TA under both storage atmosphere conditions. For fruit under CA, the 1-MCP effects on TA was more pronounced after seven days of shelf life (Figure 3 A). A noteworthy fact is that the treatment with 1-MCP had higher impact on the post-storage TA than the harvest maturity (Figure 3 B), as described above for flesh firmness.

The soluble solid contents (SSC) showed a quadratic response to the storage time (Figure 3 C) in air-stored fruit without 1-MCP, and these fruit had the lowest SSC after 6 to 8 months of storage.

The response of SSC to storage period interacted with that to the harvest maturity. SSC response decreased linearly over the storage period, in fruit harvested at more advanced maturity (H2) that showed a quadratic response to the storage time when harvested at the optimum maturity (H1) (Figure 3 D). A similar response to harvest maturity and to storage period was observed in 'Luiza' (Argenta et al., 2022b) and 'Red Delicious' apples (Ahmad et al., 2021). SSC to TA ratio increased linearly along the storage period, regardless of the harvest maturity and storage conditions (Figure 3 E and F), as described for other apple cultivars (Argenta et al., 2022b). The highest SSC to TA ratio was observed in fruit harvested at more advanced

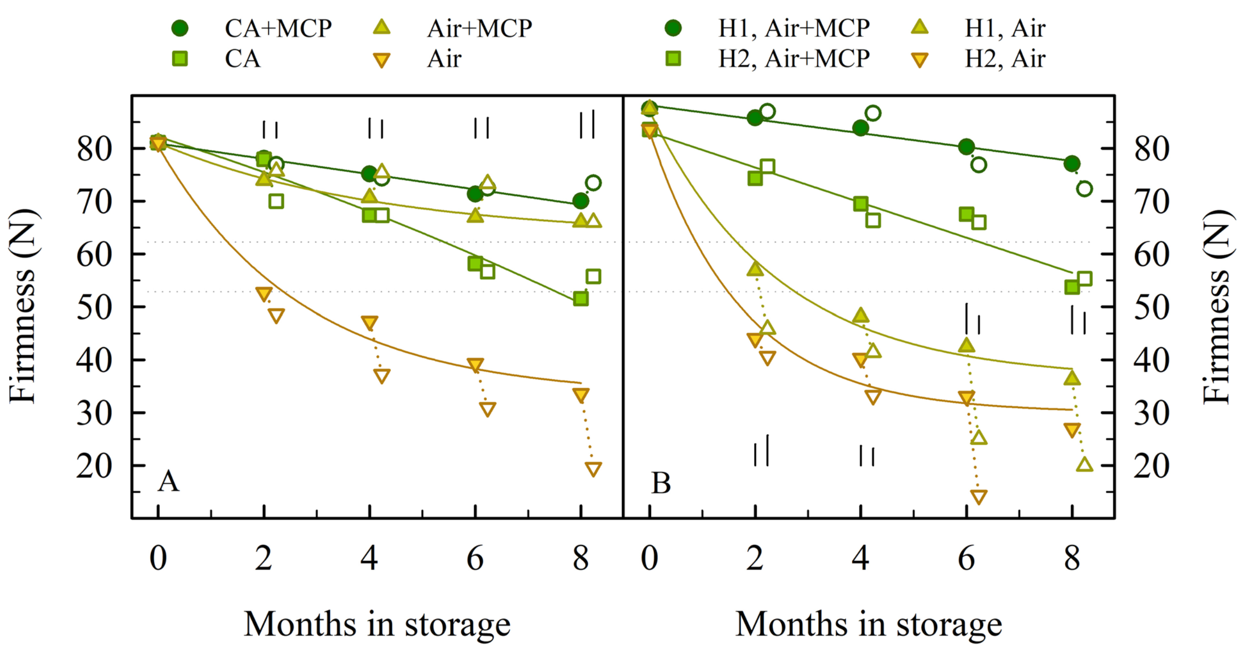

Figure 2. Flesh firmness of 'SCS417 Monalisa' apple (*Malus domestica*) at harvest and after storage. Fruit were treated (+MCP, 1 μL L^{-1}) or not treated with 1-MCP and stored at 0.8°C in the air or under controlled atmosphere conditions (CA, 1.5 kPa O_2 and <0.5 kPa CO_2), from two to eight months. Fruit were held at 22°C, for one day (filled symbols) or seven days (open symbols) after the removal from storage. A, fruit of one harvest maturity were stored in the air or under CA conditions (experiment 1). Data of two years were averaged for this analysis. B, fruit of early (H1) and advanced (H2) maturity were stored in the air (experiment 2). Lines of statistical models (Table 2) are presented when fitted (at 5% probability) to data by a regression analysis. Inserted vertical lines are Fishers' LSD values, at 5% probability, for treatment effects in each assessment date. Caçador, Santa Catarina state, Brazil.

