

Article

Key Determinants of Postharvest Quality in ‘Gala Schniga’[®] SchniCo Red(s)’ Apples: Firmness Retention at the Target Market After Long-Distance Transport

Maria Małachowska *, Józef Grzębski and Kazimierz Tomala

Department of Pomology and Horticulture Economics, Institute of Horticultural Sciences, Warsaw University of Life Sciences (SGGW-WULS), ul. Nowoursynowska 159 C, 02-787 Warsaw, Poland; jozef_grzebski@sggw.edu.pl (J.G.); kazimierz_tomala@sggw.edu.pl (K.T.)

* Correspondence: maria_malachowska@sggw.edu.pl; Tel.: +48-22-593-2103

Abstract

The objective of this study was to identify the factors that most strongly influence the postharvest quality of ‘Gala Schniga’[®] SchniCo Red(s)’ apples under conditions of simulated transport and simulated trading at elevated temperature following long-term storage. The study was conducted over two storage seasons (2022/2023 and 2023/2024) on fruit originating from the experimental orchard of the Warsaw University of Life Sciences (SGGW-WULS) in Warsaw. The effects of harvest date (optimal—OHD and delayed by 14 days—DH), four variants of 1-MCP (1-methylcyclopropene) application: (control, Harvista[™]—preharvest, SmartFresh[™]—postharvest, and Harvista[™] + SmartFresh[™]), controlled-atmosphere storage technology (ULO 1: 1.2% CO₂ and 1.2% O₂; ULO 2: 0.6% CO₂ and 0.6% O₂), storage period (5, 7, and 9 months), duration of simulated transport (4 or 6 weeks at 1 °C in normal atmosphere), and shelf life (0, 7, and 14 days at 25 °C) were analyzed. Five quality parameters were evaluated: firmness (F), soluble solids content (SSC), titratable acidity (TA), SSC/TA ratio, and 1-aminocyclopropane-1-carboxylic acid (ACC) content. Stepwise regression with backward elimination was applied to identify significant predictors, and partial eta squared (η^2) was calculated to compare the relative strength of effects. Postharvest 1-MCP application had the greatest impact on maintaining firmness and TA (F: $\eta^2 = 75.8\%$; TA: $\eta^2 = 56.3\%$), whereas shelf life was the key factor in the deterioration of quality parameters after removal from storage (F: $\eta^2 = 55.5\%$; TA: $\eta^2 = 30.1$) and in increasing the SSC/TA ratio ($\eta^2 = 29.6\%$). Harvest date strongly differentiated firmness ($\eta^2 = 51.3$) and significantly affected TA ($\eta^2 = 14.4$), while storage period had the greatest effect on ACC content ($\eta^2 = 14.2$) and TA decline ($\eta^2 = 15.6$). Preharvest 1-MCP application had a smaller effect on F and TA but significantly reduced SSC ($\eta^2 = 24.9$), highlighting the importance of the timing of ethylene inhibitor application. The effects of simulated transport and preharvest weather indicators were statistically significant but relatively small compared with the effects of postharvest technological decisions and exposure time under retail conditions. The results indicate that maintaining target quality parameters throughout an extended supply chain requires precise determination of the harvest date, prioritizing postharvest 1-MCP application, and limiting shelf life under elevated-temperature conditions.

Keywords: apple; quality; 1-MCP; ULO; ethylene; firmness; titratable acidity

Academic Editor: Perla A. Gómez

Received: 15 April 2026

Revised: 4 June 2026

Accepted: 25 June 2026

Published: 26 June 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article

distributed under the terms and

conditions of the [Creative Commons](https://creativecommons.org/licenses/by/4.0/)

[Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Apples are among the most important fruits of the temperate climate and constitute a significant segment of the global fresh fruit market, both in terms of production volume and economic importance. Global apple production exceeds 90 million tons annually, and a substantial proportion is intended for long-term storage and international trade, which imposes high requirements on maintaining postharvest quality [1,2]. Therefore, a key challenge remains maintaining stable fruit quality throughout an extended storage and distribution chain, including storage, transport, and shelf life [3,4].

The postharvest quality of apples results from a complex interaction of pre- and post-harvest factors. Among the preharvest factors, meteorological conditions during the growing season, water availability, air temperature, and the degree of fruit maturity at harvest are of major importance [5–7]. Weather conditions affect the rate of sugar accumulation, the metabolism of organic acids, and the synthesis of ethylene precursors, thereby determining the storage potential of apples at harvest [8].

One of the key regulators of apple ripening and senescence processes is ethylene—a phytohormone responsible for initiating and regulating a range of metabolic processes, including cell wall degradation [9], starch hydrolysis [10–12], changes in the profile of organic acids [13,14], and the synthesis of aroma compounds [15]. In response, 1-methylcyclopropene (1-MCP), an ethylene receptor inhibitor, is widely used in storage practices, effectively slowing flesh softening, limiting decreases in acidity, and delaying metabolic changes during storage [7,8]. At the same time, it has been demonstrated that the effectiveness of 1-MCP depends not only on the applied dose but also on the timing of application—preharvest or postharvest—and on interactions with harvest maturity and storage conditions [3,16].

At the same time, storage technology plays an important role in maintaining apple quality. Storage under controlled atmosphere (CA), ultra-low oxygen (ULO), and dynamic controlled atmosphere (DCA) conditions allows limiting respiration rate and senescence by reducing oxygen concentration and increasing carbon dioxide content [17,18]. However, the effectiveness of these technologies varies widely depending on cultivar, harvest maturity, and the use of additional ethylene-regulating tools, such as 1-MCP [18]. It has been reported that when 1-MCP is applied simultaneously, differences between ULO and DCA in basic quality parameters may be reduced, becoming more apparent in the profiles of volatile aroma compounds and sensory quality [19]. This highlights the need for a comprehensive evaluation of storage technologies, not only in terms of physicochemical parameters but also in terms of their potential impact on consumer acceptance.

Increasing attention is also being paid to the final stages of the supply chain, such as transport and shelf life, which may significantly affect the quality of fruit delivered to consumers. Studies indicate that even under optimal storage conditions, exposure of fruit to higher temperatures and lower relative humidity during distribution results in accelerated firmness loss, decreased acidity, and an increase in the SSC/TA ratio [4,20]. In the present study, fruit were subjected to a shelf-life temperature of 25 °C, which exceeds the standard temperature range typically applied in shelf-life assessments (18–20 °C). This experimental condition was selected to simulate a more challenging postharvest scenario, representative of prolonged transportation, and commercialization in distant markets characterized by elevated ambient temperatures. Accordingly, the obtained results should be interpreted as an evaluation of the fruit's ability to preserve quality under increased thermal stress throughout the postharvest supply chain, rather than as a prediction of quality changes occurring under optimally controlled retail storage and distribution conditions.

Despite numerous studies on the effects of individual factors on apple quality, there remains a lack of comprehensive analyses that simultaneously account for preharvest weather conditions, harvest date, pre- and postharvest 1-MCP applications, storage technology, and simulated transport and shelf-life conditions. In particular, it is essential to determine the relative strength of these factors in shaping key quality parameters, such as flesh firmness, titratable acidity (TA), soluble solids content (SSC), SSC/TA ratio, and the content of 1-aminocyclopropane-1-carboxylic acid (ACC) as an ethylene precursor.

The aim of this study was to provide a comprehensive assessment of the impact of selected pre- and postharvest factors on the quality of ‘Gala Schniga® SchniCo Red(s)’ apples under simulated retail conditions at elevated temperature (25 °C), following long-term simulated transport and varying storage period.

The study presented in this paper extends and complements the authors’ previous work [21], which focused on the quality assessment of apples intended for local markets characterized by short distribution chains. In the previously published study, the shelf-life period was defined as 7 days at 20 °C and was applied immediately after cold storage, thereby reflecting conditions typical of short supply chains in markets located in close proximity to the production area. That study investigated the effects of harvest date, 1-MCP treatment, storage technology, storage duration, shelf-life period, and selected meteorological factors over two consecutive storage seasons; however, it did not include an extended postharvest stress scenario representative of export conditions to distant markets.

A novel aspect of the present study is the explicit incorporation of long-distance logistics into the experimental design. After 5, 7, or 9 months of cold storage, fruit were subjected to 4- or 6-week simulated transport at 1 °C, followed by a shelf-life period of 0, 7, or 14 days at 25 °C. This experimental design enables the assessment of the relative importance of harvest date, timing of 1-MCP application, storage regime, transport duration, and shelf-life conditions under elevated temperature, corresponding to supply chains directed toward distant and warmer export markets. In particular, the present study allows for the identification of the key factors determining the maintenance of fruit quality and marketable life throughout the entire period encompassing storage, transport, and shelf life, an aspect not addressed in the previous publication.

2. Materials and Methods

2.1. Plant Material

The study was conducted over two consecutive storage seasons (2022/2023 and 2023/2024) on fruit of the apple (*Malus domestica* Borkh.) cultivar ‘Gala Schniga® SchniCo Red(s)’. The apples originated from the experimental orchard of the Warsaw University of Life Sciences (SGGW-WULS) in Warsaw (52°14′ N, 21°01′ E). Trees grafted on M.9 rootstock were planted in 2014 at a spacing of 3.0 × 1.0 m and were managed according to the principles of integrated fruit production.

In both seasons, the fruit were uniform in size (140–150 g) and originated from trees of similar vigor. Only fruit free from mechanical damage and disease symptoms were selected for analysis.

2.2. Harvest Date and 1-MCP Treatments

In each season, fruit were harvested at two maturity stages determined by the Streif index, which combines firmness, soluble solids content, and the starch degradation index. The first harvest corresponded to the optimal harvest date (OHD), whereas the second was performed 14 days later and was defined as a delayed harvest (DH).

In the 2022/2023 season, fruit at OHD was harvested on 13 September 2022, corresponding to 122 days after full bloom (DAFB), while the delayed harvest was conducted on 27 September 2022 (136 DAFB). In the 2023/2024 season, the respective harvest dates were 12 September 2023 for OHD (121 DAFB) and 26 September 2023 for DH (135 DAFB).

The experiment included three active 1-MCP treatments and one untreated control. The active treatments were: preharvest 1-MCP application (Harvista™), postharvest 1-MCP treatment (SmartFresh™), and combined Harvista™ + SmartFresh™ treatment. Untreated fruit served as the control and received no 1-MCP exposure.

