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Effect of Storage Conditions on the Storability and Nutritional Value of New Polish Apples Grown in Central Poland

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Abstract: The aim of this study is to assess the storability and nutritional value of new Polish apple cultivars recommended for cultivation after storage under low-oxygen atmospheric conditions (ULO and DCA). Fruit characteristics of 'Chopin' and clone 'JB' were evaluated in relation to commonly grown apple cultivars. Fruits of six selected apple cultivars were stored for a period of 9 months in conventional (0.04% CO_2: 21% O_2), Ultra-Low Oxygen (1.5% CO_2: 1.5% O_2), and Dynamic Controlled Atmosphere (0.6% CO_2: 0.6% O_2) cold storage. Physicochemical characteristics of the apples (firmness, soluble solids, acidity, and fibre content), nutritional and antioxidant values of the fruit (P, K, Ca, Mg, Fe, Cu, Zn, total polyphenols, total flavonoids, and antioxidant capacity), and safety of consumption (residues of pesticides) were assessed. The new cultivar 'Chopin' and clone 'JB' were characterised by above-average acidity and clone 'JB' stood out in terms of antioxidant properties. Storage in a low-oxygen atmosphere in DCA was more effective in limiting fruit ripening than conventional cold storage, contributing to the preservation of the high potential of biologically active compounds in the apples. Apples after 9 months of storage were characterised by higher firmness (from 3.5 to 14 N), higher total polyphenol content in the flesh (from 8 to 23 mg·100 g^{-1} FW) and peel (from 32 to 97 mg·100 g^{-1} FW), as well as higher antioxidant capacity in the flesh (from 15 to 37 mg AAE·100 g^{-1} FW) and peel (from 28 to 59 mg AAE·100 g^{-1} FW) when stored in DCA compared to cold storage.

Keywords: Dynamic Controlled Atmosphere; Ultra-Low Oxygen; fruit quality; antioxidant properties; polyphenols

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1. Introduction

In European countries, apples are considered a staple in the human diet, valued for their various health-promoting properties [1–3]. Being a potential source of many nutrients like vitamins (C, B group, and E), pigments (beta carotene), minerals (N, P, K, Ca, Mg, and Fe) [4], dietary fibre [5,6], and a number of phytochemicals (polyphenols), they have gained recognition for their high nutritional potential affecting the human body [6–8]. Thanks to the widespread cultivation of this species in temperate countries, apples are readily available to consumers [9,10]. However, the preservation of valuable nutrients in apples during the storage period, transportation, or distribution on the store shelf is a key determinant of the technology in which the fruit is stored [11].

In a healthy diet, emphasis is placed on fruits and vegetables, due to the polyphenols found in them that play a very important role in human nutrition. These bioactive compounds play a key role in reducing free radicals that cause various diseases in the human body, often referred to as diseases of civilisation [1,6–8,12]. They protect against the risk of neurodegenerative diseases, reduce asthma symptoms, and are widely used in the prevention of many chronic diseases such as diabetes, hypertension, and cancer. The conditions under which the fruit is stored after harvest affect the maintenance of polyphenol

level in apples [12,13]. Previous research results indicate that the low oxygen concentration in the atmosphere in the cold storage chamber is conducive to maintaining the high physicochemical quality of apples [14,15]. The effect of storage conditions on fruit quality is widely reported in the literature [16–18]. Radenkovs and Juhnevica-Radenkova [17] demonstrated that the use of low oxygen concentration in the storage chamber favours the reduction in weight loss of apples when confronted with fruit stored in cold storage. Many authors argue that the maintenance of high firmness, acidity, or low soluble solids content in apples is favoured by storage under ULO conditions [16,17,19]. Further lowering the oxygen concentration to the limit of aerobic and anaerobic respiration in apples (DCA technology) measurably reduces fruit ripening. However, the effect of DCA conditions correlates with the varietal characteristics of the apples. According to Gasser and van Arx [20], storing the cultivars 'Topaz' and 'Otava' in DCA has no positive effect on fruit quality compared to ULO conditions, while in the case of the cultivar 'Ariane', fruit stored in DCA retained firmness and acidity better compared to fruit stored under ULO conditions. The higher storage efficiency of apples in DCA than ULO or cold storage is reported by many researchers [19,21–23]. Oxygen levels used during storage in DCA are maintained at the limit of the anaerobic compensation point (ACP), the point at which O_2 uptake and CO_2 production are minimal. Storing apples under these conditions maximally reduces respiration rates and metabolite production [21,24]. Currently, much attention is being paid to assessing the relationship between storage conditions, involving traditional and innovative technologies and the nutritional, antioxidant, and physicochemical properties of apples [13,24]. Due to the evidence that the polyphenol content is dependent on the genetic traits of the variety, there is a lack of consistency in the literature in describing the results for the postharvest storage of apple fruit. In a study by Carbone et al. [25], the total phenolic content of 'Braeburn' apples was significantly reduced after storage at low temperature (1 °C), by 50% and 20% in the peel and flesh, respectively. Also, Kolniak-Ostek et al. [26] found that in apples stored for 6 months, the total polyphenol concentration decreased up to 27%, depending on the cultivar. However, Napolitano et al. [27] reported an increase in flesh catechin and phloridzin content, as well as antioxidant activity, after cold storage of the Italian cultivar 'Annurca'. The highly effective respiration rate reduction in ULO and DCA significantly slows down apple metabolism. According to Putnik et al. [28], an increase in total phenolic compounds can occur in apple flesh after storage in CA and ULO. The high stability of phenolic compounds during storage in ULO and DCA is reported by many authors [16,17,19,29]. Putnik et al. [28] demonstrated a lack of correlation between total phenolic content and antioxidant activity. The general opinion is that during long-term storage, antioxidant activity decreases in both peel and flesh tissues [30,31].

With the promotion of healthy diets and lifestyles among consumers in developed countries, this knowledge enables producers to make informed choices about fruit distribution, optimizing the health benefits consumers receive. Properly selected storage technology makes it possible to extend the supply period of apples with minimal loss of their health-promoting properties [17,19,21,32]. The nutritional potential of apples is influenced by their mineral content (e.g., Ca, K, Mg, Zn, and Se) but additionally determines their storability. High calcium content in the middle lamella of the cell wall stabilises the permeability of compounds between cells. This is conducive to reducing the occurrence of physiological disorders, contributing to improving the storability of apples [33,34].

Dietary fibre is a group of food components that are resistant to the action of digestive enzymes and are mainly found in cereals, fruits, and vegetables [35]. Dietary fibre is studied in two groups: water-soluble and water-insoluble organic compounds, which can be divided into many different fractions including arabinoxylan, inulin, pectin, bran, cellulose, β-glucan, and resistant starch [36,37]. Dietary fibre is a major component of low-energy products, which have become increasingly important in recent years. Dietary fibre also has technological and functional properties that can be used in food formulation, as well as numerous beneficial effects on human health. The dietary fibre content of apples

is influenced by varietal characteristics [36], storage conditions that cause the softening of the fruit [38,39], as well as dehydration [40].

To ensure a holistic understanding of apple distribution management, pesticide residue evaluation appears to be a critically important issue [41]. Foods that are classified as functional products should not only have elevated nutrient values, but they should also be safe for consumption [42]. In EU countries, the Integrated Plant Production System was introduced in 2014. Integrated Production (IP) is a modern food production system that makes sustainable use of technical and biological progress, plant protection and fertilisation, and pays special attention to protecting the environment and human health. This system has facilitated quality control at all stages of production.

The link between apple storage technology and the preservation of their nutritional integrity and antioxidant capacity is an important one [12]. The aim of this study is to evaluate the influence of dynamically controlled atmosphere and ultra-low atmosphere technology, as well as the storage period, on the physicochemical properties and nutritional value of apples grown in central Poland, with particular emphasis on two new Polish apple tree selections. In the experiment, representative fruit characteristics of the 'Chopin' variety and the 'JB' clone were evaluated in relation to commercially grown apple tree varieties in Poland.

2. Materials and Methods

2.1. Location of the Experiment and Research Material

Apples of varieties commonly grown in Poland were used for the tests performed in the 2021–2022 season: 'Gala Brookfield', 'Idared', 'Šampion', and 'Ligol'. In addition, the new Polish cultivar 'Chopin' recommended for commodity cultivation and the red-fleshed clone 'JB' were evaluated. The fruit of the evaluated varieties came from the experimental orchard of the Institute of Horticultural Sciences 'Wilanów', WULS-SGGW. The orchard is located in central Poland (52.259° N, 21.020° E), in an area with a warm temperate transitional climate, with an annual rainfall of 500–550 mm. The orchard has very fertile soils, dominated by mads (alluvial soils), characterised by a significant content of humus and clay materials. Fruits for the experiment were harvested from trees aged 10 years, growing on M.9 rootstock. The trees grow at a spacing of 1 m × 3.5 m. Fruits were harvested from 10 selected trees for each cultivar. Fruit harvest date was determined using the Streif index and starch test. In addition, the ethylene content in the seed chambers of the apples was evaluated to determine the maturity of the fruit after harvest.

2.2. Experimental Layout

During fruit harvesting, selections were made by rejecting fruit with visible damage or signs of rotting. After harvesting, the fruits were transported to a cold store, where the apples were randomly divided into 3 groups—according to the technology in which they were stored. The apples were stored in 3 containers of 1 m^3 each. Approximately 600 pieces of fruit in 6 packs of 15 kg plastic were placed in one container. Gas levels in the containers were regulated automatically using an Oxystat 200 system (David Bishop Ltd., Heathfield, UK), correcting CO_2 and O_2 content every 4 h. The fruit was stored for a period of 9 months. Assessment of fruit quality and nutritional value was performed immediately after apple harvest and every 3 months during storage. Testing of individual fruit characteristics at each date was performed in three repetitions and one repetition consisted of 10–20 fruits depending on the analysis conducted.

Analyses of biologically active compounds were evaluated separately in apple peel and flesh. Immediately after harvesting, peel and flesh were frozen using liquid nitrogen and then stored in a deep freezer at −78 °C. The frozen material was ground in the presence of liquid nitrogen in an analytical mill A11 basic and the extraction of biologically active compounds was carried out in powdered material.