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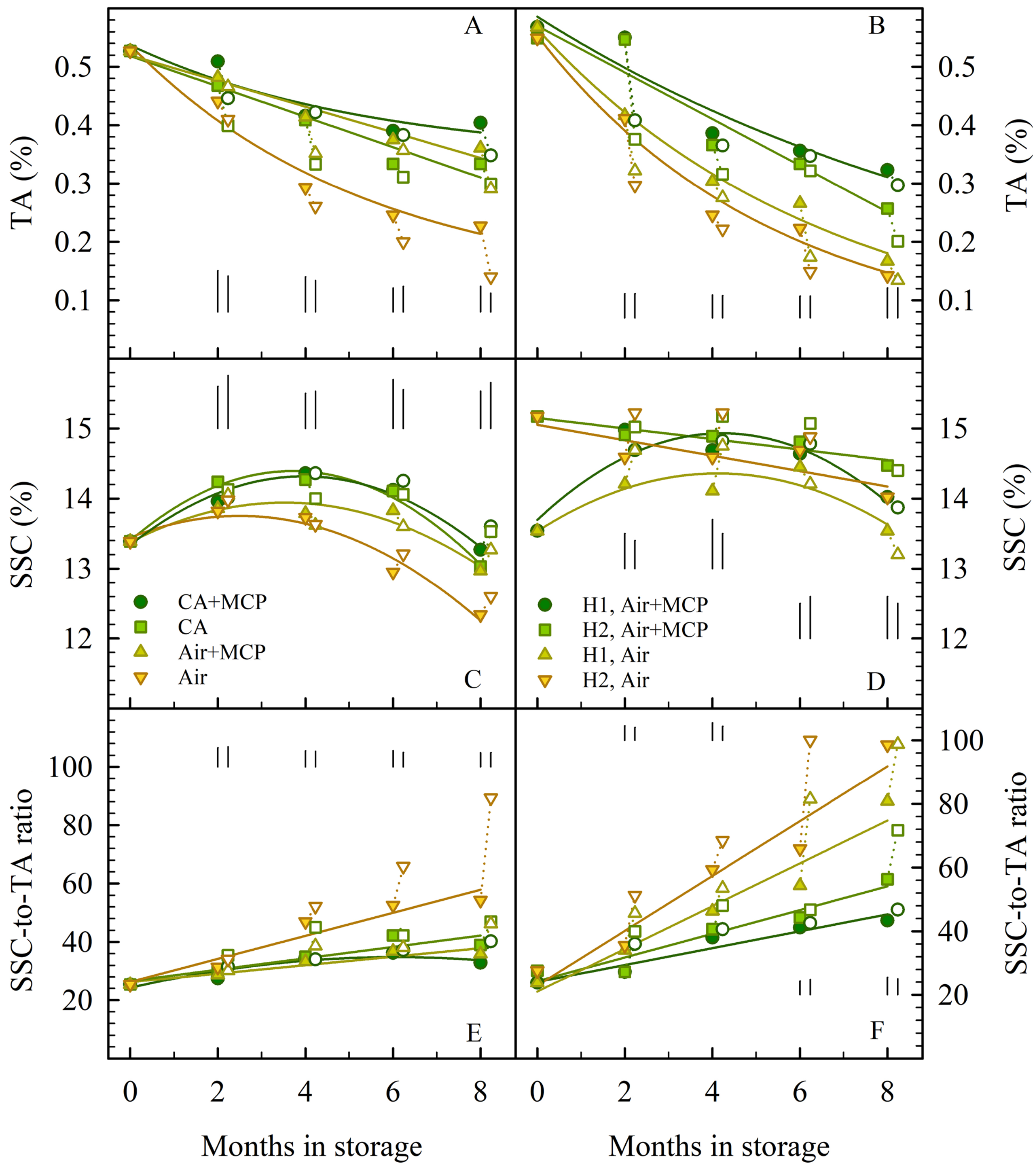

