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Assessment of the Quality of 'Red Jonaprince' Apples during Storage after Delayed Harvesting and 1-Methylcyclopropene (1-MCP) Preharvest and Postharvest Treatment

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Abstract: Changing the harvesting time of apples from the optimum harvest window to delayed harvesting may be applied if it is impossible to harvest apples at the optimal time, but it requires changing other factors, as they influence the quality of fruits and shelf life. The aim of the study was to assess the quality of 'Red Jonaprince' apples during storage after delayed harvesting and 1-methylcyclopropene (1-MCP) preharvest and postharvest treatment for various storage times. Apples were studied within four groups subjected to preharvest and postharvest treatments, as follows: Group 0—no 1-MCP treatment; Group 1—1-MCP preharvest treatment; Group 2—1-MCP postharvest treatment; and Group 3—1-MCP preharvest and postharvest treatment. All apples were subjected to ultra-low oxygen (ULO) storage conducted for 3, 5 or 6 months, while the analyses were conducted directly after ULO storage (simulated shelf life—0 days) and after simulated shelf life (7 days). For firmness, in the case of 1-MCP applied only preharvest (Group 1) and only postharvest (Group 2), before shelf life, the longer ULO storage resulted in obtaining lower values of firmness ($p < 0.0001$). If 1-MCP was not applied postharvest (Group 0 and Group 1), and short ULO storage was applied (3 and 5 months for Group 0; 3 months for Group 1), after shelf-life lower values of firmness were observed ($p < 0.0001$). For soluble solids content (SSC), in the case of 1-MCP not applied preharvest (Group 0 and Group 2), before shelf life, and for 1-MCP applied postharvest (Group 2) after shelf life, the longer ULO storage resulted in obtaining lower values of SCC ($p < 0.0001$). For titratable acidity (TA), in the case of all the studied groups after shelf life, as well as in case of 1-MCP applied only preharvest (Group 1) also before shelf life, the longer ULO storage resulted in obtaining lower values of TA ($p < 0.0001$). Except for the 1-MCP applied only postharvest (Group 2), in the case of short ULO storage applied (3 and 5 months for Group 0; 5 months for Group 1; 5 months for Group 3), after shelf-life lower values of TA were observed ($p < 0.0001$). If delayed harvesting must be conducted, applying 1-MCP not only postharvest, but also preharvest, allows obtaining the most stable firmness and SSC, which do not decrease during storage and shelf life. Taking this into account, it may be concluded, that in the case of delayed harvesting, combining 1-MCP applied preharvest and postharvest should be recommended to keep the quality parameters stable during storage and shelf life.

Keywords: apple; 1-methylcyclopropene; 1-MCP; delayed harvesting; storage; firmness; soluble solids; titratable acidity

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1. Introduction

Apple production in Poland is constantly increasing, and in 2022, among the European Union countries, the production per member state was the highest in Poland, while the increase in the production in 2022 compared with 2019–2021 was the highest in Poland as well [1]. The increasing production results in the need for the proper storage of apples, with appropriate temperature, humidity, atmosphere, and the other conditions [2].

The proper storage of apples, which allows maintaining the quality of fruits and extended shelf life, may be challenging, as it should be conducted at the lowest acceptable temperature, in order to reduce the risk of senescence and fungal decay (resulting from too high temperature), and at the same time—to reduce the risk of freezing and chilling-induced disorders (resulting from too low temperature) [3]. The impact of storage must also be taken into account while applying delayed harvesting, which results in shortening of the storage period, but it may also reduce the quality of fruits [4]. Once apples are harvested, some metabolic changes begin, but is should be noted that delayed harvesting means that fruit remains on the tree longer, which could contribute to increased size and mass of the fruits, and other related consequences [5]. For example, in the case of 'Golden Delicious' apples, after delayed harvesting, reduced firmness is observed as well [6]. However, the delayed harvesting must sometimes be applied if there is no possibility to apply harvesting in the optimum harvest window, e.g., due to weather conditions, availability of seasonal workers, or storage capacity [7].

Taking this into account, determination of the optimum harvest window and deciding on harvesting time is crucial for planning the further postharvest treatment and to maintain the quality of fruits [8]. The adequate postharvest treatments that may be applied for apples include: edible coating, antimicrobial and anti-browning agents, nitric oxide, sulfur dioxide, ozone, 1-methylcyclopropene (1-MCP), and controlled atmosphere storage, while the listed elements may be applied alone or combined [9].