2.3. Storage Technology

Apples were stored using the following technologies:

NA—ordinary cold storage, CO_2 = 0.04%, O_2 = 21%, temperature ≈ 1 °C, Rh ≈ 80%;
ULO—Ultra-Low Oxygen, CO_2 = 1.5%, O_2 = 1.5%, temperature ≈ 1 °C, Rh ≈ 95%;
DCA—Dynamic Controlled Atmosphere, CO_2 = 0.6%, O_2 = 0.6%, temperature ≈ 1 °C, Rh ≈ 95%.

The composition of the atmosphere in the containers was regulated automatically by an Oxystat 200 system (David Bishop Ltd., Heathfield, UK). In addition, DCA technology used Handy PEA fluorimeters (Hansatech Industries Ltd., Pentney, UK) to assess apple stress caused by a too low oxygen concentration. The composition of the atmosphere under DCA conditions was maintained at about 0.6% CO_2 and about 0.6% O_2, changing the oxygen content during periods of apple stress by 0.1%.

2.4. Research Methodology

The starch test, the Streif index method, and the ethylene content of the seed chambers of apples were used to evaluate the timing of harvest and the maturity of the fruit immediately after harvest.

The starch test (SI) is the simplest and cheapest way to determine harvest date. Representative fruit samples are cut crosswise and soaked or sprayed with a reagent (Lugol's fluid). The starch test involves staining the starch contained in the apple flesh by iodine found in potassium iodide (Lugol's liquid). The resulting image (the starch has been stained a dark blue colour) is compared with reference plates. As we approach harvest and later during storage, the phenomenon of starch decomposition into simple sugars takes place, so that more and more of the area is left uncoloured. The starch index (SI) was estimated according to Tomala et al. [43]. The Streif index was evaluated based on three components, i.e., firmness, soluble solids content, and starch index, according to the formula:

$$\text{Index Streif} = \frac{\text{firmness}}{\text{soluble solids content} \times \text{starch index}}$$

Ethylene content in the seed chambers was assessed according to the method described in an earlier study [14]. Ethylene content was evaluated using a gas chromatograph (HP 5890, Hewlett Packard, Palo Alto, CA, USA), equipped with a packed column, and FID detector. The oven temperature was 150 °C and the retention time was about 1.5 min.

The following indices were used to assess fruit quality: flesh firmness, soluble solids content, and apple acidity. Flesh firmness (FF) was measured using a 10 mm diameter probe mounted in a universal testing machine (TM 5542; Instron, High Wycombe, UK). The measurement speed was 240 mm-min^{-1}. Firmness was measured at two opposite locations on the apple, after the peel was removed. The location for the first test was visually selected in the reddest area or opposite the greenest area for the 'Chopin' cultivar. The testing machine was programmed to detect contact with the sample and then move to a depth of 10 mm, collecting force data every 0.0254 mm. The indicator value was expressed as the maximum force used to plunge the mandrel to the indicated depth and was expressed in Newton (N). The soluble solids content (SSC) of the juice obtained from the apples was determined using a PR^{-32} alpha handheld refractometer (Atago, Tokyo, Japan). The results were expressed in degrees Brix (°Brix) [14].

Acidity (TA) was measured in an aqueous extract from a medium fruit sample by titration with 0.1 N sodium hydroxide (NaOH) to a pH endpoint of 8.1, using a TitroLine 5000 system (Si Analytics, Mainz, Germany). Results were expressed as a percentage of malic acid [14].

The nutritional value and mineral composition of apples were described by the content of fibre, total polyphenols (TPC), and total flavonoids (TFC); antioxidant capacity was assessed as well as the composition of micro- and macronutrients. The official AOAC 985.29 method for measuring TDF in foods was used to assess fibre content. The method

is based on the enzymatic removal of starch and protein from samples by amylase and protease at 90 °C and 60 °C, respectively. Insoluble dietary fibre (IDF) is then separated by filtration, and soluble high-molecular-weight dietary fibre is precipitated with 78% etalon and collected by filtration. Both fibre fractions are dried and weighed, which together give the total dietary fibre content of the sample. The results are expressed as a percentage of fresh weight. Analysis of the total polyphenol content was carried out according to the Waterhouse method [44]. Total polyphenols were measured using a Marcel s330 PRO spectrophotometer (Marcel S.A., Warsaw, Poland) with Folin-Ciocalteau reagent, at λ = 700 nm. The results are expressed in milligrams of gallic acid per 100 g^{-1} FW (fresh weight). Total flavonoids were analysed using the modified method of Marinova et al. [45]. An amount of 5 g of fruit powdered in liquid nitrogen was mixed with 25 mL of 80% methanol and extracted for 15 min. The extractions were carried out twice. Distilled water, 5% $NaNO_2$, 10% $AlCl_3$, and 1 M NaOH were added successively to the resulting samples at specified intervals. We took measurements using a Marcel s330 PRO spectrophotometer (Marcel S.A., Warsaw, Poland) at 510 nm. The total flavonoid content of the fruit was expressed as mg quercetin equivalent per 100 g^{-1} FW (fresh weight). Antioxidant capacity was determined according to the method of Saint Criq de Gaulejac et al. [46] based on the reduction of free radicals obtained from DPPH (1,1-diphenyl-2-picrylhydrazine, Sigma-Aldrich, Poznań). Antioxidant capacity was calculated from absorbance measurements for the specific sample (fruit extract + $DPPH^+$) taken after 20 min at λ = 517 nm relative to the control sample (H_2O + $DPPH^+$). Results were expressed in mg per g F.W. of ascorbic acid (AAE). Macro- and micronutrient (P, K, Ca, Mg, Fe, Cu, and Zn) analyses were performed at the J.S. Hamilton accredited laboratory (OiB accreditation scope No. 53/MON/2016). Mineralisation was performed in a closed-pressure system in a so-called 'Teflon bomb' using microwave energy from electromagnetic radiation at 2450 MHz. Pressure mineralisation involves the reaction of sample components with mineral acids at elevated temperatures in a closed Teflon vessel, known as a Teflon bomb. The pressure created by the release of gases allows for higher temperatures than the boiling points of the acids in open systems. The final determination was performed by inductively coupled plasma ionisation mass spectrometry (ICP-MS). The principle of ICP-MS is to measure the intensity of the ion flux generated in the plasma. The ions are produced in the inductively coupled plasma and then separated using a mass analyser, where the separation is achieved due to the value of the mass-to-charge ratio. For the analysis of solid samples, a laser evaporation (LA) technique was used, which involves surface atomisation of the sample material using a focused laser beam. The gas phase and aerosol generated are transferred to the ICP plasma by means of an auxiliary gas stream—argon.

Food safety analysis was carried out based on the results of residues of pesticides in apples. The tests were performed using gas chromatography (GC-MS/MS) at the J.S. Hamilton accredited laboratory (OiB accreditation scope No. 53/MON/2016).

2.5. Statistical Analysis

Statistical analysis of the obtained test results was performed using Statistica 13.3 software (StatSoft Poland, Krakow, Poland). Two-factor analysis of variance was used, and the analysed factors were variety and storage technology. The Tukey test was used to assess the significance of differences between the averages, assuming a significance level of 5%.

3. Results

Data describing the physiological state of the fruits of the studied varieties are shown in Figures 1–3. Fruit maturity immediately after harvesting was at a similar level. The slightly lower ethylene content in the seed chamber of apples of clone 'JB' does not indicate a less advanced level of fruit maturity and may be due to its individual characteristics (Figure 2). The values presented in Figure 3 indicate that the fruit was harvested at the optimal time of harvest, just after the onset of climacteric ripening.

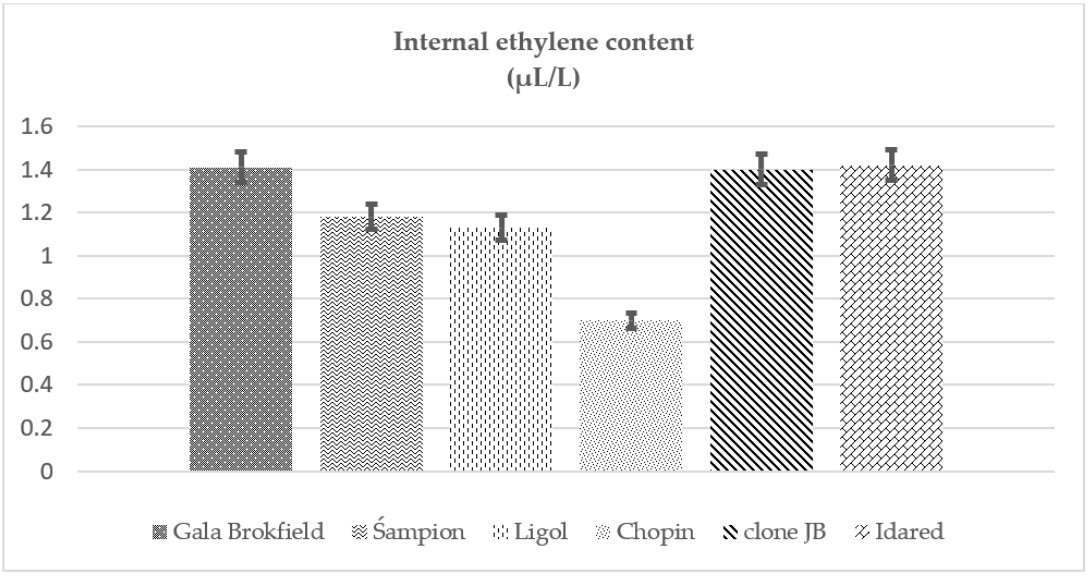

Figure 1. The values of internal ethylene content (µL/L), characteristic of the maturity stage of apples assessed directly after harvest. Data are presented as mean ± standard deviation.

Figure 2. The values of Streif index (−), characteristic of the maturity stage of apples assessed directly after harvest. Data are presented as mean ± standard deviation.

