

Article

The Influence of 1-Methylcyclopropene on the Quality Parameters of Idared Apples after 8 Weeks of Storage Simulating Long-Distance Transportation

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Abstract: 1-Methylcyclopropene (1-MCP), being applied in postharvest treatment of apples as an inhibitor of ethylene perception, contributes to improved quality of apples during 6 weeks of simulated long-distance transportation, but it was not studied if this period may be prolonged. The aim of the present study was to assess the possibility to apply 1-MCP treatment to maintain the quality of Idared apples for long-distance transportation prolonged for 8 weeks. The 1-MCP treatment was applied either alone, or combined with modified atmosphere packaging (MAP) in selected gas permeability bags and was compared with control group. Postharvest, the storage in Ultra Low Oxygen (ULO) chamber was applied (3 periods: 0, 10, or 20 weeks), followed by simulated long distance transportation (storage duration of 8 weeks) and simulated distribution (4 periods: 0, 5, 10, or 15 days). Each studied group (36 groups: 3 postharvest treatments × 3 storage periods × 4 distribution periods) constituted 4 batches with 10 random apples each. After simulated distribution period, each sample was analyzed to assess the differences of firmness, total soluble solids (TSS) and titratable acidity (TA). The applied treatment influenced observed values of firmness, TSS and TA within each applied storage duration and duration of distribution ($p < 0.05$). For the majority of the studied durations of storage and distribution, the highest values of firmness, TSS and TA were observed for the samples from the group of 1-MCP applied combined with MAP, while only for some of them, the highest values of firmness and TA, but not TSS, were observed for the samples from the group of 1-MCP applied alone. It may be concluded that applying 1-MCP in the case of Idared apples for long-distance transportation allows prolonging it to 8 weeks without decreasing quality of fruits. Applying 1-MCP combined with MAP allows obtaining even better results than 1-MCP alone, after 8 weeks of transportation. It may be recommended to apply 1-MCP combined with MAP in order to slow the ripening process and to maintain the quality of apples during a long-distance transportation.

Keywords: apples; Idared; transportation; long distance transportation; modified atmosphere packaging; 1-methylcyclopropene; 1-MCP; firmness; total soluble solids; titratable acidity

1. Introduction

The World Health Organization (WHO) emphasizes that fruit and vegetables are important component of diet that may reduce the risk of diet-related diseases [1]. At the

same time, it is indicated that obtaining the recommended intake of fruit and vegetables, namely 400 g daily, is challenging and actions promoting its consumption are necessary [2]. In general it is recommended to have the intake of vegetables higher than in case of fruit [3], but the meaningful benefits associated with consumption of specific fruit may be also listed.

In the National Health and Nutrition Examination Survey (NHANES) 2003–2010, conducted in United States, it was revealed that in the studied group of children, including any apple to a diet contributed not only to higher general fruit intake, but also improved the diet quality and was associated with lower body mass [4]. In the study by Hodgson et al. [5], that was conducted in Australia, it was observed that in a group of elderly women, a higher apple intake was associated with lower risk of all-cause mortality and cancer mortality. Similarly, in the systematic review and meta-analysis by Gayer et al. [6], it was proven that apple intake significantly decreased body mass, while the intake of apples or pears significantly decreased risk of cerebrovascular disease, cardiovascular death, type 2 diabetes mellitus, and all-cause mortality, reducing the general risk of cardio-vascular diseases. Moreover, the recent systematic review by Głabska et al. [7] emphasized that apples are within those fruit which are related to better mental health, similarly as bananas, citrus, berries, grapefruit and kiwifruit, that was revealed by Brookie et al. [8].

The indicated numerous benefits associated with apple consumption, are associated with their nutritional value and content of phytochemicals [9], which may cause reduction of the risk of chronic diseases by various mechanisms, including antioxidant, antiproliferative, and cell signaling effects [10]. The role of potential health promoting properties of fruit is becoming especially important in the period of the Coronavirus Disease 2019 (COVID-19) global pandemic, caused by the spread of SARS-CoV-2 virus, when health is perceived as more important food choice determinant than before [11]. Moreover, the hesperidin [12] and vitamin C, being components of various fruit, including apples [13], are now indicated as potential effective candidates to counteract the cell infection by SARS-CoV-2, and to modulate the systemic immunopathological phases of the disease [14].

For the apple and other fruit production, the period of the COVID-19 global pandemic was also important, as the governmental restrictions aspiring to slow down the spread of the virus, caused serious impairments for economic operations, including maritime, rail, air, and trucking transportation networks [15]. It caused the serious problem of food waste management along the supply chain and forced industries to develop a proper policy to protect them from increasing economic costs of the global situation [16].