Figure 3. Titratable acidity (TA), soluble solid contents (SSC) and SSC-to-TA ratio of 'SCS417 Monalisa' apple (*Malus domestica*) at harvest and after storage. Fruit were treated (+MCP, 1 µL L^{-1}) or not treated with 1-MCP and stored at 0.8°C in the air or under controlled atmosphere conditions (CA, 1.5 kPa O_2 and <0.5 kPa CO_2), from two to eight months. Fruit were held at 22°C, for one day (filled symbols) or seven days (open symbols) after the removal from storage. Left graphics (A, C, E): fruit of one harvest maturity were stored in the air or under CA conditions (experiment 1). Data of two years were averaged for this analysis. Right graphics (B, D, F): fruit of early (H1) and advanced (H2) maturity were stored in the air (experiment 2). Lines of statistical models (Table 2) are presented when fitted (at 5% probability) to data by a regression analysis. Inserted vertical lines are Fishers' LSD values, at 5% probability, for treatment effects in each assessment date. Caçador, Santa Catarina state, Brazil.

maturity, air-stored and not exposed to 1-MCP; this fact was associated to the faster reduction of TA during storage (Figure 3 B).

Fungal decay is the main cause of apple losses after harvest, representing 60 to 80% of total losses of 'Gala' and 'Fuji' apples, respectively, under commercial conditions in Brazil (Argenta et al., 2021). The severity of fungal decay increased during storage in 'SCS417 Monalisa' apples which were highly affected by the harvest maturity, 1-MCP treatment, and storage atmosphere conditions (Tables 3 and 4). Air-stored fruit without 1-MCP treatment had the highest decay indices (Table 3), similarly to what was reported for 'Fuji' fruit affected by superficial scald (Amarante et al., 2010). The higher decay severity on air-stored apples is likely due to their lower flesh firmness (Figure 2 A) and to the incidence of the physiological disorder ‘scald-like’, which might have reduced the fruit resistance to fungal infection. A negative

Table 3. Severity and incidence of fungal decay, ‘Scald like’, and flesh browning in 'SCS417 Monalisa' apple (*Malus domestica*) treated (+MCP, 1 μL L^{-1}) or not treated with 1-MCP at harvest and stored in the air or under controlled atmosphere conditions (CA, 1.5 kPa O_2 and <0.5 kPa CO_2) at 0.8°C, from two to eight months, followed by one and seven days at 22°C. Data of 2019 and 2021 (experiment 1) were pooled (n=100). Caçador, Santa Catarina state, Brazil[(1)].

Month	Severity[(2)]				Incidence (%)[(3)]			
	Air	Air+MCP	CA	CA+MCP	Air	Air+MCP	CA	CA+MCP
Decay								
One day in shelf life								
2	1.02Ac	1.01Aab	1.02Ac	1.06Aabc	1.2	0.6	1.2	2.9
4	1.24Ab	1.00Bb	1.06Bbc	1.01Bbc	11.8	0.0	2.9	0.6
6	1.59Aa	1.05Ba	1.11Bab	1.07Bab	27.1	2.4	5.3	3.5
8	1.68Aa	1.04Bab	1.15Ba	1.08Ba	33.3	1.7	7.5	4.2
Seven days in shelf life								
2	1.05Ad	1.03Ab	1.06Ab	1.06Aa	2.4	1.4	2.9	2.9
4	1.74Ac	1.03Cb	1.21Ba	1.05Ca	37.1	1.4	10.5	2.4
6	2.07Ab	1.12Ba	1.18Ba	1.10Ba	53.3	6.2	9.0	5.2
8	2.54Aa	1.16Ba	1.25Ba	1.10Ba	76.9	8.1	12.5	5.0
‘Scald like’								
One day in shelf life								
2	1.00Ac	1.00Ac	1.00Ac	1.00Ab	0.0	0.0	0.0	0.0
4	1.44Ab	1.02Bbc	1.08Bbc	1.00Bb	14.9	0.8	2.7	0.0
6	1.93Aa	1.04Ba	1.29Ba	1.03Ca	31.4	1.2	9.8	0.8
8	1.89Aa	1.03Bb	1.11Bb	1.00Bb	30.0	1.1	3.9	0.0
Seven days in shelf life								
2	1.16Ab	1.00Bb	1.00Bb	1.00Bb	5.4	0.0	0.0	0.0
4	1.89Aa	1.00Ba	1.29Ba	1.05Ca	29.5	0.0	9.8	1.6
6	2.05Aa	1.09Ba	1.43Ba	1.01Cab	34.9	2.9	14.3	0.3
8	1.35Ab	1.06Bb	1.07Bb	1.00Bb	11.7	2.1	2.5	0.0
Flesh browning								
One day in shelf life								
2	1.05Ac	1.01Ab	1.02Ac	1.01Ab	1.6	0.4	0.8	0.4
4	1.15Abc	1.00Cb	1.09ABbc	1.01BCb	5.1	0.0	3.1	0.4
6	1.21ABb	1.06Ca	1.25Aa	1.07BCa	7.1	2.0	8.2	2.4
8	1.36Aa	1.01Bb	1.11Bb	1.01Bb	12.2	0.0	3.3	0.0
Seven days in shelf life								
2	1.06Ab	1.00Bb	1.03ABc	1.01ABa	1.9	0.0	1.0	0.3
4	1.12Ab	1.02Bb	1.06ABbc	1.02Ba	4.1	0.6	1.9	0.6
6	1.70Aa	1.10BCa	1.22Ba	1.00Ca	23.5	3.2	7.3	0.0
8	1.21Ab	1.09ABa	1.16Aab	1.00Ba	7.1	2.9	5.4	0.0