The preharvest treatment was applied 7 days before the optimal harvest date (OHD) to 100 trees using Harvista™ (AgroFresh Solutions Inc., Philadelphia, PA, USA), at a dose equivalent to 150 g·ha⁻¹ of 1-MCP as the active ingredient, in accordance with the manufacturer's recommendations. The product was applied as a foliar spray using an orchard sprayer equipped with a dedicated dosing system and a Harvista™ application unit. During application, the sprayer tank contained only water, while the product concentrate was metered separately and mixed with water immediately prior to spraying. The treatment was performed under dry field conditions, with no rainfall during application and under weather conditions conducive to uniform coverage of fruit and foliage.

For the postharvest treatment, fruit harvested at the OHD were stored in air at 1 °C for 7 days prior to exposure to SmartFresh™ ProTabs (AgroFresh Solutions Inc., Philadelphia, PA, USA), delivering 1-MCP at a concentration of 0.65 µL·L⁻¹ active ingredient. This 7-day interval was introduced to standardize postharvest handling and to reflect a practical short-term cold storage period prior to treatment. The application was conducted for 24 h in sealed chambers at 1 °C, without prior warming of the fruit, in order to minimize temperature-induced changes in quality before the initiation of long-term storage.

2.3. Storage Conditions and Simulated Trading

After harvest, the fruit were stored at 1 °C and approximately 95% relative humidity under two controlled-atmosphere storage technologies:

- ULO 1 (Ultra-Low Oxygen): 1.2% CO₂ and 1.2% O₂,
- ULO 2: 0.6% CO₂ and 0.6% O₂.

The storage period was 5, 7, or 9 months. After storage, the fruit were subjected to simulated transport lasting 4 or 6 weeks under conditions corresponding to long-distance refrigerated transport (temperature 1 °C, normal atmosphere: 78% N₂; 21% O₂; 0.05% CO₂).

Subsequently, the fruit were held at 25 °C under normal atmosphere conditions to simulate elevated-temperature handling in a warm target market. Quality assessments were performed at three time points: directly after the end of transport (0 days), after 7 days, and after 14 days at 25 °C. The 25 °C condition was selected as a deliberately severe shelf-life scenario, allowing comparison of fruit resistance to post-storage temperature elevation across different treatments.

The inclusion of three assessment time points at 25 °C resulted in 288 experimental groups in each season, yielding a total of 576 independent analytical combinations over the two-year experimental cycle.

2.4. Determination of Fruit Quality Parameters

All analyses were carried out in four replicates per experimental combination, with 10 fruits in each replicate.

Flesh firmness was measured using a universal testing machine (Instron 5542, Instron, Norwood, MA, USA) equipped with an 11 mm-diameter cylindrical puncture probe. Measurements were performed after peel removal. Two measurements were taken on opposite sides of each fruit, and the results were expressed in newtons (N).

Soluble solids content (SSC) was determined refractometrically (Atago, Palette PR-32, Atago Co., Ltd., Tokyo, Japan) in fresh fruit juice, and the results were expressed in degrees Brix ($^{\circ}\text{Bx}$).

Titrateable acidity (TA) was measured with an automatic titrator (TitroLine 5000, Xylem Analytics Germany GmbH, Weilheim, Germany) by neutralizing the juice sample to pH 8.1 with 0.1 M NaOH. The results were expressed as a percentage of malic acid. The SSC/TA ratio was calculated as the quotient of soluble solids content and titrateable acidity.

The content of 1-aminocyclopropane-1-carboxylic acid (ACC) was determined by gas chromatography (HP 5890, Hewlett Packard, Palo Alto, CA, USA) using procedures adapted from previously published methodologies [22–24]. The methodological modifications included the collection of gas samples for ethylene analysis 2 min after conversion, as well as the inclusion of ACC-spiked samples at concentrations of 0.1 and 0.2 mM in the calculations. This approach was implemented to standardize the analytical response across samples differing in ripening stage and postharvest treatment, thereby improving the comparability of ethylene measurements.

Ethylene production was determined for individual fruits during a 14-day storage period at 25 $^{\circ}\text{C}$. The fruit were weighed and placed in hermetically sealed containers with a capacity of 1500 mL. After 1 h, a 1 mL air sample was collected from the headspace and analyzed by gas chromatography (HP 5890, Hewlett Packard, Palo Alto, CA, USA). Measurements were performed on five fruits per experimental combination, and the results were expressed in $\mu\text{L}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$. A detailed description of the analytical procedure is provided in previous studies [3,20]. The results illustrating these parameters are presented in the Supplementary Materials.

Respiration rate was determined on fruit placed in hermetically sealed 1500 mL jars at 25 $^{\circ}\text{C}$ over a 14-day storage period. After 1 h, the CO_2 concentration was measured using an F-950 Three Gas Analyzer (Felix Instruments, Camas, WA, USA). Measurements were performed on the same five individual fruits from each experimental combination that had previously been used to determine ethylene production. The results were expressed as $\text{mL CO}_2\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$. The results illustrating these parameters are presented in the Supplementary Materials.

The F-950 analyzer was selected for gas analysis due to its ability to provide rapid and simple measurements. The instrument is equipped with a sampling and gas-transfer system fitted with a needle, allowing air to be drawn from inside the container. The determination of carbon dioxide concentration is based on an electrochemical cell.

2.5. Independent Variables and Their Coding

For statistical analysis, nine independent variables (X_1 – X_9) were defined, encompassing weather conditions, technological treatments, harvest parameters, storage conditions, and simulated commercial turnover.

Weather-related variables included the number of days with an average air temperature below 15 $^{\circ}\text{C}$ within the last 30 (or 44) days before harvest (X_1) and the number of days with cumulative precipitation above 6 mm (X_2). The application of 1-MCP before harvest (X_3) and after harvest (X_5), as well as the date of harvest (X_4), were coded as binary variables.

Storage technology (X_6) was coded as a binary variable (ULO 1 = 0, ULO 2 = 1), storage period (X_7) as an ordinal variable (5, 7, or 9 months), length of simulated transport (X_8) as a numerical variable (4 or 6 weeks), whereas shelf life (X_9) was coded as an ordinal variable, where 0 corresponded to no simulated shelf life, 1 to 7 days, and 2 to 14 days of holding at 25 $^{\circ}\text{C}$ under conditions representative of warmer-climate markets.

This approach to variable coding allowed for the simultaneous inclusion of factors of different types (continuous, binary, and categorical) in stepwise regression analysis, enabling the assessment of both their statistical significance and their relative influence on the

analyzed quality parameters of ‘Gala Schniga® SchniCo Red(s)’ apples. A detailed description of the variables and their numerical coding is provided in Table 1.

Table 1. List of independent variables included in the models, their categorical levels, and the numerical codes assigned for the purposes of regression modeling and partial eta squared (η^2) calculations.

Independent Variables		Category	Code
Number of days with an average air temperature below 15 °C within the last 30 (or 44) days before harvest (X_1) *	2022/2023	optimal harvest date	13
		delayed harvest	25
	2023/2024	optimal harvest date	1
		delayed harvest	3
Number of days when cumulated precipitation was above 6 mm (X_2) *	2022/2023	optimal harvest date	22
		delayed harvest	22
	2023/2024	optimal harvest date	15
		delayed harvest	17
1-MCP treatment before harvest (X_3)	without treatment		0
	with treatment		1
Date of harvest (X_4)	optimal harvest date		0
	delayed harvest		1
1-MCP treatment after harvest (X_5)	without treatment		0
	with treatment		1
Storage technology (X_6)	ULO 1 (Ultra-Low Oxygen)		0
	ULO 2		1
Storage period (X_7)	5 months		5
	7 months		7
	9 months		9
Length of simulated transport (X_8)	4 weeks		4
	6 weeks		6
Shelf life (X_9)	0 days (no simulated shelf life)		0
	7 days		1
	14 days		2

* Code explanation: The values represent the number of days in the final 30- or 44-day period before harvest during which the specified condition was recorded. For example, for OHD the count was 13 in 2022/23 and 1 in 2023/24, whereas for DH it was 25 and 3, respectively. In the case of “days with cumulated precipitation > 6 mm,” the counts for OHD and DH were the same (for instance, both were 22 in 2022/23), indicating that no such days were noted in the interval between OHD and DH.

2.6. Statistical Analysis

To identify factors significantly affecting apple quality parameters, a multiple-stepwise regression analysis with backward elimination was applied. The initial model included all defined independent variables (X_1 – X_9).

In subsequent steps, predictors with the lowest p -values were removed from the model until the final model included only variables significant at the $\alpha = 0.05$ level. The analysis was performed separately for five dependent variables: firmness, SSC, TA, SSC/TA ratio, and ACC content.

Both unstandardized and standardized regression coefficients (β) were reported, together with their corresponding p -values. In addition, partial eta squared (η^2) values were calculated as a measure of effect size, indicating the proportion of variance in the dependent variable explained by a given independent variable while controlling for the remaining predictors. Partial η^2 values are not additive because each value expresses the effect of

a given factor after accounting for the other factors included in the model; consequently, the values should not be summed to 100%.

All statistical analyses were conducted using Statistica 13.3 (StatSoft Inc., Tulsa, OK, USA) and IBM SPSS Statistics version 31 (IBM Corp., Armonk, NY, USA).

3. Results

3.1. Meteorological Conditions During the Growing Periods (2022–2023)

Monthly mean air temperatures and monthly sums of atmospheric precipitation recorded at the Wilanów meteorological station in Warsaw (52°9'36.1" N, 21°5'58.2" E) from April to September in 2022 and 2023 were analyzed using climatodiagrams developed according to the Walter and Lieth method [25]. This approach allows temperature and precipitation to be presented simultaneously on a scale where 1 °C corresponds to 4.5 mm of precipitation. It also allows distinguishing wet periods, when precipitation exceeds temperature, from dry periods, when temperature exceeds precipitation.

In 2022, air temperature increased gradually from approximately 7 °C in April to around 21 °C in August, and then declined to about 13 °C in September. The highest precipitation total, exceeding 120 mm, was recorded in June, indicating a temporary moisture surplus. From July to September, dry conditions predominated.

In 2023, the temperature pattern was similar; however, September remained distinctly warmer than in the previous year. The distribution of precipitation was less favorable: precipitation exceeded temperature only in April, while dry conditions persisted from May to September, potentially exacerbating plant water stress.

A comparison of the two years indicates that the 2023 growing season was generally warmer and drier than that of 2022, particularly in the second half of the analyzed period. These differences may have affected plant growth, fruit ripening dynamics, and fruit quality and storage potential. A detailed characterization of the weather conditions was presented by Małachowska and Tomala [21].

