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Maintaining the Quality of 'Red Jonaprince' Apples during Storage by 1-Methylcyclopropene Preharvest and Postharvest Treatment

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Abstract: 'Red Jonaprince' cultivar production is rapidly increasing; therefore, the interest in harvesting in various regions, as well as in improving and maintaining the quality of the apple, is also increasing. The aim of this study was to analyze the possibility of applying 1-MCP treatment in pre- and postharvest treatment for 'Red Jonaprince' apples for maintaining the quality of the apple after Ultra-Low Oxygen (ULO) storage. The studied apples were assessed in four groups: 0—control group without any specific treatment applied; group 1—1-MCP applied preharvest; group 2—1-MCP applied postharvest; group 3—1-MCP applied preharvest and postharvest. Measurements were conducted directly after 3, 5 and 6 months of ULO storage and additionally after 7 days of simulated distribution for each period of storage. The 24 groups obtained (four treatments × three storage periods × two simulated distribution periods) were evaluated for firmness, soluble solids content (SSC) and titratable acidity (TA). No statistically significant impact on the SSC of 'Red Jonaprince' for all groups was stated ($p > 0.05$), while for the firmness and TA values, there was a statistically significant impact of applied treatment (ULO storage period and simulated distribution) ($p < 0.05$). Longer ULO storage as well as longer simulated distribution were associated with decreasing firmness and decreasing TA of apples ($p < 0.05$). For samples subjected to 1-MCP treatment postharvest and those subjected to 1-MCP treatment preharvest and postharvest combined, the apples in the majority of analyses were protected against decreasing firmness and decreasing TA. It may be concluded that postharvest 1-MCP treatment applied for 'Red Jonaprince' apples allows maintaining its quality parameters, including firmness and TA of fruits. Taking this into account, our recommendation is that the postharvest 1-MCP treatment should be sufficient, in order to avoid unreasonable management of 1-MCP, which is not justified to be applied preharvest, or preharvest and postharvest combined, for 'Red Jonaprince' apples.

Keywords: apples; 'Red Jonaprince'; 1-MCP; storage; distribution; firmness; soluble solids content; titratable acidity

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1. Introduction

Poland is among the largest fruit producers in Europe, especially for apples, cherries, raspberries, currants, and gooseberries [1]. Among various apple cultivars, in the European Union, the most common ones are Golden Delicious, Idared, and Jonagold with its mutants [2]. A Jonagold mutant that is characterized by a significantly increasing impact in Poland is 'Red Jonaprince', as its production has even recently doubled in a single year [3]. 'Red Jonaprince' is a mutant of the 'Jonagold' cultivar from the Netherlands, which is characterized by a color of fruit that is attractive and highly appreciated by consumers [4].

Attractive color is a key parameter of the quality of apples for consumers, as it determines its acceptance; and especially for red apples, it is very important for the first consumer assessment [5]. However, the texture may be the other extremely important sensory modality influencing the liking of a solid food product, so the texture of apples may determine final acceptance or rejection [5]. Moreover, even in cross-cultural comparisons of consumer preferences, the texture of apples plays crucial role [6]. The texture of apples combined with its flavor is important for consumer preference, being critical targets for selection of cultivars, as color and texture are the most important determinants for consumers; other important features include appearance, blemishes and aroma, which may be sometimes even negligible [7]. In terms of the texture of apples, its crispness, hardness, juiciness, and skin toughness are considered important determinants [8], and its high hardness accompanied by high juiciness are perceived as the demanded texture of apples [9].

In the study by Adamczyk et al. [10], authors indicated that 'Jonagold' apples, as well as their mutants, are more prone to decreasing sensory features during storage compared to the other cultivars. Taking into account the characteristics of the 'Red Jonaprince' cultivar, it is necessary to plan actions to maintain the quality of 'Red Jonaprince' apples during storage.

In general, to optimize the quality of fruits after storage and distribution, some methods of preharvest and postharvest treatment must be applied [11]. However, it should be mentioned that, in general, fruit storage after harvesting, including apples storage, is an important challenge [12]. In general, apples are commonly stored at low temperatures under normal or controlled atmosphere conditions for some time, but during this time apples slowly lose their quality, which is related to enzymatic, oxidative and metabolic changes [13].

So far, several studies associated with pre- and/or postharvest application of 1-MCP for apples and its influence on various quality parameters were conducted for 'Cripps Pink' [14], 'Fuji' [15,16], 'Golden Delicious' [17], 'Empire' [18,19], 'Jonah king' [20], 'Jonagold' [18,21], 'Summer King' [22], 'Cortland' [23], 'McIntosh' [18,23], 'Pink Lady' [24], 'Granny Smith' [25], 'Aroma' [26], 'Red Gravenstein' [26], 'Summered' [26], 'Scarletspur Delicious' [27], 'Cameo' [27], 'Delicious' [18], 'Gala' [18], 'Macoun' [18], 'Honeycrisp' [18], and 'Green Ball' [22]. However, the results of the above-mentioned studies indicate that the effect of application of 1-MCP on fruit quality parameters is variable and it often depends on type or cultivar [28]. Taking this into account, it is necessary to assess various cultivars with pre- and postharvest application of 1-MCP, in order to compare results for various cultivars.

The 1-MCP inhibits ripening by binding to ethylene receptors to form an ethylene-receptor complex and its influence can be directly reflected in ethylene production, as well as in activities of the enzymes which are involved in ethylene production [29]. The 1-MCP treatment inhibits also the activities of pectin methylesterase (PME) and polygalacturonase (PG), causing sustained integrity of the cell wall, and as a consequence delayed fruit softening [30].