[(1)]Means of severity followed by equal letters, lowercases in the columns and uppercases in the rows, do not differ by Kruskal-Wallis’ test, at 5% probability. [(2)]Scales of 1 to 3 for decay, and 1 to 4 for skin browning and flesh browning. [(3)]Incidence weighted by severity.

correlation between the incidence of fungal decay and flesh firmness may occur especially for early season cultivars, depending on the growing season (Argenta et al., 2021). A remarkable fact is that the CA storage conditions reduced the decay severity to a similar level as that of air storage with 1-MCP treatment. Worth of notice is also the fact that 1-MCP treatment under CA storage showed no additional effects on the reduction of decay severity (Table 3). The effect of 1-MCP on the decay incidence is variable. A comprehensive study under commercial condition showed that 1-MCP had no effect on the decay of 'Gala' and 'Fuji' apples (Argenta et al., 2021), while studies under laboratory conditions have shown that 1-MCP can reduce (Argenta et al., 2022b) or have no effect on apple decay (Weber et

Table 4. Severity and incidence of fungal decay, ‘scald like’, and flesh browning in 'SCS417 Monalisa' apple (*Malus domestica*) treated (+MCP, 1 µL L^{-1}) or not treated with 1-MCP at harvest and stored in the air at 0.8°C, from two to eight 8 months, followed by one and seven days at 22°C. Fruit harvested at early (H1) and advanced (H2) maturity. Experiment 2, in 2020 season. Caçador, Santa Catarina state, Brazil(1).

Month	Severity(2)				Incidence (%)(3)			
	Air		Air+MCP		Air		Air+MCP	
	H1	H2	H1	H2	H1	H2	H1	H2
				Decay				
				One day in shelf life				
2	1.00AB	1.08Ad	1.00Aa	1.00Ab	0.0	4.0	0.0	0.0
4	1.00Bb	1.76Ac	1.05Ba	1.00Bb	0.0	38.0	2.5	0.0
6	1.30Bb	2.18Ab	1.08Ba	1.08Bb	15.0	58.9	3.8	4.0
8	1.90Ba	2.58Aa	1.10Ca	1.36Ca	45.0	79.0	5.0	18.0
				Seven days in shelf life				
2	1.18ABc	1.32Ac	1.05Bb	1.08Bc	8.8	16.0	2.5	4.0
4	1.17Bc	2.10Ab	1.07Bab	1.12Bc	8.3	55.0	3.3	6.0
6	1.55Bb	2.84Aa	1.03Cb	1.40Bb	27.5	90.0	1.3	20.0
8	2.55Ba	3.00Aa	1.20Da	1.64Ca	82.0	100.0	10.0	32.0
				‘Scald like’				
				One day in shelf life				
2	1.15Bb	2.32Aa	1.00Ba	1.00Aa	5.0	44.0	0.0	0.0
4	1.60Ba	2.52Aa	1.00Ca	1.24Aa	20.0	50.7	0.0	8.0
6	1.95Aa	1.64Bb	1.10Ca	1.22Bb	31.7	21.5	5.0	7.3
8	1.85Aa	1.42Bb	1.00Ca	1.38Bb	28.3	14.0	0.0	12.7
				Seven days in shelf life				
2	1.98Bb	3.10Aa	1.00Cb	1.04Aa	32.5	70.0	0.0	1.3
4	1.75Bb	2.80Aa	1.00Db	1.30Aa	25.0	60.0	0.0	10.0
6	2.40Aa	1.16Bb	1.08Bb	1.16Bb	46.7	5.3	3.7	5.3
8	1.78Ab	1.00Bb	1.25Ba	1.36Bb	25.8	0.0	12.5	12.0
				Flesh browning				
				One day in shelf life				
2	1.00Bb	1.16Abc	1.00Ba	1.00Bb	0.0	5.3	0.0	0.0
4	1.05ABb	1.16Abc	1.00Ba	1.00Bb	1.7	5.3	0.0	0.0
6	1.28Bab	1.71Aa	1.03Ba	1.12Bab	9.2	23.7	0.8	4.0
8	1.40Aa	1.38Ab	1.00Ba	1.20ABa	13.3	12.7	0.0	6.7
				Seven days in shelf life				
2	1.00Bb	1.32Ac	1.00Bb	1.02Bb	0.0	10.7	0.0	0.7
4	1.08Bb	1.78Ab	1.00Bb	1.10Bb	2.8	26.0	0.0	3.3
6	2.10Ba	4.00Aa	1.00Cb	1.12Cb	36.7	100.0	0.0	4.0
8	1.80Aa	- d	1.18Ba	1.80Aa	26.7	-	5.8	26.7

