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Effect of Preharvest and Postharvest Application of 1-MCP on the Quality of Gala Schniga® SchniCo Red(s) Apples during Long-Term Storage

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Abstract: Fruit growers are looking for effective solutions to preserve the high quality of apples after storage. Therefore, the aim of this study was to assess the impact of pre- and postharvest use of 1-MCP on the quality of 'Gala Schniga® SchniCo Red(s)' apples harvested at the optimal harvest date and at a delayed harvest date and stored for 9 months under conditions similar to DCA (0.6% CO_2 and 0.6% O_2). Four treatments: control (1-MCP untreated), 1-MCP treated 7 days before harvest (Harvista™), 1-MCP treated 7 days after harvest (Smart-Fresh™), and 1-MCP treated before and after harvest (Harvista™ + SmartFresh™) were used, respectively, for each of the above harvest dates. After 5, 7, and 9 months of storage and after an additional 7-day shelf-life period, the following properties were determined: flesh firmness, soluble solids content, titratable acidity, and ethylene production rate. The harvest date and the 1-MCP application date affected ethylene production rate which was reflected in fruit flesh firmness and acidity ($p < 0.05$). Apples collected at the optimal harvest date from trees sprayed with Harvista™ before harvest retained high firmness (>55 N) after 7 days of shelf-storage at 20 °C, even if previously stored for 9 months. Apples collected later showed firmness similar to the best preferred by consumers only if treated with 1-MCP after harvest.

Keywords: apples; ethylene; firmness; 'Gala'; Harvista™; SmartFresh™; storage; titratable acidity

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1. Introduction

Apple consumers pay a great deal of attention to the attractiveness of blush [1], which is why the 'Gala Schniga® SchniCo Red(s)' cultivar, the fruits of which are one colour with a striped blush, deserves special notice. As a small fruit cultivar, it is an ideal snack for children at school. According to the WAPA (the World Apple and Pear Association), Poland, with an apple production of 4.3 million tonnes, was the leader in the European Union and the third largest apple producer in the world in 2021. Such a large production volume makes it necessary to export apples, including to sales markets in remote locations. A big challenge is to keep the high quality of apples to be sold on the market after long-term storage.

The apple is a climacteric fruit species in which ethylene stimulates the ripening process [2], which promotes the formation of the fruit's typical taste, and at the same time, results in a change in flesh texture. In terms of storage, the effect of ethylene is undesirable, because ethylene leads to the production of still more ethylene in fruit, and thus, accelerates fruit ripening. Ethylene causes a decrease in organic acids and weakens the connections between cells, which leads to the relaxation of the structure of the flesh and deterioration of its texture, thus negatively affecting the postharvest quality of apples [3]. The less firm and juicy is the apple flesh, the more strongly pronounced is the mealy taste which is characteristic of overripe apples and disliked by consumers [4]. The flesh firmness threshold acceptable to consumers is approximately 55 N for apples considered to be hard, such as various mutations of the 'Gala' cultivar [5].

There are several ways to limit the production of ethylene and thus, to slow down the ripening of apples. The most effective of them is the postharvest treatment of apples with 1-methylcyclopropene (1-MCP). The use of this compound helps preserve the high quality of apples during long-term storage, and thus, enables their export to distant markets [6,7]. The effectiveness of 1-MCP depends largely on the species or cultivar [8–10], the ripening stage of fruit at harvest [11–13], the number of applications, and the concentration of the active substance [14], as well as the time interval between the harvest and the application [15].

Fruits intended for storage should be harvested at the correct maturity stage [16–19]. With the declining availability of harvest workers, this is becoming increasingly difficult to achieve. A delayed harvest results in worse quality and a significantly shorter shelf life of apples. This can be prevented by using 1-MCP before harvest [20,21]. Through preharvest treatment, 'Fuji' apples retained high firmness and titratable acidity even after 9 months of storage at 0.5 °C [22], 'Honeycrisp' apples were less susceptible to soft scald [23], and 'Gala' apples lost firmness more slowly and suffered less from disorders caused by a delay in harvest [24].

To extend the storage period, modern technologies applying low oxygen atmosphere are used. Fruit of 'Royal Gala' [25–27], 'Fuji Suprema' [28], 'Golden Delicious' [29], and 'Elstar' [30] stored in ULO (Ultra Low Oxygen) or DCA (Dynamic Control Atmosphere) conditions were distinguished by higher firmness than those stored in standard CA. 'Royal Gala' apples after 8 months of storage under DCA conditions had also a higher content of organic acids compared to those stored in CA [26]. In contrast, Thewes et al. [25] did not observe any significant differences in the SSC (soluble solids content) and acidity of 'Royal Gala' apples stored under DCA, ULO, and CA conditions. According to some researchers, apples stored in DCA (0.7–0.8% CO_2 and 0.3–0.4% O_2) are characterised by a better taste than those stored in ULO or CA (3.0% CO_2 and 2.0% O_2) [31,32]. Studies conducted on the 'Pinova' and 'Jonagold' cultivars also showed that consumers preferred apples stored in DCA to those stored in ULO [33]. In turn, 'Granny Smith' apples stored in DCA were perceived as being tastier than apples of the same cultivar treated with 1-MCP [34]. To improve the fruit taste, it is worth considering the use of 1-MCP in combination with low oxygen storage technologies such as ULO and DCA [35].

The effect of the use of 1-MCP before and/or after harvest on the rate of changes in the quality of apples stored under ULO (1.2% CO_2 and 1.2% O_2) conditions is already quite well recognized [20,21,36], while there are few studies showing how 1-MCP affects quality changes in apples stored under DCA conditions. Therefore, the objective of this paper was to focus on the impact of the pre- and post-harvest application of 1-MCP on the quality changes in 'Gala Schniga® SchniCo Red(s)' apples collected at two harvest dates and stored for a long term in an atmosphere containing 0.6% CO_2 and 0.6% O_2 (referred to as DCA in this paper).