The 1-MCP treatments resulting in delayed fruit ripening and the success of 1-MCP technology for apples is associated with the fact that for the apple, the maintenance of 'at harvest' quality is needed and only a moderate softening texture is desirable [29]. Such treatment for 'Red Jonaprince' is commonly applied during storage (postharvest), and such treatment has been shown to delay softening [31]. However, recently, its preharvest application has also been studied and it was indicated that it may allow delayed harvesting and reduce the quality deterioration during storage [32]. Taking this into account, it is necessary to assess the various quality features of apples subjected to pre- and postharvest application of 1-MCP, in order to assess its effectiveness.

Therefore, the aim of this study was to analyze the possibility of maintaining the quality of 'Red Jonaprince' apples during Ultra-Low Oxygen (ULO) storage by 1-MCP preharvest and postharvest treatment.

2. Materials and Methods

2.1. Study Design

The studied 'Red Jonaprince' cultivar apples were obtained on 22 September 2020, from the orchard in the experimental orchard managed by the Warsaw University of Life Sciences (SGGW-WULS) (Warsaw—52°14′ N, 21°1′ E). In the experimental orchard, planted in 2013 year, 'Red Jonaprince' cultivar trees were planted with a distance of 3.2 m by 1.0 m, as described in previous study, based on experiment conducted in 2017 [32]. The experiment presented in the current study was conducted in 2020 (three years after the previously presented [32]). The observations may be compared with those from the previous study; however, the study design differed.

The maturity-related parameters of the apple fruit harvested were assessed. The average weight of apples ranged from 200 to 220 g. In the period of 3–4 weeks before harvest, 'Red Jonaprince' apples were of an intensive dark red overcolor on the whole surface.

The Streif index was calculated to analyze optimum harvesting time [33], while a starch index was used to define the optimum harvest maturity [34].

Apples were randomly divided into 4 groups: 3 experimental groups and 1 control group: group 0—control group without any specific treatment applied; group 1—1-MCP applied preharvest (Harvista™, AgroFresh Solutions Inc., Philadelphia, PA, USA; 150 g/ha; applied 7 days before harvesting); group 2—1-MCP applied postharvest (SmartFresh™ ProTabs, AgroFresh Solutions Inc., Philadelphia, PA, USA; 0.65 μL/L; applied 7 days after harvesting for 24 h); group 3—1-MCP applied preharvest and postharvest. Furthermore, two different variants were analyzed: Variant 1—measurements conducted after ULO storage (after 3, 5 and 6 months); Variant 2—measurements conducted after ULO storage (after 3, 5 and 6 months) followed by 7 days of simulated distribution (retailer and shelf life).

The applied dose of preharvest 1-MCP was in agreement with the commonly applied doses, and the same as in previous study [35], namely 150 g per ha, while the solution was applied with 400 L of water in the morning (by spraying).

After harvesting, 24 boxes of apples, with a capacity of approximately 16 kg, were taken, either from trees treated or those non treated with Harvista™, which were cooled down to 1 °C during 24 h. After 7 days, half of the boxes (12 boxes of apples—6 treated with Harvista™ and 6 non treated with Harvista™) were treated with SmartFresh™. After 8 days after harvesting, all apples were stored in the ULO chambers of the Institute of Horticultural Sciences (IHS) of the SGGW-WULS in Warsaw. The ULO condition was as follows: 1.2% CO_2, 1.2% O_2; temperature of 1 °C; humidity of 95%. The simulated distribution (retailer and shelf life) was not carried out or carried out for 7 days in the temperature of 20 °C.

In Figure 1, the experiment including 24 studied groups (4 treatments × 3 storage periods × 2 simulated distribution periods) is presented. Each group constituted 4 batches, 10 random apples each.

2.2. Measurements

The following measurements were conducted in each period of ULO storage and stimulated distribution: firmness, soluble solids content (SSC) and titratable acidity (TA), internal ethylene content (IEC), and ethylene production, while the Streif index and the starch index were used to define optimum harvesting time.

The firmness was assessed according to a previously described method [31]. After removing the peel, the firmness was measured in duplicate for each sample. Each measurement was conducted for opposite sides of the apple. For firmness measurements, 4 batches were assessed, 10 apples each. The firmness was estimated while using an Instron 5542 (Instron, Norwood, MA, USA), equipped with the stainless steel plunger tip (head speed: 4 mm/s; diameter: 11 mm). The results of firmness are expressed in *N*.