Significantly different varietal characteristics were noted between the cultivars studied. After harvesting, 'Gala Brookfield' had the highest firmness value and 'Šampion' had the lowest. The difference in index values between the two varieties was as high as 28.8% (Figure 4). Clone 'JB' and the cultivars 'Chopin' and 'Idared' posed a group of apples with similar firmness, intermediate to the above-mentioned cultivar. Cultivar characteristics determined the storage quality of the fruit (Table 1). The 'Šampion' cultivar had the lowest firmness immediately after harvest and after storage, regardless of the period as well as the conditions under which the fruit was stored. 'Šampion' fruit firmness after 6 and 9 months of storage was characterised by a value lower than acceptable to consumers, determined at 45 N. A similarly rapid loss of firmness was found in the 'JB' clone. In addition, very intense rotting symptoms were observed, which prevented the 'JB' clone from being stored for longer than 3 months. The cultivar 'Ligol' had the lowest loss of firmness, amounting to only 10.9% of the period of 9 months of apple storage under DCA conditions. In general,

fruit stored in ULO or DCA cold storage had significantly higher firmness than after storage in NA. It should be emphasised that after 9 months of storage in NA, most of the cultivars evaluated did not have acceptable firmness. After the same storage period with DCA, the cultivars 'Ligol', 'Chopin', 'Gala Brookfield', and 'Idared' retained high flesh firmness. Only in the case of the Idared variety was the effect of storage conditions on flesh firmness after this storage period not proven.

Figure 3. The values of starch index (−), characteristic of the maturity stage of apples assessed directly after harvest. Data are presented as mean ± standard deviation.

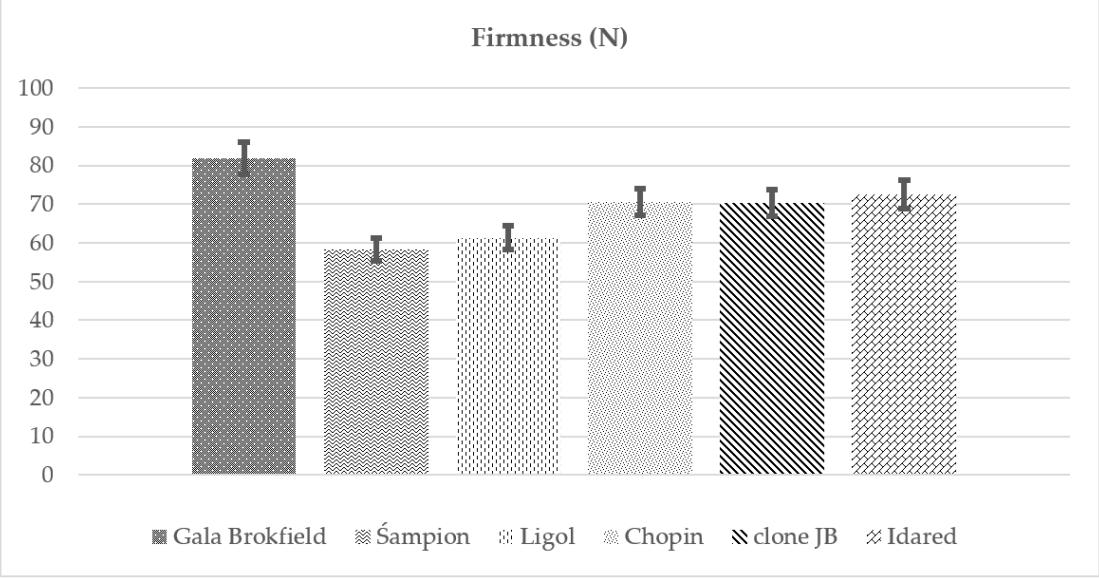

Figure 4. The values of firmness (N) for apples depending on cultivars after harvesting. Data are presented as mean ± standard deviations.

Table 1. The values of firmness (N) for apples depending on cultivars and storage technology.

Cultivars	NA	ULO	DCA	*p*-Value
		3 months		
Gala Brookfield	53.3 ± 0.9	58.5 ± 0.3	60.9 ± 0.2	<0.01
Šampion	42.5 ± 0.3	42.6 ± 0.3	50.7 ± 0.2	<0.01
Ligol	54.5 ± 0.3	58.6 ± 0.3	60.1 ± 0.2	<0.01
clone JB	41.7 ± 0.6	47.5 ± 1.0	51.3 ± 1.0	<0.01
Chopin	52.6 ± 0.7	59.1 ± 1.4	62.5 ± 0.8	<0.01
Idared	51.3 ± 0.6	55.0 ± 0.4	57.6 ± 0.8	<0.01
p-value	<0.01	<0.01	<0.01	
		6 months		
Gala Brookfield	47.2 ± 0.8	50.9 ± 1.2	56.6 ± 0.8	<0.01
Šampion	26.8 ± 0.8	31.0 ± 0.4	37.4 ± 1.3	<0.01
Ligol	50.5 ± 0.3	52.4 ± 0.4	57.3 ± 0.3	<0.01
clone JB	-	-	-	
Chopin	42.7 ± 1.0	55.1 ± 0.4	57.7 ± 0.3	<0.01
Idared	45.8 ± 0.7	43.5 ± 0.7	51.6 ± 1.4	<0.01
p-value	<0.01	<0.01	<0.01	
		9 months		
Gala Brookfield	39.4 ± 0.2	43.4 ± 1.0	46.9 ± 0.5	<0.01
Šampion	20.9 ± 0.6	29.6 ± 0.6	34.9 ± 0.5	<0.01
Ligol	41.4 ± 0.7	44.6 ± 0.7	54.6 ± 0.2	<0.01
clone JB	-	-	-	
Chopin	38.5 ± 1.0	43.9 ± 1.2	49.6 ± 1.3	<0.01
Idared	41.2 ± 0.5	43.7 ± 1.1	44.7 ± 1.2	0.028
p-value	<0.01	<0.01	<0.01	

Data are presented as mean ± standard deviation; NA—ordinary cold storage; ULO—Ultra-Low Oxygen; DCA—Dynamic Controlled Atmosphere.

The soluble solids content after fruit harvest varied depending on the apple cultivar (Figure 5). Unexpectedly, the lowest SSC content was found in 'Gala Brookfield' apples, a cultivar considered sweet by consumers. The group with significantly higher SSC included 'Ligol', the 'JB' clone, and 'Idared'. The effect of storage technology was variable and depended on the storage period and the variety evaluated (Table 2). It was observed that DCA technology stabilises the soluble solids of fruit between different cultivars with increasing storage period. A similar but weaker effect was observed after storage in ULO but was not found in NA. Overall, SSC fluctuated during the course of the study, making it impossible to clearly indicate the direction of these changes for all varieties. However, it is possible to isolate an increase in SSC in most varieties stored in NA.

The analysis of acidity in postharvest fruit showed a large difference between cultivars, with the TA value of the 'JB' clone and 'Chopin' cultivar being more than twice as high as the other cultivars (Figure 6). 'Idared' was also distinguished by higher acidity, while the 'sweet' cultivar 'Gala Brookfield' was lower. TA in the fruit of the evaluated cultivars was more strongly determined by varietal characteristics than by storage conditions (Table 3). It should be noted, however, that the influence of storage conditions increased with the extension of the storage period. Analysis of the data showed that the 'JB' clone and 'Chopin' and 'Idared' cultivars had higher TA, while the 'Gala Brookfield', 'Šampion', and 'Ligol' cultivars had lower TA. The described cultivars' differences were proven during 9 months of storage, regardless of storage conditions. The effect of storage technology depended on the cultivar group. After 3 months, significantly higher TA was found in 'Gala Brookfield', 'Šampion', 'Ligol', and 'Chopin', while after 9 months of storage, more effective inhibition of TA loss was proven in all cultivars after storage in DCA.

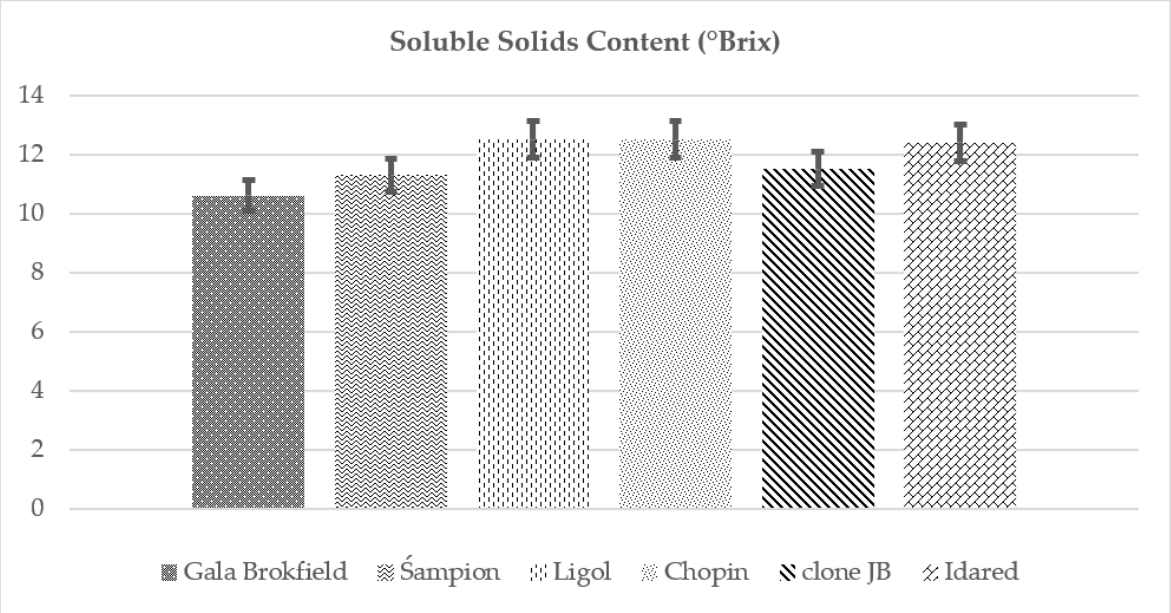

Figure 5. The values of soluble solids content (°Brix) for apples depending on cultivars after harvesting. Data are presented as mean ± standard deviations.

Table 2. The values of soluble solids content (°Brix) for apples depending on cultivars and storage technology.