Within possible methods to be applied to protect product and reduce losses, there are dedicated packaging systems which allow to prolong the shelf life [17]. Such systems include controlled and modified atmosphere packaging (MAP) [18], which refer to the technique of sealing actively respiring produce in polymeric film packages to modify the O₂ and CO₂ levels within the package atmosphere [19]. MAP is especially valuable for fruit, as they allow reduction of fruit loss, due to reduced respiration, ethylene production, and sensitivity to ethylene, as well as retarded softening and compositional changes, alleviation of certain physiological disorders, and reduced decay [20]. Moreover, MAP is more cost-effective than other methods. It also may be more acceptable for consumers because it utilizes only the natural components of air; synthetic chemicals are not used, no toxic residue is left, and there is little environmental impact [21].

Within such gases, which may be used for MAP, there is 1-methylcyclopropene (1-MCP), being an inhibitor of ethylene perception, which may be used to maintain during storage the quality of climacteric fruits, including apples [22]. As a result, 1-MCP maintains the quality of fruit, not only during storage but also through the entire marketing chain [23]. However, the effect of 1-MCP is not universal and depends on few factors, including not only the type of fruit, but also the concentration, treatment time, or temperature [24].

If applied immediately after harvesting and combined with cold storage, 1-MCP is indicated even as an affordable alternative to controlled atmosphere, to maintain the quality of fruits [25]. The studies conducted so far revealed that 1-MCP applied postharvest contributed to improved quality of Idared apples during 6 weeks of simulated long-distance

transportation [26], but it was not studied if this period of transportation may be prolonged. Taking into account the current unpredictable global situation, which imposes taking into account the possible difficulties and planning adjustable solutions for international transportation [27], the aim of the present study was to assess the possibility to apply 1-MCP treatment to maintain the quality of Idared apples for long-distance transportation prolonged for 8 weeks.

2. Materials and Methods

2.1. Studied Groups

The studied fruit were the Idared cultivar apples obtained 23 October 2018, from the orchard in Julianów (51°46' N 20°49' E), in the Belsk Duży district, which were afterwards stored until 2019. The studied apples were from the same orchard, same season and same harvesting, as studied previously [26], so the observations may be compared with those from the previous study.

In the orchard, 15-years old apple trees were planted at 4 m by 1.5 m. The Streif index was calculated to define optimum harvesting time, using a commonly applied equation, based on the firmness, total soluble solids content (TSS), and starch index [28], while a starch index was assessed using a 10-point scale after reaction with Lugol's iodine solution (potassium triiodide) (LifeChem, Szczecin, Poland) [29].

After harvesting, apples were randomly divided into 3 groups: 2 experimental groups and a control group: (I) control group (neither 1-MCP nor MAP applied); (II) 1-MCP applied alone (SmartFresh ProTabs™, AgroFresh Solutions Inc., Philadelphia, PA, USA; 0.65 µL/L; applied directly after harvesting); (III) 1-MCP applied combined with MAP in selected gas permeability bags (Xtend®, StePac L.A. Ltd., Tefen, Israel; applied before simulated long-distance transport).

Afterwards, samples were stored in the experimental storage Ultra Low Oxygen (ULO) chambers of the Institute of Horticultural Sciences of the Warsaw University of Life Sciences (SGGW-WULS). The storage was conducted in the chamber characterized by the following conditions: 1.2% CO₂, 1.2% O₂; temperature of 1 °C; humidity of 95% and it was conducted for 0 weeks (samples not subjected to storage), 10 weeks and 20 weeks.

After ULO storage, 8 weeks of storage simulating long-distance transportation was applied in the experimental storage chamber of the Institute of Horticultural Sciences of the Warsaw University of Life Sciences (SGGW-WULS). The simulated long-distance transportation storage was conducted in the chamber characterized by the temperature of 1 °C.

After simulated long-distance transportation, the simulated distribution was applied at the temperature of 25 °C and it was conducted for 0 days (samples not subjected to distribution), 5 days, 10 days and 15 days.

The experiment included 36 studied groups (3 postharvest treatments × 3 storage periods × 4 distribution periods), as presented in Figure 1. Each studied group constituted 4 batches, 10 random apples each.

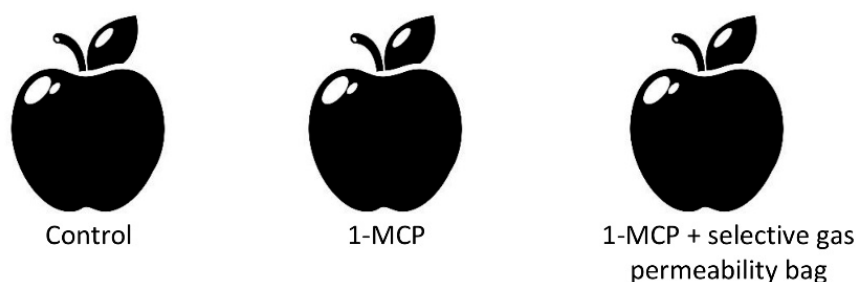


Figure 1. Cont.