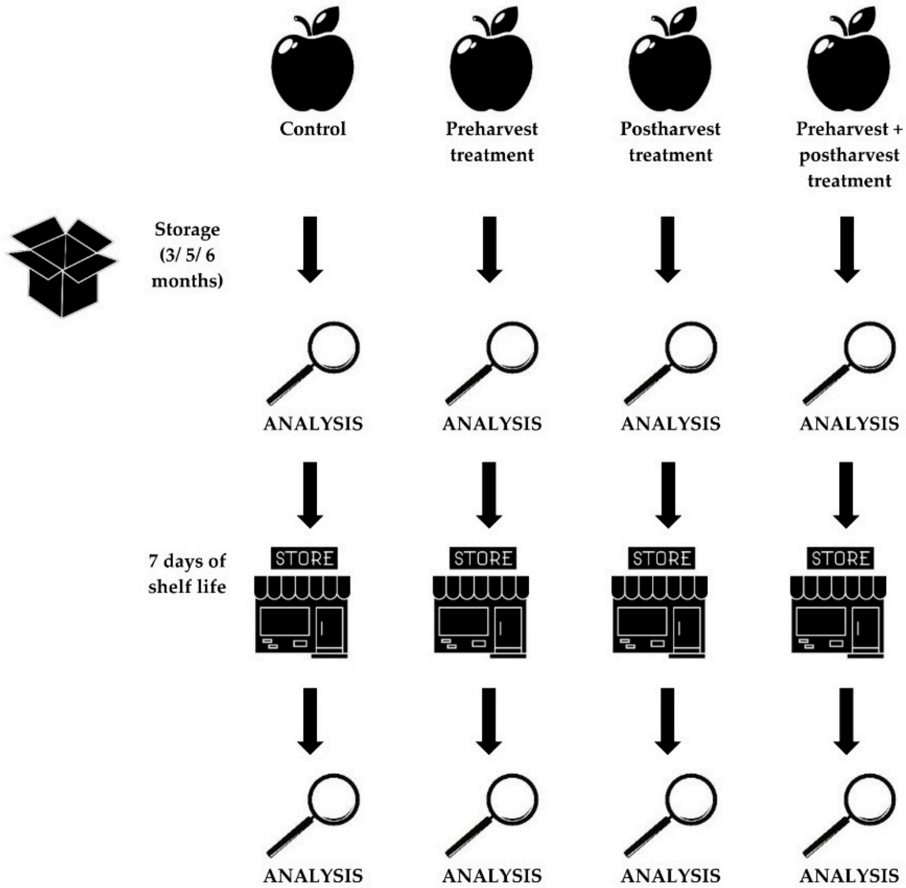

Figure 1. The flow chart of the presented study of 'Red Jonaprince' apples.

The SSC was assessed according to a previously described method [34]. The SSC was assessed from juice that was extracted from 4 batches, 10 apples each. The juice was extracted with the simple extractor. The measurement was conducted using Atago Palette PR-32 (digital refractometer, Atago Co., Ltd., Tokyo, Japan). The results of SSC are expressed in $^{\circ}Bx$.

The TA was assessed according to a previously described method [34]. The TA content was assessed from juice that was extracted from 4 batches, 10 apples each. The measurement was conducted using the automatic titrator (TitroLine 5000, Xylem Analytics Germany GmbH, Weilheim, Germany) to titrate the obtained juice with NaOH solution (0.1 M) to obtain the pH value of 8.1. The results of TA are expressed in % after recalculation for malic acid content.

The IEC was measured in the core space of each apple. To collect the air samples in the core space of apples, a gas sample (1 mL) was used. The measurement was conducted using gas chromatography (HP 5890, Hewlett Packard, Palo Alto, CA, USA). Measurements were conducted in 4 replications using 10 apples each. The results of IEC are expressed in μL/L.

The ethylene production was assessed according to a previously described method [34]. The apples were relocated to a sealed 1400 mL glass jar at 20 °C. The measurement was conducted after 1 h of incubation. From each glass jar, a gas sample (1 mL) was collected using a syringe. The measurement was conducted using gas chromatography (HP 5890, Hewlett Packard, Palo Alto, CA, USA) for ethylene analysis. Within a studied group, 4 batches were assessed, 6 apples each. The results of ethylene production are expressed in $\mu L \cdot kg^{-1} \cdot h^{-1}$.

The starch index was estimated based on the colorimetric reaction with Lugol's solution (I_3K), and comparison with the standards, while using a dedicated 10-point scale. Measurements were conducted in 4 replications using 10 apples each.

The Streif index was used to describe a harvest window. The Streif index was calculated based three maturity parameters (firmness, percentage soluble solids content and the starch index) according to the following equation:

$$IS = \frac{F}{R \cdot S} \quad (1)$$

where *IS*—the Streif index, *F*—firmness in kg, *R*—percentage of soluble solids content in °Brix, and *S*—the starch index in scale 1–10.

2.3. Statistical Analysis

The normality of distribution was checked using the Shapiro–Wilk test. Due to the fact that majority of the data were characterized by non-parametric distribution, the following non-parametric tests were applied: the Mann–Whitney U test to compare differences between two independent groups; the Kruskal–Wallis one-way ANOVA of ranks with post hoc test for compare differences between more than two independent groups.

The $p \leq 0.05$ means that the test hypothesis is false and showed significant differences between groups. The statistical analysis was conducted using Statistica, 13.3 (Statsoft Inc., Tulsa, OK, USA).

3. Results

The characteristics of the internal ethylene content, the starch index, soluble solids content, firmness, titratable acidity and the Streif index of 'Red Jonaprince' apples measured directly after harvesting are demonstrated in Table 1. While the Streif index was used to analyze optimum harvesting time and the starch index was used to define the optimum harvest maturity, all apples were harvested at the same time, so it may be indicated that the preharvest application of 1-MCP did not influence apple maturity, and it could be concluded that preharvest 1-MCP-treated and non-treated apples were at a similar maturity stage.

Table 1. Characteristics of 'Red Jonaprince' apples after harvest.