Table 2 presents the descriptive statistics of the quality parameters of apples analyzed in the 2022/2023 and 2023/2024 storage seasons. A total of 2304 observations ensured high representativeness of the sample and the reliability of the results. Firmness exhibited a wide range of variability—from 28.6 to 81.4 N—with a mean of 53.3 N and a standard deviation of 12.1 N. The high values of the coefficient of determination ($R^2 = 0.93$; adjusted $R^2 = 0.86$) indicate a very good fit of the model describing the trait's variability, suggesting its strong dependence on the analyzed factors.

Titrateable acidity ranged from 0.10 to 0.41% malic acid, with a mean value of 0.21% and relatively low variability ($SD = 0.04$). The values of the coefficient of determination ($R^2 = 0.82$) and adjusted R^2 (0.68) indicate a good, although clearly weaker than in the case of firmness, level of explanation of the observed variability.

Soluble solids content (SSC) ranged from 10.4 to 15.7 °Bx, with a mean of 12.9 °Bx. The low standard deviation (0.8 °Bx) indicates a relatively homogeneous level of this trait in the studied population. Compared with flesh firmness, the values of the coefficient of determination ($R^2 = 0.70$) and adjusted R^2 (0.49) were lower, suggesting a limited effectiveness of the model in explaining the variability of this parameter.

The SSC/TA ratio exhibited a very wide range (33–118), reflected in a high standard deviation (12.4). The mean value of this parameter was 62.6. The relatively high values of the coefficient of determination ($R^2 = 0.78$) and adjusted R^2 (0.61) indicate that the variability of this index was explained to a large extent by the applied model.

ACC content showed the greatest relative variability, with values ranging from 0.001 to 4.22 nmol·kg^{−1}, a mean of 0.29 nmol·kg^{−1}, and a standard deviation of 0.32. The low values of the coefficient of determination ($R^2 = 0.57$) and the adjusted R^2 (0.33) indicate a

relatively poor model fit, suggesting substantial influence from random factors or nonlinear physiological processes associated with fruit ripening and storage.

Table 2. Summary statistics for analytical results of ‘Gala Schniga® SchniCo Red(s)’ apples across the 2022/2023 and 2023/2024 storage seasons.

Indicator	<i>n</i>	Min.	Max.	Average	SD *	R ²	Corrected R ²
Firmness (N)		28.6	81.4	53.3	12.1	0.93	0.86
Titrateable acidity (% malic acid)		0.10	0.41	0.21	0.04	0.82	0.68
Soluble solids content (°Bx)	2304	10.4	15.7	12.9	0.8	0.70	0.49
SSC/TA		33.0	118	62.6	12.4	0.78	0.61
ACC (nmol·kg ^{−1})		0.001	4.22	0.29	0.32	0.57	0.33

* SD—standard deviation.

3.2. Firmness (*F*)

Based on the results of stepwise multiple regression analysis (Table 3), firmness of ‘Gala Schniga® SchniCo Red(s)’ apples was found to be significantly influenced by both preharvest weather conditions and technological factors related to harvest as well as storage period and conditions ($p < 0.001$ for all variables included in the model).

The strongest positive effect on firmness was observed with postharvest 1-MCP application ($\beta = 0.656$), confirming its key role in delaying fruit ripening and senescence. A significant, although markedly weaker, positive effect was also observed for the number of days with precipitation exceeding 6 mm ($\beta = 0.208$) and the number of days with an average air temperature below 15 °C in the preharvest period ($\beta = 0.186$), indicating a beneficial influence of cooler and wetter conditions on maintaining flesh firmness.

The date of harvest proved to be one of the main factors reducing firmness ($\beta = -0.442$), highlighting the importance of precise harvest timing for maintaining postharvest quality. Similarly, shelf life had a strong negative effect on firmness ($\beta = -0.414$), reflecting the progressive degradation of fruit tissue during the final stages of the distribution chain.

Variables with a smaller yet statistically significant effect included storage period ($\beta = -0.058$) and length of simulated transport ($\beta = -0.050$), both of which contributed to a gradual decline in firmness. Preharvest 1-MCP application showed a positive but relatively minor effect ($\beta = 0.069$).

The final regression Equation (1) indicates that, among all factors considered, post-harvest treatments—particularly the application of 1-MCP—together with the date of harvest and shelf life, played the most important roles in maintaining high apple firmness under commercial conditions. In contrast, preharvest weather conditions played a supportive role, shaping the fruit’s initial quality.

The resulting regression equation is as follows:

$$F = (0.24 \times X_1) + (0.81 \times X_2) + (1.68 \times X_3) + (-10.68 \times X_4) + (15.86 \times X_5) + (-0.43 \times X_7) + (-0.61 \times X_8) + (-6.13 \times X_9) + 54.7 \quad (1)$$

where X_1 —number of days with an average air temperature below 15 °C within the last 30 (or 44) days before harvest; X_2 —number of days when cumulative precipitation was above 6 mm; X_3 —1-MCP treatment before harvest; X_4 —date of harvest; X_5 —1-MCP treatment after harvest; X_7 —storage period; X_8 —length of simulated transport; X_9 —shelf life.

Table 3. Stepwise multiple regression results for the firmness of ‘Gala Schniga® SchniCo Red(s)’ apples derived from a model including the number of days with an average air temperature below 15 °C, within the last 30 (or 44) days before harvest, the number of days when cumulated precipitation was above 6 mm, 1-MCP treatment before harvest, the date of harvest, 1-MCP treatment after harvest, storage technology, storage period, length of simulated transport and shelf life. (n = 2304).

	Unstandardized Coefficients		Standardized Coefficients β	<i>p</i>
	β	SE *		
Constant			54.726	<0.001
Number of days with an average air temperature below 15 °C within the last 30 (or 44) days before harvest	0.24	0.024	0.186	<0.001
Number of days when cumulated precipitation was above 6 mm	0.81	0.071	0.208	<0.001
1-MCP treatment before harvest	1.68	0.187	0.069	<0.001
Date of harvest	−10.68	0.217	−0.442	<0.001
1-MCP treatment after harvest	15.86	0.187	0.656	<0.001
Storage period	−0.43	0.057	−0.058	<0.001
Length of simulated transport	−0.61	0.094	−0.050	<0.001
Shelf life	−6.13	0.115	−0.414	<0.001

* SE—standard error.

The results of the eta squared (η^2) analysis, presented in Table 4, provide a quantitative assessment of the contribution of individual factors to the explained variability in flesh firmness of ‘Gala Schniga® SchniCo Red(s)’ apples. All analyzed variables had a statistically significant effect on this trait ($p < 0.001$), although their relative importance differed markedly.

The greatest proportion of variance in apple firmness was explained by postharvest 1-MCP application, with η^2 reaching 75.8%. This result confirms the dominant role of post-harvest application of this compound in maintaining flesh structure during storage. A similarly high contribution to firmness variability was observed for shelf life ($\eta^2 = 55.5\%$) and date of harvest ($\eta^2 = 51.3\%$), indicating that both harvest timing and the final stage of the distribution chain are of key importance for preserving firmness in ‘Gala Schniga® SchniCo Red(s)’ apples.

Preharvest weather conditions showed a moderate but statistically significant effect on fruit firmness. The number of days with precipitation exceeding 6 mm accounted for 5.49% of the variability in this trait, while the number of days with an average air temperature below 15 °C explained 3.99%. A comparable level of variability was observed for preharvest 1-MCP treatment ($\eta^2 = 3.39\%$), suggesting that it shapes the fruit’s initial quality.

The smallest contribution to the explained variability in flesh firmness was associated with variables related to the duration of individual logistical stages. Storage period accounted for 2.40% of the variability, whereas length of simulated transport accounted for 1.79%, indicating that their effects, although statistically significant, were relatively small compared with the key factors discussed above.

These results are consistent with those from the multiple regression analysis and confirm that flesh firmness of ‘Gala Schniga® SchniCo Red(s)’ apples was primarily determined by date of harvest and postharvest 1-MCP treatment, whereas preharvest weather conditions, storage period, and commercial turnover-related factors played complementary roles.

Table 4. Partial eta squared (η^2) values for the firmness of ‘Gala Schniga® SchniCo Red(s)’ apples estimated using a model comprising the following variables: the number of days with an average air temperature below 15 °C within the last 30 (or 44) days before harvest, the number of days when cumulated precipitation was above 6 mm, 1-MCP treatment before harvest, the date of harvest, 1-MCP treatment after harvest, storage period, length of simulated transport, and shelf life.

Independent Variables	η^2 (%)	<i>p</i>
Number of days with an average air temperature below 15 °C within the last 30 (or 44) days before harvest	3.99	<0.001
Number of days when cumulated precipitation was above 6 mm	5.49	<0.001
1-MCP treatment before harvest	3.39	<0.001
Date of harvest	51.3	<0.001
1-MCP treatment after harvest	75.8	<0.001
Storage period	2.40	<0.001
Length of simulated transport	1.79	<0.001
Shelf life	55.5	<0.001

Note: partial η^2 values are not additive, because each value represents the variance explained by a given factor after controlling for the remaining factors in the model.

3.3. Titratable Acidity (TA)

The results of stepwise multiple regression analysis (Table 5) indicate that the titratable acidity of apples was significantly affected by both preharvest and postharvest factors, although the pattern of their influence differed from that observed for flesh firmness. All variables included in the regression equation were significant ($p < 0.001$); however, the standardized β coefficients were generally of moderate magnitude, confirming the more distributed nature of the regulation of this trait.

The strongest positive effect on titratable acidity was associated with postharvest 1-MCP application ($\beta = 0.643$), clearly demonstrating the high effectiveness of this treatment in limiting the decline of this parameter during apple storage. A significant, although much weaker, positive effect was also found for storage technology ($\beta = 0.063$), preharvest 1-MCP treatment ($\beta = 0.065$), and the number of days with precipitation before harvest ($\beta = 0.067$), indicating their supportive role in maintaining the fruit’s initial acidity.

The factor with the strongest negative effect on titratable acidity was date of harvest ($\beta = -0.235$), indicating progressive depletion of organic acids with advancing harvest maturity. A comparable negative effect was observed for storage period ($\beta = -0.244$), whereas shelf life was associated with an even stronger decline in acidity ($\beta = -0.372$). The length of simulated transport also had a significant effect, though its impact was clearly weaker ($\beta = -0.071$).