However, it should be emphasized that not only postharvest treatment, but also preharvest treatment matters, while the methods applied within preharvest treatment are sometimes similar as for postharvest treatment. Such a situation is observed in the case of 1-MCP treatment, which is commonly applied within postharvest treatment of apples [10], but recently its application within preharvest treatment of apples was also tested [11], as well as the possibility of combined application within preharvest and postharvest treatment was verified [12].

The application of 1-MCP is intended as the factor extending shelf life, due to the fact that it is responsible for ripening inhibition, obtained by its binding to ethylene receptors, while as a consequence the created complex may reduce activity of enzymes involved in ethylene production [9]. At the same time, 1-MCP also inhibits the activity of pectin methylesterase and polygalacturonase, influencing the integrity of the cell wall, which as a result similarly causes sustaining of the firmness of fruit [10].

Based on the described state of knowledge, it may be indicated that changing the harvesting time from the optimum harvest window to delayed harvesting, requires also changing other preharvest and postharvest factors, including applied 1-MCP treatment, but also storage time, as they influence the quality of fruits and the shelf life. Taking this into account, the aim of the study was to assess the quality of 'Red Jonaprince' apples during storage after delayed harvesting and 1-MCP preharvest and postharvest treatment for various storage times.

2. Materials and Methods

2.1. Experimental Design

The experiment was conducted in the experimental orchard of the Warsaw University of Life Sciences (SGGW-WULS) (Warsaw—52°14′ N, 21°1′ E) within the 'Red Jonaprince' cultivar orchard, planted in 2013 (trees planted 3.2 m by 1.0 m [13]). The experiment included 2 parts, planned for harvesting conducted in 22 September 2020 (optimum harvest window) [14], and in 6 October 2020 (delayed harvesting).

In order to confirm maturity and establish the optimum harvest window, the following parameters were controlled: mass of fruits (with a target mass of 200–220 g), color (with a target of dark red color), as well as Streif index [15] and starch index [8]. Within the experiment conducted for delayed harvesting, 24 boxes of apples, with a capacity of 10 kg each, were studied (each constituting 4 batches, 10 apples each—40 apples per box studied), within 4 groups and 2 variants (in total 960 apples studied within the experiment), subjected additionally to various periods of storage (3 months, 5 months, and 6 months).

Apples harvested within the delayed harvesting window were studied within 4 groups subjected to various preharvest and postharvest treatments, while the treatments were randomly assigned as follows:

- Group 0 (6 boxes), being a control group with 1-MCP treatment applied neither preharvest, nor postharvest;
- Group 1 (6 boxes), being a studied group with 1-MCP treatment applied preharvest (150 g/ha, sprayed in the morning 7 days before the optimum harvest window in 400 L of water-based solution; Harvista, AgroFresh Solutions Inc., Philadelphia, PA, USA);
- Group 2 (6 boxes), being a studied group with 1-MCP treatment applied postharvest (0.65 μL/L, 7 days after harvesting, for 24 h; SmartFresh ProTabs, AgroFresh Solutions Inc., Philadelphia, PA, USA);
- Group 3 (6 boxes), being a studied group with 1-MCP treatment applied both preharvest (150 g/ha, sprayed in the morning 7 days before optimum harvest window in 400 L of water-based solution; Harvista, AgroFresh Solutions Inc., Philadelphia, PA, USA) and postharvest (0.65 μL/L, 7 days after harvesting, for 24 h; SmartFresh ProTabs, AgroFresh Solutions Inc., Philadelphia, PA, USA).

Apples were subjected to ultra-low oxygen (ULO) storage, which was conducted for various periods of time, including 3 months, 5 months, and 6 months, while the analyses were conducted for 2 variants, as follows:

- Variant 1 (3 boxes within each studied group—one for each ULO storage time), being apples not subjected to any shelf life (assessments conducted directly after ULO storage);
- Variant 2 (3 boxes within each studied group—one for each ULO storage time), being apples subjected to a shelf life (assessments conducted after 7 days of simulated shelf life following ULO storage).

Directly after harvesting, apples were cooled for 24 h, to reduce the temperature to 1 °C in this period (all the studied boxes) and after 7 days, they were subjected to 1-MCP treatment applied postharvest (6 boxes within Group 2 and 6 boxes within Group 3).

Afterwards, the ULO storage was conducted in the storage chamber of the Institute of Horticultural Sciences (IHS) of the SGGW-WULS in Warsaw (1.2% CO_2, 1.2% O_2; temperature 1 °C; humidity 95%). After ULO storage, the apples subjected to simulated shelf life (3 boxes within each studied group) were stored for an additional 7 days in shelf-life conditions (20 °C).