Cultivars	NA	ULO	DCA	*p*-Value
		3 months		
Gala Brookfield	11.4 ± 0.1	11.5 ± 0.1	11.3 ± 0.4	0.757
Šampion	11.3 ± 0.1	11.9 ± 0.1	11.5 ± 0.1	<0.01
Ligol	12.5 ± 0.1	11.4 ± 0.2	12.5 ± 0.1	<0.01
clone JB	12.1 ± 0.2	12.4 ± 0.2	12.5 ± 0.1	0.155
Chopin	12.2 ± 0.1	11.9 ± 0.1	12.6 ± 0.1	0.139
Idared	11.3 ± 0.1	11.9 ± 0.2	12.1 ± 0.2	0.014
p-value	<0.01	<0.01	<0.01	
		6 months		
Gala Brookfield	12.0 ± 0.1	11.9 ± 0.2	12.7 ± 0.5	0.072
Šampion	11.6 ± 0.1	12.1 ± 0.2	11.9 ± 0.2	0.061
Ligol	11.8 ± 0.1	11.4 ± 0.1	12.6 ± 0.4	0.005
clone JB	-	-	-	
Chopin	12.6 ± 0.1	12.8 ± 0.1	12.8 ± 0.1	0.301
Idared	10.9 ± 0.1	11.7 ± 0.1	11.7 ± 0.1	<0.01
p-value	<0.01	<0.01	0.024	
		9 months		
Gala Brookfield	12.7 ± 0.1	12.0 ± 0.2	12.2 ± 0.1	0.023
Šampion	11.9 ± 0.1	11.5 ± 0.2	11.5 ± 0.2	0.105
Ligol	13.0 ± 0.2	11.1 ± 0.6	11.7 ± 0.4	0.011
clone JB	-	-	-	
Chopin	12.6 ± 0.2	12.4 ± 0.4	11.9 ± 0.2	0.083
Idared	11.6 ± 0.2	11.8 ± 0.3	11.7 ± 0.3	0.872
p-value	<0.01	0.052	0.146	

Data are presented as mean ± standard deviation; NA—ordinary cold storage; ULO—Ultra-Low Oxygen; DCA—Dynamic Controlled Atmosphere.

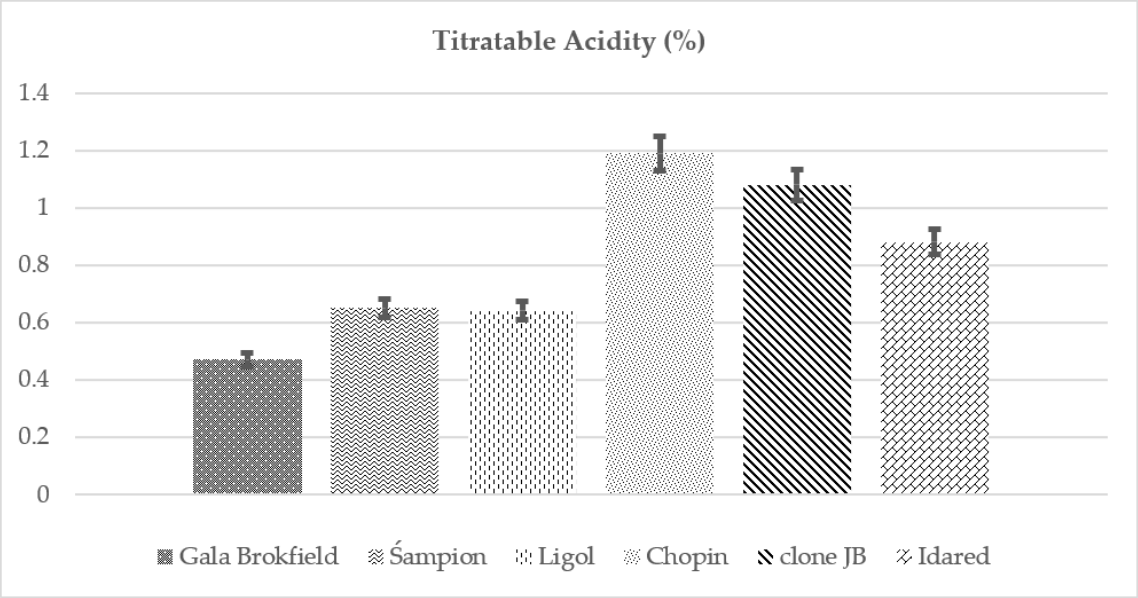

Figure 6. The values of titratable acidity (%) for apples depending on cultivars after harvesting. Data are presented as mean ± standard deviations.

Table 3. The values of titratable acidity (%) for apples depending on cultivars and storage technology.

Cultivars	NA	ULO	DCA	*p*-Value
		3 months		
Gala Brookfield	0.38 ± 0.02	0.38 ± 0.01	0.42 ± 0.01	0.013
Šampion	0.50 ± 0.01	0.54 ± 0.01	0.56 ± 0.02	0.008
Ligol	0.50 ± 0.01	0.53 ± 0.01	0.60 ± 0.02	<0.01
clone JB	1.03 ± 0.04	1.11 ± 0.03	1.15 ± 0.04	0.053
Chopin	0.71 ± 0.01	0.78 ± 0.01	0.81 ± 0.03	<0.01
Idared	0.68 ± 0.01	0.67 ± 0.02	0.69 ± 0.02	0.522
p-value	<0.01	<0.01	<0.01	
		6 months		
Gala Brookfield	0.35 ± 0.01	0.30 ± 0.01	0.31 ± 0.01	<0.01
Šampion	0.44 ± 0.01	0.40 ± 0.02	0.44 ± 0.01	0.021
Ligol	0.46 ± 0.01	0.46 ± 0.01	0.50 ± 0.01	<0.01
clone JB	-	-	-	-
Chopin	0.64 ± 0.01	0.77 ± 0.01	0.71 ± 0.02	<0.01
Idared	0.67 ± 0.04	0.65 ± 0.01	0.63 ± 0.02	0.320
p-value	<0.01	<0.01	<0.01	
		9 months		
Gala Brookfield	0.24 ± 0.01	0.25 ± 0.01	0.28 ± 0.01	<0.01
Šampion	0.28 ± 0.01	0.30 ± 0.01	0.35 ± 0.01	<0.01
Ligol	0.26 ± 0.01	0.29 ± 0.02	0.32 ± 0.01	<0.01
clone JB	-	-	-	-
Chopin	0.36 ± 0.01	0.39 ± 0.01	0.49 ± 0.01	<0.01
Idared	0.47 ± 0.01	0.47 ± 0.01	0.46 ± 0.01	<0.01
p-value	<0.01	<0.01	<0.01	

Data are presented as mean ± standard deviation; NA—ordinary cold storage; ULO—Ultra-Low Oxygen; DCA—Dynamic Controlled Atmosphere.

Of the cultivars tested, lower postharvest fibre content was found in 'Gala Brookfield' and 'Idared'. Both cultivars were characterised by an almost 50% lower value of the index than in other cultivars, among which 'Ligol' and 'Chopin' should be singled out as cultivars

characterised by higher fibre content (Figure 7). Fibre content in fruit highly significantly depended on the cultivar as well as storage conditions. In general, most cultivars showed an increase in fibre content at successive analysis dates after storage (Table 4). On the first date of analysis after storage (after 3 months), the increase in the index value was insignificant in fruit stored in NA but much higher in fruit from DCA. The increase in fibre content with DCA technology, compared to postharvest values, was found especially in the 'Gala Brookfield' and 'Idared' cultivars. At subsequent analysis dates, after 6 and 9 months of storage, there was a further increase in fibre content, faster with DCA or ULO technology than NA. Unexpectedly, 'Gala Brookfield' and 'Idared', classified after harvest as low-fibre varieties, after 9 months of storage in DCA or ULO, were characterised by a higher index value than the other cultivars. 'Chopin', on the other hand, stood out in terms of fibre content among cultivars stored under NA conditions, throughout the end of the study.

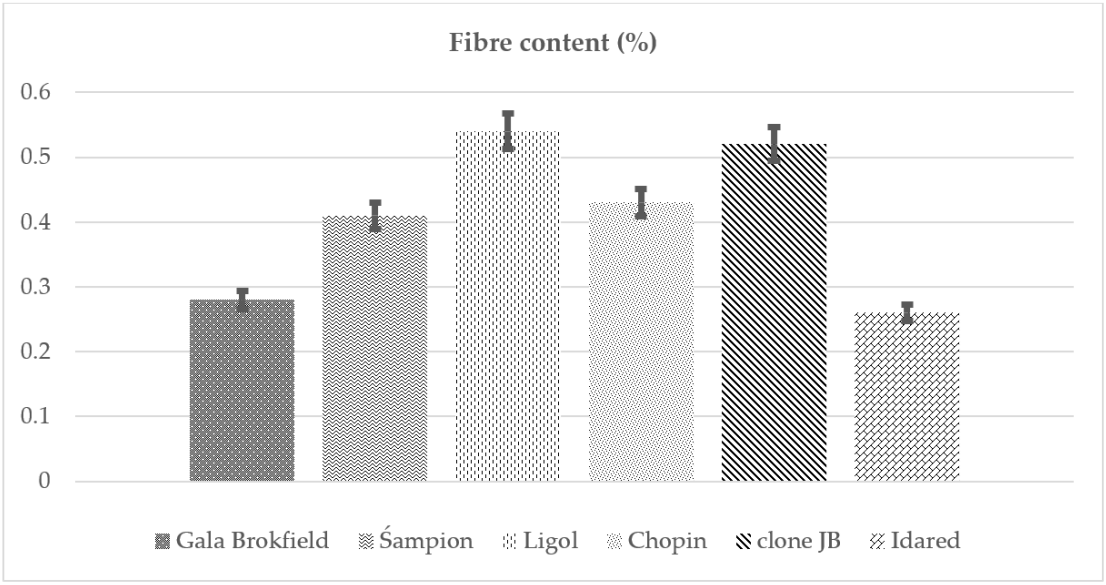

Figure 7. The values of dietary fibre (%) for apples depending on cultivars after harvesting. Data are presented as mean ± standard deviation.