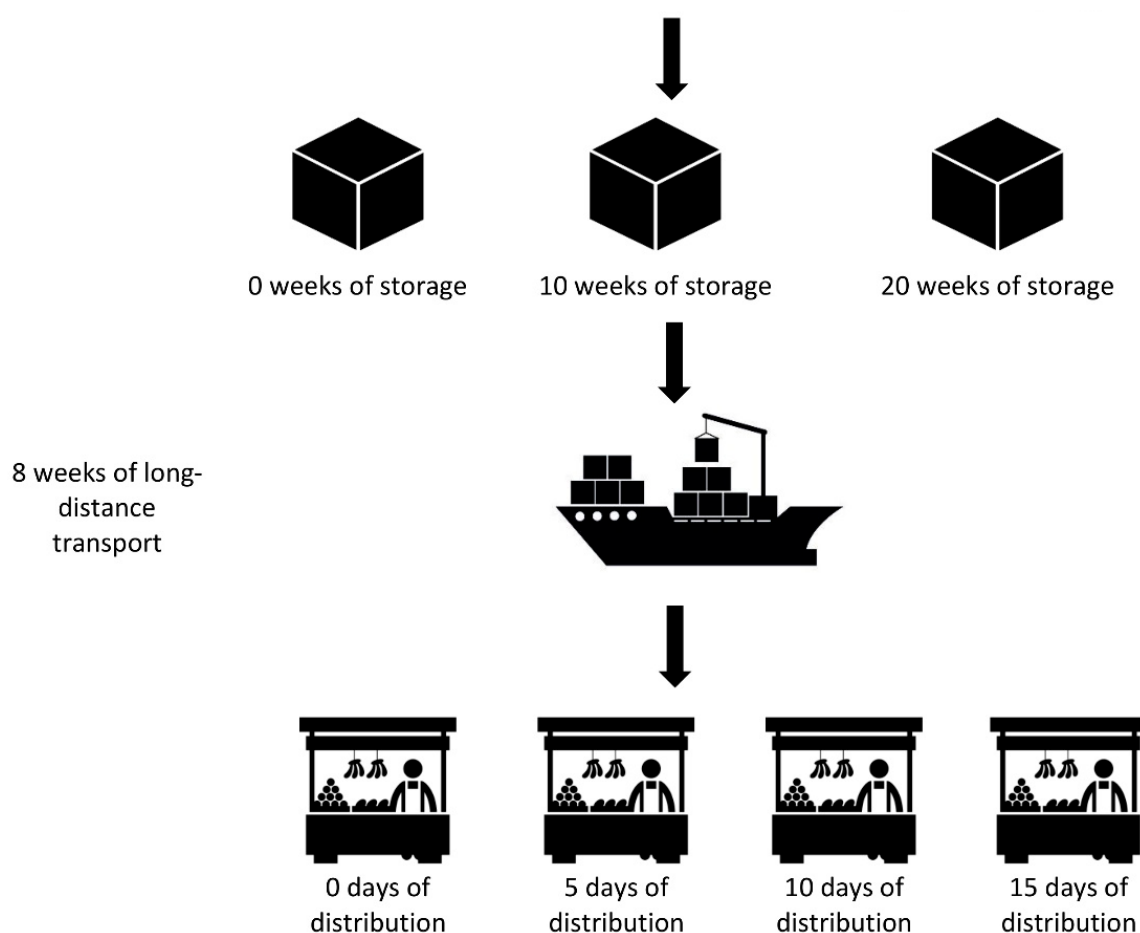


Figure 1. The studied groups of Idared apples; 1-MCP—methylcyclopropene.

2.2. Measurements

The characteristics of the quality parameters of Idared apples assessed directly after harvesting are presented in Table 1. The observed values of ethylene production ($\mu\text{L}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$) for Idared apples after 8 weeks of simulated transportation, for the subgroups subjected to various postharvest treatments, storage duration, and duration of distribution, are presented in Supplementary Table S1.

Table 1. Characteristics of Idared apples assessed directly after harvesting.

Characteristic	Mean $\pm$ SD	Median (25th–75th)
Internal ethylene content [$\mu\text{L}/\text{L}$]	2.90 ± 6.26	0.50 * (0.23–1.81)
Starch index [–]	8.3 ± 1.0	8.0 * (8.0–9.0)
Total soluble solids content [$^{\circ}\text{Bx}$]	13.2 ± 0.3	13.2 (12.9–13.4)
Firmness [N]	59.0 ± 2.2	58.9 (57.1–60.8)
Titrateable acidity [–]	0.51 ± 0.03	0.51 (0.488–0.535)
Streif index [–]	0.054 ± 0.004	0.053 (0.0515–0.0564)

* non-parametric distribution (verified using Shapiro–Wilk test— $p \leq 0.05$).