Characteristic	Mean (SD)	Median (IQR)
Internal ethylene content (µL/L)	0.1175 (0.0519)	0.1094 * (0.0833)
Starch index (-)	8.1 (0.33)	8.2 * (0.43)
Soluble solids content (°*Bx*)	13.85 (0.17)	13.8 * (0.20)
Firmness (*N*)	68.79 (2.28)	68.99 * (3.25)
Titratable acidity (-)	0.6526 (0.0245)	0.6447 * (0.0300)
Streif index (-)	0.0615 (0.0044)	0.06 * (0.0059)

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

The values of firmness (*N*) for 'Red Jonaprince' apples for the sub-groups stratified by applied preharvest and postharvest 1-MCP treatment, storage duration, and simulated distribution are demonstrated in Table 2. The storage period in ULO has statistically significant impact on the firmness of 'Red Jonaprince' for group 0 (control group without any specific treatment applied), group 1 (group with 1-MCP applied preharvest), and group 3 (Variant 2) (group with 1-MCP applied pre- and postharvest), whereas for group 2 (group with 1-MCP applied postharvest) and group 3 (Variant 1) (group with 1-MCP applied pre- and postharvest), no difference in firmness was observed. At the same time, while comparing variant groups (Variant 1—firmness measured after ULO chamber storage vs. Variant 2—firmness measured after ULO storage and 7 days of shelf life), significant differences were observed for group 0 and group 1, while for group with postharvest 1-MCP treatment (group 2 and group 3), no difference in firmness was observed after 7 days of shelf life.

Table 2. The values of firmness (*N*) for 'Red Jonaprince' apples for the sub-groups stratified by applied preharvest and postharvest 1-MCP treatment, storage duration, and shelf life.

Treatment Group			Ultra-Low Oxygen Storage Time			p **
			3 Months	5 Months	6 Months	
Group 0	Variant 1	mean (SD)	62.79 (0.72)	50.43 (1.69)	52.58 (2.73)	0.0194
		Median (IQR)	62.86 * (1.05) [a]	50.45 * (2.55) [b]	51.45 * (3.35) [ab]	
	Variant 2	mean (SD)	47.73 (0.97)	43.33 (2.21)	43.53 (2.53)	0.0388
		Median (IQR)	47.93 * (1.23) [a]	42.70 * (2.75) [b]	44.40 * (3.45) [b]	
		p ***	0.0304	0.0303	0.0209	
Group 1	Variant 1	mean (SD)	63.17 (1.44)	50.55 (1.01)	48.98 (0.56)	0.0109
		Median (IQR)	62.49 (1.52) [a]	50.85 * (1.30) [ab]	48.90 * (0.85) [b]	
	Variant 2	mean (SD)	50.62 (3.11)	43.58 (2.04)	41.53 (1.26)	0.0154
		Median (IQR)	50.53 * (4.98) [a]	44.25 * (2.55) [ab]	41.30 * (1.85) [b]	
		p ***	0.0209	0.0209	0.0209	
Group 2	Variant 1	mean (SD)	67.14 (1.80)	66.78 (0.76)	65.75 (1.86)	0.4826
		Median (IQR)	67.12 * (2.78)	66.65 * (1.05)	65.50 * (2.90)	
	Variant 2	mean (SD)	66.08 (2.55)	66.70 (0.88)	65.75 (0.99)	0.5498
		Median (IQR)	66.21 * (3.93)	66.55 * (1.20)	65.45 * (1.50)	
		p ***	0.5637	0.7728	0.7715	
Group 3	Variant 1	mean (SD)	67.80 (2.42)	69.03 (3.99)	66.80 (3.09)	0.7351
		Median (IQR)	67.77 * (4.16)	68.15 * (6.25)	68.10 (3.50)	
	Variant 2	mean (SD)	69.26 (1.52)	68.7 (2.08)	65.18 (1.96)	0.0373
		Median (IQR)	69.11 * (2.54) [a]	69.15 * (2.70) [ab]	65.65 * (2.35) [b]	
		p ***	0.3865	1.0000	0.2482	

Group 0—control group without any specific treatment applied; group 1—1-MCP preharvest; group 2—1-MCP postharvest; group 3—1-MCP preharvest and postharvest; Variant 1—measurements conducted after Ultra-Low Oxygen storage; Variant 2—measurements conducted after Ultra-Low Oxygen storage and after 7 days of shelf life; * non-parametric distribution (normality was checked using the Shapiro–Wilk test—$p \leq 0.05$); ** Mann–Whitney U test; *** Kruskal–Wallis one-way ANOVA of ranks accompanied by the post hoc test; [a,b] statistically significant differences in rows; 1-MCP—1-methylcyclopropene; IQR—interquartile range; SD—standard deviation.

The values of SSC (°*Bx*) for 'Red Jonaprince' apples for the sub-groups stratified by applied preharvest and postharvest 1-MCP treatment, storage duration, and simulated distribution are demonstrated in Table 3. The storage period in ULO has no statistically significant impact on the SSC of 'Red Jonaprince' for all groups. Moreover, while comparing variant groups (Variant 1 vs. Variant 2), no significant differences were observed for all groups of 'Red Jonaprince' apples after 7 days of shelf life. Therefore, it can be stated that the applied 1-MCP treatments regardless of the time of ULO and time of simulated distribution, have no impact on SSC values.

The values of TA (%) for 'Red Jonaprince' apples for the sub-groups stratified by applied preharvest and postharvest 1-MCP treatment, storage duration, and simulated distribution are demonstrated in Table 4. The storage period in ULO has statistically significant impact on the TA values of 'Red Jonaprince' for group 0 (control group without any specific treatment applied), group 1 (group with 1-MCP applied preharvest), and group 3 (Variant 1) (group with 1-MCP applied pre- and postharvest), whereas for group 2 (group with 1-MCP applied postharvest) and group 3 (Variant 2) (group with 1-MCP applied pre- and postharvest), no difference in TA was observed. At the same time, while comparing variant groups (Variant 1 vs. Variant 2), significant differences were observed for group 0, group 2 and group 3, while for group with preharvest 1-MCP treatment (group 1), no difference in TA was observed after 7 days of shelf life.