The flow chart summarizing experimental design of the study is presented in Figure 1.

2.2. Study Measurements

In order to specify the physiological state of apples during harvest, the following parameters were assessed: starch index and Streif index, while additionally internal ethylene content was assessed, and afterwards the following parameters were studied for each group: firmness, soluble solids content (SSC), and titratable acidity (TA).

The starch index was defined after conducting colorimetric reaction with I_3K being provided within the Lugol's solution, according to a commonly applied method [8]. Apples being cut across the equator were dipped in Lugol's solution for 1 min and afterwards dried. Based on the comparison of the obtained color with the visual Eurofru scale (Ctifl, Bellegarde, France), the result from 1 (totally stained surface) to 10 (surface not stained at all) was attributed, while the assessment was conducted in 4 repetitions of 10 apples each (in total 40 apples).

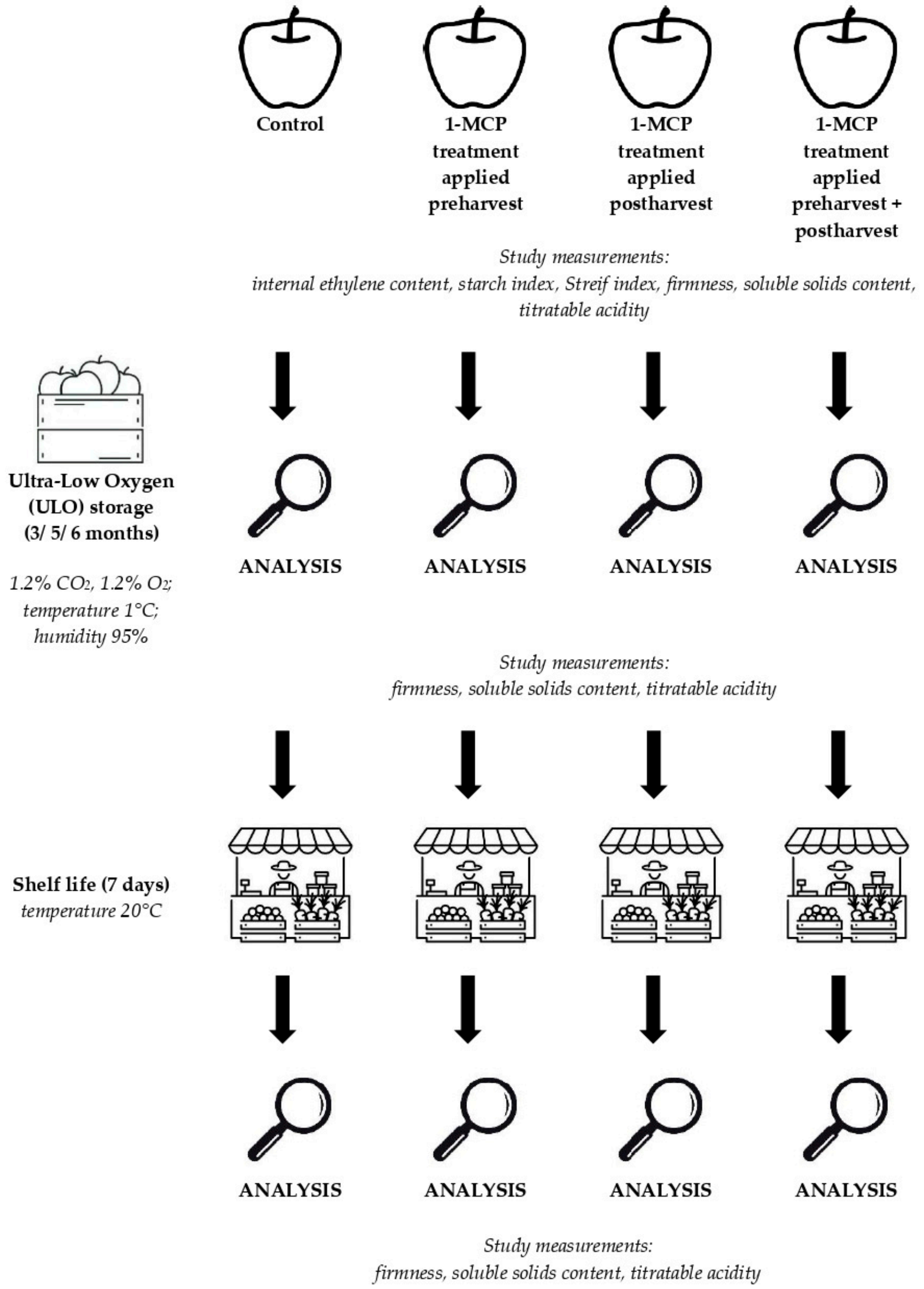

Figure 1. The flow chart summarizing experimental design of the study.