Varietal traits strongly influenced the content of total polyphenols in the flesh (Figure 8) and peel (Figure 9) of apples. A high TPC content was recorded in the flesh of clone 'JB', while a twofold lower TPC content was characteristic of 'Ligol' flesh. Even greater differences were found in apple peel. In this case, the value of TPC in the peel of clone 'JB' was more than four times higher than in the peel of 'Ligol'. High TPC content was also distinguished by 'Gala Brookfield' and 'Idared'. Analysis of the results indicates that a stronger determinant of TPC is the cultivar ($p < 0.01$) than the storage technology ($p > 0.01$ for most analyses) in both apple elements evaluated (Tables 5 and 6). After 3 months of storage, an increase in TPC values versus postharvest values was found in both apple flesh and peel in almost all varieties. In contrast, a decrease in TPC was observed at subsequent analysis dates in relation to the earlier analysis date. On the first post-storage analysis date, 'Gala Brookfield' and 'Idared', as well as clone 'JB', were characterised by higher flesh and peel TPC contents than the other cultivars. The cultivar with the lowest TPC content was 'Ligol'. Analyses at subsequent storage dates confirmed the previously noted relationship. The dynamics of change in TPC content were conditioned by the technology in which the fruit was stored. After 3 months of storage in NA, a higher TPC value was found in apples stored in NA than in ULO or DCA (with the exception of clone JB). In contrast, on subsequent analysis dates (after 6 and 9 months), a higher TPC was found in apples after storage in DCA than in NA.

Table 4. The values of dietary fibre (%) for apples depending on cultivars and storage technology.

Cultivars	NA	ULO	DCA	*p*-Value
		3 months		
Gala Brookfield	0.32 ± 0.01	0.49 ± 0.01	0.64 ± 0.01	<0.01
Šampion	0.46 ± 0.02	0.57 ± 0.01	0.66 ± 0.02	<0.01
Ligol	0.62 ± 0.01	0.71 ± 0.05	0.78 ± 0.01	<0.01
clone JB	0.53 ± 0.02	0.78 ± 0.02	1.07 ± 0.05	<0.01
Chopin	0.69 ± 0.02	0.73 ± 0.01	0.82 ± 0.02	<0.01
Idared	0.29 ± 0.01	0.56 ± 0.02	0.63 ± 0.01	<0.01
p-value	<0.01	<0.01	<0.01	
		6 months		
Gala Brookfield	0.57 ± 0.05	0.92 ± 0.02	1.33 ± 0.05	<0.01
Šampion	0.53 ± 0.05	0.62 ± 0.02	1.13 ± 0.05	<0.01
Ligol	0.73 ± 0.05	0.84 ± 0.01	0.97 ± 0.05	<0.01
clone JB	-	-	-	-
Chopin	1.07 ± 0.05	1.08 ± 0.05	1.13 ± 0.02	<0.01
Idared	0.53 ± 0.05	1.30 ± 0.04	2.07 ± 0.05	<0.01
p-value	<0.01	<0.01	<0.01	
		9 months		
Gala Brookfield	0.83 ± 0.05	1.13 ± 0.05	1.63 ± 0.05	<0.01
Šampion	0.57 ± 0.05	0.70 ± 0.01	1.20 ± 0.01	<0.01
Ligol	0.77 ± 0.05	0.96 ± 0.01	1.23 ± 0.05	<0.01
clone JB	-	-	-	-
Chopin	1.10 ± 0.05	1.33 ± 0.01	1.27 ± 0.09	<0.01
Idared	0.77 ± 0.05	1.57 ± 0.05	2.42 ± 0.02	<0.01
p-value	<0.01	<0.01	<0.01	

Data are presented as mean ± standard deviation; NA—ordinary cold storage; ULO—Ultra-Low Oxygen; DCA—Dynamic Controlled Atmosphere.

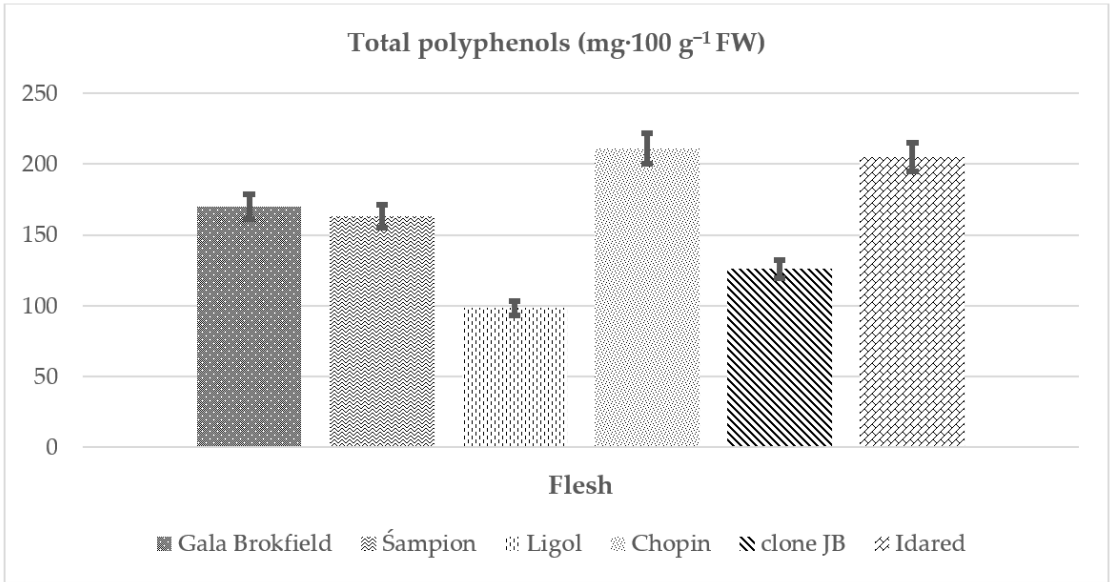

Figure 8. The values of total polyphenols content (mg·100 g^{-1} FW) for the flesh of apples depending on cultivars after harvesting. Data are presented as mean ± standard deviation.

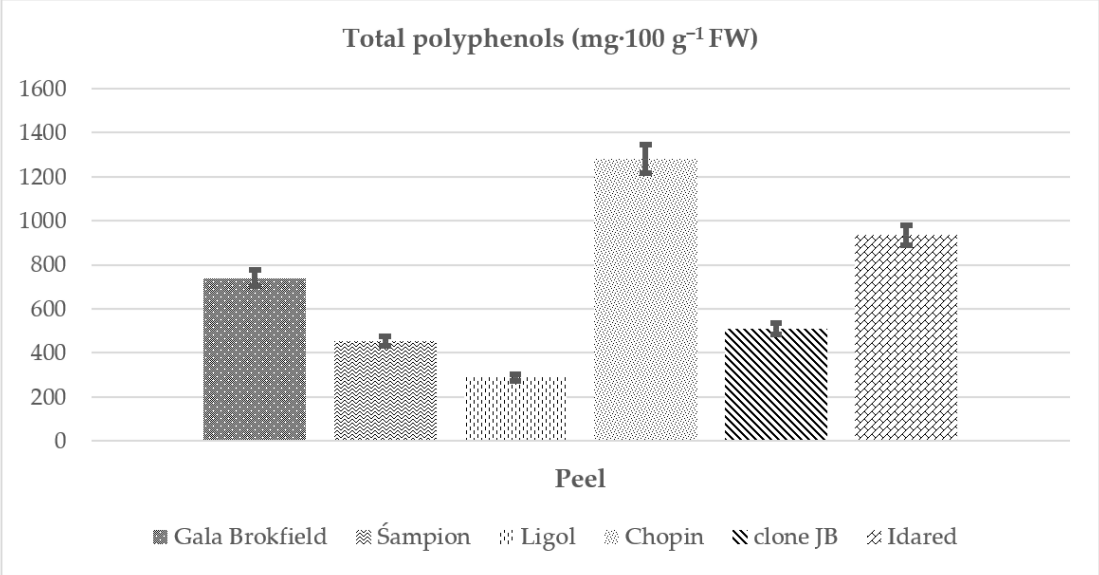

Figure 9. The values of total polyphenols content (mg·100 g^{-1} FW) for the peel of apples depending on cultivars after harvesting. Data are presented as mean ± standard deviation.

Table 5. The values of total polyphenols content (mg·100 g^{-1} FW) for the flesh of apples depending on cultivars and storage technology.

Cultivars	NA	ULO	DCA	*p*-Value
		3 months		
Gala Brookfield	207 ± 3	200 ± 1	198 ± 1	0.027
Šampion	181 ± 4	171 ± 2	168 ± 4	0.019
Ligol	121 ± 2	110 ± 2	109 ± 3	0.010
clone JB	147 ± 11	172 ± 8	180 ± 13	0.041
Chopin	139 ± 3	133 ± 3	130 ± 3	0.049
Idared	227 ± 8	213 ± 4	209 ± 5	0.023
p-value	<0.01	<0.01	<0.01	
		6 months		
Gala Brookfield	169 ± 13	186 ± 9	195 ± 7	0.040
Šampion	143 ± 5	153 ± 7	160 ± 8	0.013
Ligol	99 ± 5	106 ± 4	107 ± 5	0.037
clone JB	-	-	-	-
Chopin	114 ± 7	128 ± 6	127 ± 3	0.021
Idared	192 ± 6	204 ± 3	200 ± 7	0.034
p-value	<0.01	<0.01	<0.01	
		9 months		
Gala Brookfield	154 ± 8	171 ± 6	169 ± 4	<0.01
Šampion	136 ± 2	144 ± 4	144 ± 3	0.038
Ligol	87 ± 6	99 ± 5	97 ± 7	0.047
clone JB	-	-	-	-
Chopin	104 ± 3	117 ± 4	127 ± 8	0.028
Idared	183 ± 9	197 ± 3	202 ± 1	<0.01
p-value	<0.01	<0.01	<0.01	

Data are presented as mean ± standard deviation; NA—ordinary cold storage; ULO—Ultra-Low Oxygen; DCA—Dynamic Controlled Atmosphere.

Table 6. The values of total polyphenols content (mg·100 g^{-1} FW) for the peel of apples depending on cultivars and storage technology.