The measurements included assessment of firmness, TSS and titrateable acidity (TA), as well as Streif index and starch index to define optimum harvesting time.

The firmness was assessed after removing the peel of apple and it was measured twice for each apple (for two opposite sides of the fruit). Within a studied group, 4 batches were assessed, 10 apples each. The measurement was conducted while using the universal testing machine (Instron 5542, Instron, Norwood, MA, USA), with the stainless steel plunger tip (diameter: 11 mm; head speed: 4 mm/s) [30,31]. The results of the assessment of firmness were expressed in Newtons (N).

The TSS was assessed after the firmness analysis and juice extraction from the 4 batches, 10 apples each. The juice was pressed while using the simple extractor and afterwards the measurement was conducted while using the digital refractometer (Atago Palette PR-32, Atago Co., Ltd., Tokyo, Japan) [30,31]. The results of the assessment of TSS were expressed in Degrees Brix ($^{\circ}\text{Bx}$).

The TA was assessed after the firmness analysis and juice extraction from the 4 batches, 10 apples each. The juice was pressed while using the simple extractor and afterwards the measurement was conducted while 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 [30,31]. The results of the assessment of TA were expressed in % after recalculation for malic acid content.

The ethylene production rate [$\mu\text{L}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$] was assessed according Zucoloto et al. [32] with slight modification in regards of temperature. The apples were transferred to a sealed 1400 mL glass jar at 25 $^{\circ}\text{C}$ and after 1 h incubation, and a gas sample (1 mL) was collected in a syringe. For each apple, 1 mL of air was injected and assessed while using the gas chromatography (HP 5890, Hewlett Packard, CA, USA) for ethylene analysis.

2.3. Statistical Analysis

The statistical analysis included analysis of the normality of distribution and comparison of values obtained for the studied groups. The analysis of the normality of distribution was conducted while using Shapiro-Wilk test. The normally distributed variables were compared while using analysis of variance ANOVA with post-hoc Tukey's test for multiple comparisons, while the other variables were compared while using Kruskal–Wallis one-way ANOVA of ranks with post-hoc test. The values of $p \leq 0.05$ indicated significant differences between compared groups. The statistical analysis was conducted using Statistica, 8.0 (Statsoft Inc., Tulsa, OK, USA).

3. Results

The observed values of firmness [N] for Idared apples after 8 weeks of simulated transportation, for the sub-groups subjected to various postharvest treatments, storage duration and duration of distribution are presented in Table 2. It was stated that the applied treatment influenced observed values of firmness within each applied storage duration and duration of distribution ($p < 0.05$). For the majority of the studied durations of storage and distribution, the highest values of firmness were observed for the samples from the group of 1-MCP applied combined with MAP. Only for the samples not subjected to storage and distribution (0 weeks of storage, 0 days of distribution), the highest values of firmness were observed for the samples from the group of 1-MCP applied alone ($p = 0.0157$).

The observed values of TSS [$^{\circ}\text{Bx}$] for Idared apples after 8 weeks of simulated transportation, for the sub-groups subjected to various postharvest treatments, storage duration and duration of distribution are presented in Table 3. It was stated that the applied treatment influenced observed values of TSS within almost each applied storage duration and duration of distribution ($p < 0.05$). Only for samples not subjected to storage and distribution (0 weeks of storage, 0 days of distribution), as well as samples subjected to 10 weeks of storage with 5 days of distribution, 20 weeks of storage with 10 and 15 days of distribution, there was no significant difference between applied treatment groups ($p > 0.05$). For the studied durations of storage and distribution, while there was a significant difference, the highest values of TSS were observed for the samples from the group of 1-MCP applied combined with MAP.

Table 2. The observed values of firmness (N) for Idared apples after 8 weeks of simulated transportation, for the sub-groups subjected to various postharvest treatments, storage duration and duration of distribution.