Table 3. The values of soluble solids content (SSC) (°*Bx*) for 'Red Jonaprince' apples for the subgroups stratified by applied preharvest and postharvest 1-MCP treatment, storage duration, and shelf life.

Treatment Group			Ultra-Low Oxygen Storage Time			p **
			3 Months	5 Months	6 Months	
Group 0	Variant 1	mean (SD)	13.35 (0.44)	13.38 (0.13)	13.25 (0.19)	0.3428
		Median (IQR)	13.50 * (0.50)	13.40 * (0.15)	13.30 * (0.30)	
	Variant 2	mean (SD)	13.68 (0.28)	13.35 (0.21)	13.3 (0.22)	0.1361
		Median (IQR)	13.65 * (0.45)	13.35 * (0.30)	13.25 * (0.30)	
		p ***	0.3749	0.7674	0.8839	
Group 1	Variant 1	mean (SD)	12.83 (0.55)	13.45 (0.54)	13.18 (0.26)	0.3653
		Median (IQR)	12.95 * (0.85)	13.30 * (0.80)	13.25 * (0.35)	
	Variant 2	mean (SD)	13.33 (0.29)	12.98 (0.22)	12.85 (0.31)	0.0922
		Median (IQR)	13.30 * (0.35)	13.00* (0.35)	12.95 * (0.40)	
		p ***	0.1391	0.1913	0.1489	
Group 2	Variant 1	mean (SD)	13.28 (0.57)	13.5 (0.48)	13.33 (0.68)	0.7875
		Median (IQR)	13.40 * (0.85)	13.50 * (0.80)	13.65 (0.75)	
	Variant 2	mean (SD)	14.05 (0.45)	13.65 (0.39)	13.35 (0.21)	0.0694
		Median (IQR)	13.90 * (0.60)	13.65 * (0.60)	13.35 * (0.30)	
		p ***	0.0591	0.5590	0.3065	
Group 3	Variant 1	mean (SD)	13.10 (0.33)	13.73 (0.45)	13.65 (0.39)	0.0999
		Median (IQR)	13.10 * (0.40)	13.85 * (0.65)	13.65 * (0.60)	
	Variant 2	mean (SD)	13.5 (0.39)	13.53 (0.35)	13.68 (0.22)	0.7339
		Median (IQR)	13.45 * (0.60)	13.55 * (0.55)	13.6 * (0.25)	
		p ***	0.1391	0.3807	0.8839	

Group 0—control group without any specific treatment applied; group 1—1-MCP preharvest; group 2—1-MCP postharvest; group 3—1-MCP preharvest and postharvest; Variant 1—measurements conducted after Ultra-Low Oxygen storage; Variant 2—measurements conducted after Ultra-Low Oxygen storage and after 7 days of shelf life; * non-parametric distribution (normality was checked using the Shapiro–Wilk test—$p \leq 0.05$); ** Mann–Whitney U test; *** Kruskal–Wallis one-way ANOVA of ranks accompanied by the post hoc test; 1-MCP—1-methylcyclopropene; IQR—interquartile range; SD—standard deviation.

The values of ethylene production for 'Red Jonaprince' apples after 3 months of storage, for 7 days in the temperature of 20 °C, are demonstrated in Figure 2. The 7 days of shelf life after 3 months of storage period in ULO has statistically significant impact on the ethylene production values of 'Red Jonaprince' for group 0 (control group without any specific treatment applied) and group 1 (group with 1-MCP applied preharvest), whereas for group 2 (group with 1-MCP applied postharvest) and group 3 (group with 1-MCP applied pre- and postharvest), no impact of storage on ethylene production was observed. At the same time, group 2 and group 3 had significantly lower values of ethylene production than group 0 and group 1.

The values of ethylene production for 'Red Jonaprince' apples after 5 months of storage, for 7 days in the temperature of 20 °C, are demonstrated in Figure 3. The 7 days of shelf life after 5 months of storage period in ULO has statistically significant impact on the ethylene production values of 'Red Jonaprince' for group 0 (control group without any specific treatment applied) and group 1 (group with 1-MCP applied preharvest), whereas for group 2 (group with 1-MCP applied postharvest) and group 3 (group with 1-MCP applied pre- and postharvest), no impact of storage on ethylene production was observed. At the same time, group 2 and group 3 had significantly lower values of ethylene production than group 0 and group 1.

Table 4. The values of titratable acidity (TA) [%] for 'Red Jonaprince' apples for the sub-groups stratified by applied preharvest and postharvest 1-MCP treatment, storage duration, and shelf life.