Cultivars	NA	ULO	DCA	*p*-Value
		3 months		
Gala Brookfield	821 ± 25	774 ± 31	765 ± 17	0.033
Šampion	484 ± 7	461 ± 9	454 ± 16	0.049
Ligol	357 ± 24	316 ± 15	317 ± 12	<0.01
clone JB	1154 ± 18	1167 ± 22	1205 ± 19	0.035
Chopin	578 ± 11	542 ± 10	517 ± 12	<0.01
Idared	1085 ± 37	1020 ± 21	973 ± 19	<0.01
p-value	<0.01	<0.01	<0.01	
		6 months		
Gala Brookfield	775 ± 18	732 ± 10	739 ± 26	0.012
Šampion	407 ± 12	431 ± 8	449 ± 13	0.014
Ligol	275 ± 9	310 ± 13	308 ± 18	<0.01
clone JB	-	-	-	-
Chopin	478 ± 11	503 ± 12	519 ± 8	0.031
Idared	924 ± 32	991 ± 28	1010 ± 34	<0.01
p-value	<0.01	<0.01	<0.01	
		9 months		
Gala Brookfield	630 ± 24	711 ± 27	718 ± 16	<0.01
Šampion	358 ± 23	417 ± 18	435 ± 28	0.029
Ligol	259 ± 12	294 ± 19	291 ± 14	<0.01
clone JB	-	-	-	-
Chopin	418 ± 18	463 ± 9	484 ± 6	<0.01
Idared	776 ± 21	842 ± 27	870 ± 17	<0.01
p-value	<0.01	<0.01	<0.01	

Data are presented as mean ± standard deviation; NA—ordinary cold storage; ULO—Ultra-Low Oxygen; DCA—Dynamic Controlled Atmosphere.

Total flavonoid content, like TPC, highly significantly depended on the characteristics of the cultivar studied. Again, clone 'JB' was distinguished from other cultivars by high TFC in the flesh (Figure 10) and peel (Figure 11) of apples after harvest. 'Gala Brookfield' and 'Idared' were also characterised by high TFC values in both apple elements, and the flesh of 'Šampion' contained higher TFC values than 'Ligol' and 'Chopin' immediately after fruit harvest. The differences in TFC content between varieties found after fruit harvest were observed at further stages of the study after storage. TFC values for apple flesh and peel did not change significantly between analysis dates, after storage in NA (Tables 7 and 8). A fluctuation of TFC content in apples stored in ULO or DCA was noted, but the changes referred to few cases and varieties. Higher TFC in the apple flesh after storage in DCA and ULO was registered in the 'Chopin' cultivar. TFC changes in apple peel were inconclusive. 'Gala Brookfield' and 'Ligol' peel showed a decrease in TFC after storage in ULO, while 'Šampion' peel registered an increase in TFC after storage in ULO.

Antioxidant capacity is determined by the content of TPC and TFC. The clone 'JB', which stood out in terms of the aforementioned indices, was characterised by the highest antioxidant capacity both in the flesh (Figure 12) and in the peel (Figure 13) of the apples. Among the other cultivars, only 'Ligol' was characterised by low antioxidant capacity, especially in the flesh (65% lower than clone 'JB'). As in the previously discussed studies, it was shown that the varietal factor is highly significant in determining antioxidant capacity, but storage conditions modify its values. After 3 months of storage, an increase in antioxidant capacity was found in the flesh of the cultivars studied (with the exception of clone 'JB'). The process of antioxidant capacity growth was faster in apples stored in NA than in ULO or DCA. (Tables 9 and 10) The growth of antioxidant capacity in the fruit peel after

storage for 3 months was found only in 'Ligol' apples. Extending the storage period to 6 and 9 months resulted in a decrease in the antioxidant capacity between the analysis dates in both the flesh and peel of apples. Among the cultivars, 'Gala Brookfield', clone 'JB' (only after 3 months), 'Chopin', and 'Idared' were distinguished by higher antioxidant capacity in apple flesh and peel. The recorded process of antioxidant capacity loss between 3 and 9 months of storage progressed more slowly if apples were stored in ULO or DCA than NA. The dynamics of this process were faster for the antioxidant capacity of the flesh than for that of the peel.

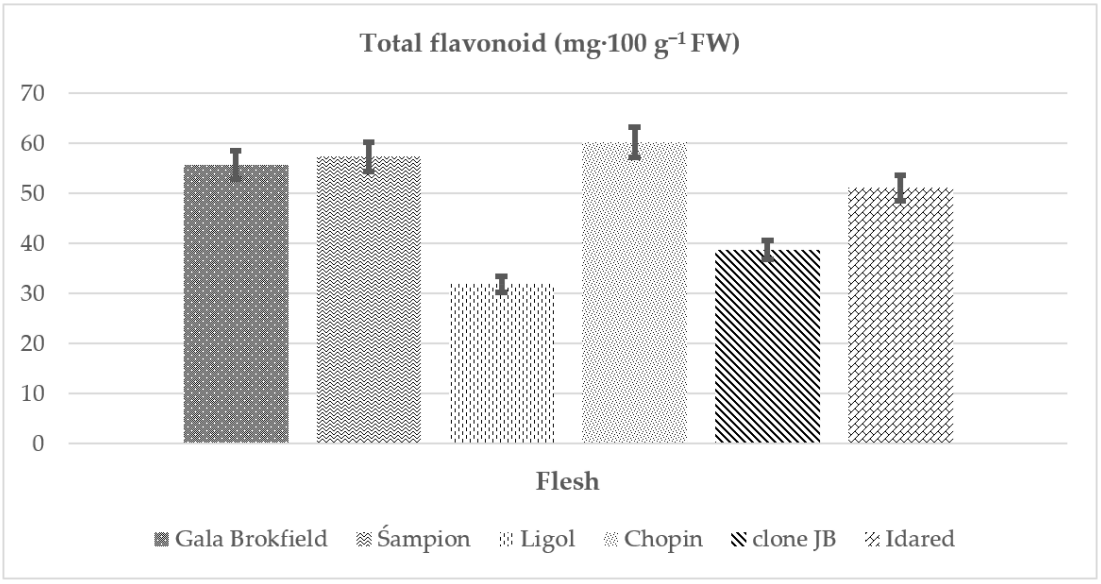

Figure 10. The values of total flavonoids (mg·100 g^{-1} FW) for the flesh of apples depending on cultivars after harvesting. Data are presented as mean ± standard deviation.

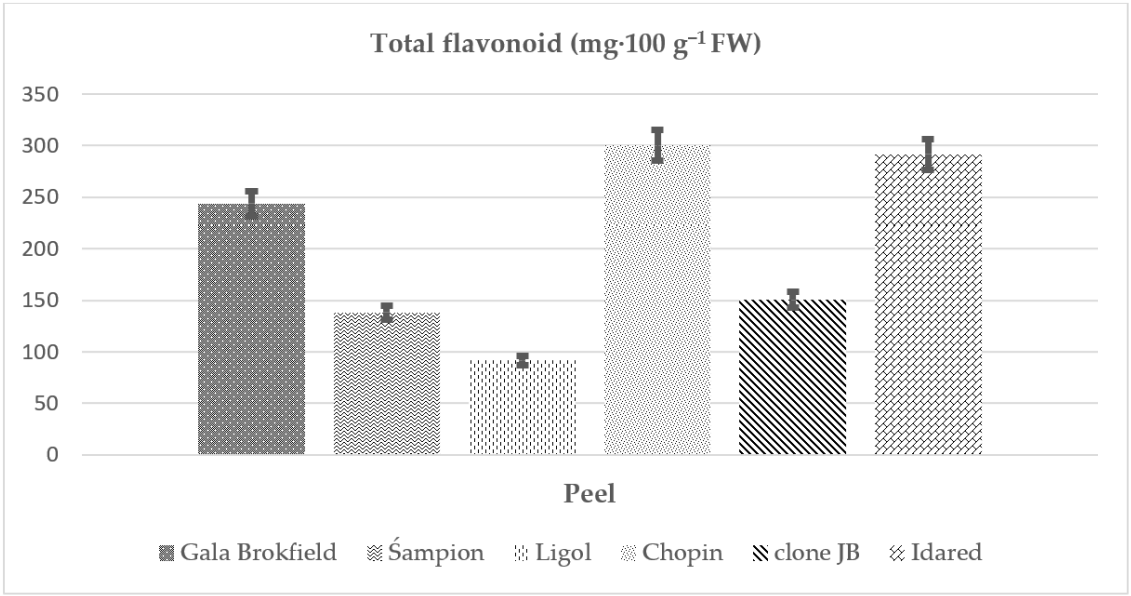

Figure 11. The values of total flavonoids (mg·100 g^{-1} FW) for the peel of apples depending on cultivars after harvesting. Data are presented as mean ± standard deviation.

Table 7. The values of total flavonoids (mg·100 g^{-1} FW) for the flesh of apples depending on cultivars and storage technology.

Cultivars	NA	ULO	DCA	*p*-Value
		3 months		
Gala Brookfield	57.63 ± 1.25	58.00 ± 1.28	59.43 ± 1.97	0.506
Šampion	58.00 ± 0.22	55.90 ± 1.06	57.50 ± 0.80	0.079
Ligol	34.37 ± 1.94	33.53 ± 0.91	30.53 ± 0.87	0.062
clone JB	63.43 ± 0.96	65.20 ± 2.29	67.37 ± 1.40	0.133
Chopin	37.13 ± 1.72	48.17 ± 2.19	47.00 ± 1.48	<0.01
Idared	53.77 ± 1.09	53.97 ± 1.03	54.17 ± 1.72	0.955
p-value	<0.01	<0.01	<0.01	
		6 months		
Gala Brookfield	57.47 ± 1.35	59.81 ± 2.47	60.70 ± 1.19	0.244
Šampion	56.30 ± 2.13	55.99 ± 2.00	56.43 ± 1.57	0.972
Ligol	36.20 ± 2.79	37.64 ± 2.27	28.96 ± 2.15	0.024
clone JB	-	-	-	-
Chopin	36.64 ± 1.80	42.83 ± 2.02	50.20 ± 1.59	<0.01
Idared	55.17 ± 1.39	54.23 ± 1.69	52.42 ± 1.89	0.729
p-value	<0.01	<0.01	<0.01	
		9 months		
Gala Brookfield	58.60 ± 2.30	60.27 ± 1.96	60.93 ± 1.40	0.499
Šampion	59.17 ± 1.47	57.79 ± 1.12	59.92 ± 4.86	0.780
Ligol	34.17 ± 1.11	37.20 ± 1.63	32.47 ± 1.02	0.027
clone JB	-	-	-	-
Chopin	41.20 ± 0.90	51.72 ± 4.37	49.03 ± 2.01	0.023
Idared	55.67 ± 1.89	54.60 ± 0.51	56.04 ± 1.08	0.547
p-value	<0.01	<0.01	<0.01	

Data are presented as mean ± standard deviation; NA—ordinary cold storage; ULO—Ultra-Low Oxygen; DCA—Dynamic Controlled Atmosphere.