(1)Means of severity followed by equal letters, lowercases in the columns and uppercases in the rows, do not differ by Kruskal-Wallis’ test, at 5% probability. (2)Scales of 1 to 3 for decay, and 1 to 4 for skin browning. (3)Incidence weighted by severity. (-)Not assessed, due to high incidence of decay.

al., 2017; Anese et al., 2020). In 'SCS417 Monalisa' apples, the treatment with 1-MCP was beneficial for the reduction of decay, especially under air storage conditions, regardless of the harvest maturity (Table 3 and 4). 'SCS417 Monalisa' apples harvested at more advanced maturity (H2) were more susceptible to decay (Table 4), showing that late harvested fruit should not be stored for long periods.

'SCS417 Monalisa' apple was very susceptible to skin browning, a ‘scald-like’ physiological disorder. The brown patches affected mainly the non-red portions (shade side) of the fruit surface, but it can also develop on the red skin tissue (sun-exposed side) that may become slightly rough (Table 4). These symptoms resemble the senescent scald of 'Golden Delicious' apples (Pierson et al., 1971). The severity of the ‘scald-like’ disorder was higher in control fruit stored in the air (Table 3) and, unlike the ordinary superficial scald, the ‘scald-like’ in 'SCS417 Monalisa' apples was more severe in late harvested fruit (Table 4). In general, the ‘scald-like’ disorder incidence increased along the storage. A reduction of ‘scald-like’ incidence after 6- or 8-month storage, depending on the postharvest treatment and harvest maturity, is likely due to the development of severe decay symptoms that prevented the disorder’s visual assessment. The treatment with 1-MCP and CA reduced the severity of this physiological disorder from 4 to 8 months of storage at both harvest maturities (Tables 3 and 4).

A diffuse flesh browning disorder in 'SCS417 Monalisa' apples (Figure 4) increased with the storage duration, especially in air-stored fruit not treated with 1-MCP, after seven days of shelf life (Tables 3 and 4). This disorder was more severe in late harvested fruit and was reduced by CA and 1-MCP treatment. There was an additive effect of CA and 1-MCP on the inhibition of flesh browning development in the fruit. These results suggest that flesh browning in 'SCS417 Monalisa' apples is likely a senescent-related disorder. Physiological disorders associated with senescence are usually prevented by early harvest, CA storage and 1-MCP treatment (DeLong et al., 2014; Watkins et al., 2015; Argenta et al., 2023). Flesh browning is caused by the loss of cell compartmentalization, which increases the electrolyte leakage and induces the phenol oxidation that leads to brown pigment synthesis in the fruit (Gago et al., 2015; Thewes et al., 2017; 2021). The effect of 1-MCP on the flesh browning incidence has been shown to be variable, depending on the apple cultivar, harvest maturity, and storage temperature (Lee et al., 2012; Thewes et al., 2017; Weber et al., 2017; Anese et al., 2020).