Type of Treatment		Days of Simulated Distribution			
		0	5	10	15
0 Weeks of Storage					
Control	Mean $\pm$ SD	43.3 $\pm$ 0.5	39.5 $\pm$ 1.4	37.5 $\pm$ 1.8	34.8 $\pm$ 2.4
	Median	43.1 ^{a*}	39.8 ^a	38.1 ^a	34.4 ^a
	(25th–75th)	(43.1–43.6)	(38.4–40.7)	(36.3–38.7)	(32.8–36.8)
1-MCP alone	Mean $\pm$ SD	58.3 $\pm$ 1.5	50.5 $\pm$ 2.7	46.0 $\pm$ 3.3	46.9 $\pm$ 3.6
	Median	58.7 ^b	50.4 ^a	45.8 ^b	48.6 ^{a*}
	(25th–75th)	(57.3–59.4)	(48.6–52.5)	(43.6–48.5)	(44.8–49.1)
1-MCP with MAP	Mean $\pm$ SD	57.0 $\pm$ 1.2	56.2 $\pm$ 2.0	53.4 $\pm$ 3.3	58.6 $\pm$ 5.4
	Median	57.1 ^a	57.2 ^{b*}	53.1 ^c	57.4 ^b
	(25th–75th)	(56.1–58.0)	(55.2–57.3)	(50.7–56.1)	(54.7–62.5)
<i>p</i> -value		0.0157	0.0097	<0.0001	0.0073
10 Weeks of Storage					
Control	Mean $\pm$ SD	45.7 $\pm$ 1.7	40.8 $\pm$ 0.8	37.5 $\pm$ 0.5	37.2 $\pm$ 0.9
	Median	46.4 ^a	40.6 ^a	37.4 ^a	37.1 ^a
	(25th–75th)	(44.6–46.9)	(40.3–41.3)	(37.2–37.9)	(36.4–37.9)
1-MCP alone	Mean $\pm$ SD	56.9 $\pm$ 3.2	53.1 $\pm$ 1.8	52.6 $\pm$ 1.7	49.7 $\pm$ 2.6
	Median	56.6 ^b	53.2 ^b	52.8 ^b	49.3 ^b
	(25th–75th)	(54.9–58.9)	(52.0–54.3)	(51.3–54.0)	(48.1–51.3)
1-MCP with MAP	Mean $\pm$ SD	53.2 $\pm$ 2.9	51.0 $\pm$ 3.1	50.7 $\pm$ 2.5	51.9 $\pm$ 0.9
	Median	53.4 ^b	51.0 ^b	50.7 ^b	52.3 ^b
	(25th–75th)	(51.1–55.4)	(48.3–53.6)	(48.8–52.6)	(51.4–52.5)
<i>p</i> -value		0.0007	<0.0001	<0.0001	<0.0001
20 Weeks of Storage					
Control	Mean $\pm$ SD	41.1 $\pm$ 1.1	38.4 $\pm$ 1.0	38.4 $\pm$ 1.9	37.2 $\pm$ 1.0
	Median	41.0 ^a	38.6 ^a	38.2 ^a	37.5 ^a
	(25th–75th)	(40.3–42.0)	(37.7–39.1)	(37.2–39.6)	(36.5–38.0)
1-MCP alone	Mean $\pm$ SD	51.2 $\pm$ 2.4	50.1 $\pm$ 4.6	52.3 $\pm$ 2.3	45.4 $\pm$ 2.6
	Median	51.3 ^b	51.2 ^b	52.4 ^b	45.1 ^b
	(25th–75th)	(49.6–52.9)	(47.0–53.3)	(50.4–54.2)	(43.5–47.4)
1-MCP with MAP	Mean $\pm$ SD	54.6 $\pm$ 1.9	53.4 $\pm$ 2.5	51.9 $\pm$ 6.5	50.4 $\pm$ 1.9
	Median	55.1 ^b	53.7 ^b	51.3 ^b	50.2 ^c
	(25th–75th)	(53.3–55.9)	(51.3–55.5)	(47.9–55.9)	(49.0–51.9)
<i>p</i> -value		<0.0001	0.0002	0.0015	<0.0001

* distribution different than normal (verified by Shapiro–Wilk test— $p \leq 0.05$); 1-MCP—methylcyclopropene; MAP—Modified Atmosphere Packaging; (N)–Newtons; differing superscript letters indicate significance of differences between compared values within various treatments, storage duration and duration of distribution.

The observed values of (TA) [%] for Idared apples after 8 weeks of simulated transportation, for the sub-groups subjected to various postharvest treatments, storage duration and duration of distribution are presented in Table 4. It was stated that the applied treatment influenced observed values of TA within majority of applied storage duration and duration of distribution ($p < 0.05$). Only for samples not subjected to storage and distribution (0 weeks of storage, 0 days of distribution), samples not subjected to storage with 5 days of distribution, as well as samples subjected to 10 weeks of storage with 15 days of distribution, and 20 weeks of storage with no distribution, there was no significant difference between applied treatment groups ($p > 0.05$). For the majority of studied durations of storage and distribution, while there was a significant difference, the highest values of TA were observed for the samples from the group of 1-MCP applied combined with MAP. Only for the samples subjected to 10 weeks of storage with 5 days of distribution ($p = 0.0073$) and 10 days of distribution ($p = 0.0005$), as well as 20 weeks of storage with

15 days of distribution, the highest values of TA were observed for the samples from the group of 1-MCP applied alone ($p = 0.0352$).

Table 3. The observed values of Total Soluble Solids content (TSS) (°Bx) for Idared apples after 8 weeks of simulated transportation, for the sub-groups subjected to various postharvest treatments, storage duration and duration of distribution.