2. Materials and Methods

2.1. Research Plan

The experiment was carried out on apples of the 'Gala Schniga® SchniCo Red(s)' cultivar in the storage season 2021/2022. The apples came from trees grafted on the M.9 rootstock planted in 2014 at a spacing of 3.0 × 1.0 m in an experimental orchard of the Warsaw University of Life Sciences (SGGW-WULS; Warsaw—52°14′ N, 21°1′ E). The fruit was harvested at two harvest dates: the optimal harvest date (OHD)—118 days after full bloom (DAFB)—9 September 2021 and a delayed date (DH)—132 DAFB (23 September 2021).

The Streif Index [37] was used to determine the optimal harvest date. Seven days before the harvest date (2 September 2021), one hundred (100) trees were sprayed using the 1-MCP compound (Harvista™; AgroFresh Solutions Inc., Philadelphia, PA, USA; 150 g/ha). After 7 days (9 September 2021—OHD), 12 boxes of apples (approximately 15 kg each box) were collected from the unsprayed and sprayed trees, respectively. After another 7 days, during which the fruit was stored in a normal atmosphere (1 °C), half of the samples (6 control boxes and 6 boxes with apples sprayed with Harvista™) were treated with 1-

MCP (SmartFresh™ ProTabs, AgroFresh Solutions Inc., Philadelphia, PA, USA; 0.65 µL/L) for 24 h. Next, the apples were placed in 1 m^3 containers in which the target atmosphere composition (0.6% CO_2 and 0.6% O_2) was achieved within 24 h. The composition of the atmosphere was obtained by connecting two gas cylinders to the container—one cylinder contained N_2 (98%) to quickly displace oxygen from the volume of the container, the next cylinder contained CO_2 (5%) to increase its concentration in the container.

The same was done with the apples harvested on 23 September 2021 (DH). The fruit from each treatment was stored in a separate 1 m^3 container for 5, 7, and 9 months at a temperature of 1 °C and relative humidity of approximately 95%. The following treatments were applied in the experiment:

Control—OHD (fruit harvested at the optimal harvest date, not treated with 1-MCP either before or after harvest);

Harvista™—OHD (fruit harvested at the optimal harvest date from trees sprayed with Harvista™);

SmartFresh™—OHD (fruit harvested at the optimal harvest date from trees not sprayed with Harvista™, and treated with SmartFresh™ 7 days after harvest);

Harvista™ + SmartFresh™—OHD (fruit harvested at the optimal harvest date from trees sprayed with Harvista™, and treated with SmartFresh™ 7 days after harvest);

Control—DH (fruit harvested at the delayed harvest date, not treated with 1-MCP either before or after harvest);

Harvista™—DH (fruit harvested at the delayed harvest date from trees sprayed with Harvista™);

SmartFresh™—DH (fruit harvested at the delayed harvest date from trees not sprayed with Harvista™, and treated with SmartFresh™ 7 days after harvest);

Harvista™ + SmartFresh™—DH (fruit harvested at the delayed harvest date from trees sprayed with Harvista™ and treated with SmartFresh™ 7 days after harvest).

The quality of the apples was assessed immediately after storage in the above-described conditions and after 7 days of storage at 20 °C. The experiment involved 48 fruit groups (4 treatments with 1-MCP × 2 harvest dates × 3 storage periods × 2 shelf-life periods). In each combination, the quality of apples was assessed in 4 replications, 10 apples per replication.

2.2. Measurements

The optimal harvest date was determined using the Streif Index. For this purpose, fruit flesh firmness and soluble solids content (SSC) was determined and a starch test was performed three times, every 5 days. The Streif Index was calculated according to the following formula:

$$\mathrm{SI} = \frac{F}{R * S} \tag{1}$$

where: SI—Streif Index, *F*—firmness (expressed in kG), *R*—soluble solids content (°Bx), *S*—starch test result (scale 1–10). The results from three consecutive measurements (at intervals of 4 days) were used to draw a graph on the basis of which the optimal date of the harvestu was determined. The Streif Index for the optimal harvest date of 'Gala' apple range from 0.20 to 0.14 [37].

On the day of harvest, F and SSC were determined and a starch test was performed once again. In addition, the concentration of ethylene in apple cores was analysed and the colour of the blush was measured. Immediately after 5, 7, and 9 months of storage, respectively, and after 7 days of keeping apples at 20 °C following each storage period, the following measurements were carried out: ethylene production intensity, F, titratable acidity (TA), and SSC.

To determine the internal ethylene concentration in apple cores, 1 mL of air was taken from the core using a syringe. The samples were analysed using a gas chromatograph (HP 5890, Hewlett Packard, Palo Alto, CA, USA), and the results were given in μL/L. Internal ethylene concentration was determined in 4 replications, 10 apples per replication [36].

The starch test was performed on the cross sections of apples by spraying them with iodine solution in potassium iodide (I_2 in KI), and the obtained coloration of the fruit flesh was compared with the standard table assigning values from 1 to 10. The end result was the average of each replication. The starch test was performed in 4 replications, 10 apples per replication [38].

Flesh firmness was determined from two opposite sides of the fruit (two readings per each apple per replication), after removal of the peel, using a metal probe (measurement speed: 4 mm/s; probe diameter: 11 mm) of a penetrometer (Instron 5542, Instron, Norwood, MA, USA). The results were expressed in Newtons (N) [36].