Treatment Group			Ultra-Low Oxygen Storage Time			p **
			3 Months	5 Months	6 Months	
Group 0	Variant 1	mean (SD)	0.5298 (0.0231)	0.4573 (0.0057)	0.3897 (0.0152)	0.0073
		Median (IQR)	0.5375 * (0.02850) [a]	0.4565 * (0.0080) [ab]	0.3898 * (0.0241) [b]	
	Variant 2	mean (SD)	0.5143 (0.0145)	0.3970 (0.0238)	0.3833 (0.0080)	0.0194
		Median (IQR)	0.5105 (0.0175) [a]	0.3868 (0.0265) [ab]	0.3822 * (0.0125) [b]	
		p ***	0.3094	0.0209	0.5637	
Group 1	Variant 1	mean (SD)	0.4728 (0.0132)	0.4908 (0.0239)	0.4331 (0.0049)	0.0178
		Median (IQR)	0.4720 * (0.0215) [ab]	0.4894 * (0.0375) [b]	0.4325 * (0.0079) [a]	
	Variant 2	mean (SD)	0.4878 (0.0136)	0.4621 (0.0152)	0.4405 (0.0238)	0.0362
		Median (IQR)	0.4875 * (0.0235) [a]	0.4580 * (0.0235) [ab]	0.4449 * (0.0381) [b]	
		p ***	0.2454	0.1102	0.5637	
Group 2	Variant 1	mean (SD)	0.5035 (0.0269)	0.4874 (0.0133)	0.4408 (0.0192)	0.1083
		Median (IQR)	0.5000 * (0.041) [a]	0.4873 * (0.0180) [ab]	0.4395 * (0.0289) [b]	
	Variant 2	mean (SD)	0.4823 (0.0132)	0.4311 (0.0134)	0.4547 (0.0324)	0.0627
		Median (IQR)	0.4850 * (0.0205)	0.4312 * (0.0216)	0.4468 * (0.0506)	
		p ***	0.3865	0.0209	0.7728	
Group 3	Variant 1	mean (SD)	0.5530 (0.0263)	0.4816 (0.0156)	0.4842 (0.0191)	0.0249
		Median (IQR)	0.5585 * (0.0400) [a]	0.4784 * (0.0235) [b]	0.4833 * (0.0317) [b]	
	Variant 2	mean (SD)	0.5273 (0.0212)	0.5295 (0.0423)	0.5269 (0.0072)	0.9969
		Median (IQR)	0.5320 * (0.0335)	0.5284 * (0.0527)	0.5250 * (0.0109)	
		p ***	0.1489	0.0833	0.0209	

Group 0—control group without any specific treatment applied; group 1—1-MCP preharvest; group 2—1-MCP postharvest; group 3—1-MCP preharvest and postharvest; Variant 1—measurements conducted after Ultra-Low Oxygen storage; Variant 2—measurements conducted after Ultra-Low Oxygen storage and after 7 days of shelf life; * non-parametric distribution (normality was checked using the Shapiro–Wilk test—$p \leq 0.05$); ** Mann–Whitney U test; *** Kruskal–Wallis one-way ANOVA of ranks accompanied by the post hoc test; [a,b] statistically significant differences in rows; 1-MCP—1-methylcyclopropene; IQR—interquartile range; SD—standard deviation.

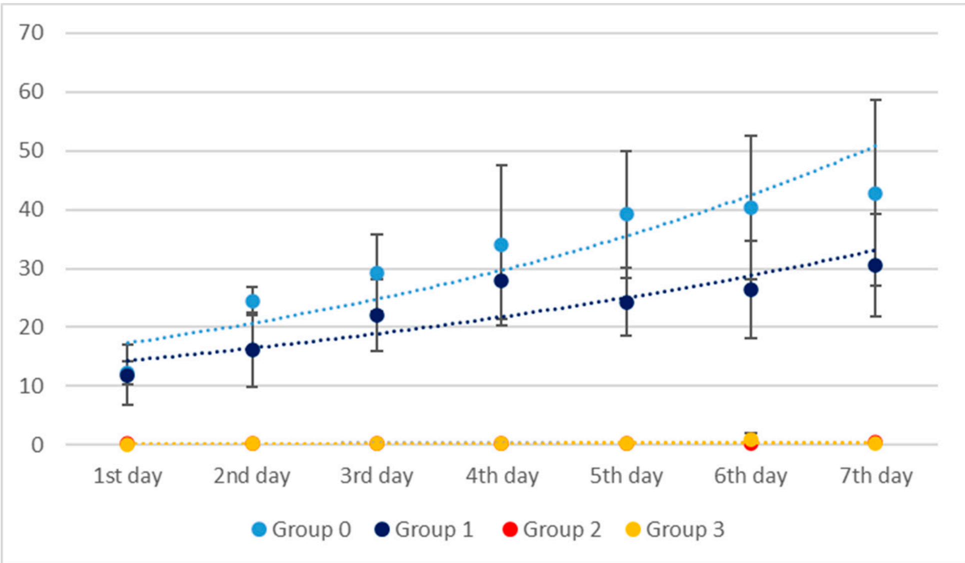

Figure 2. The values of ethylene production for 'Red Jonaprince' apples after 3 months of storage, for 7 days in the temperature of 20 °C; group 0—control group without any specific treatment applied; group 1—1-MCP applied preharvest; group 2—1-MCP applied postharvest; group 3—1-MCP applied preharvest and postharvest.