The final regression Equation (2) demonstrates that changes in TA in apples occurred gradually and resulted from the combined influence of multiple factors rather than from the dominance of a single variable.

The resulting regression equation is as follows:

$$TA = (0.001 \times X_2) + (0.006 \times X_3) + (-0.020 \times X_4) + (0.056 \times X_5) + (0.005 \times X_6) + (-0.006 \times X_7) + (-0.003 \times X_8) + (-0.020 \times X_9) + 0.274 \quad (2)$$

where X_2 —number of days when cumulative precipitation was above 6 mm; X_3 —1-MCP treatment before harvest; X_4 —date of harvest; X_5 —1-MCP treatment after harvest; X_6 —storage technology; X_7 —storage period; X_8 —length of simulated transport; X_9 —shelf life.

Table 5. Stepwise multiple regression results for the titratable acidity (TA) of ‘Gala Schniga® SchniCo Red(s)’ apples derived from a model including the number of days with an average air temperature below 15 °C within the last 30 (or 44) days before harvest, the number of days when cumulated precipitation was above 6 mm, 1-MCP treatment before harvest, the date of harvest, 1-MCP treatment after harvest, storage technology, storage period, length of simulated transport, and shelf life (n = 2304).

	Unstandardized Coefficients		Standardized Coefficients β	<i>p</i>
	β	SE *		
Constant			0.274	<0.001
Number of days when cumulated precipitation was above 6 mm	0.001	0.000	0.067	<0.001
1-MCP treatment before harvest	0.006	0.001	0.065	<0.001
Date of harvest	−0.020	0.001	−0.235	<0.001
1-MCP treatment after harvest	0.056	0.001	0.643	<0.001
Storage technology	0.005	0.001	0.063	<0.001
Storage period	−0.006	0.000	−0.244	<0.001
Length of simulated transport	−0.003	0.001	−0.071	<0.001
Shelf life	−0.020	0.001	−0.372	<0.001

* SE—standard error.

The eta squared (η^2) analysis presented in Table 6 clearly identifies the factors with the greatest contribution to the explained variability in titratable acidity. The strongest effect was observed for postharvest 1-MCP application ($\eta^2 = 56.3\%$), highlighting the key role of postharvest inhibition of apple ripening processes and the associated changes in organic acids. A substantial share of the variability in TA was also explained by shelf life ($\eta^2 = 30.1\%$) and storage period ($\eta^2 = 15.6\%$), confirming the strong dependence of this trait on the duration of postharvest processes. The effect of date of harvest was clearly smaller ($\eta^2 = 14.4\%$), yet still significant, underlining the importance of fruit maturity at the beginning of the postharvest chain.

The remaining factors evaluated in the experiment, such as the number of days with precipitation exceeding 6 mm ($\eta^2 = 1.34\%$), preharvest 1-MCP treatment ($\eta^2 = 1.31\%$), storage technology ($\eta^2 = 1.20\%$), and length of simulated transport ($\eta^2 = 1.54\%$), showed only a small, although statistically significant, contribution to the variability in TA. These results indicate that the titratable acidity of ‘Gala Schniga® SchniCo Red(s)’ apples was determined primarily by postharvest factors regulating ripening rate and by the duration of successive stages of the logistics chain, whereas the effects of weather conditions and the applied technological solutions remained relatively limited, influencing mainly the dynamics of the ongoing processes rather than their overall direction.

Table 6. Partial eta squared (η^2) values for the titratable acidity (TA) of ‘Gala Schniga® SchniCo Red(s)’ apples estimated using a model comprising the following variables: the number of days when cumulated precipitation was above 6 mm, 1-MCP treatment before harvest, the date of harvest, 1-MCP treatment after harvest, storage technology, storage period, length of simulated transport, and shelf life (n = 2304).

Independent Variables	η^2 (%)	<i>p</i>
Number of days when cumulated precipitation was above 6 mm	1.34	<0.001
1-MCP treatment before harvest	1.31	<0.001
Date of harvest	14.4	<0.001

1-MCP treatment after harvest	56.3	<0.001
Storage technology	1.20	<0.001
Storage period	15.6	<0.001
Length of simulated transport	1.54	<0.001
Shelf life	30.1	<0.001

Note: partial η^2 values are not additive, because each value represents the variance explained by a given factor after controlling for the remaining factors in the model.

3.4. Soluble Solids Content (SSC)

Stepwise multiple regression analysis revealed significant effects of selected weather factors, preharvest and postharvest 1-MCP applications, and storage conditions on soluble solids content in ‘Gala Schniga® SchniCo Red(s)’ apples ($n = 2304$). The final form of the regression model is presented in Equation (4), whereas detailed values of the regression coefficients, their standard errors, standardized β coefficients, and significance levels are shown in Table 7.

The strongest positive effect on SSC was observed for postharvest 1-MCP application ($\beta = 0.417$; $p < 0.001$), indicating that this treatment favored the maintenance and, in some cases, even an increase in soluble solids content in apples during storage and shelf life. In contrast, preharvest 1-MCP treatment significantly reduced SSC ($\beta = -0.409$; $p < 0.001$), underscoring the importance of the timing of ethylene inhibitor application.

Among the weather-related factors, significant positive effects on SSC were observed for the number of days with an average air temperature below 15 °C before harvest ($\beta = 0.146$; $p < 0.001$) and the number of days with precipitation exceeding 6 mm ($\beta = 0.205$; $p < 0.001$). These results indicate that cooler days and more rainy days in September promoted sugar accumulation in apples.

Date of harvest showed a significant negative relationship with SSC ($\beta = -0.148$; $p < 0.001$), indicating that delayed harvest was associated with lower SSC in the fruit. A similar relationship was observed for storage period, which also significantly reduced SSC ($\beta = -0.199$; $p < 0.001$), confirming the progressive consumption of sugars by apples during prolonged storage.

The remaining variables evaluated in the experiment—storage technology ($\beta = 0.033$; $p = 0.025$) and shelf life ($\beta = 0.039$; $p = 0.008$)—also had a statistically significant effect on SSC, although their impact was relatively small. The intercept of the model was 12.745 ($p < 0.001$), corresponding to the baseline SSC value at zero values of all independent variables, as shown in Equation (3).

The resulting regression equation is as follows:

$$\text{SSC} = (0.012 \times X_1) + (0.051 \times X_2) + (-0.623 \times X_3) + (-0.225 \times X_4) + (0.636 \times X_5) + (0.051 \times X_6) + (-0.093 \times X_7) + (0.037 \times X_9) + 12.7 \quad (3)$$

where X_1 —number of days with an average air temperature below 15 °C within the last 30 (or 44) days before harvest; X_2 —number of days when cumulative precipitation was above 6 mm; X_3 —1-MCP treatment before harvest; X_4 —date of harvest; X_5 —1-MCP treatment after harvest; X_6 —storage technology; X_7 —storage period; X_9 —shelf life.

Table 7. Stepwise multiple regression results for the soluble solids content (SSC) of ‘Gala Schniga® SchniCo Red(s)’ apples derived from a model including the number of days with an average air temperature below 15 °C within the last 30 (or 44) days before harvest, the number of days when cumulated precipitation was above 6 mm, 1-MCP treatment before harvest, the date of harvest, 1-MCP treatment after harvest, storage technology, storage period, length of simulated transport, and shelf life (n = 2304).

	Unstandardized Coefficients		Standardized Coefficients β	p
	β	SE *		
Constant			12.745	<0.001
Number of days with an average air temperature below 15 °C within the last 30 (or 44) days before harvest	0.012	0.003	0.146	<0.001
Number of days when cumulated precipitation was above 6 mm	0.051	0.009	0.205	<0.001
1-MCP treatment before harvest	−0.623	0.023	−0.409	<0.001
Date of harvest	−0.225	0.026	−0.148	<0.001
1-MCP treatment after harvest	0.636	0.023	0.417	<0.001
Storage technology	0.051	0.023	0.033	0.025
Storage period	−0.093	0.007	−0.199	<0.001
Shelf life	0.037	0.014	0.039	0.008

* SE—standard error.

The eta squared (η^2) analysis made it possible to assess the relative contribution of individual independent variables to the explained variability in soluble solids content (SSC) of ‘Gala Schniga® SchniCo Red(s)’ apples (Table 8). All included factors showed a statistically significant effect on SSC ($p < 0.05$), although their influence varied.

The largest share of SSC variability was attributed to treatments with 1-MCP, an ethylene regulator. Postharvest 1-MCP application showed the highest η^2 value (25.7%; $p < 0.001$), underlining the key role of this treatment in shaping soluble solids content. A comparably high effect was also observed for preharvest 1-MCP application ($\eta^2 = 24.9\%$; $p < 0.001$), confirming the dominant importance of this ethylene inhibitor in regulating the metabolic processes determining this apple quality parameter.

Atmospheric factors showed a relatively small, although statistically significant, effect on SSC. The number of days with an average air temperature below 15 °C before harvest explained only 0.69% of the variability of this trait ($p < 0.001$), whereas the number of days in which cumulative precipitation exceeded 6 mm accounted for 1.52% of the variability ($p < 0.001$). storage technology ($\eta^2 = 0.22\%$; $p = 0.026$) and shelf life ($\eta^2 = 0.31\%$; $p = 0.008$) were also characterized by a marginal contribution to explaining the variability of soluble solids content.

In summary, soluble solids content in ‘Gala Schniga® SchniCo Red(s)’ apples was determined mainly by factors related to the regulation of ripening processes, in particular by the application of 1-MCP before and after harvest, both of which showed a high contribution to the explained variability of this trait. This conclusion is fully consistent with the results of the multiple regression analysis presented in Equation (3) and Table 7.

Table 8. Partial eta squared (η^2) values for the soluble solids content (SSC) of ‘Gala Schniga® SchniCo Red(s)’ apples estimated using a model comprising the following variables: the number of days with an average air temperature below 15 °C within the last 30 (or 44) days before harvest, the number of days when cumulated precipitation was above 6 mm, 1-MCP treatment before harvest, the date of harvest, 1-MCP treatment after harvest, storage technology, storage period, and shelf life.

Independent Variables	η^2 (%)	<i>p</i>
Number of days with an average air temperature below 15 °C within the last 30 (or 44) days before harvest	0.69	<0.001
Number of days when cumulated precipitation was above 6 mm	1.52	<0.001
1-MCP treatment before harvest	24.9	<0.001
Date of harvest	3.10	<0.001
1-MCP treatment after harvest	25.7	<0.001
Storage technology	0.22	0.026
Storage period	7.26	<0.001
Shelf life	0.31	0.008

Note: partial η^2 values are not additive, because each value represents the variance explained by a given factor after controlling for the remaining factors in the model.