'SCS417 Monalisa' apple fruit were affected by skin and flesh cracking, which occurred mainly from the shoulder to over the cheek. This disorder was more severe in late harvested fruit (H2) and after a long-term storage in the air, without the treatment with 1-MCP (Tables 5 and 6), showing that it is likely associated to advanced fruit ripening and senesce. This type of cracking has been reported for 'Gala' apples harvested at more advanced maturity, which can be reduced by lower relative humidity under storage atmosphere conditions (Weber et al., 2012). These results suggest that 'SCS417 Monalisa' apples are susceptible to high relative humidity, especially when stored in the air for more than two months.

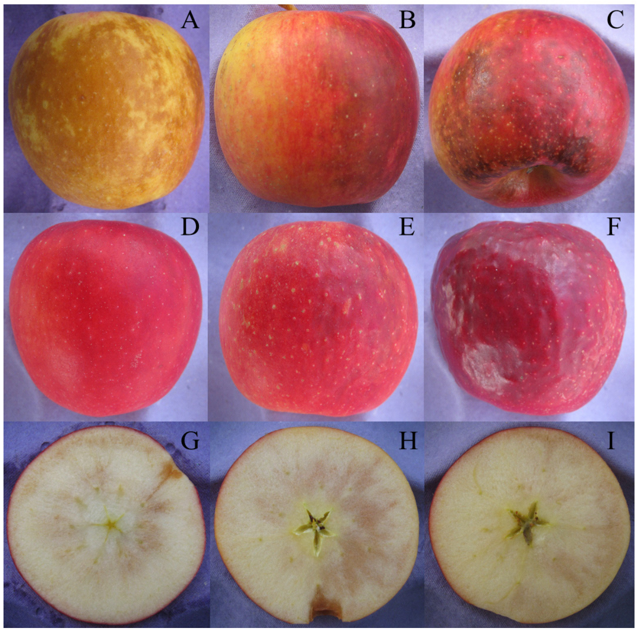

Figure 4. 'SCS417 Monalisa' apple (*Malus domestica*) grown in southern Brazil showing symptons of skin disorders. ‘Scald-like’ symptoms: A, at shade side; B and C, sun side. D: no skin disorders. Wrinkly skin symptoms: E, light; F, severe. Diffuse flesh browning symptoms: G, light; H and I, moderate. Photos by Luiz Carlos Argenta.

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Wrinkly skin (Figure 4 E and F) occurred in 'SCS417 Monalisa' apples during storage. Storage time, harvest maturity, and 1-MCP treatment had no consistent effects on the wrinkly skin incidence, especially in the experiment two (Tables 5 and 6). In experiment one, the severity of this disorder increased for fruit along the storage under CA conditions, and it was higher for fruit under CA and under CA with 1-MCP treatment than in air-stored fruit not treated with 1-MCP, after 6 and 8 months of storage (Table 5). More studies are necessary to better understand the etiology of this physiological disorder in 'SCS417 Monalisa' apples. Bitter pit incidence in 'SCS417 Monalisa' apples was very low, regardless of the harvest maturity, 1-MCP treatment, and storage atmosphere (Tables 5 and 6), suggesting that there is a low susceptibility of this cultivar to this disorder.

The study shows that 'SCS417 Monalisa' fruit ripens rapidly following harvest, even at 0.8°C,

Table 5. Severity and incidence of fruit cracking, wrinkly skin, and bitter pit on 'SCS417 Monalisa' apple (*Malus domestica*) treated (+MCP, 1 µL L^{-1}) or not treated with 1-MCP at harvest and stored in the air or under controlled atmosphere conditions (CA, 1.5 kPa O_2 and <0.5 kPa CO_2) at 0.8°C, from two to eight months, followed by one and seven days at 22°C. Data of 2019 and 2021 (experiment 1) were pooled (n=100). Caçador, Santa Catarina state, Brazil[(1)].