Type of Treatment		Days of Simulated Distribution			
		0	5	10	15
0 Weeks of Storage					
Control	Mean ± SD	13.08 ± 0.45	12.65 ± 0.38	13.00 ± 0.12	13.10 ± 0.14
	Median	12.95 ^a	12.80 ^a	13.00 ^{ab*}	13.05 ^a
	(25th–75th)	(12.75–13.4)	(12.4–12.9)	(12.9–13.1)	(13–13.2)
1-MCP alone	Mean ± SD	13.25 ± 0.21	12.5 ± 0.08	12.75 ± 0.17	13.23 ± 0.33
	Median	13.25 ^a	12.50 ^a	12.80 ^a	13.20 ^b
	(25th–75th)	(13.10–13.4)	(12.45–12.55)	(12.65–12.85)	(12.95–13.50)
1-MCP with MAP	Mean ± SD	13.38 ± 0.24	13.18 ± 0.32	13.83 ± 0.10	13.80 ± 0.08
	Median	13.30 ^a	13.15 ^b	13.85 ^b	13.80 ^c
	(25th–75th)	(13.20–13.55)	(12.90–13.45)	(13.75–13.90)	(13.75–13.85)
<i>p</i> -value		0.4390	0.0224	0.0321	0.0027
10 Weeks of Storage					
Control	Mean ± SD	12.58 ± 0.38	12.85 ± 0.19	12.80 ± 0.18	12.90 ± 0.08
	Median	12.50 ^a	12.80 ^a	12.80 ^a	12.90 ^a
	(25th–75th)	(12.35–12.80)	(12.70–13.00)	(12.65–12.95)	(12.85–12.95)
1-MCP alone	Mean ± SD	13.30 ± 0.12	13.30 ± 0.32	12.88 ± 0.10	12.85 ± 0.25
	Median	13.30 ^{a*}	13.25 ^a	12.85 ^a	12.80 ^a
	(25th–75th)	(13.20–13.40)	(13.05–13.55)	(12.80–12.95)	(12.70–13.00)
1-MCP with MAP	Mean ± SD	13.50 ± 0.24	13.08 ± 0.25	13.25 ± 0.25	13.28 ± 0.10
	Median	13.45 ^b	13.05 ^a	13.30 ^b	13.25 ^b
	(25th–75th)	(13.30–13.70)	(12.90–13.25)	(13.10–13.40)	(13.20–13.35)
<i>p</i> -value		0.0173	0.0974	0.0173	0.0095
20 Weeks of Storage					
Control	Mean ± SD	12.53 ± 0.10	12.08 ± 0.21	12.50 ± 0.48	12.78 ± 0.52
	Median	12.55 ^a	12.05 ^a	12.50 ^a	13.00 ^{a*}
	(25th–75th)	(12.45–12.60)	(11.90–12.25)	(12.10–12.90)	(12.50–13.05)
1-MCP alone	Mean ± SD	12.53 ± 0.24	12.58 ± 0.36	12.53 ± 0.33	13.08 ± 0.30
	Median	12.60 ^a	12.65 ^b	12.40 ^a	13.00 ^a
	(25th–75th)	(12.35–12.70)	(12.30–12.85)	(12.30–12.75)	(12.90–13.25)
1-MCP with MAP	Mean ± SD	12.85 ± 0.06	12.80 ± 0.12	13.15 ± 0.24	13.00 ± 0.12
	Median	12.85 ^b	12.80 ^b	13.15 ^a	13.00 ^a
	(25th–75th)	(12.80–12.90)	(12.70–12.90)	(12.95–13.35)	(12.90–13.10)
<i>p</i> -value		0.0204	0.0073	0.0529	0.9409

* distribution different than normal (verified by Shapiro–Wilk test— $p \leq 0.05$); 1-MCP—methylcyclopropene; MAP—Modified Atmosphere Packaging; (°Bx)—Degrees Brix; differing superscript letters indicate significance of differences between compared values within various treatments, storage duration and duration of distribution.

Table 4. The observed values of Titratable Acidity (TA) (%) for Idared apples after 8 weeks of simulated transportation, for the sub-groups subjected to various postharvest treatments, storage duration and duration of distribution.

Type of Treatment		Days of Simulated Distribution			
		0	5	10	15
0 Weeks of Storage					
Control	Mean ± SD	0.481 ± 0.048	0.452 ± 0.009	0.387 ± 0.008	0.384 ± 0.012
	Median	0.477 ^a	0.451 ^a	0.386 ^a	0.383 ^a
	(25th–75th)	(0.442–0.521)	(0.444–0.460)	(0.380–0.393)	(0.376–0.393)

Table 4. Cont.