The Streif index (maturity index) was calculated based on the standard equation for firmness, SSC, and starch index, as follows: firmness (in kilograms) divided by SSC (in °Brix) and divided by starch index (dimensionless quantity) [8].

The internal ethylene content (expressed in µL/L) was measured in the core space of apples, using a syringe with a volume of 1 mL to collect the air samples [16]. For each assessed apple, 1 mL of air was withdrawn from the apple's core using a syringe and analyzed while using gas chromatography (HP 5890, Hewlett Packard, Palo Alto, CA, USA). The assessment was conducted in 4 repetitions of 10 apples each (in total 40 apples).

The firmness (expressed in N) was assessed after removing the peel, while using a universal testing machine [8] with 500 N load cell and standard puncture test with a cylindrical probe with a diameter of 11 mm and head speed of 4 mm/s (Instron 5542, Instron, Norwood, MA, USA). The assessment was conducted twice for each apple (opposite sides of apple), in 4 repetitions of 10 apples each (in total 40 apples).

The SSC (expressed in °Brix) was assessed from juice obtained from filtrated pulp while using a digital refractometer [8]. The Atago Palette PR-32 (Atago Co., Ltd., Tokyo, Japan) refractometer was used and the assessment was conducted 5 times for each sample, in 4 repetitions of 10 apples each (in total 40 apples).

The TA (expressed in % recalculated for malic acid content) was assessed from juice obtained from filtrated pulp using an automatic titrator (TitroLine 5000, Xylem Analytics Germany GmbH, Weilheim, Germany). Pulp (40 g) was mixed with 100 mL of deionized water, heated to boiling point, cooled to room temperature, and afterwards deionized water was added to 250 mL. The obtained sample was filtrated and the extract (50 mL) was titrated with NaOH solution (0.1 M) to a pH value of 8.1. The assessment was conducted 3 times for each sample, in 4 repetitions of 10 apples each (in total 40 apples).

2.3. Statistical Analysis

The data distribution was verified using the Shapiro–Wilk test and turned out to present non-parametric distribution for the majority of parameters. The nonparametric Mann–Whitney *U* test was used when comparing 2 groups and the nonparametric Kruskal–Wallis one-way ANOVA of ranks was used when comparing more than 2 groups.

A value of $p \leq 0.05$ was considered statistically significant. The statistical analysis was conducted using Statistica, 13.3 (Statsoft Inc., Tulsa, OK, USA).

3. Results

The general characteristics of the studied 'Red Jonaprince' apples directly after harvesting, depending on the preharvest 1-MCP treatment (with no 1-MCP postharvest treatment applied, before storage and with no simulated shelf life), are presented in Table 1. No differences between apples subjected and not subjected to 1-MCP treatment were observed.

Table 1. The general characteristics of 'Red Jonaprince' apples directly after harvesting, depending on the preharvest 1-MCP treatment.

Characteristic	No 1-MCP Preharvest Treatment		1-MCP Preharvest Treatment		*p*
	Mean (SD)	Median (IQR)	Mean (SD)	Median (IQR)	
Internal ethylene content (μL/L)	2.1815 (4.933)	0.3380 * (0.690)	0.6292 (0.5323)	0.427 * (0.320)	0.9016
Starch index (-)	9.75 (0.44)	10.0 * (0.5)	9.7 (0.5)	10 * (1.0)	0.4154
Streif index (-)	0.0474 (0.0008)	0.0478 * (0.001)	0.0501 (0.0008)	0.0501 (0.0013)	0.3521
Firmness (N)	62.98 (1.73)	63.69 * (2.16)	64.43 (1.89)	64.84 (2.35)	0.1489
Soluble solids content (°Bx)	13.62 (0.20)	13.6 (0.25)	13.33 (0.29)	13.45 * (0.35)	0.1124
Titratable acidity (% of malic acid)	0.6105 (0.0221)	0.6067 * (0.0271)	0.6374 (0.0487)	0.6338 (0.0603)	0.5637

* non-parametric distribution (normality was checked using the Shapiro–Wilk test—$p \leq 0.05$); IQR—interquartile range.