3.5. SSC/TA Ratio

The results of stepwise multiple regression analysis indicate that, among the variables considered in the modeling procedure—covering weather conditions as well as pre-harvest, postharvest, and logistical factors—only the predictors included in the final model had a statistically significant effect on the SSC/TA ratio ($p < 0.001$). The resulting regression equation allows for the determination of both the direction and the relative strength of the influence of individual factors on the variability of the analyzed parameter (Table 9).

The strongest negative effect on the SSC/TA ratio was observed with postharvest 1-MCP application ($\beta = -0.561$), indicating that blocking ethylene receptors significantly reduced this parameter. It should be noted that preharvest 1-MCP application also exerted a significant negative effect ($\beta = -0.215$), confirming the role of ethylene in regulating the complex ripening processes determining fruit quality. A negative, although clearly weaker, effect was also recorded for storage technology ($\beta = -0.073$).

The strongest positive effect on the SSC/TA ratio was associated with shelf life ($\beta = 0.406$), indicating that extending the distribution period after storage increased this ratio. A significant positive effect was also found for date of harvest ($\beta = 0.204$) and storage period ($\beta = 0.172$), clearly confirming the key role of time-related factors in the progression of physiological and biochemical processes reflected by this parameter. Although a similar direction of change was observed for length of simulated transport, the effect of this factor was relatively small ($\beta = 0.067$), indicating its limited importance compared with the other predictors (4).

The resulting regression equation is as follows:

$$\text{SSC/TA} = (-5.317 \times X_3) + (5.047 \times X_4) + (-13.855 \times X_5) + (-1.806 \times X_6) + (1.304 \times X_7) + (0.834 \times X_8) + (6.148 \times X_9) + 46.03 \quad (4)$$

where X_3 —1-MCP treatment before harvest; X_4 —date of harvest; X_5 —1-MCP treatment after harvest; X_6 —storage technology; X_7 —storage period; X_8 —length of simulated transport; X_9 —shelf life.

Table 9. Stepwise multiple regression results for the SSC/TA ratio of ‘Gala Schniga® SchniCo Red(s)’ apples derived from a model including the number of days with an average air temperature below 15 °C within the last 30 (or 44) days before harvest, the number of days when cumulated precipitation was above 6 mm, 1-MCP treatment before harvest, the date of harvest, 1-MCP treatment after harvest, storage technology, storage period, length of simulated transport, and shelf life (n = 2304).

	Unstandardized Coefficients		Standardized Coefficients β	<i>p</i>
	β	SE *		
Constant			46.027	<0.001
1-MCP treatment before harvest	−5.317	0.324	−0.215	<0.001
Date of harvest	5.047	0.324	0.204	<0.001
1-MCP treatment after harvest	−13.855	0.324	−0.561	<0.001
Storage technology	−1.806	0.324	−0.073	<0.001
Storage period	1.304	0.099	0.172	<0.001
Length of simulated transport	0.834	0.162	0.067	<0.001
Shelf life	6.148	0.198	0.406	<0.001

* SE—standard error.

The importance of individual factors in shaping the SSC/TA ratio was confirmed by the effect size analysis presented in Table 10. The greatest contribution to the explained variability of this parameter was associated with postharvest 1-MCP application, which accounted for 44.4% of the total variance.

The second most important factor was shelf life, which explained 29.6% of the variability in the analyzed parameter. Other important contributors to the SSC/TA ratio were factors related to harvest timing and storage conditions. Preharvest 1-MCP application ($\eta^2 = 10.5\%$) and date of harvest ($\eta^2 = 9.59\%$) showed comparable effect sizes, whereas storage period accounted for 7.02% of the total variance. The remaining predictors were characterized by a clearly smaller effect size—storage technology and length of simulated transport explained 1.33% and 1.14% of the variability in the SSC/TA ratio, respectively, indicating their marginal importance compared with the other factors.

This distribution of η^2 values indicates that the variability of the analyzed parameter was determined mainly by postharvest 1-MCP application and the duration of commercial turnover of apples, whereas weather-related factors—although considered at the modeling stage—did not show a statistically significant effect and were therefore not included in the final model.

Table 10. Partial eta squared (η^2) values for the SSC/TA ratio of ‘Gala Schniga® SchniCo Red(s)’ apples estimated using a model comprising the following variables: 1-MCP treatment before harvest, the date of harvest, 1-MCP treatment after harvest, storage technology, storage period, length of simulated transport, and shelf life.

Independent Variables	η^2 (%)	<i>p</i>
1-MCP treatment before harvest	10.5	<0.001
Date of harvest	9.59	<0.001
1-MCP treatment after harvest	44.4	<0.001
Storage technology	1.33	<0.001
Storage period	7.02	<0.001
Length of simulated transport	1.14	<0.001
Shelf life	29.6	<0.001

Note: partial η^2 values are not additive, because each value represents the variance explained by a given factor after controlling for the remaining factors in the model.

3.6. 1-Aminocyclopropane-1-carboxylic Acid (ACC)

Stepwise multiple regression analysis showed that, among the variables considered in the modeling procedure, only the predictors included in the final model exerted a statistically significant effect on the content of 1-aminocyclopropane-1-carboxylic acid (ACC) in ‘Gala Schniga® SchniCo Red(s)’ apples ($p < 0.001$). The final form of the regression equation is presented in Equation (5), whereas detailed coefficient values are given in Table 11.

The strongest positive effect on ACC content was associated with storage period ($\beta = 0.334$), indicating a gradual increase in the pool of the ethylene precursor with prolonged fruit storage. A significant positive effect was also observed for shelf life ($\beta = 0.261$), suggesting a further increase in the ethylene precursor pool, which may intensify metabolic processes during the commercial distribution stage. A positive, although clearly weaker, effect was also found for storage technology ($\beta = 0.138$) and date of harvest ($\beta = 0.059$).

The strongest negative effect was observed for postharvest 1-MCP application ($\beta = -0.313$), confirming its effectiveness in limiting ACC accumulation and, consequently, suppressing ethylene-dependent processes. A negative, although distinctly weaker, effect was also recorded for preharvest 1-MCP application ($\beta = -0.075$). A negative relationship was also found for the number of days with heavy precipitation (> 6 mm) ($\beta = -0.144$), suggesting a possible indirect effect of weather conditions on physiological processes related to ACC synthesis.

The length of simulated transport showed a positive effect, although its magnitude was relatively small ($\beta = 0.065$), indicating the limited importance of this stage of apple handling compared with the storage period and shelf life. The intercept of the model was not statistically significant ($p = 0.217$), suggesting that ACC variability was largely explained by the predictors included in the regression model presented in the following equation.

The resulting regression equation is as follows:

$$\text{ACC} = (-0.015 \times X_2) + (-0.045 \times X_3) + (0.038 \times X_4) + (-0.203 \times X_5) + (0.090 \times X_6) + (0.066 \times X_7) + (0.021 \times X_8) + (0.104 \times X_9) - 0.065 \quad (5)$$

where X_2 —number of days when cumulative precipitation was above 6 mm; X_3 —1-MCP treatment before harvest; X_4 —date of harvest; X_5 —1-MCP treatment after harvest; X_6 —storage technology; X_7 —storage period; X_8 —length of simulated transport; X_9 —shelf life.

Table 11. Stepwise multiple regression results for the 1-aminocyclopropane-1-carboxylic acid (ACC) content of ‘Gala Schniga® SchniCo Red(s)’ apples derived from a model including the number of days with an average air temperature below 15 °C within the last 30 (or 44) days before harvest, the number of days when cumulated precipitation was above 6 mm, 1-MCP treatment before harvest, the date of harvest, 1-MCP treatment after harvest, storage technology, storage period, length of simulated transport, and shelf life ($n = 2304$).

	Unstandardized Coefficients		Standardized Coefficients β	p
	β	SE *		
Constant			−0.065	0.217
Number of days when cumulated precipitation was above 6 mm	−0.015	0.002	−0.144	<0.001
1-MCP treatment before harvest	−0.045	0.011	−0.075	<0.001
Date of harvest	0.038	0.011	0.059	<0.001
1-MCP treatment after harvest	−0.203	0.011	−0.313	<0.001
Storage technology	0.090	0.011	0.138	<0.001
Storage period	0.066	0.003	0.334	<0.001
Length of simulated transport	0.021	0.006	0.063	<0.001
Shelf life	0.104	0.007	0.261	<0.001

* SE—standard error.

The importance of individual factors in shaping the variability of ACC content was confirmed by the eta squared (η^2) analysis presented in Table 12. The largest share of the explained variance was attributed to the storage period, accounting for 14.2% of the total variability in ACC, underscoring the key role of this factor in the accumulation of this ethylene precursor.

The second most important factor was postharvest 1-MCP application ($\eta^2 = 12.7\%$), confirming its crucial role in regulating ripening during the postharvest period. A substantial contribution to ACC variability was also observed for shelf life ($\eta^2 = 9.22\%$), indicating a further intensification of metabolic changes after the end of cold storage.

Storage technology showed a moderate effect size ($\eta^2 = 2.77\%$), whereas preharvest 1-MCP application ($\eta^2 = 0.83\%$) and date of harvest ($\eta^2 = 0.61\%$) had clearly smaller, although statistically significant, effects. The weakest predictors of ACC variability were length of simulated transport ($\eta^2 = 0.59\%$) and the number of days with cumulative precipitation exceeding 6 mm ($\eta^2 = 0.21\%$).

The distribution of η^2 values indicates that ACC content in apples was determined primarily by storage period and postharvest treatments, whereas weather-related and logistical factors played a secondary role. The observed distribution of effect sizes was fully consistent with the results of the multiple regression analysis (Table 11; Equation 5), underscoring the decisive importance of processes regulating ethylene biosynthesis during the postharvest period.

Table 12. Partial eta squared (η^2) values for the 1-aminocyclopropane-1-carboxylic acid (ACC) content of ‘Gala Schniga® SchniCo Red(s)’ apples estimated using a model comprising the following variables: the number of days when cumulated precipitation was above 6 mm, 1-MCP treatment before harvest, the date of harvest, 1-MCP treatment after harvest, storage technology, storage period, length of simulated transport, and shelf life.