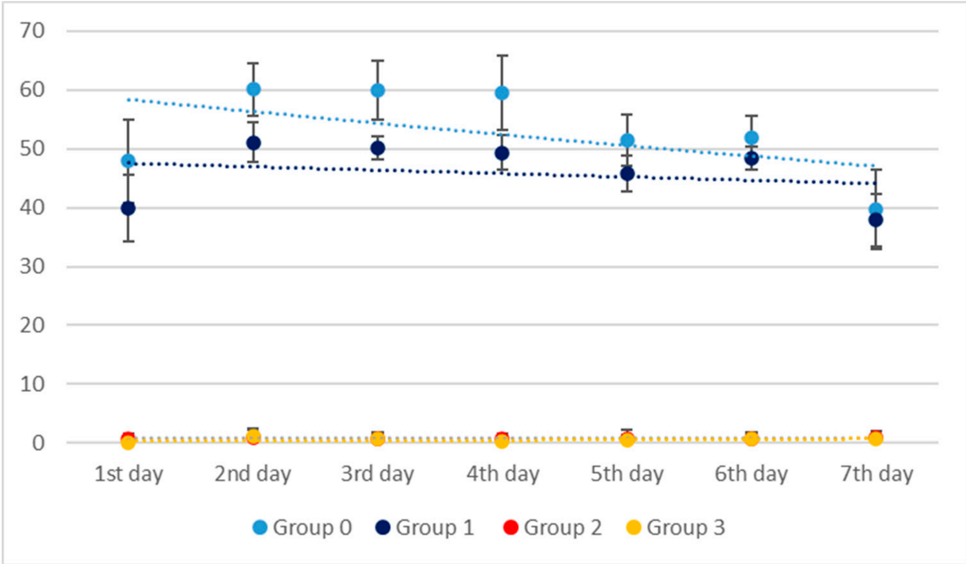

Figure 3. The values of ethylene production for 'Red Jonaprince' apples after 5 months of storage, for 7 days in the temperature of 20 °C; group 0—control group without any specific treatment applied; group 1—1-MCP applied preharvest; group 2—1-MCP applied postharvest; group 3—1-MCP applied preharvest and postharvest.

The values of ethylene production for 'Red Jonaprince' apples after 6 months of storage, for 7 days in the temperature of 20 °C, are demonstrated in Figure 4. The 7 days of shelf life after 6 months of storage period in ULO has statistically significant impact on the ethylene production values of 'Red Jonaprince' for group 0 (control group without any specific treatment applied) and group 1 (group with 1-MCP applied preharvest), whereas for group 2 (group with 1-MCP applied postharvest) and group 3 (group with 1-MCP applied pre- and postharvest), no impact of storage on ethylene production was observed. At the same time, group 2 and group 3 had significantly lower values of ethylene production than group 0 and group 1.

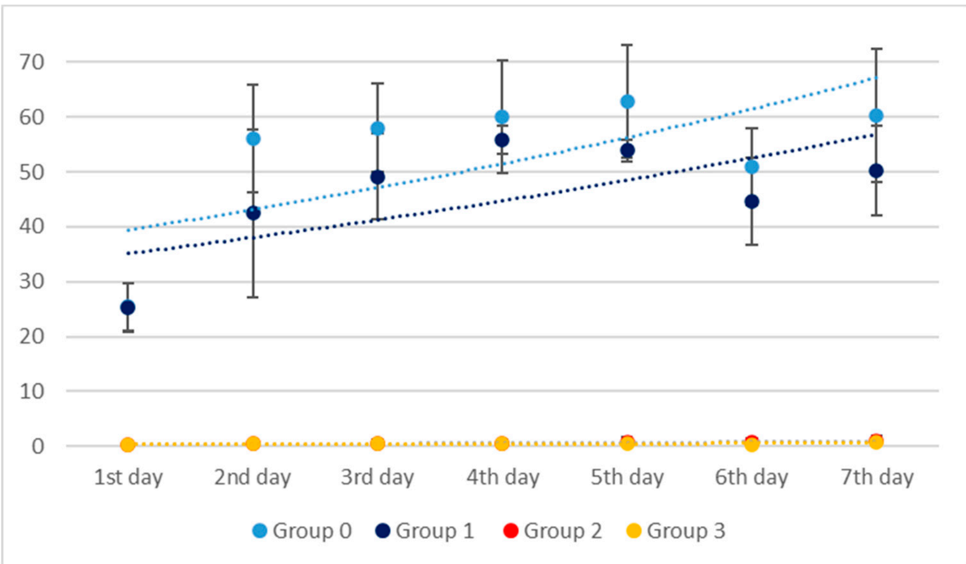

Figure 4. The values of ethylene production for 'Red Jonaprince' apples after 6 months of storage, for 7 days in the temperature of 20 °C; group 0—control group without any specific treatment applied; group 1—1-MCP applied preharvest; group 2—1-MCP applied postharvest; group 3—1-MCP applied preharvest and postharvest.

4. Discussion

Within the conducted study, the most important quality features of apples, including firmness, SSC and TA, after 3, 5 and 6 months of ULO storage, were studied. The influence of ULO storage and simulated distribution was stated for firmness and TA, indicating the decreasing quality of apples due to ripening process during a storage and distribution. In the presented study, the 1-MCP treatment did not affect SSC in apples as it was also proven by other authors [15].

The described findings are in an agreement with the results of the study of Lee et al. [16], as they stated that preharvest 1-MCP treatment positively affected 'Fuji' apple fruit quality attributes. However, in the presented study, we could not confirm the detailed observations by Lee et al. [16] that a combination of preharvest and postharvest 1-MCP treatments are more effective than preharvest 1-MCP treatment alone.

In terms of climacteric fruits, such as apples, the ripening progression is controlled mainly by ethylene, and just after harvest and during storage, the loss of fruit quality begins. Such changes are associated with ethylene production, and this process is a major challenge in the maintenance of the quality of climacteric fruits [36]. Among the methods to prolong the quality of climacteric fruits is controlled atmosphere (CA) storage that could significantly extend the storability of fruits, the other is a 1-MCP application, but both of them, apart from maintaining the quality of fruits, may also negatively affect the volatile profile of some fruits [37,38]. The ULO storage and 1-MCP treatment resulted in 'Red Jonaprince' apples with a high maintaining of firmness during shelf life. However, for apples from group with 1-MCP applied postharvest only, such strong influence was not observed. Taking this into account, it should be noticed that the time of application of 1-MCP may be crucial. Such example of influence of time of application was observed in the study of Delong et al. [23] for 'Cortland' and 'McIntosh' apples, where authors stated that the midstorage application of 1-MCP, during the long-term storage, did not improve fruit quality as strong as prestorage treatment.