The firmness of 'Red Jonaprince' apples, depending on the applied preharvest and postharvest treatment, storage period, and simulated shelf-life period, is presented in Table 2. It was observed, that in the case of 1-MCP only applied preharvest (Group 1) and only postharvest (Group 2), before shelf life (Variant 1), the longer ULO storage resulted in obtaining statistically significantly lower values of firmness ($p = 0.0010$ and $p = 0.0012$, respectively). At the same time, if 1-MCP was not applied postharvest (Group 0 and Group 1), and short ULO storage was applied (3 and 5 months for Group 0; 3 months for Group 1), after shelf life, statistically significantly lower values of firmness were observed ($p = 0.0209$, $p = 0.0049$, and $p = 0.0209$, respectively).

Table 2. The firmness [N] of 'Red Jonaprince' apples, depending on the applied preharvest and postharvest treatment, storage period, and simulated shelf-life period.

Treatment Group			Ultra-Low Oxygen Storage Time			p **
			3 Months	5 Months	6 Months	
Group 0	Variant 1	Mean ± SD	55.33 ± 3.49	50.83 ± 1.76	45.38 ± 3.11	0.0604
		Median (IQR)	55.4 * (6.04)	51.15 (2.65)	46.55 (3.85)	
	Variant 2	Mean ± SD	45.85 ± 3.07	46.28 ± 1.1	43.23 ± 2.24	0.8021
		Median (IQR)	45.94 (4.44)	46.35 (1.65)	43.55 (3.35)	
		p ***	0.0209	0.0046	0.3050	
Group 1	Variant 1	Mean ± SD	52.78 ± 2.5 [a]	43.99 ± 1.51 [b]	46.78 ± 3.08 [b]	0.0010
		Median (IQR)	52.34 (4.15)	43.5 (2.08)	46.85 (4.45)	
	Variant 2	Mean ± SD	43.29 ± 1.93	41.91 ± 2.32	44.13 ± 2.83	0.3679
		Median (IQR)	44.1 * (2.38)	42.27 (3.69)	44.6 (4.65)	
		p ***	0.0209	0.1835	0.2526	
Group 2	Variant 1	Mean ± SD	64.51 ± 1.86 [a]	58.53 ± 0.89 [b]	58 ± 2.58 [b]	0.0012
		Median (IQR)	64.38 (2.41)	58.4 (1.45)	58.4 (4.3)	
	Variant 2	Mean ± SD	62.1 ± 1.45	59.43 ± 2.09	58.2 ± 2.34	0.0775
		Median (IQR)	62.74 * (1.55)	59.15 (3.45)	58.05 (3.1)	
		p ***	0.14891	0.4582	0.9123	
Group 3	Variant 1	Mean ± SD	57.9 ± 3.81	60.68 ± 1.35	59.45 ± 3.23	0.2185
		Median (IQR)	57.7 (5.3)	61.05 (1.95)	58.65 (4.3)	
	Variant 2	Mean ± SD	60.65 ± 4.66	60.48 ± 2.94	57.58 ± 2.11	0.4347
		Median (IQR)	59.5 (7.26)	61.75 * (3.45)	56.95 (2.75)	
		p ***	0.3957	0.5637	0.3684	

Group 0—no 1-MCP treatment; Group 1—1-MCP preharvest treatment; Group 2—1-MCP postharvest treatment; Group 3—1-MCP preharvest and postharvest treatment; Variant 1—assessments directly after ultra-low oxygen storage (simulated shelf life—0 days); Variant 2—apples subjected to a simulated shelf life (simulated shelf life—7 days); * non-parametric distribution (Shapiro–Wilk test; $p \leq 0.05$); ** Mann–Whitney *U* test; *** Kruskal–Wallis one-way ANOVA of ranks with post-hoc test; 1-MCP—1-methylcyclopropene; IQR—interquartile range; SD—standard deviation; [a,b]—values with different letters in rows are significantly different.

The SSC of 'Red Jonaprince' apples, depending on the applied preharvest and postharvest treatment, storage period, and simulated shelf-life period is presented in Table 3. It was observed, that in case of 1-MCP not applied preharvest (Group 0 and Group 2), before shelf life (Variant 1), and for 1-MCP applied postharvest (Group 2) after shelf life (Variant 2), the longer ULO storage resulted in obtaining statistically significantly lower values of SCC ($p = 0.0434$, $p = 0.0221$, and $p = 0.0458$, respectively). At the same time, no influence of shelf life on SSC was observed ($p > 0.05$).

Table 3. The soluble solids content (SSC) (°Bx) of 'Red Jonaprince' apples, depending on the applied preharvest and postharvest treatment, storage period, and simulated shelf-life period.