In the next step, SSC was determined [38]. For this purpose, a piece of flesh with peel was taken from each apple to produce juice in a juicer. SSC in the juice was measured using a refractometer (Atago, Palette PR-32, Atago, Co., Ltd., Tokyo, Japan). The measurements were performed in 4 replications, 10 apples per replication and the results were expressed in Brix degrees (°Bx).

TA was determined using the solution of 10 mL apple juice (obtained in a juicer for the purpose of determining SSC) and 100 mL of distilled water in 150 mL flasks. The solution was titrated with 0.1 M NaOH to pH = 8.1. TA was measured by an automatic titrator (TitroLine 5000, Xylem Analytics Germany GmbH, Weilheim, Germany) and the results were expressed as malic acid content in %. The measurements were performed in 4 replications, 10 apples per replication [36].

Blush intensity was evaluated using a Minolta colorimeter (Spectrophotometer CM 508i, Minolta, Co., Ltd., Japan) calibrated with a white plate. Measurements were made on the blush side of 20 apples per replication according to the CIE L*a*b* system, in which L* is a value in the range of 0–100 (dark–light), parameter a* is a value in the range between −60 (green) and +60 (red) and parameter b* is a value in the range between −60 (blue) and +60 (yellow) [38].

Ethylene production rate was determined by placing apples in air-tight jars of 1500 mL at 20 °C. After 1 h, a sample of 1 mL of air was taken from the jar and injected into a gas chromatograph (HP 5890, Hewlett Packard, Palo Alto, CA, USA). Measurements were made on 6 individual apples from each treatment, and the results were expressed in $\mu L \cdot kg^{-1} \cdot hr^{-1}$ [36].

2.3. Statistical Analysis

The Shapiro–Wolf test was carried out to check whether the results showed a normal distribution. In the case of nonparametric distribution, the following tests were used: the Mann–Whitney U test to compare the differences between two independent groups; the Kruskal–Wallis test to compare differences between more than two independent groups. For the normal distribution, the results were analysed by a one-way ANOVA with the Newman–Keuls post hoc test. Differences between average values were reported as significant at $p = 0.05$. Statistical analyses were performed using Statistica 13.3 (Statsoft Inc., Tulsa, OK, USA).

3. Results

The results illustrating the physiological stage of apples at the time of harvest are presented in Table 1. According to the recommendations, 'Gala' apples intended for long-term storage should have a starch test value of 4–6 [39,40] and a Streif Index value in the range from 0.20 to 0.14 [37]. Based on the analysis of the results, it can be assumed that the apples picked at the first harvest date had the optimal maturity for long-term storage. Apples harvested 2 weeks later were characterized by much more advanced maturity, and those treated with Harvista's™ had ethylene at a concentration below 0.5 (μL/L) in their cores.

Table 1. Gala Schniga® SchniCo Red(s) apples maturity at optimal harvest date and at delayed harvest date.

Maturity Indices	Optimal Harvest Date		Delayed Harvest	
	Control	Harvista™	Control	Harvista™
	Mean ± SD			
Internal ethylene content (μL/L)	1.18 ± 0.17	0.48 ± 0.19	1.23 ± 0.64	0.42 ± 0.12
Starch index (-)	3.3 ± 0.3	4.1 ± 1.0 [1]	9.0 ± 0.4	6.8 ± 1.2
Soluble solids content (°Bx)	11.8 ± 0.2	10.8 ± 0.2	13.1 ± 0.3	11.5 ± 0.4
Firmness (N)	85.1 ± 1.8	85.3 ± 1.0	70.6 ± 3.7	75.9 ± 2.2
Titratable acidity (%)	0.409 ± 0.029	0.375 ± 0.032	0.333 ± 0.018	0.350 ± 0.015
Streif Index (IS) (-)	0.22 ± 0.02	0.20 ± 0.04	0.06 ± 0.01	0.10 ± 0.02
L*	44.3 ± 1.2	43.2 ± 0.2	45.5 ± 1.3	44.8 ± 1.2
a*	23.1 ± 1.1	21.5 ± 1.3	23.8 ± 1.7	25.0 ± 2.0
b*	9.98 ± 1.2	10.5 ± 1.1	11.4 ± 1.7	12.2 ± 1.3

L*, a*, and b*—correct name of fruit color space values [1] no normal distribution (verified using Shapiro–Wilk test: $p \leq 0.05$). ™—trademark.

3.1. Ethylene Production

The ethylene production rate after 5 months of storage is shown in Figure 1. Spraying trees with Harvista™ was shown to ensure very low ethylene production, but only in apples picked at OHD, while the ethylene production rate was similarly high in apples from both the control DH and Harvista™ DH samples. On the other hand, apples treated with SmartFresh™ were characterized by very low ethylene production, regardless of whether the trees were previously sprayed with Harvista™ and regardless of the date of harvest.