Independent Variables	η^2 (%)	<i>p</i>
Number of days when cumulated precipitation was above 6 mm	0.21	0.030
1-MCP treatment before harvest	0.83	<0.001
Date of harvest	0.61	<0.001
1-MCP treatment after harvest	12.7	<0.001
Storage technology	2.77	<0.001
Storage period	14.2	<0.001
Length of simulated transport	0.59	<0.001
Shelf life	9.22	<0.001

Note: partial η^2 values are not additive, because each value represents the variance explained by a given factor after controlling for the remaining factors in the model.

3.7. Dynamics of Ethylene Production and Respiration Rate

Additionally, the Supplementary Materials (Figures S1–S24) present detailed patterns of changes in ethylene production and respiration rate of ‘Gala Schniga® SchniCo Red(s)’ apples during 14 days of holding at 25 °C following 6 weeks of simulated transport, preceded by 5, 7, or 9 months of storage under ULO 1 and ULO 2 conditions, in both analyzed storage seasons. The presented graphs indicate a clear increase in the intensity of physiological processes during holding at 25 °C, reflecting the stress-like character of the elevated-temperature shelf-life treatment.

Only the results obtained after 6 weeks of simulated transport are included, as this variant represents the most demanding and relevant scenario for long-distance distribution. Preliminary analysis indicated that the patterns observed after 4 weeks of transport

were qualitatively similar, although less pronounced, and did not provide additional interpretative value.

In most variants, a tendency toward a faster increase in ethylene production and respiration rate was observed in fruit harvested at the delayed date (DH), confirming their more advanced ripening stage. At the same time, extending the storage period (from 5 to 9 months) intensified these processes, particularly during the final days of storage under simulated commercial conditions.

Differences between ULO 1 and ULO 2 technologies were relatively small, consistent with the statistical analyses and suggesting the dominant role of postharvest factors, such as 1-MCP application and storage duration. The graphs also confirm that the key stage determining the dynamics of physiological changes is the simulated commercial handling (shelf life) period at 25 °C.

4. Discussion

The results clearly indicate that the final quality of ‘Gala Schniga® SchniCo Red(s)’ apples was primarily determined by postharvest technological decisions and factors in the final stages of the supply chain, whereas atmospheric conditions during the preharvest period mainly modulated fruit quality at harvest. This pattern is consistent with current research trends in postharvest physiology management, in which key importance is placed on regulating ethylene action, precisely determining harvest maturity, and controlling temperature and storage and distribution conditions [26–29].

The importance of these factors is further emphasized by increasing market pressure associated with export expansion and higher consumer expectations for maintaining high firmness, juiciness, and stable quality of apples throughout the year [30–32]. In this context, postharvest management represents a key component of quality strategies, clearly outweighing the influence of environmental variables during the growing season.

The comparison between the 2022 and 2023 seasons showed that 2023 featured higher temperatures and a significant precipitation deficit during a key phase of the growing season. The literature indicates that water stress may affect the metabolism of sugars and organic acids, as well as the ripening process, thereby directly influencing SSC and TA and indirectly affecting the postharvest storage potential of fruit [33]. These relationships are linked to mechanisms regulating plant water balance, which in turn affect carbohydrate metabolism and responses to environmental stress [6]. At the same time, the results of the multifactorial analyses indicate that, despite noticeable weather-related differences, postharvest factors played the dominant role in shaping final quality, highlighting the overriding importance of storage technology and distribution conditions [34].

Regarding maintaining apple firmness, the strongest effect was observed with postharvest 1-MCP application, whereas preharvest treatments had a significant but clearly weaker impact. This finding is consistent with numerous studies demonstrating that 1-MCP effectively inhibits ethylene action and slows down fruit softening during long-term storage [8,35–37]. At the same time, the significant negative effects of date of harvest and shelf life on firmness confirm that the duration of postharvest exposure is a key factor accelerating structural degradation of fruit tissue [28].

It should be emphasized that the importance of individual factors may vary across cultivars. In the case of ‘Granny Smith’, date of harvest and storage period were the dominant factors, while the effect of the distribution stage was moderate [38]. Cultivar-dependent variability in quality traits, including firmness, consumer evaluation, and bioactive compound content, has also been confirmed in studies on new apple hybrids [39]. In comparison with these findings, the results obtained for ‘Gala Schniga® SchniCo Red(s)’ indicate a greater sensitivity of this cultivar to prolonged “time in warm conditions” after

removal from cold storage. In practice, this implies strict management of the distribution stage and prioritizing postharvest 1-MCP application.

Variability in TA was most strongly associated with factors regulating ripening rate, including storage period and shelf life. Postharvest 1-MCP application maintained higher TA levels, suggesting a slowdown in organic acid metabolism [8,26]. This mechanism is consistent with the observation that organic acids are gradually consumed during respiration, and that reducing respiratory intensity slows their degradation [8]. In contrast to firmness, TA showed a more complex pattern of regulation, dependent on the interaction of multiple factors [40,41].

In the case of SSC and the SSC/TA ratio, both 1-MCP treatments and distribution-related factors were key. Extending the storage period and exposure under market conditions led to higher SSC/TA values, mainly because TA declined faster than SSC [8,26]. This phenomenon has important sensory and market implications—although it may be perceived as an increase in sweetness, it also indicates a progressive loss of freshness and a reduction in the fruit's commercial shelf life [4]. The observed decrease in soluble solids content following preharvest 1-MCP treatment may be interpreted as a potential trade-off associated with ethylene inhibition. Although lower SSC values may negatively affect perceived sweetness and, consequently, sensory quality, this response should be considered alongside the beneficial effects of 1-MCP on firmness preservation and acidity retention. These attributes are critical for maintaining overall fruit quality and marketability, particularly within supply chains involving prolonged storage and long-distance transportation.

ACC analysis revealed a strong association with storage period and shelf life, reflecting increasing activity of the ethylene biosynthesis pathway over time. At the same time, the clear inhibitory effect of 1-MCP application confirms its effectiveness in limiting ethylene synthesis at the biochemical level [7,28,42–46].

Simulated transport conditions showed a relatively small effect on the analyzed quality parameters, suggesting that transport itself is not a decisive factor [47]. Instead, the cumulative duration of exposure to post-storage conditions, particularly shelf life, appears to be critical [4,48]. This indicates that the key factor is the combined effect of processes accelerating senescence, rather than individual stages of the logistics chain.

The relatively small effect of storage technology (ULO 1 vs. ULO 2) can be interpreted in two ways. First, effective use of 1-MCP may reduce the importance of more advanced storage regimes by inhibiting ethylene action [49–51]. Second, the literature suggests that the effectiveness of DCA relative to ULO depends on cultivar and harvest/storage conditions, and in some cases may be comparable to CA combined with 1-MCP [19,52]. In the case of 'Gala Schniga® SchniCo Red(s)' apples, this suggests that maintaining high postharvest quality primarily depends on precise determination of harvest date, the application of 1-MCP, and limiting the duration under commercial handling conditions.

It should also be recognized that intensive suppression of ripening, achieved through either CA/ULO storage or 1-MCP application, may be associated with potential sensory trade-offs, including reduced aroma production and lower aroma intensity, which are particularly important quality attributes in premium fruit markets [53,54]. Consequently, decisions regarding postharvest management strategies should consider not only instrumental indicators of fruit quality but also the overall sensory profile, which ultimately influences consumer acceptance and market value.

One limitation of the present study is the absence of a systematic assessment of physiological storage disorders, such as internal browning and CO₂ injury. Although symptoms of these disorders were recorded during fruit evaluation, their occurrence was infrequent and largely confined to the most severe postharvest scenario, combining delayed

harvest, the longest storage period, extended transport simulation, and shelf-life exposure at 25 °C.

Because these disorders may substantially affect the commercial acceptability of ‘Gala’ apples after prolonged low-oxygen storage, and because their development is influenced by factors including fruit maturity, storage atmosphere, storage duration, and 1-MCP treatment strategy [55], caution should be exercised when extrapolating the present results to overall marketability. Therefore, the current study primarily addresses changes in physicochemical quality and ethylene-related physiology. Future investigations should incorporate quantitative assessments of storage disorder incidence and severity to enable a more comprehensive evaluation of fruit performance during extended storage and export-oriented distribution.

In summary, under conditions of an extended distribution chain, the most effective strategy for maintaining high quality of ‘Gala Schniga® SchniCo Red(s)’ apples involves precise control of date of harvest, application of postharvest 1-MCP, and limitation of shelf life [4,28,56]. Transport should be treated primarily as a means of stabilizing environmental conditions rather than as a key determinant of fruit quality.

Future research should adopt a more integrative approach by combining instrumental quality assessments with sensory analysis, aroma volatile profiling, measurements of weight loss, and systematic evaluation of physiological storage disorders. Such parameters would provide a more comprehensive understanding of the relationships between postharvest logistics, fruit physiology, and market quality. Sensory assessment, in particular, would help determine whether the beneficial effects of 1-MCP on firmness retention are accompanied by undesirable changes in aroma expression, sweetness perception, or overall consumer acceptance.

In addition, further investigation of the interactions among preharvest weather conditions, fruit physiological maturity at harvest, and 1-MCP treatment strategies is warranted. A better understanding of these interactions could improve the prediction of postharvest behavior and help optimize management practices aimed at balancing fruit quality retention with the regulation of ripening and senescence processes during extended storage and long-distance distribution [6,33].

5. Conclusions

Firmness retention in ‘Gala Schniga® SchniCo Red(s)’ apples throughout long-term storage, simulated transport, and subsequent shelf-life exposure was influenced predominantly by postharvest management factors. Of all variables examined, postharvest 1-MCP treatment exerted the strongest positive effect on firmness preservation, clearly surpassing the contributions of harvest-related factors, storage regime, and transport duration. This finding confirms that postharvest ethylene inhibition constitutes a key technological intervention for maintaining the structural quality and marketability of apples intended for long-distance export supply chains.

Firmness was also strongly influenced by harvest date and shelf-life duration. Delayed harvest significantly reduced firmness, while prolonged shelf life at elevated temperatures caused the greatest deterioration after fruit were removed from storage. In contrast, the effect of simulated transport duration was statistically significant but relatively small, indicating that firmness loss at the target market was driven more by the time spent under retail conditions than by transport itself.