Month	Severity[(2)]				Incidence (%)[(3)]			
	Air	Air+MCP	CA	CA+MCP	Air	Air+MCP	CA	CA+MCP
				Fruit cracking				
				One day in shelf life				
2	1.01Ad	1.00Aa	1.00Ab	1.00Aa	1.2	0.0	0.0	0.0
4	1.12Ac	1.00Ba	1.03Bb	1.01Ba	11.8	0.0	3.5	1.2
6	1.21Ab	1.01Ca	1.12Ba	1.01Ca	21.2	1.2	11.8	1.2
8	1.40Aa	1.00Ca	1.13Ba	1.00Ca	40.0	0.0	13.3	0.0
				Seven days in shelf life				
2	1.03Ac	1.01Aa	1.00Ab	1.01Aa	2.9	1.0	0.0	1.0
4	1.14Ab	1.00Ba	1.12Aa	1.00Ba	14.3	0.0	12.4	0.0
6	1.54Aa	1.04Ca	1.16Ba	1.00Ca	54.3	3.8	16.2	0.0
8	1.53Aa	1.04Ba	1.09Ba	1.00Ba	52.5	3.8	8.8	0.0
				Wrinkly skin				
				One day in shelf life				
2	1.01Aa	1.01Aab	1.00Ac	1.00Ab	0.6	0.6	0.0	0.0
4	1.01Aa	1.02Aab	1.02Abc	1.05Aab	0.6	1.2	1.2	2.4
6	1.00Ba	1.05ABa	1.07Ab	1.06ABa	0.0	2.4	3.5	2.9
8	1.00Ba	1.03Bab	1.13Aa	1.05Ba	0.0	1.7	6.7	2.5
				Seven days in shelf life				
2	1.00Ab	1.02Ab	1.00Ab	1.02Ac	0.0	1.0	0.0	1.0
4	1.00Bb	1.06Aab	1.02ABb	1.05Abc	0.0	2.9	1.0	2.4
6	1.03Ba	1.09ABa	1.13Aa	1.12Aab	1.4	4.3	6.7	6.2
8	1.00Bb	1.08ABab	1.11Aa	1.14Aa	0.0	3.8	5.6	6.9
				Bitter pit (1-4)				
				One day in shelf life				
2	1.00Aa	1.01Ab	1.00Ab	1.00Aa	0.0	0.4	0.0	0.0
4	1.00Ba	1.04Aab	1.00Bb	1.00Ba	0.0	1.2	0.0	0.0
6	1.00Ba	1.08Aab	1.00Bb	1.00Ba	0.0	2.7	0.0	0.0
8	1.00Aa	1.10Aa	1.10Aa	1.02Aa	0.0	3.3	3.3	0.6
				Seven days in shelf life				
2	1.00Aa	1.00Ab	1.00Ab	1.00Ab	0.0	0.0	0.0	0.0
4	1.00Ba	1.00Bb	1.04Aab	1.00Bb	0.0	0.0	1.3	0.0
6	1.01Aa	1.02Aab	1.00Ab	1.00Ab	0.3	0.6	0.0	0.0
8	1.00Aa	1.06Aa	1.06Aa	1.04Aa	0.0	2.1	2.1	1.3

(1)Means of severity followed by equal letters, lowercases in the columns and uppercases in the rows, do not differ by Kruskal-Wallis' test, at 5% probability. (2)Scales of 1 to 2 for fruit cracking, and 1 to 4 for wrinkly skin and bitter pit. (3)Incidence weighted by severity.

based on the rapid softening associated with significant increase of ethylene production. The fruit are very susceptible to physiological disorders and fungal decay. The storage life of 'SCS417 Monalisa' apples in cold air is about two months, when fruit are harvested at optimum maturity. Both 1-MCP treatment and CA storage increase markedly the storage life of 'SCS417 Monalisa' fruit by delaying the ripening and preventing disorders. Accordingly, the storage of 'SCS417 Monalisa' apples for more than two months requires the use of 1-MCP and/or CA (1.5 kPa O_2 and <0.5 kPa CO_2). The development of physiological disorders and fungal decay can be limiting factors for of 'SCS417 Monalisa' apple storage for 6 to 8 months under CA conditions. Therefore, it is recommended to monitor the physiological disorders and decay incidences in fruit samples stored under CA conditions, especially

Table 6. Severity and incidence of fruit cracking, wrinkly skin, and bitter pit on 'SCS417 Monalisa' apple (*Malus domestica*) treated (+MCP, 1 µL L^{-1}) or not treated with 1-MCP at harvest and stored in the air at 0.8°C, from two to eight months, followed by one and seven days at 22°C. Fruit harvested at early (H1) and advanced (H2) maturity. Experiment 2, in the 2020 season. Caçador, Santa Catarina state, Brazil[(1)].