Type of Treatment		Days of Simulated Distribution			
		0	5	10	15
1-MCP alone	Mean $\pm$ SD	0.446 $\pm$ 0.038	0.462 $\pm$ 0.086	0.464 $\pm$ 0.019	0.467 $\pm$ 0.011
	Median	0.454 ^a	0.426 ^{a*}	0.465 ^b	0.466 ^b
	(25th–75th)	(0.422–0.470)	(0.416–0.509)	(0.450–0.479)	(0.458–0.476)
1-MCP with MAP	Mean $\pm$ SD	0.475 $\pm$ 0.011	0.456 $\pm$ 0.018	0.447 $\pm$ 0.010	0.431 $\pm$ 0.023
	Median	0.473 ^a	0.451 ^a	0.449 ^b	0.431 ^c
	(25th–75th)	(0.468–0.483)	(0.443–0.469)	(0.440–0.454)	(0.412–0.451)
<i>p</i> -value		0.3679	0.4724	<0.0001	0.0002
10 Weeks of Storage					
Control	Mean $\pm$ SD	0.390 $\pm$ 0.010	0.3478 $\pm$ 0.008	0.356 $\pm$ 0.015	0.381 $\pm$ 0.014
	Median	0.390 ^a	0.351 ^{a*}	0.357 ^a	0.382 ^a
	(25th–75th)	(0.380–0.396)	(0.343–0.353)	(0.345–0.368)	(0.372–0.389)
1-MCP alone	Mean $\pm$ SD	0.406 $\pm$ 0.014	0.475 $\pm$ 0.013	0.402 $\pm$ 0.006	0.380 $\pm$ 0.011
	Median	0.401 ^a	0.478 ^b	0.403 ^b	0.379 ^a
	(25th–75th)	(0.396–0.416)	(0.466–0.483)	(0.398–0.406)	(0.372–0.389)
1-MCP with MAP	Mean $\pm$ SD	0.453 $\pm$ 0.010	0.416 $\pm$ 0.006	0.355 $\pm$ 0.013	0.387 $\pm$ 0.015
	Median	0.455 ^b	0.416 ^{ab}	0.356 ^a	0.381 ^a
	(25th–75th)	(0.447–0.4500)	(0.411–0.420)	(0.345–0.365)	(0.377–0.396)
<i>p</i> -value		0.0001	0.0073	0.0005	0.7693
20 Weeks of Storage					
Control	Mean $\pm$ SD	0.375 $\pm$ 0.014	0.299 $\pm$ 0.01	0.285 $\pm$ 0.006	0.207 $\pm$ 0.101
	Median	0.372 ^a	0.297 ^a	0.284 ^a	0.247 ^a
	(25th–75th)	(0.364–0.386)	(0.296–0.302)	(0.281–0.290)	(0.147–0.268)
1-MCP alone	Mean $\pm$ SD	0.378 $\pm$ 0.010	0.358 $\pm$ 0.020	0.356 $\pm$ 0.015	0.339 $\pm$ 0.011
	Median	0.376 ^a	0.364 ^b	0.357 ^b	0.343 ^b
	(25th–75th)	(0.370–0.386)	(0.346–0.369)	(0.347–0.366)	(0.332–0.346)
1-MCP with MAP	Mean $\pm$ SD	0.386 $\pm$ 0.020	0.346 $\pm$ 0.011	0.364 $\pm$ 0.026	0.267 $\pm$ 0.014
	Median	0.380 ^a	0.344 ^b	0.354 ^b	0.264 ^{ab}
	(25th–75th)	(0.372–0.400)	(0.340–0.353)	(0.349–0.380)	(0.258–0.277)
<i>p</i> -value		0.5983	0.0004	0.0002	0.0352

* distribution different than normal (verified by Shapiro–Wilk test— $p \leq 0.05$); 1-MCP—methylcyclopropene; MAP—Modified Atmosphere Packaging; differing superscript letters indicate significance of differences between compared values within various treatments storage duration and duration of distribution.

4. Discussion

The recent meta-analysis of the effects of 1-MCP treatment on climacteric fruit ripening, by Zhang et al. [20], revealed that while there are 44 ripening indicators, 1-MCP treatment reduced 20 of the 44 indicators by a minimum of 22% and increased 6 indicators by at least 20%, causing positive effects on delaying ripening and maintaining quality. At the same time, species, 1-MCP concentration, storage temperature and time had significant influence on the responses of fruit to 1-MCP treatment [20]. Taking this into account, it must be emphasized that the treatment including not only 1-MCP application, but also decreased temperature of storage that is conducted for the scheduled period, and being planned within the whole process, combined with specific 1-MCP concentration, dedicated for a specie may allow to obtain the effect of reduced fruit quality losses and increased acceptance of quality features.