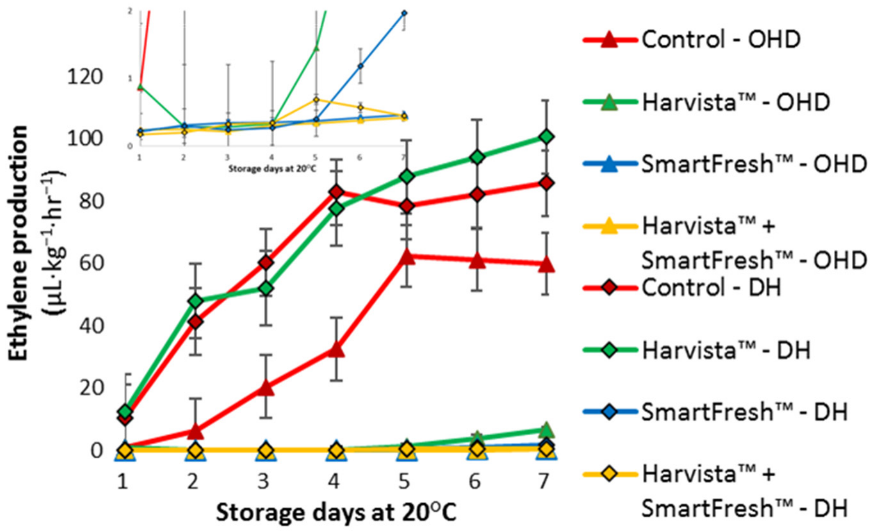

Figure 1. Ethylene production rate by Gala Schniga® SchniCo Red(s) apples after 5 months of storage at 20 °C; OHD—Optimal harvest date; DH—delayed harvest.

In general, similar relations were also recorded after 7 months of storage (Figure 2). The exception was the Harvista™ treated apples, which did not differ in terms of ethylene production intensity regardless of the harvest date. Only in the case of apples not treated with 1-MCP (control samples) did those picked at the later date produce significantly more ethylene than those picked at OHD.

After 9 months of storage, Harvista™ was more effective in counteracting the increase in ethylene production in apples picked at OHD than in those picked later (Figure 3). At the same time, it was found out that apples not treated with 1-MCP (control) and picked at the second harvest date produced more ethylene than control apples harvested at OHD. Interestingly, fruit treated with 1-MCP (SmartFresh™—OHD; SmartFresh™—DH; Harvista™ + SmartFresh™—OHD; Harvista™ + SmartFresh™—DH) after harvest produced very little ethylene, regardless of the harvest date and Harvista™ application.

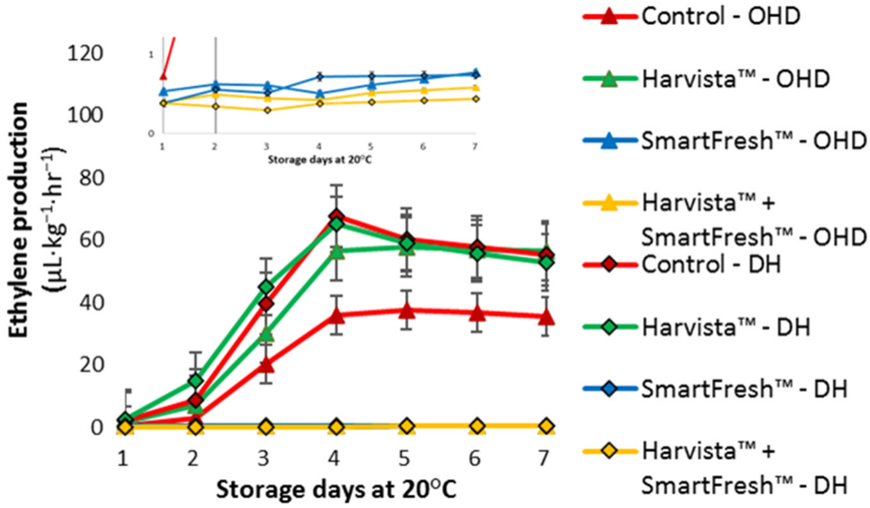

Figure 2. Ethylene production rate by Gala Schniga® SchniCo Red(s) apples after 7 months of storage at 20 °C; OHD—Optimal harvest date; DH—delayed harvest.

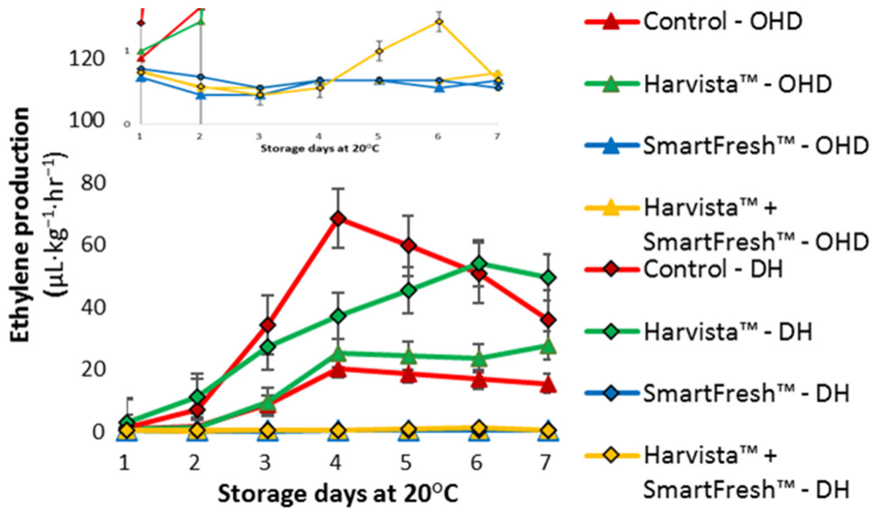

Figure 3. Ethylene production rate by Gala Schniga® SchniCo Red(s) apples after 9 months of storage at 20 °C; OHD—Optimal harvest date; DH—delayed harvest.

3.2. Flesh Firmness

Flesh firmness immediately after storage is illustrated by the data presented in Table 2. At each date of the study, apples harvested at OHD were characterized by greater firmness than those harvested later. Just as with the significant reduction of ethylene production, the use of 1-MCP effectively helped maintain high firmness, notwithstanding the date of harvest and the length of storage ($p < 0.05$). An exception was observed only in the fruit from the delayed harvest: the firmness of the Harvista™-treated apples was similar to the firmness of the control apples after 5 and 9 months of storage. At the same time, the post-harvest treatment with SmartFresh™ always resulted in apples having firmer flesh than the control ones, regardless of the date of harvest and the length of storage.