Month	Severity[(2)]				Incidence (%)[(3)]			
	Air		Air+MCP		Air		Air+MCP	
	H1	H2	H1	H2	H1	H2	H1	H2
				Fruit cracking				
				One day in shelf life				
2	1.00Bc	1.52Ac	1.00Ba	1.00Bb	0.0	26.0	0.0	0.0
4	1.10Bbc	1.68Ab	1.05Ba	1.00Bb	5.0	34.0	2.5	0.0
6	1.30Bab	1.93Aa	1.05Ca	1.10Cb	15.0	46.7	2.5	5.0
8	1.45Ba	1.96Aa	1.03Ca	1.40Ba	22.5	48.0	1.25	20.0
				Seven days in shelf life				
2	1.00Bb	1.40Ac	1.00Ba	1.02Bb	0.0	20.0	0.0	1.0
4	1.10Bb	1.74Ab	1.00Ba	1.04Bb	5.0	37.0	0.0	2.0
6	1.70Ba	2.00Aa	1.00Ca	1.12Cb	35.0	50.0	0.0	6.0
8	1.83Ba	2.00Aa	1.03Da	1.36Ca	41.2	50.0	1.25	18.0
				Wrinkly skin				
				One day in shelf life				
2	1.00Aa	1.00Aa	1.00Aa	1.00Aa	0.0	0.0	0.0	0.0
4	1.00Aa	1.00Aa	1.00Aa	1.00Aa	0.0	0.0	0.0	0.0
6	1.00Aa	1.00Aa	1.00Aa	1.02Aa	0.0	0.0	0.0	1.0
8	1.00Aa	1.00Aa	1.00Aa	1.00Aa	0.0	0.0	0.0	0.0
				Seven days in shelf life				
2	1.13ABa	1.26Aa	1.03Ba	1.18ABb	6.2	13.0	1.2	9.0
4	1.00Cb	1.26Ba	1.00Ca	1.52Aa	0.0	13.0	0.0	26.0
6	1.00Ab	1.00Ab	1.05Aa	1.00Ab	0.0	0.0	2.5	0.0
8	1.00Bb	1.00Bb	1.00Ba	1.16Ab	0.0	0.0	0.0	8.0
				Bitter pit (1-2)				
				One day in shelf life				
2	1.05Aa	1.00Aa	1.00Aa	1.00Aa	1.7	0.0	0.0	0.0
4	1.00Ab	1.00Aa	1.00Aa	1.00Aa	0.0	0.0	0.0	0.0
6	1.00Ab	1.00Aa	1.05Aa	1.00Aa	0.0	0.0	1.7	0.0
8	1.00Ab	1.00Aa	1.05Aa	1.04Aa	0.0	0.0	1.7	1.3
				Seven days in shelf life				
2	1.03Aa	1.00Aa	1.00Aa	1.00Aa	0.8	0.0	0.0	0.0
4	1.00Aa	1.00Aa	1.00Aa	1.00Aa	0.0	0.0	0.0	0.0
6	1.03Aa	1.00Aa	1.05Aa	1.00Aa	0.8	0.0	1.7	0.0
8	1.00Aa	1.00Aa	1.08Aa	1.00Aa	0.0	0.0	2.5	0.0

[(1)]Means of severity followed by equal letters, lowercases in the columns and uppercases in the rows, do not differ by Kruskal-Wallis' test, at 5% probability. [(2)]Scales of 1 to 2 for fruit cracking, and 1 to 4 for wrinkly skin and bitter pit. [(3)]Incidence weighted by severity.

from the fourth month on of CA storage, as a mean to predict the storage room opening, the time of fruit marketing, and fruit loss.

Conclusions

1. The storage life of 'SCS417 Monalisa' apples (*Malus x domestica*) is about two months under cold air conditions, and six to eight months under cold controlled atmosphere (CA) conditions, based on the time required to reach 53 N flesh firmness.

2. CA (1.5 kPa O_2 and <0.5 kPa CO_2) storage and 1-MCP (1 μL L^{-1}) treatments reduce the fruit ethylene production and respiration, and prevent the rapid softening, besides reducing the fungal decay, ‘scald like’, flesh browning, and cracking incidences in 'SCS417 Monalisa' apple.

3. In fruit exposed to 1-MCP, the rate of flesh firmness loss is reduced, regardless of the harvest maturity and growing season; fruit harvested at advanced maturity and exposed to 1-MCP retains higher firmness, after two to eight months of storage than early harvested fruit not exposed to 1-MCP.

4. There is an additive benefits of the treatment with 1-MCP and CA storage conditions for flesh firmness retention and for the inhibition of physiological disorder incidences on 'SCS417 Monalisa' apples, after a long-term storage.

Acknowledgments

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