Treatment Group			Ultra-Low Oxygen Storage Time			p **
			3 Months	5 Months	6 Months	
Group 0	Variant 1	Mean ± SD	13.58 ± 0.22 [ab]	13.18 ± 0.22 [a]	13.65 ± 0.34 [b]	0.0434
		Median (IQR)	13.6 (6.04)	13.1 (0.25)	13.7 (0.5)	
	Variant 2	Mean ± SD	13.58 ± 0.15	13.25 ± 0.25	13.3 ± 0.29	0.0683
		Median (IQR)	13.6 (4.44)	13.2 (0.3)	13.3 (0.5)	
		p ***	0.5374	0.6704	0.1716	
Group 1	Variant 1	Mean ± SD	12.93 ± 0.15	13.23 ± 0.46	13.25 ± 0.24	0.2650
		Median (IQR)	12.9 (0.25)	13.15 (0.75)	13.25 (0.4)	
	Variant 2	Mean ± SD	13.13 ± 0.21	12.88 ± 0.29	13.4 ± 0.32	0.3679
		Median (IQR)	13.1 (0.25)	12.75 * (0.35)	13.45 (0.5)	
		p ***	0.1677	0.1124	0.4772	

Table 3. *Cont.*

Treatment Group			Ultra-Low Oxygen Storage Time			p **
			3 Months	5 Months	6 Months	
Group 2	Variant 1	Mean ± SD	13.85 ± 0.34 [a]	13.25 ± 0.19 [b]	13.35 ± 0.54 [b]	0.0221
		Median (IQR)	13.9 (0.5)	13.3 (0.3)	13.2 (0.8)	
	Variant 2	Mean ± SD	13.98 ± 0.17 [a]	13.6 ± 0.24 [a]	13.4 ± 0.14 [b]	0.0458
		Median (IQR)	13.95 (0.25)	13.6 (0.3)	13.35 (0.2)	
		p ***	0.5370	0.0653	0.8648	
Group 3	Variant 1	Mean ± SD	12.98 ± 0.49	12.98 ± 0.25	13.4 ± 0.39	0.3094
		Median (IQR)	13 (0.85)	13.1 * (0.25)	13.45 (0.6)	
	Variant 2	Mean ± SD	13.33 ± 0.54	13.3 ± 0.41	13.63 ± 0.52	0.9438
		Median (IQR)	13.15 (0.75)	13.3 (0.7)	13.7 (0.85)	
		p ***	0.3769	0.5637	0.5146	

Group 0—no 1-MCP treatment; Group 1—1-MCP preharvest treatment; Group 2—1-MCP postharvest treatment; Group 3—1-MCP preharvest and postharvest treatment; Variant 1—assessments directly after ultra-low oxygen storage (simulated shelf life—0 days); Variant 2—apples subjected to a simulated shelf life (simulated shelf life—7 days); * non-parametric distribution (Shapiro–Wilk test; $p \leq 0.05$); ** Mann–Whitney *U* test; *** Kruskal–Wallis one-way ANOVA of ranks with post-hoc test; 1-MCP—1-methylcyclopropene; IQR—interquartile range; SD—standard deviation; [a,b]—values with different letters in rows are significantly different.

The TA of 'Red Jonaprince' apples, depending on the applied preharvest and postharvest treatment, storage period, and simulated shelf-life period, is presented in Table 4. It was observed, that in case of all the studied groups (Group 0, Group 1, Group 2, Group 3), after shelf life (Variant 2), as well as in case of 1-MCP applied only preharvest (Group 1) before shelf life (Variant 1), the longer ULO storage resulted in obtaining statistically significantly lower values of TA ($p = 0.0116$, $p = 0.0010$, $p = 0.0002$, $p = 0.0493$, and $p = 0.0183$, respectively). At the same time, except for the 1-MCP applied only postharvest (Group 2), in the case of short ULO storage applied (3 and 5 months for Group 0; 5 months for Group 1; 5 months for Group 3), after shelf-life, statistically significantly lower values of TA were observed ($p = 0.0035$, $p = 0.0209$, $p = 0.0209$, and $p = 0.0209$, respectively).

Table 4. The titratable acidity (TA) [%] of 'Red Jonaprince' apples, depending on the applied preharvest and postharvest treatment, storage period, and simulated shelf-life period.