Preharvest 1-MCP treatment had only a supportive effect on firmness retention, whereas postharvest 1-MCP treatment decisively improved the fruit’s storage potential and limited the intensity of softening throughout the extended supply chain. At the same time, storage technology (ULO 1 vs. ULO 2) played a comparatively minor role in firmness

preservation, suggesting that under effective ethylene inhibition, the precise static CA regime is of secondary importance for this trait.

Collectively, the results indicate that the combination of harvest at the optimal maturity stage, postharvest 1-MCP treatment, and minimization of shelf-life duration after transport represents the most effective strategy for maintaining firmness in ‘Gala Schniga® SchniCo Red(s)’ apples destined for distant markets. These findings have direct practical implications for the optimization of postharvest management systems designed to preserve fruit quality during long-term storage and export-oriented distribution. Given that the present study was limited to instrumental assessments of fruit quality, future investigations should incorporate sensory analyses and quantitative evaluations of physiological storage disorders to verify whether the observed benefits in firmness retention translate into improved overall quality and consumer acceptance.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agriculture16131397/s1>. Figures S1–S24 present changes in ethylene production and respiration rate of ‘Gala Schniga® SchniCo Red(s)’ apples during 14 days at 25 °C following 6 weeks of simulated transport after 5, 7, or 9 months of storage under ULO 1 or ULO 2 conditions in the 2022/2023 and 2023/2024 storage seasons.

Author Contributions: Conceptualization, M.M. and K.T.; methodology, M.M.; software, M.M.; validation, M.M.; formal analysis, M.M., J.G. and K.T.; investigation, M.M., J.G. and K.T.; resources, M.M. and K.T.; data curation, M.M. and K.T.; writing—original draft preparation, M.M., J.G. and K.T.; writing—review and editing, M.M., J.G. and K.T.; visualization, M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The data are contained within the article. The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Johnston, J.W.; Hewett, E.W.; Hertog, M.L.A.T.M. Postharvest softening of apple (*Malus domestica*) fruit: A review. *N. Z. J. Crop Hortic. Sci.* **2002**, *30*, 145–160. <https://doi.org/10.1080/01140671.2002.9514210>.
2. FAO. Fruit Consumption by Type, World, 1961 to 2021. Our World in Data. 2023. Available online: <https://our-worldindata.org/grapher/fruit-consumption-by-fruit-type> (accessed on 11 April 2026).
3. Małachowska, M.; Tomala, K. Effect of preharvest and postharvest application of 1-MCP on the quality of Gala Schniga® SchniCo Red(s) apples during long-term storage. *Agriculture* **2022**, *12*, 2073. <https://doi.org/10.3390/agriculture12122073>.
4. Hasan, M.U.; Singh, Z.; Shah, H.M.S.; Kaur, J.; Woodward, A. Water loss: A postharvest quality marker in apple storage. *Food Bioprocess Technol.* **2024**, *17*, 2155–2180. <https://doi.org/10.1007/s11947-023-03305-9>.
5. Musacchi, S.; Serra, S. Apple fruit quality: Overview on pre-harvest factors. *Sci. Hortic.* **2018**, *234*, 409–430. <https://doi.org/10.1016/j.scienta.2017.12.057>.
6. Tao, H.; Sun, H.; Wang, Y.; Wang, X.; Guo, Y. Effects of water stress on quality and sugar metabolism in ‘Gala Schniga’ apple fruit. *Hortic. Plant J.* **2022**, *9*, 60–72. <https://doi.org/10.1016/j.hpj.2022.03.008>.
7. Zhang, L.; Zhang, P.; Gao, M.; Zhao, Y.; Zhang, C.; Zhu, H. Integrative metabolomics and transcriptomics analyses reveal pivotal regulatory mechanisms of 1-methylcyclopropene in maintaining postharvest storage quality of ‘Fuji’ apples. *Food Qual. Saf.* **2022**, *7*, fyac063. <https://doi.org/10.1093/fqsaf/fyac063>.
8. Kwon, Y.-S.; Park, J.-T.; Yoo, J.; Do, V.G.; Kim, J.-H.; Cho, Y.S.; Yang, S.; Kang, I.-K.; Win, N.M. 1-Methylcyclopropene improves the postharvest physiological characteristics and fruit quality of ‘Colorpple’ and ‘Manhong’ apple cultivars during storage at warm and cold temperatures. *Hortic. Sci. Technol.* **2024**, *42*, 151–166. <https://doi.org/10.7235/hort.20240013>.

9. Ireland, H.S.; Gunaseelan, K.; Muddumage, R.; Tacken, E.J.; Putterill, J.; Johnston, J.W.; Schaffer, R.J. Ethylene regulates apple (*Malus × domestica*) fruit softening through a dose × time-dependent mechanism and through differential sensitivities and dependencies of cell wall-modifying genes. *Plant Cell Physiol.* **2014**, *55*, 1005–1016. <https://doi.org/10.1093/pcp/pcu034>.
10. Sun, Y.; Shi, Z.; Jiang, Y.; Zhang, X.; Li, X.; Li, F. Effects of preharvest regulation of ethylene on carbohydrate metabolism of apple (*Malus domestica* Borkh cv. Starkrimson) fruit at harvest and during storage. *Sci. Hortic.* **2021**, *276*, 109748. <https://doi.org/10.1016/j.scienta.2020.109748>.
11. Fernández-Cancelo, P.; Muñoz, P.; Echeverría, G.; Larrigaudière, C.; Teixidó, N.; Munné-Bosch, S.; Giné-Bordonaba, J. Ethylene and abscisic acid play a key role in modulating apple ripening after harvest and after cold storage. *Postharvest Biol. Technol.* **2022**, *188*, 111902. <https://doi.org/10.1016/j.postharvbio.2022.111902>.
12. Tipu, M.M.H.; Sherif, S.M. Ethylene and its crosstalk with hormonal pathways in fruit ripening: Mechanisms, modulation, and commercial exploitation. *Front. Plant Sci.* **2024**, *15*, 1475496. <https://doi.org/10.3389/fpls.2024.1475496>.
13. Forlani, S.; Masiero, S.; Mizzotti, C. Fruit ripening: The role of hormones, cell wall modifications, and their relationship with pathogens. *J. Exp. Bot.* **2019**, *70*, 2993–3006. <https://doi.org/10.1093/jxb/erz112>.
14. Akcay, U.C.; Baloglu, M.C.; Altunoglu, Y.C.; Baloglu, P.; Koyuncu, M.A.; Erbas, D.; Horuz, E.; Arslan, B.; Turkoglu, S. Comparative transcriptomic analysis provides novel insights on the hormonal regulation of postharvest apples under cold storage. *Hortic. Environ. Biotechnol.* **2025**, *66*, 1089–1105. <https://doi.org/10.1007/s13580-025-00710-1>.
15. Wei, J.; Ma, F.; Shi, S.; Qi, X.; Zhu, X.; Yuan, J. Changes and postharvest regulation of activity and gene expression of enzymes related to cell wall degradation in ripening apple fruit. *Postharvest Biol. Technol.* **2010**, *56*, 147–154. <https://doi.org/10.1016/j.postharvbio.2009.12.003>.
16. Cao, Y.; Lv, J.; Tai, R.; Tang, W.; Ge, Y. Impacts of 1-methylcyclopropene (1-MCP) and ethephon treatments on expression of aquaporin (AQP) genes during apple fruit ripening. *Sci. Hortic.* **2024**, *331*, 113126. <https://doi.org/10.1016/j.scienta.2024.113126>.
17. Büchele, F.; Khera, K.; Wagner, R.; Thewes, F.R.; Neuwald, D.A. Interaction between dynamic controlled atmosphere (DCA-CD), 1-methylcyclopropene and elevated temperatures in the long-term storage of organic ‘Santana’ apples. *Postharvest Biol. Technol.* **2023**, *204*, 112471. <https://doi.org/10.1016/j.postharvbio.2023.112471>.
18. Khalifeh, P.; Sadar, N.; Panarese, A.; Stürz, S.; Ebner, I.; Zanella, A.; Costa, F. Texture and volatile profiling of four modern apple cultivars stored using ultra-low oxygen, 1-MCP and dynamic controlled atmosphere strategies. *Postharvest Biol. Technol.* **2025**, *229*, 113718. <https://doi.org/10.1016/j.postharvbio.2025.113718>.
19. de Candido de Oliveira, F.; Balzan, M.M.; Deon, B.C.; Cordeiro, M.W.; Batista, C.B.; Soldateli, F.J.; Wendt, L.M.; Thewes, F.R.; Both, V.; Brackmann, A.; et al. Static and dynamic controlled atmosphere storage and 1-methylcyclopropene treatment of ‘Cripps Pink’ apples: Linking sensory perception, volatile compounds, and quality. *Food Res. Int.* **2025**, *214*, 116669. <https://doi.org/10.1016/j.foodres.2025.116669>.
20. Małachowska, M.; Tomala, K. Apple quality during shelf life after long-term storage and simulated transport. *Agriculture* **2023**, *13*, 2045. <https://doi.org/10.3390/agriculture13112045>.
21. Małachowska, M.; Tomala, K. Determinants of postharvest quality in ‘Gala Schniga® SchniCo Red(s)’ apples: The role of harvest date, storage duration, and 1-MCP application. *Agriculture* **2025**, *15*, 2363. <https://doi.org/10.3390/agriculture15222363>.
22. Buffer, G. Ethylene-promoted conversion of 1-aminocyclopropane-1-carboxylic acid to ethylene in the peel of apple at various stages of fruit development. *Plant Physiol.* **1986**, *80*, 539–543.
23. Jobling, J.; McGlasson, W.B.; Dilley, D.R. Induction of ethylene-synthesizing competency in Granny Smith apples by exposure to low temperature in air. *Postharvest Biol. Technol.* **1991**, *1*, 111–118.
24. Bulens, I.; Van de Poel, B.; Hertog, M.L.A.T.M.; De Proft, M.P.; Geeraerd, A.H.; Nicolaï, B.M. Protocol: An updated integrated methodology for analysis of metabolites and enzyme activities of ethylene biosynthesis. *Plant Methods* **2011**, *7*, 17.
25. Walter, H.; Lieth, H.; Rehder, H.; Harnickell, E. *Klimadiagramm-Weltatlas*; G. Fischer: Jena, Germany, 1960.
26. Zhang, Y.; Zhu, D.; Ren, X.; Shen, Y.; Cao, X.; Liu, H.; Li, J. Quality changes and shelf life prediction model of postharvest apples using partial least squares and artificial neural network analysis. *Food Chem.* **2022**, *394*, 133526. <https://doi.org/10.1016/j.foodchem.2022.133526>.
27. Keller-Przybyłkowicz, S.; Lewandowski, M.; Kuras, A.; Strączyńska, K.; Czarnecka, R.; Idczak, B.; Rutkowski, K.P.; Skorupińska, A. Interactions between seasonal temperature changes, activities of selected genes and fruit quality in *Malus domestica* Borkh. *Agronomy* **2025**, *15*, 908. <https://doi.org/10.3390/agronomy15040908>.
28. Weigl, T.; Børve, J.; Follett, E.; Magerøy, M.H.; Larsen, H.; Fossdal, C.G.; Remberg, S.F. Modulating postharvest apple fruit physiology by managing the harvest date and 1-MCP application. *Postharvest Biol. Technol.* **2026**, *231*, 113938. <https://doi.org/10.1016/j.postharvbio.2025.113938>.