Table 2. Flesh firmness (N) of 'Gala Schniga® SchniCo Red(s)' apples directly after storage as affected by 1-MCP treatment with respect to harvest date in separate storage length.

Harvest Date	Control	Harvista™	SmartFresh™	Harvista™ + SmartFresh™	*p*-Value **
			After 5 Months of Storage		
Harvest I (OHD)	63.7 ± 2.5 [a]	78.4 ± 5.9 [b]	78.7 ± 1.4 [b]	85.1 ± 1.5 [c]	<0.0001
Harvest II (DH)	53.2 ± 2.2 [a]	53.7 ± 0.3 [a]	63.0 ± 4.0 [b]	68.8 ± 6.2 [b]	0.0002
p-value ***	0.0210	<0.0001	0.0048	0.0458	
			After 7 Months of Storage		
Harvest I (OHD)	58.5 ± 1.1 [a]	69.9 ± 1.0 [b]	74.4 ± 4.7 [bc]	78.6 ± 5.6 [c]	0.0010
Harvest II (DH)	50.8 ± 4.5 [a]	59.1 ± 0.8 [b]	63.5 ± 4.5 [b]	65.1 ± 5.1 [b]	0.0008
p-value **	0.1437	0.0002	0.1491	0.1470	
			After 9 Months of Storage		
Harvest I (OHD)	57.1 ± 1.1 [a]	71.8 ± 4.0 [b]	76.4 ± 2.2 [c]	79.6 ± 0.9 [c]	<0.0001
Harvest II (DH)	49.9 ± 1.2 [a]	52.7 ± 0.5 [a]	65.7 ± 3.1 [b]	67.7 ± 6.1 [b]	<0.0001
p-value **	0.0045	0.0028	0.0052	0.0091	

** Kruskal–Wallis one-way ANOVA of ranks accompanied by the post hoc test; normal distribution (normality was checked using the Shapiro–Wilk test—$p \leq 0.05$); *** Newman–Keuls test; small letters in a line are used to compare the effect of 1-MCP application; OHD—optimal harvest date; DH—delayed harvest; ™—trademark.

The firmness of the fruit after the 7-day shelf-life period is presented in Table 3. In most samples, the firmness value depended significantly on the date of harvest ($p < 0.05$). Among the apples harvested at OHD, only the control sample after 7 and 9 months of storage had a firmness value below the optimal consumption maturity (<55 N). Interestingly, apples harvested at OHD from Harvista™-sprayed trees maintained firmness above 55 N even after 9 months of storage. On the other hand, among the fruit harvested at the delayed harvest date, only the fruit treated with SmartFresh™ after harvest had firmness above 55 N after the shelf-life period, regardless of the treatment with Harvista™ and the length of the storage. In the case of the apples picked after OHD, spraying trees with Harvista™ proved to be insufficiently effective when it comes to ensuring appropriate firmness after up to 5 months of storage. By contract, the high firmness values achieved for apples treated with SmartFresh™ both alone and in combination with Harvista™ suggest that these treatment options extend the shelf-life period by a few days.

3.3. Titratable Acidity (TA)

Table 4 presents TA values immediately after storage, taking into account the influence of 1-MCP application and the harvest date in the individual storage period. The effect of 1-MCP treatment on TA was usually significant ($p < 0.05$), with the exception of the fruit harvested at OHD and stored for 7 months ($p = 0.2055$). It should be noted, however, that the TA of the Harvista™-treated apples was generally similar to that of the control apples. On the other hand, the Harvista™ + SmartFresh™-treated apples showed higher TA values than the control apples. This relationship was statistically insignificant only after 7 months of storage of the apples picked at OHD. In turn, no clear influence of the harvest date on the TA of apples could be shown—it was significant ($p < 0.05$) only in 5 out of 12 cases.

The experiment also revealed a significant effect of 1-MCP treatment on the TA of apples after 7-day shelf-life period ($p < 0.05$), with the TA value showing some variability depending on the harvest date and storage length (Table 5). Nevertheless, regardless of the harvest date and the length of storage, Harvista™ + SmartFresh™-treated apples were always more acidic than the control apples. After 5 and 9 months of storage, the apples treated with SmartFresh™ alone were also more acidic than the control apples, regardless of the harvest date. However, the harvest date had a significant impact on the TA value after the shelf-life period of mainly the Harvista™-treated fruit. In this case, the TA of the apples harvested at OHD was greater than that of the apples harvested later, but this was only true for the apples stored for 5 and 7 months, while the opposite relationship was noted after 9 months of storage.

Table 3. Flesh firmness (N) of 'Gala Schniga® SchniCo Red(s)' apples directly after 7 days of shelf-life storage as affected by 1-MCP treatment with respect to harvest date in separate storage length.