Treatment Group			Ultra-Low Oxygen Storage Time			p **
			3 Months	5 Months	6 Months	
Group 0	Variant 1	Mean ± SD	0.5001 ± 0.0165	0.4820 ± 0.0280	0.4218 ± 0.0434	0.2853
		Median (IQR)	0.5037 (0.0232)	0.4821 * (0.0485)	0.4164 (0.0731)	
	Variant 2	Mean ± SD	0.4463 ± 0.0169 [a]	0.4014 ± 0.0186 [b]	0.4069 ± 0.0293 [ab]	0.0116
		Median (IQR)	0.4474 (0.0246)	0.3987 (0.0274)	0.4041 (0.0420)	
		p ***	0.0035	0.0209	0.5897	
Group 1	Variant 1	Mean ± SD	0.4573 ± 0.0573	0.5153 ± 0.0181	0.4328 ± 0.0394	0.0183
		Median (IQR)	0.4559 (0.0971) [ab]	0.5229 * (0.0219) [a]	0.4249 (0.0524) [b]	
	Variant 2	Mean ± SD	0.4332 ± 0.0175 [a]	0.3778 ± 0.0062 [b]	0.4313 ± 0.0426 [a]	0.0010
		Median (IQR)	0.4267 (0.0228)	0.3783 (0.0106)	0.4246 (0.0700)	
		p ***	0.4522	0.0209	0.9598	
Group 2	Variant 1	Mean ± SD	0.4752 ± 0.055	0.4296 ± 0.0197	0.3866 ± 0.0092	0.1690
		Median (IQR)	0.4593 (0.0795)	0.4249 (0.0247)	0.3853 (0.0120)	
	Variant 2	Mean ± SD	0.4921 ± 0.0162 [a]	0.4000 ± 0.0165 [b]	0.3848 ± 0.0071 [b]	0.0002
		Median (IQR)	0.4955 (0.0213)	0.4063 (0.0204)	0.3859 (0.0095)	
		p ***	0.5772	0.0611	0.7627	

Table 4. *Cont.*

Treatment Group			Ultra-Low Oxygen Storage Time			p **
			3 Months	5 Months	6 Months	
Group 3	Variant 1	Mean ± SD	0.4704 ± 0.0890	0.4758 ± 0.0132	0.4244 ± 0.0059	0.9070
		Median (IQR)	0.4647 (0.1526)	0.4803 (0.0192)	0.4261 (0.0077)	
	Variant 2	Mean ± SD	0.5049 ± 0.0493	0.4474 ± 0.0149	0.4520 ± 0.0217	0.0493
		Median (IQR)	0.5010 (0.0847) [a]	0.4507 (0.0177) [b]	0.4608 (0.0237) [b]	
		p ***	0.5222	0.0290	0.1489	

Group 0—no 1-MCP treatment; Group 1—1-MCP preharvest treatment; Group 2—1-MCP postharvest treatment; Group 3—1-MCP preharvest and postharvest treatment; Variant 1—assessments directly after ultra-low oxygen storage (simulated shelf life—0 days); Variant 2—apples subjected to a simulated shelf life (simulated shelf life—7 days); * non-parametric distribution (Shapiro–Wilk test; $p \leq 0.05$); ** Mann–Whitney U test; *** Kruskal–Wallis one-way ANOVA of ranks with post-hoc test; 1-MCP—1-methylcyclopropene; IQR—interquartile range; SD—standard deviation; [a,b]—values with different letters in rows are significantly different.

The summary of the results obtained within the conducted experiment for 'Red Jonaprince' apples, depending on the applied preharvest and postharvest treatments, for influence of ULO storage and simulated shelf life is presented in Table 5. It may be concluded that no changes during the simulated shelf life were observed only for 1-MCP postharvest treatment applied alone, but the ULO storage caused the changes of all assessed parameters for 1-MCP postharvest treatment applied alone. At the same time, when 1-MCP postharvest treatment was applied combined with 1-MCP preharvest treatment, no influence of ULO storage and simulated shelf life was observed for firmness and SSC.

Table 5. The summary of the results obtained within the conducted experiment for 'Red Jonaprince' apples, depending on the applied preharvest and postharvest treatment, for influence of ULO storage and simulated shelf life.

Treatment Applied		Firmness	Soluble Solids Content (SSC)	Titratable Acidity (TA)
No 1-MCP treatment	ULO storage *	-	Changes	Changes
	Simulated shelf life **	Changes	-	Changes
1-MCP preharvest treatment	ULO storage *	Changes	-	Changes
	Simulated shelf life **	Changes	-	Changes
1-MCP postharvest treatment	ULO storage *	Changes	Changes	Changes
	Simulated shelf life **	-	-	-
1-MCP preharvest and postharvest treatment	ULO storage *	-	-	Changes
	Simulated shelf life **	-	-	Changes

* Influence of ULO storage (3–5–6 months); ** influence of simulated shelf life (0–7 days).