1-MCP may be applied in various systems—both preharvest [33,34] and postharvest [32,35], while in the case of apples both options are studied. Moreover, the postharvest treatment is indicated as especially promising in long-term storage of apples to maintain the quality of fruits, in spite of the fact that some studies revealed that it may in some extent reduce the antioxidant compounds content [36]. The indicated conclusions by Kolniak-Ostek et al. [36] are in agreement with the presented results of the own study,

which revealed not only positive effect of the 1-MCP, but also even better results of 1-MCP combined with MAP. Such effect was observed, in spite of the fact that the applied 1-MCP concentration (0.65 $\mu\text{L/L}$) was lower than the optimal concentration of 1.0 $\mu\text{L/L}$ (which was defined by the meta-analysis by Zhang et al. [22]), as well as both storage and distribution temperature (1 $^{\circ}\text{C}$ and 25 $^{\circ}\text{C}$, respectively) were higher than the optimal temperatures of 0 $^{\circ}\text{C}$ and 20 $^{\circ}\text{C}$, respectively (also defined by the meta-analysis by Zhang et al. [22]). Taking this into account, it may be supposed that applying higher concentration of 1-MCP and lower temperature may allow to observe even better results of maintained quality of fruits.

The observed results of the conducted study must be indicated as especially promising, as the applied 1-MCP treatment influenced all the studied quality features of fruit—firmness, TSS and TA and the influence was stated within each applied storage duration and duration of distribution. The firmness, TSS and TA are the quality features especially important for the consumers. The firmness is defined as one of the most important features of apples, associated with its quality [37]. Based on the study which was conducted for various apple cultivars, it was stated that the optimum firmness depends on the cultivar, but it is on the level of 50–60 N [38]. At the same time it is indicated that apples characterized by the firmness lower than 44.5 N may be perceived by consumers as too soft [39]. In the presented study, while 1-MCP was applied either alone or combined with MAP, firmness was always higher than 44.5 N, but if it was applied combined with MAP, firmness was always even higher than 50 N. At the same time, if 1-MCP was not applied, depending on the storage time and distribution time, firmness was 34–46 N (lowest for the longest period of simulated distribution), which means firmness lower than optimum [38] and sometimes even lower than acceptable [39].

While firmness is perceived by consumers as associated with the freshness of apples, similarly as juiciness [40], the TSS and TA are related to consumers recognition of the nutritional value [41], as they are associated with taste of apple [42]. During the natural ripening of the apple fruit, both TSS and TA are decreasing [43], while the decrease depends on the storage conditions, including temperature and time [44]. Similarly, as observed for firmness, the higher values of TSS and TA, which were observed while 1-MCP was applied, may be associated with the higher acceptability of apples, while for the majority of cases applying 1-MCP combined with MAP allowed obtaining even higher values than 1-MCP applied alone.

The indicated benefits of the 1-MCP may also be associated with the potential influence on the frequency of chilling injury that may be caused by low-temperature storage, which was applied [45]. It is especially important that 1-MCP may suppress disorders related to low temperature; thus, near-freezing temperatures of 0 $^{\circ}\text{C}$ were indicated in a meta-analysis by Zhang et al. [22] as optimum while applying 1-MCP. At the same time, carbohydrates and amino acids play protective roles in chilling injury development, so the influence may differ depending on the type of apples [46]. As this problem was not studied within the conducted research, it should be indicated as a potential area of further analysis.

While compared the results observed in the present study with the results of the study which was conducted for the shorter period of simulated long-distance transportation (6 weeks) [26], it must be stated that longer period of transportation allowed observing more recognizable differences between the studied groups (while the conditions of storage, transportation and distribution were the same and the duration of transportation was the only difference). While the 6 weeks of transportation was applied, it was stated that even if 1-MCP contributed to higher results of TSS and TA, combining this treatment with MAP did not cause any further differences [26]. Based on the described comparison, it may be stated that especially while prolonging the transportation of apples, it is necessary to apply not only dedicated 1-MCP treatment, but also combining it with MAP to increase the observed positive effect.

In spite of the fact that within the study the possibility to apply 1-MCP treatment to maintain the quality of Idared apples for prolonged long-distance transportation was

assessed, and important observations were made, the limitations of the study should be described. The most important issue results from the fact that observations were described on the basis of the experiment conducted for one harvesting and one storage season, while the experiment was not reproduced during the following seasons. The other limitation is associated with the fact that the respiration rate was not measured, which is an important parameter for climacteric fruit, and it would allow to strengthen observations from the study. Moreover, within the study it was decided to prolong the transportation to 8 weeks, but it was not verified if this period may be even longer, so it should also be studied in the future.

5. Conclusions

It may be concluded that applying 1-MCP in the case of Idared apples for long-distance transportation allows prolonging it to 8 weeks without decreasing quality of fruits. Applying 1-MCP combined with MAP allows obtaining even better results than 1-MCP alone, after 8 weeks of transportation. It may be recommended to apply 1-MCP combined with MAP in order to slow the ripening process and to maintain the quality of apples during long-distance transportation.

Supplementary Materials: The following are available online at <https://www.mdpi.com/2073-4395/11/3/528/s1>, Table S1: The observed values of ethylene production ($\mu\text{L}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$) for Idared apples after 8 weeks of simulated transportation, for the sub-groups subjected to various postharvest treatments, storage duration, and duration of distribution.

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