Harvest Date	Control	Harvista™	SmartFresh™	Harvista™ + SmartFresh™	*p*-Value **
			After 5 Months of Storage		
Harvest I (OHD)	55.8 ± 1.7 [a]	76.0 ± 6.0 [b]	78.8 ± 1.0 [b]	79.3 ± 2.6 [c]	0.0340
Harvest II (DH)	46.5 ± 3.1 [a]	46.8 ± 3.1 [a]	62.6 ± 5.2 [b]	66.7 ± 4.6 [b]	0.0079
p-value ***	0.0304	0.0304	0.0304	0.0304	
			After 7 Months of Storage		
Harvest I (OHD)	52.5 ± 2.3 [a]	70.3 ± 5.2 [b]	75.9 ± 2.4 [b]	81.3 ± 3.2 [c]	0.0051
Harvest II (DH)	46.4 ± 4.8 [a]	50.1 ± 2.5 [b]	67.6 ± 4.0 [d]	60.7 ± 7.7 [c]	0.0103
p-value ***	0.1124	0.0304	0.0304	0.0304	
			After 9 Months of Storage		
Harvest I (OHD)	52.3 ± 1.4 [a]	68.6 ± 7.4 [b]	73.8 ± 3.2 [b]	78.5 ± 3.0 [c]	0.0084
Harvest II (DH)	44.5 ± 0.4 [a]	48.0 ± 2.5 [a]	64.0 ± 2.3 [b]	66.5 ± 5.4 [b]	0.0053
p-value ***	0.0304	0.0304	0.0294	0.0304	

** Kruskal–Wallis one-way ANOVA of ranks accompanied by the post hoc test; *** Mann–Whitney U test; small letters in a line are used to compare the effect of 1-MCP application; OHD—optimal harvest date; DH—delayed harvest; ™—trademark.

Table 4. Titratable acidity (TA) [%] of 'Gala Schniga® SchniCo Red(s)' apples directly after storage as affected by 1-MCP treatment with respect to harvest date in separate storage length.

Harvest Date	Control	Harvista™	SmartFresh™	Harvista™ + SmartFresh™	*p*-Value ***
			After 5 Months of Storage		
Harvest I (OHD)	0.320 ± 0.008 [a]	0.334 ± 0.012 [a]	0.354 ± 0.011 [b]	0.358 ± 0.016 [b]	0.0025
Harvest II (DH)	0.308 ± 0.015 [a]	0.299 ± 0.038 [a]	0.307 ± 0.020 [a]	0.368 ± 0.011 [b]	0.0046
p-value **	0.2046	0.1378	0.0059	0.3480	
			After 7 Months of Storage		
Harvest I (OHD)	0.305 ± 0.010 [a]	0.331 ± 0.027 [a]	0.322 ± 0.022 [a]	0.334 ± 0.018 [a]	0.2055
Harvest II (DH)	0.280 ± 0.017 [a]	0.272 ± 0.011 [a]	0.317 ± 0.017 [b]	0.340 ± 0.025 [b]	0.0006
p-value **	0.0493	0.0061	0.7215	0.7255	
			After 9 Months of Storage		
Harvest I (OHD)	0.211 ± 0.013 [a]	0.250 ± 0.017 [b]	0.284 ± 0.011 [c]	0.245 ± 0.017 [b]	0.0002
Harvest II (DH)	0.239 ± 0.003 [a]	0.263 ± 0.034 [ab]	0.268 ± 0.012 [ab]	0.297 ± 0.022 [b]	0.0178
p-value **	0.0057	0.5402	0.1134	0.0085	

** Mann–Whitney U test; normal distribution (normality was checked using the Shapiro–Wilk test—$p \leq 0.05$); *** Newman–Keuls test; small letters in a line are used to compare the effect of 1-MCP application; OHD—optimal harvest date; DH—delayed harvest; ™—trademark.

3.4. Soluble Solids Content (SSC)

The SSC of apples immediately after storage is shown in Table 6. It should be emphasized that in 9 out of 12 cases, there was no significant impact of the harvest date on the SSC value ($p > 0.05$), regardless of 1-MCP application and storage length. However, in the other three cases, the delay in the harvest date resulted in an SSC reduction either after 5 months (SmartFresh™-treated apples) or after 9 months of storage (Harvista™ and Harvista™ +

SmartFresh™-treated apples). 1-MCP treatment had a significant impact on the SSC of the fruit harvested at OHD and stored for 5 months, and on the SSC of the fruit harvested later and stored for 7 and 9 months. For these latter apple samples, treatment with SmartFresh™ alone as well as in combination with Harvista™ resulted in a higher soluble solids content than that observed after treatment only with Harvista™.

Table 5. Titratable acidity (TA) [%] of 'Gala Schniga® SchniCo Red(s)' apples after 7-day shelf-life period as affected by 1-MCP treatment with respect to harvest date in separate storage length.

Harvest Date	Control	Harvista™	SmartFresh™	Harvista™ + SmartFresh™	*p*-Value **
			After 5 Months of Storage		
Harvest I (OHD)	0.269 ± 0.022 [a]	0.320 ± 0.010 [b]	0.315 ± 0.019 [b]	0.329 ± 0.019 [b]	0.0388
Harvest II (DH)	0.262 ± 0.006 [b]	0.247 ± 0.009 [a]	0.288 ± 0.003 [c]	0.344 ± 0.009 [d]	0.0029
p-value ***	0.4705	0.0294	0.1080	0.2454	
			After 7 Months of Storage		
Harvest I (OHD)	0.275 ± 0.019 [a]	0.303 ± 0.021 [b]	0.274 ± 0.016 [a]	0.333 ± 0.037 [b]	0.0489
Harvest II (DH)	0.251 ± 0.017 [a]	0.249 ± 0.011 [a]	0.259 ± 0.020 [a]	0.322 ± 0.016 [b]	0.0358
p-value ***	0.1939	0.0294	0.3094	0.6631	
			After 9 Months of Storage		
Harvest I (OHD)	0.206 ± 0.012 [a]	0.226 ± 0.008 [b]	0.267 ± 0.024 [c]	0.236 ± 0.018 [b]	0.0135
Harvest II (DH)	0.193 ± 0.019 [a]	0.264 ± 0.019 [b]	0.262 ± 0.011 [b]	0.283 ± 0.013 [b]	0.0124
p-value ***	0.3123	0.0304	1.0000	0.0304	

** Kruskal–Wallis one-way ANOVA of ranks accompanied by the post hoc test; *** Mann–Whitney U test; small letters in a line are used to compare the effect of 1-MCP application; OHD—optimal harvest date; DH—delayed harvest; ™—trademark.