4. Discussion

Determining the optimum harvest window, meaning the optimal time to harvest a specific apple cultivar, often requires extensive experience and knowledge acquired over several years of work with a particular cultivar [17]. In spite of the fact that later harvesting time promotes better taste [18], delayed harvesting is not recommended, as other quality features begin to decrease, especially texture of fruits [6]. Taking this into account, fruit are generally harvested at an early stage of ripening to improve their texture maintenance during handling and reduce loss of firmness, and as a consequence to reduce losses in the marketing chain [18].

If only the recommendations of optimum harvest window are known, the time may be predicted [19], and it may be controlled by using Streif index [15] and starch index [8], but also the mass of fruits and color. However, sometimes the optimum harvest window is harder to predict due to climate change and global warming, which may also change the physiology of apple trees and fruits, while even controlled parameters do not provide valid information about optimum harvest windows to maximize the gain and reduce the risk of quality features unsatisfactory for consumers [6]. Similarly, sometimes even if the optimum harvest window is known, conducting harvesting in the optimum harvest window becomes hindered, due to weather conditions or management of activities in the orchard [7]. Last but not least, sometimes farmers are not satisfied with the quality features of apples, so they delay the harvesting in order to obtain an increase in size and mass of their fruits, as they believe that due to the climate changes the optimum harvest window should be later, which was confirmed by more than 80% of farmers in the study conducted in the Himalayan states of India [20].

The consequence of delayed harvesting is associated with decreased quality of fruits, which must be taken into account if harvesting is not conducted in optimum harvest window [6]. The most serious consequence, due to unsatisfactory texture features, may be the inability to distribute apples as unprocessed fresh fruit, being the typical form of apples worldwide [21]. Taking this into account, if the optimum harvest window was not met, the challenge is to maintain the quality of apples to be able to distribute them in a form of unprocessed fruit.

As the texture is among the critical quality features of apples, being the most important for consumers due to the fact that they demand apples with firm, crisp texture [22], and this feature is deteriorated in the case of delayed harvesting [6], it must be considered for fruit allocation. However, the presented study revealed that there is a combination of preharvest and postharvest treatments, which allows reducing the influence of delayed harvesting on the texture of apples, namely, 1-MCP preharvest and postharvest treatments applied in combination. This treatment not only reduced deterioration of texture, but also reduced the decline of SSC.

Besides its other benefits, 1-MCP is proven to delay modification of cell wall pectin and fruit softening in apples during cold storage [23], which may result in keeping the texture parameters stable during storage and shelf life, as observed in the presented study where 1-MCP preharvest and postharvest treatments were applied in combination. At the same time, it must be indicated, that when applied preharvest, 1-MCP not only influences the quality features of apples, but also reduces dropping rate [24], which is associated with the possibility of delaying fruit harvest time, while supporting the weight and firmness of fruits [25]. Last but not least, it must be indicated that during storage, apples treated with 1-MCP are characterized by a lower frequency of fruit storage disorders [26]. All the described mechanisms may contribute to the observed stable quality of apples during storage and shelf life, even if the delayed harvesting is applied.

Numerous studies have investigated the effects of 1-MCP treatment on various apple cultivars [26–29], regarding 'Red Jonaprince' apples [14], but no other study assessed this influence in the case of delayed harvesting. As currently, the novel papers present the impact of 1-MCP application on fruit quality, not only at the optimal harvest date but also at a delayed harvesting [30], the question arises of what the influence would be in the case of 'Red Jonaprince' apples.

However, it must be emphasized that even if 1-MCP preharvest and postharvest treatments were applied in combination, the influence of storage and shelf life on TA was observed. Nevertheless, it was observed for all studied treatments, that 1-MCP preharvest and postharvest treatment applied in combination should still be indicated as the most beneficial for 'Red Jonaprince' apples after delayed harvesting to obtain the most stable firmness and SSC, which do not decrease during storage and shelf life.

5. Conclusions

If delayed harvesting must be conducted, applying 1-MCP not only postharvest, but also preharvest, allows obtaining the most stable firmness and SSC, which do not decrease during storage and shelf life. Taking this into account, it may be concluded, that in the case of delayed harvesting, combining 1-MCP applied preharvest and postharvest should be recommended to keep the quality parameters stable during storage and shelf life. **Author**

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