29. Łysiak, G. The sum of active temperatures as a method of determining the optimum harvest date of ‘Šampion’ and ‘Ligol’ apple cultivars. *Acta Sci. Pol. Hortorum Cultus* **2012**, *11*, 3–13.
30. Trajer, M.; Dyngus, M. Krajowa produkcja, spożycie oraz promocja owoców i warzyw. *Biul. Inform.* **2013**, *3*, 6–27.
31. O’Neil, C.E.; Nicklas, T.A.; Fulgoni, V.L. Consumption of apples is associated with a better diet quality and reduced risk of obesity in children. *Nutr. J.* **2015**, *14*, 48.
32. Chen, B.; Mao, J.; Huang, B.; Mi, B.; Liu, Y.; Hu, Z. Effect of bagging and time of harvest on fruit quality of ‘Red Fuji’ apple in high altitude area in China. *Fruits* **2017**, *72*, 36–46.
33. Do, V.G.; Lee, Y.; Park, J.; Win, N.M.; Kwon, S.-I.; Yang, S.; Kim, S. Heat stress and water irrigation management effects on the fruit color and quality of ‘Hongro’ apples. *Agriculture* **2024**, *14*, 761. <https://doi.org/10.3390/agriculture14050761>.
34. Łysiak, G.P.; Michalska-Ciechanowska, A.; Wojdyło, A. Postharvest changes in phenolic compounds and antioxidant capacity of apples cv. Jonagold growing in different locations in Europe. *Food Chem.* **2020**, *310*, 125912.
35. Lee, J.; Kang, I.-K.; Nock, J.F.; Watkins, C.B. Effects of preharvest and postharvest applications of 1-methylcyclopropene on fruit quality and physiological disorders of ‘Fuji’ apples during storage at warm and cold temperatures. *HortScience* **2019**, *54*, 1375–1383. <https://doi.org/10.21273/hortsci14062-19>.
36. Doerflinger, F.C.; Al Shoffe, Y.; Sutanto, G.; Nock, J.F.; Watkins, C.B. Preharvest 1-methylcyclopropene (1-MCP) treatment effects on quality of spot and strip picked ‘Gala Schniga’ apples at harvest and after storage as affected by postharvest 1-MCP and temperature conditioning treatments. *Sci. Hortic.* **2024**, *325*, 112682. <https://doi.org/10.1016/j.scienta.2023.112682>.
37. Zhang, S.; Li, Y.; Du, M.; Li, X.; Wang, J.; Ban, Z.; Jiang, Y. Practical 1-methylcyclopropene technology for increasing apple (*Malus domestica* Borkh.) storability in the Aksu region. *Foods* **2024**, *13*, 2918. <https://doi.org/10.3390/foods13182918>.
38. Sredojevic, A.; Radivojevic, D.; Levic, S.M.; Fotiric Aksic, M.; Milivojevic, J.; Djordjevic, M.; Spasojevic, S.; Djekic, I. Postharvest quality of ‘Granny Smith’ apples: Interplay of harvest stage, storage duration, and shelf life. *Horticulturae* **2025**, *11*, 868. <https://doi.org/10.3390/horticulturae11080868>.
39. Szpadzik, E.; Molska-Kawulok, K.; Krupa, T.; Przybyłko, S. Physico-chemical analysis of the fruits and consumer preferences of new apple (*Malus × domestica* Borkh) hybrids bred in Poland. *Agriculture* **2024**, *14*, 1. <https://doi.org/10.3390/agriculture14010001>.
40. Brizzolara, S.; Manganaris, G.A.; Fotopoulos, V.; Watkins, C.B.; Tonutti, P. Primary metabolism in fresh fruits during storage. *Front. Plant Sci.* **2020**, *11*, 80. <https://doi.org/10.3389/fpls.2020.00080>.
41. Win, N.M.; Yoo, J.; Naing, A.H.; Kwon, J.-G.; Kang, I.-K. 1-Methylcyclopropene (1-MCP) treatment delays modification of cell wall pectin and fruit softening in ‘Hwangok’ and ‘Picnic’ apples during cold storage. *Postharvest Biol. Technol.* **2021**, *180*, 111599. <https://doi.org/10.1016/j.postharvbio.2021.111599>.
42. Guo, J.; Wei, X.; Lü, E.; Wang, Y.; Deng, Z. Ripening behavior and quality of 1-MCP treated d’Anjou pears during controlled atmosphere storage. *Food Control* **2020**, *117*, 107364. <https://doi.org/10.1016/j.foodcont.2020.107364>.
43. Zhang, J.; Ma, Y.; Dong, C.; Terry, L.A.; Watkins, C.B.; Yu, Z.; Cheng, Z.-M. Meta-analysis of the effects of 1-methylcyclopropene (1-MCP) treatment on climacteric fruit ripening. *Hortic. Res.* **2020**, *7*, 208. <https://doi.org/10.1038/s41438-020-00405-x>.
44. Li, R.; Wang, Y.; Li, W.; Shao, Y. Comparative analyses of ripening, texture properties and cell wall composition in three tropical fruits treated with 1-methylcyclopropene during cold storage. *Horticulturae* **2023**, *9*, 126. <https://doi.org/10.3390/horticulturae9020126>.
45. Sidhu, R.S.; Bound, S.A.; Hunt, I.; Swarts, N.D. Impact of pre-harvest application of 1-methylcyclopropene (1-MCP) on fruit quality, physiological disorders and respiration rate of ‘Scilate’ apple. *Hortic. Environ. Biotechnol.* **2024**, *65*, 877–890. <https://doi.org/10.1007/s13580-024-00616-4>.
46. Błaszczuk, J.; Gasparski, K. Influence of 1-methylcyclopropene (1-MCP) on the quality and storability of ‘Red Jonaprince’ apples stored in different conditions. *Acta Sci. Pol. Hortorum Cultus* **2019**, *18*, 7–15.
47. Walkowiak-Tomczak, D.; Idaszewska, N.; Łysiak, G.P.; Bieńczyk, K. The effect of mechanical vibration during transport under model conditions on the shelf life, quality and physico-chemical parameters of four apple cultivars. *Agronomy* **2021**, *11*, 81. <https://doi.org/10.3390/agronomy11010081>.
48. Shoji, K.; Schudel, S.; Shrivastava, C.; Onwude, D.; Defraeye, T. Optimizing the postharvest supply chain of imported fresh produce with physics-based digital twins. *J. Food Eng.* **2022**, *329*, 111077. <https://doi.org/10.1016/j.jfoodeng.2022.111077>.
49. Thewes, F.R.; Anese, R.O.; Ludwig, V.; Klein, B.; Wagner, R.; Nora, F.R.; Rombaldi, C.V.; Brackmann, A. Dynamic controlled atmosphere (DCA) and 1-MCP: Impact on volatile esters synthesis and overall quality of ‘Galaxy’ apples. *Food Packag. Shelf Life* **2020**, *26*, 100563. <https://doi.org/10.1016/j.fpsl.2020.100563>.

50. Ludwig, V.; Thewes, F.R.; Brackmann, A.; Both, V.; Wagner, R.; Mallmann Wendt, L.; Pasquetti Berghetti, M.R.; dos Santos, I.D.; Soldateli, F.J. Volatile compounds profile and quality of ‘Cripps Pink’ apple: Impact of dynamic controlled atmosphere combined with delayed storage and 1-MCP treatment. *J. Food Process. Preserv.* **2022**, *46*, e17184. <https://doi.org/10.1111/jfpp.17184>.
51. Tuna Güneş, N.; Horzum, Ö. Influence of storage technology and 1-methylcyclopropene on postharvest behavior of ‘Ankara’ pear. *Turk. J. Agric. For.* **2024**, *48*, 81–94. <https://doi.org/10.55730/1300-011x.3164>.
52. Thewes, F.R.; Wood, R.M.; Both, V.; Keshri, N.; Geyer, M.; Pansera-Espíndola, B.; Hagemann, M.H.; Brackmann, A.; Wünsche, J.N.; Neuwald, D.A. Dynamic controlled atmosphere: A review of methods for monitoring fruit responses to low oxygen. *Communicata Sci.* **2021**, *12*, e3782. <https://doi.org/10.14295/cs.v12.3782>.
53. Al Shoffe, Y.; Rudell, D.; Park, D.; Algul, B.E.; Qin, M.; Shi, M.; Dando, R.; Watkins, C.B. Aroma volatiles and sensory quality of organically-grown apple cultivars after dynamic controlled atmosphere (DCA) storage and comparison with CA-stored fruit with and without 1-methylcyclopropene (1-MCP). *Postharvest Biol. Technol.* **2024**, *218*, 113162. <https://doi.org/10.1016/j.postharvbio.2024.113162>.
54. Khera, K.; Büchele, F.; Wood, R.M.; Thewes, F.R.; Wagner, R.; Hagemann, M.H.; Neuwald, D.A. Impact of different storage conditions with combined use of ethylene blocker on ‘Shalimar’ apple variety. *Sci. Rep.* **2024**, *14*, 8485. <https://doi.org/10.1038/s41598-024-57688-6>.
55. DeEll, J.R.; Lum, G.B.; Mostofi, Y.; Lesage, S.K. Timing of ethylene inhibition affects internal browning and quality of ‘Gala’ apples in long-term low oxygen storage. *Front. Plant Sci.* **2022**, *13*, 914441. <https://doi.org/10.3389/fpls.2022.914441>.
56. Błaszczuk, J. The influence of harvest date on the storability of ‘Topaz’ apples. *Zesz. Nauk. Inst. Sadow. Kwiac. Skiern.* **2006**, *14*, 87–93. (In Polish)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.