Table 6. Soluble solids content (SSC) (°Bx) of 'Gala Schniga® SchniCo Red(s)' apples directly after storage as affected by 1-MCP treatment with respect to harvest date in separate storage length.

Harvest Date	Control	Harvista™	SmartFresh™	Harvista™ + SmartFresh™	*p*-Value ***
			After 5 Months of Storage		
Harvest I (OHD)	12.7 ± 0.2 [a]	12.2 ± 0.6 [a]	13.6 ± 0.2 [b]	12.3 ± 0.7 [a]	0.0048
Harvest II (DH)	12.3 ± 0.7 [a]	12.5 ± 0.2 [a]	12.9 ± 0.4 [a]	12.3 ± 0.7 [a]	0.3588
p-value ***	0.3202	0.2731	0.0213	0.9610	
			After 7 Months of Storage		
Harvest I (OHD)	13.4 ± 0.7 [a]	12.5 ± 0.2 [a]	12.9 ± 0.5 [a]	13.3 ± 0.5 [a]	0.0962
Harvest II (DH)	12.6 ± 0.4 [ab]	11.9 ± 0.7 [a]	13.2 ± 0.4 [b]	13.5 ± 0.8 [b]	0.0126
p-value ***	0.0934	0.1345	0.4755	0.7290	
			After 9 Months of Storage		
Harvest I (OHD)	13.1 ± 0.3 [a]	12.7 ± 0.3 [a]	13.2 ± 0.9 [a]	13.4 ± 0.6 [a]	0.5078
Harvest II (DH)	13.0 ± 0.2 [b]	11.1 ± 0.7 [a]	13.9 ± 0.7 [c]	12.4 ± 0.4 [b]	<0.0001
p-value ***	0.5127	0.0046	0.2148	0.0434	

*** Newman–Keuls post hoc test; small letters in a line are used to compare the effect of 1-MCP application; OHD—optimal harvest date; DH—delayed harvest; ™—trademark.

After additional storage of apples for 7 days at a temperature of 20 °C, relationships similar to those noted immediately after storage (Table 7) were observed. The harvest date affected significantly the SSC of apples ($p < 0.05$) only in four cases. Fruit harvested at OHD had a higher SSC than the fruit from the delayed harvest. At the same time, as was the case immediately after storage, the 1-MCP application had a significant impact only on the SSC of the apples harvested after OHD and after 7 and 9 months of storage. Usually, the highest SSC was observed in apples treated with SmartFresh™ (both alone and in combination with Harvista™). Significantly lower soluble solids content was observed in the control apples, and the lowest, in the Harvista™-treated apples.

Table 7. Soluble solids content (TSS) (°Bx) of 'Gala Schniga® SchniCo Red(s)' apples after 7-day shelf-life period as affected by 1-MCP treatment with respect to harvest date in separate storage length.

Harvest Date	Control	Harvista™	SmartFresh™	Harvista™ + SmartFresh™	*p*-Value **
			After 5 Months of Storage		
Harvest I (OHD)	13.1 ± 0.9 [a]	12.3 ± 0.4 [a]	13.2 ± 0.2 [a]	13.0 ± 0.4 [a]	0.1538
Harvest II (DH)	12.6 ± 0.7 [a]	12.0 ± 0.3 [a]	12.9 ± 0.3 [a]	12.4 ± 0.4 [a]	0.1000
p-value ***	0.3094	0.2425	0.1489	0.0384	
			After 7 Months of Storage		
Harvest I (OHD)	13.5 ± 0.4 [a]	12.2 ± 0.4 [a]	13.1 ± 0.5 [a]	13.1 ± 0.8 [a]	0.0867
Harvest II (DH)	12.4 ± 0.2 [b]	11.8 ± 0.7 [a]	13.1 ± 0.4 [c]	13.1 ± 0.8 [c]	0.0238
p-value ***	0.0209	0.3836	0.6631	0.8845	
			After 9 Months of Storage		
Harvest I (OHD)	13.2 ± 0.4 [a]	13.1 ± 0.4 [a]	13.4 ± 0.6 [a]	13.5 ± 0.5 [a]	0.6658
Harvest II (DH)	12.4 ± 0.3 [b]	11.3 ± 0.4 [a]	14.1 ± 0.3 [c]	12.3 ± 0.3 [b]	0.0047
p-value ***	0.0202	0.0202	0.0575	0.0209	

** Kruskal–Wallis one-way ANOVA of ranks accompanied by the post hoc test; *** Mann–Whitney U test; small letters in a line are used to compare the effect of 1-MCP application; OHD—Optimal harvest date; DH—delayed harvest; ™—trademark.

4. Discussion

This paper assessed the impact of pre- and post-harvest use of 1-MCP on the quality of 'Gala Schniga® SchniCo Red(s)' apples picked at two harvest dates and stored for 9 months under conditions similar to a dynamically controlled atmosphere (DCA). The study showed a significant impact of 1-MCP application and harvest date on such quality features of apples as: ethylene production rate, flesh firmness, SSC, and TA after 5, 7, and, 9 months of storage. Apple is a climacteric fruit species, so its ripening process is controlled by ethylene. After harvesting, apples undergo aging processes that lead to a deterioration of their quality [41]. In order to slow down this process, measures are taken to reduce ethylene production. They include, among other things, using 1-MCP and storing apples in low-oxygen atmospheres. However, some studies mention the negative impact of both of these methods on the production of aromatic compounds in fruit, which may negatively affect the assessment of its quality by consumers [42,43].