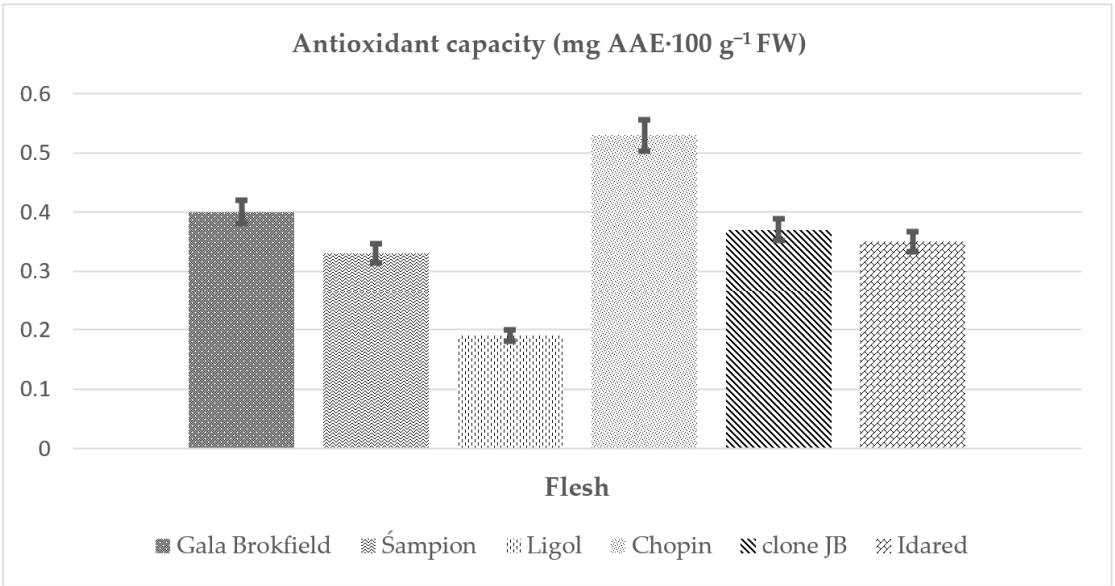

Figure 12. The values of antioxidant capacity (mg AAE·100 g^{-1} FW) for the flesh of apples depending on cultivars after harvesting. Data are presented as mean ± standard deviation.

Table 8. The values of total flavonoids (mg·100 g^{-1} FW) for the peel of apples depending on cultivars and storage technology.

Cultivars	NA	ULO	DCA	*p*-Value
		3 months		
Gala Brookfield	250.1 ± 3.4	239.2 ± 1.8	257.1 ± 3.6	<0.01
Šampion	144.4 ± 5.1	152.4 ± 3.7	151.1 ± 3.7	0.208
Ligol	99.5 ± 3.3	99.7 ± 2.1	102.7 ± 5.0	0.643
clone JB	315.3 ± 10.8	311.1 ± 11.6	316.8 ± 7.9	0.852
Chopin	164.2 ± 1.8	173.2 ± 3.8	166.2 ± 2.7	0.047
Idared	292.6 ± 3.5	300.5 ± 1.4	303.8 ± 3.2	0.018
p-value	<0.01	<0.01	<0.01	
		6 months		
Gala Brookfield	254.4 ± 2.1	230.4 ± 9.7	255.3 ± 5.7	0.015
Šampion	146.7 ± 1.4	196.5 ± 5.1	142.8 ± 11.6	<0.01
Ligol	107.7 ± 4.0	96.5 ± 3.6	103.8 ± 1.7	0.034
clone JB	-	-	-	-
Chopin	162.4 ± 4.3	163.3 ± 13.7	120.9 ± 5.0	<0.01
Idared	286.3 ± 15.4	304.1 ± 1.8	285.4 ± 15.8	0.326
p-value	<0.01	<0.01	<0.01	
		9 months		
Gala Brookfield	256.0 ± 4.9	242.1 ± 3.5	260.8 ± 6.6	0.026
Šampion	147.0 ± 1.0	171.3 ± 11.2	153.4 ± 3.6	0.028
Ligol	102.9 ± 3.8	98.7 ± 2.3	103.9 ± 4.2	0.355
clone JB	-	-	-	-
Chopin	163.7 ± 3.6	173.2 ± 4.8	168.7 ± 1.2	0.094
Idared	295.1 ± 11.4	299.4 ± 19.1	311.8 ± 13.2	0.546
p-value	<0.01	<0.01	<0.01	

Data are presented as mean ± standard deviation; NA—ordinary cold storage; ULO—Ultra-Low Oxygen; DCA—Dynamic Controlled Atmosphere.

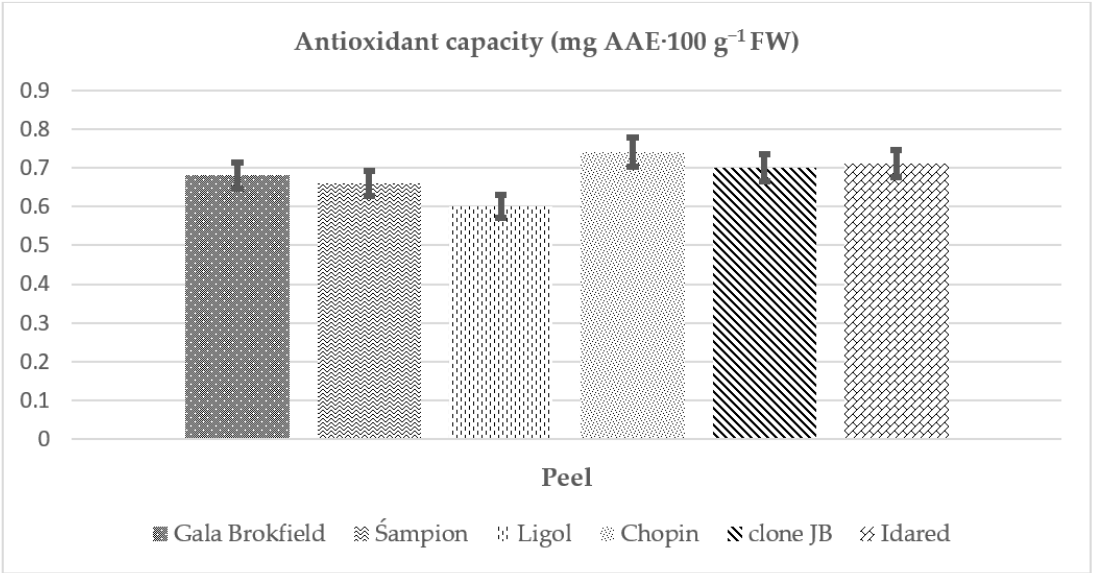

Figure 13. The values of antioxidant capacity (mg AAE·100 g^{-1} FW) for the peel of apples depending on cultivars after harvesting. Data are presented as mean ± standard deviation.

Table 9. The values of antioxidant capacity (mg AAE·100 g^{-1} FW) for the flesh of apples depending on cultivars and storage technology.

Cultivars	NA	ULO	DCA	*p*-Value
		3 months		
Gala Brookfield	0.495 ± 0.007	0.457 ± 0.004	0.441 ± 0.003	<0.01
Šampion	0.369 ± 0.004	0.355 ± 0.007	0.342 ± 0.004	<0.01
Ligol	0.241 ± 0.006	0.230 ± 0.006	0.222 ± 0.005	0.029
clone JB	0.438 ± 0.014	0.476 ± 0.015	0.487 ± 0.009	0.039
Chopin	0.494 ± 0.011	0.461 ± 0.016	0.447 ± 0.007	0.011
Idared	0.492 ± 0.008	0.428 ± 0.009	0.417 ± 0.010	<0.01
p-value	<0.01	<0.01	<0.01	
		6 months		
Gala Brookfield	0.418 ± 0.006	0.404 ± 0.003	0.395 ± 0.004	0.022
Šampion	0.289 ± 0.003	0.309 ± 0.001	0.319 ± 0.004	<0.01
Ligol	0.193 ± 0.004	0.204 ± 0.005	0.212 ± 0.002	0.016
clone JB	-	-	-	-
Chopin	0.393 ± 0.009	0.404 ± 0.006	0.425 ± 0.004	0.033
Idared	0.369 ± 0.008	0.389 ± 0.009	0.396 ± 0.005	0.048
p-value	<0.01	<0.01	<0.01	
		9 months		
Gala Brookfield	0.306 ± 0.005	0.333 ± 0.003	0.344 ± 0.006	<0.01
Šampion	0.232 ± 0.002	0.262 ± 0.003	0.269 ± 0.003	<0.01
Ligol	0.164 ± 0.004	0.175 ± 0.003	0.179 ± 0.004	0.018
clone JB	-	-	-	-
Chopin	0.321 ± 0.007	0.335 ± 0.008	0.346 ± 0.008	0.043
Idared	0.320 ± 0.009	0.332 ± 0.002	0.346 ± 0.005	0.045
p-value	<0.01	<0.01	<0.01	

Data are presented as mean ± standard deviation; NA—ordinary cold storage; ULO—Ultra-Low Oxygen; DCA—Dynamic Controlled Atmosphere.

The analysis of the results showed no significant effect of the cultivar characteristics of the evaluated cultivars on the content of macronutrients in apples (Table 11). Only the calcium content was significantly higher in 'Gala Brookfield' and 'Idared' apples than in the other cultivars. Higher, but not statistically shown, phosphorus content was characterised by the cultivar 'Chopin' and clone 'JB', potassium by 'Chopin' and 'Šampion', and magnesium content in all cultivars was at a similar level. Among the analysed micronutrients, significantly higher iron content was found in 'Idared' apples and zinc content in 'Gala Brookfield' and 'Idared' apples (Table 12).

Eight chemical compounds, residues of synthetic pesticides, were found in the fruit of the evaluated cultivars. It should be noted that none of the identified compounds were found in 'Chopin' apples, while only Kaptan was found in slim quantities in clone 'JB'. None of the identified compounds exceeded the permitted EU standards. The highest number of pesticide residues was identified in 'Šampion' (five compounds) and in 'Gala Brookfield' and 'Ligol', with three chemical compounds each (Table 13).