The 1-MCP is an ethylene action inhibitor in plant cells, so it may be applied in order to control ethylene production, which is associated with delaying the fruit ripening mechanism [35,39]. The 1-MCP may be applied in apple production both preharvest [35] and postharvest [39], while the standard treatment includes its postharvest application [26].

Within the conducted study, it was revealed that depending on 1-MCP application, its effect on apple ripening may differ. For samples subjected to 1-MCP treatment postharvest and those subjected to 1-MCP treatment preharvest and postharvest combined, the apples in the majority of analyses were protected against decreasing firmness and decreasing TA. Such observations were formulated independently from ULO storage and simulated distribution, so it may be indicated that those stages may be prolonged due to 1-MCP treatment. However, in such situation, if samples subjected to postharvest treatment and those subjected to preharvest and postharvest treatment combined are comparable, it should be indicated if such treatment is economically viable [37], so applying only postharvest 1-MCP treatment should be indicated as more effective and justified.

However, it should be mentioned that a preharvest 1-MCP treatment to 'Scarletspur Delicious' and 'Cameo' apples reveled that obtained results of firmness were comparable with the results of postharvest 1-MCP treatment and with the results of treatment with a plant regulator (aminoethoxyvinylglycine) [27]. The impact of 1-MCP postharvest treatment on the quality of apples differs among cultivars, but also variability exists while compared the same cultivar from different regions, which may reflect the effect of climate on the underlying physiology [40]. The meta-analysis by Zhang et al. [30] revealed that depending on the specie of climacteric fruit, application of 1-MCP reduced 20 of 44 indicators by a minimum of 22% and increased 6 indicators by at least 20%. Such effects were associated with positive effects on delaying ripening and maintaining the quality of fruits, which was also observed in the presented study. When highlighting the fact that fruits from various species have various responses to 1-MCP treatment, it must be mentioned that the most pronounced responses are observed in rosaceous fruits, especially apples, European pear fruits, and tropical fruits [30].

During the shelf life, when apples are placed in room temperature after cold storage, production of ethylene increases due to increase in the temperature [21]. As a consequence, the reduction in firmness and acidity of apples is observed both during ULO storage (conducted for few months, in decreased temperature), and during simulated distribution (conducted for few days, but in quite high temperature). This observation is of particular importance for the firmness of apples, due to the fact that for consumers it is the crucial quality determinant [5], while they prefer firmness for apple fruits on the level of about 50 N [41]. After harvesting the firmness decreases systematically due to the ethylene production, being a major determinant of softening of climacteric fruit [42]. Therefore, the application of inhibitors of ethylene action, such as 1-MCP, allows maintaining quality, as it blocks ethylene access to the ethylene-binding receptors [43], and as a consequence maintaining the quality of apples, mainly the firmness.

In spite of important influence of 1-MCP, it should be indicated that maturation and ripening of fruits are not completely controlled by ethylene, as there is some degree of ethylene-independent progression of maturation and ripening [44], so the 1-MCP treatment has some limitations and it cannot stop the maturation and ripening. As fruit ripens, starch is degraded, while the sugar content increases, causing the sweetness increase. Some studies indicated that starch degradation in some apple cultivars is ethylene independent, as for the 'Fuji' cultivar, while in another, it may be more ethylene dependent, as for 'Tsugaru' cultivar [42,45]. The results obtained within the presented study are in agreement with the ethylene independent processes described, associated with starch degradation, as in case of TA, for samples subjected to 1-MCP treatment, there were more changes during ULO storage and shelf life than for firmness, which indicates that even if ethylene-controlled changes are slowed, the acidity of 'Red Jonaprince' apples is decreasing.

It should be mentioned that the results obtained in the presented study may not be affected only by the cultivar, but also by climate [28] and applied conditions of storage and distribution [21]. Further research in the presented areas are needed to define the optimal application of 1-MCP to maintain the quality of apples during storage and distribution to reduce the loss of the commercial value of fruits.

In spite of the fact that important observations were made in regard to the possibility of applying 1-MCP treatment to maintain the quality of 'Red Jonaprince' apples, some limitations of this study must be also listed. The most important limitation is associated with the fact that the respiration rate, being among the most important parameters for climacteric fruit, was not measured within this study and it does not allow to strengthen the observations. The other quality indicators, which would allow to deepen the observations, but were not controlled, are enzyme activities in apples, which could have been also measured to confirm the effectiveness of the 1-MCP treatment. Last but not least, fruit drop and the possibility of extending the harvest window are also important parameters, which are associated not with the quality of fruits itself, but with apple management and are also interesting. Taking this into account, further studies are needed in order to broaden the observations and assess the mechanisms.

5. Conclusions

For samples subjected to 1-MCP treatment postharvest and those subjected to 1-MCP treatment preharvest and postharvest combined, the apples in the majority of analyses were protected against decreasing firmness and decreasing TA. It may be concluded that postharvest 1-MCP treatment applied for 'Red Jonaprince' apples allows maintaining its quality parameters, including firmness and TA of fruits. Taking this into account, our recommendation is that the postharvest 1-MCP treatment should be sufficient, in order to avoid unreasonable management of 1-MCP, which is not justified to be applied preharvest, or preharvest and postharvest combined, for 'Red Jonaprince' apples.

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