In this paper, it was shown that apples treated with 1-MCP before and/or after harvest had firmer flesh after storage than 1-MCP non-treated apples. This is important because firmness is one of the most important properties affecting the consumers' perception of fruit quality [1]. When choosing a firm cultivar, consumers expect apples with flesh firmness above 55 N [5,44], which is characteristic of, e.g., 'Gala Schniga® SchniCo Red(s)' apples. The study has shown that the use of Harvista™ in the orchard before harvest enabled maintaining the firmness of apples at a level acceptable to the consumer (>55 N) after the shelf-life period following even 9 months of storage, provided that the fruit was harvested at OHD. However, if picked at the delayed harvest date (DH) from trees sprayed with Harvista™, the apples were much less firm than expected already after 5 months of storage. Apples picked at the delayed harvest date had to be treated with 1-MCP (either alone or in combination with Harvista™) after harvest to ensure the flesh firmness above 55 N also after 9 months of storage and an additional 7-day shelf-life period at 20 °C. Based on the data provided in Table 3, it can be assumed that the effectiveness of the 1-MCP application is closely related to the date of harvest. This can be suppressed by the fact that fruits remaining attached to the tree may be capable of creating new ethylene receptors uninhibited by previous 1-MCP treatments, that would restore ethylene response. Such a thesis seems to be likely, especially since the effect of field-applied 1-MCP to reduce the rate of fruit softening during storage is more effective when applied closer to the harvest date [45,46]. McArtney et al. [47] suggest that ethylene receptor formation in ripening fruit is influenced by the cultivar. Therefore, preharvest spraying with 1-MCP may be less useful as a harvest management tool for varieties that rapidly form new ethylene receptors as the fruit ripens. The data from another paper [36] show that the use of 1-MCP in an orchard of the apple cultivar 'Red Jonaprince' was sufficient to maintain fruit firmness at a level acceptable to the consumer, even after 6 months of storage under ULO conditions if the apples were harvested at the optimal time. These data also prove that the effectiveness of both the pre- and post-harvest use of 1-MCP is largely related to the cultivar, and probably also to the atmospheric conditions prevailing in a given location, which is emphasized by many researchers [21,36,48].

Increased ethylene production contributes to a faster decline in apple firmness [27], while 1-MCP by limiting ethylene biosynthesis slows down this process [7,49]. This was confirmed in this paper because apples treated with 1-MCP after harvest were characterized by low ethylene production and high firmness for 7 days at 20 °C, even after 9 months of storage under DCA conditions. These data also confirm other finding according to which ethylene plays an important role in the ripening and aging process of apples [50]. The activity of 1-MCP allows its use both in the orchard [20,21] and after harvest [38]. The composition of the atmosphere in which fruit is stored can be an important factor in enhancing the effect of 1-MCP, since Bekele et al. [51] reported low ethylene production by 'Jonagold' apples treated with 1-MCP, which were stored under CA conditions. Other studies emphasize the high effectiveness of 1-MCP in preventing the increase in ethylene production in apples both stored under DCA conditions [52] and when placed at room temperature [53]. A similar relationship was noted in this paper, especially in the case of apples treated with 1-MCP 7 days after harvest, regardless of the harvest date.

Despite 1-MCP's effective inhibition of the rate of ethylene production, the stored fruit continues to ripen. This is evidenced by changes such as the decrease in TA and the increase in SSC during storage [54–56]. In this paper, a similar pattern occurred in the case of TA. The presented study also found out that the apples treated with 1-MCP had higher TA than the fruit from the control sample, which was particularly noticeable after a total of 9 months of storage and 7 days of shelf life. The possible explanation is that apples treated with 1-MCP produced less ethylene, and therefore matured more slowly and breathed less intensively, which led to a slower consumption of organic acids as a substrate in the respiration process. According to Steffens et al. [57], the higher TA content can be explained by a lower respiration rate and ethylene production, which physiologically characterize the lower metabolic activity of apples treated with 1-MCP. The influence of 1-MCP can be attributed to the lower respiratory activity of 1-MCP-treated fruit. Some studies indicate that the post-harvest treatment of apples with 1-MCP had a negligible effect on SSC [23,58]. This study has shown that the SSC level in apples is only slightly dependent on 1-MCP application before harvest.

Just like higher firmness, higher TA and SSC values noted after using 1-MCP can contribute to better acceptance of fruit by consumers. It should be stressed that consumers often perceive higher content of TA and SSC as increased content of nutrients [59].

Although the study provides information that can facilitate the effective storage of 'Gala Schniga® SchniCo Red(s)' apples while maintaining sufficient firmness after storage, it is worth pointing out the possibilities of expanding the research in this area. First of all, it would be worth identifying the quality changes in apples first stored for different periods and then exported to distant markets, e.g., by sea, which can take from 6 to 8 weeks. Secondly, the analyses could be extended to include the respiration rate of apple which, together with the rate of ethylene production, is a decisive factor in the rate of loss of firmness of the stored fruit.

5. Conclusions

To sum up, the SmartFresh™ post-harvest treatment of apples of the 'Gala Schniga® SchniCo Red(s)' cultivar, including apples harvested 2 weeks after the optimal harvest date, helps to maintain ethylene production at a very low level, even after 9 months of storage under DCA conditions. Interestingly, a very slow rate of firmness loss during this time is ensured by spraying trees with Harvista™ before harvest, provided that apples are harvested at the optimal time. Sufficient firmness is more difficult to maintain after storage if there is a delay in the harvest date. In such a case, appropriate firmness of long-stored apples can only be ensured by the post-harvest use of 1-MCP.

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