Table 10. The values of antioxidant capacity (mg AAE·100 g^{-1} FW) for the peel of apples depending on cultivars and storage technology.

Cultivars	NA	ULO	DCA	*p*-Value
		3 months		
Gala Brookfield	0.708 ± 0.007	0.692 ± 0.003	0.689 ± 0.005	0.047
Šampion	0.657 ± 0.005	0.653 ± 0.004	0.640 ± 0.005	0.022
Ligol	0.660 ± 0.011	0.643 ± 0.010	0.635 ± 0.010	0.126
clone JB	0.695 ± 0.004	0.717 ± 0.004	0.724 ± 0.002	<0.01
Chopin	0.714 ± 0.004	0.708 ± 0.001	0.706 ± 0.003	0.155
Idared	0.736 ± 0.010	0.728 ± 0.008	0.726 ± 0.010	0.602
p-value	<0.01	<0.01	<0.01	
		6 months		
Gala Brookfield	0.616 ± 0.007	0.636 ± 0.006	0.643 ± 0.009	0.015
Šampion	0.580 ± 0.004	0.613 ± 0.006	0.620 ± 0.003	<0.01
Ligol	0.560 ± 0.009	0.581 ± 0.006	0.590 ± 0.010	0.046
clone JB	-	-	-	-
Chopin	0.646 ± 0.003	0.671 ± 0.004	0.674 ± 0.003	<0.01
Idared	0.669 ± 0.009	0.690 ± 0.010	0.701 ± 0.011	0.036
p-value	<0.01	<0.01	<0.01	
		9 months		
Gala Brookfield	0.561 ± 0.012	0.602 ± 0.009	0.609 ± 0.014	<0.01
Šampion	0.521 ± 0.017	0.567 ± 0.012	0.580 ± 0.009	<0.01
Ligol	0.530 ± 0.009	0.554 ± 0.009	0.560 ± 0.010	0.033
clone JB	-	-	-	-
Chopin	0.626 ± 0.004	0.653 ± 0.009	0.660 ± 0.010	<0.01
Idared	0.648 ± 0.009	0.683 ± 0.004	0.676 ± 0.007	0.017
p-value	<0.01	<0.01	<0.01	

Data are presented as mean ± standard deviation; NA—ordinary cold storage; ULO—Ultra-Low Oxygen; DCA—Dynamic Controlled Atmosphere.

Table 11. The values of macroelements (mg·kg^{-1} FW) for apples depending on cultivars after harvesting.

	Gala Brookfield	Šampion	Ligol	Clone JB	Chopin	Idared	*p*-Value
			Macroelements				
Phosphorus	68.7 ± 15.1	81.2 ± 17.9	77.8 ± 17.1	98.6 ± 21.7	107 ± 23	84.6 ± 18.6	0.225
Potassium	854 ± 179	1035 ± 217	909 ± 191	911 ± 191	1297 ± 272	921 ± 193	0.185
Calcium	55.1 ± 13.2	30.0 ± 7.2	25.1 ± 6.0	36.8 ± 8.8	29.2 ± 7.0	43.8 ± 10.5	0.015
Magnesium	43.0 ± 7.7	45.7 ± 8.2	44.7 ± 8.0	43.7 ± 7.9	40.4 ± 7.3	46.6 ± 8.4	0.941

Data are presented as mean ± standard deviation.

Table 12. The values of microelements (mg·kg^{-1} FW) for apples depending on cultivars after harvesting.

	Gala Brookfield	Šampion	Ligol	Clone JB	Chopin	Idared	*p*-Value
			Microelements				
Iron	0.95 ± 0.22	0.90 ± 0.21	1.07 ± 0.25	1.11 ± 0.25	1.31 ± 0.30	2.13 ± 0.49	<0.01
Copper	0.31 ± 0.06	0.34 ± 0.02	0.39 ± 0.08	0.41 ± 0.08	0.35 ± 0.07	0.28 ± 0.06	<0.01
Zinc	0.43 ± 0.10	0.21 ± 0.05	0.28 ± 0.06	0.24 ± 0.05	0.22 ± 0.05	0.33 ± 0.07	<0.01

Data are presented as mean ± standard deviation.

Table 13. Pesticide residues in apples depending on cultivars after harvesting.

	Gala Brookfield	Šampion	Ligol	Clone JB	Chopin	Idared	Limit
Kaptan	0.011 ± 0.006	0.011 ± 0.006	0.010 ± 0.005	0.013 ± 0.007		0.47 ± 0.24	≤10.0
Tebuconazole	0.046 ± 0.023	0.028 ± 0.014	0.015 ± 0.008				≤0.3
Fluopyram	0.051 ± 0.026	0.028 ± 0.014	0.018 ± 0.009				≤0.8
Fludioxonil		0.019 ± 0.010					≤5.0
Cyprodinil		0.037 ± 0.019					≤2.0
Boscalid						0.14 ± 0.07	≤2.0
Flonicamid						0.059 ± 0.030	≤0.3
Pyraclostrobin						0.091 ± 0.046	≤0.5

Data are presented as mean ± standard deviation.

4. Discussion

The production of apples in terms of commodity weight tops the list of fruit species grown in Poland [47,48]. According to information from the U.S. Department of Agriculture (USDA) [49], world apple production was about 80 million tons in 2022, of which about 12 million tons of apples were produced in the EU. Poland's share of EU production was more than 30% (about 4 million tons), which puts Poland in the 4th–5th position on the list of world apple producers. In the commodity orchards of the European Union, the most common varieties are 'Golden Delicious', 'Idared', and mutations of 'Jonagold' or 'Gala' [48]. In Poland, 74 apple tree cultivars are registered with COBORU (Research Center for Cultivar Testing), of which the orchards are dominated by 'Gala' (17.9% of production), 'Red Jonaprince' (15.3%), 'Golden Delicious' (15.2%), 'Idared' (11.2%), and 'Šampion' (9.6%). A similar selection of cultivars in Poland and the EU increases competitiveness, which translates into the search for new apple cultivars that are attractive in terms of cultivation but also in terms of nutritional value [50–52].

'Chopin' is a Polish apple cultivar, selected by Prof. Emilian Pitera (WULS- SGGW in Warsaw). It was created from a cross between the 'Granny Smith' cultivar and U 211 (scab-resistant clone). The apples are distinguished by the green base colour of the peel among other cultivars and the lack of blush (like 'Golden Delicious'). The 'Chopin' cultivar is scab-resistant, characterised by high acidity, good storage ability in NA, and according to consumers, low allergenicity. It is listed in COBORU and has been protected by law (PBR) since 2016. Clone 'JB' was bred by Prof. A. Przybyla (WULS- SGGW in Warsaw), currently under registration. Like 'Chopin', it is a scab-resistant cultivar. It is characterised by the formation of anthocyanins in the flesh, which places it in the group of apples with red flesh. The red pigmentation is present throughout the fruit's development. The vegetative tissues and flowers of these cultivars are also intensely coloured.

The study evaluated new apple cultivars of the WULS-SGGW selection with reference to commonly grown cultivars in the EU. A key element of the research was to define the impact of different storage technologies on the storage quality and nutritional value of the tested cultivars. The storability of fruit is a strategic element of distribution that enables the supply of apples beyond their ripening period on the tree. The results of the study unfortunately showed low storability of clone 'JB'. After 6 months of storage, advanced signs of rot were found in the fruit, which disqualified it for further testing. In addition to varietal characteristics, the reason for such intensive fruit rot in cold storage could have been the lack of applied protection during the growing season, caused by the 'JB' clone's resistance to apple scab—the main disease occurring during the growing season. However, it should be noted that the second scab-resistant cultivar 'Chopin' was characterised by high storage capacity, as were the other cultivars. The use of technologically advanced storage conditions, i.e., ULO and DCA, promoted the better preservation of fruit quality.

In general, fruit stored in ULO or DCA cold storage was characterised by higher firmness than after storage in NA, and the favourable effect was stronger with an increasing storage period. It should be noted that only under DCA conditions, after 9 months of

storage, were most cultivars characterised by acceptable firmness (above 45 N), including the cultivar 'Chopin'. DCA conditions proved to be exceptionally effective in maintaining high firmness for the cultivar 'Ligol'. The decrease in firmness after 9 months of storage in DCA was only 10.9% in relation to postharvest values. The success of the use of DCA technology in inhibiting the loss of firmness by different fruit cultivars was reported by Mditshwa et al. [53], Thewes et al. [21], and Krupa et al. [54]. Stabilisation of ripening processes at a low level in the ULO and DCA technologies promoted lower soluble solids content and higher acidity in apples. The values of both indicators changed slightly during apple storage in DCA. The low oxygen concentration in DCA effectively inhibited the respiration process, in which simple sugars as well as organic acids are consumed, as confirmed by the results of our own study. Nevertheless, many authors point out that varietal characteristics are mainly responsible for the accumulation of sugars and acids [55,56]. Prominent in terms of high acidity were the 'Chopin' cultivar and the 'JB' clone. Despite the sour taste, apples deacidify the body, because they have a lot of alkaline potassium (regulates water balance) and iron (prevents anaemia). Fibre content was very low in the apples evaluated immediately after harvest. A significant increase in the fibre content of the fruit was observed during storage. An exceptionally large increase was observed after storing apples in ULO and DCA advanced technologies, and in 'Idared' apples after 9 months of storage in DCA, the increase in the value of the index was fourfold. Under NA conditions, an increase in fibre content was observed only after 6 and 9 months of storage. In the literature, we find information indicating the effect of the storage period on fibre content. These fractions include arabinoxylan, inulin, pectin, cellulose, β-glucan, and resistant starch [35,37]. Marlet [36] indicates that storage had no effect on the total or insoluble fibre content of apples but that Klason lignin concentrations were higher in samples stored for 12 months than in those stored for 4 or 8 months. The increase in certain dietary fibre fractions is related to the softening of the apples or to ripening processes causing, for example, softening or an increase in sugars [38]. Differences in the fibre content of stored apples are often due to obtaining data by different analytical methods and also as a result of the analysis of different apple varieties [37,38]. Some of these procedures do not completely remove the simple sugars from the residual fibre. In our study, the observed increase in dietary fibre content in fresh fruit (without conversion to dry matter) may be related to the factors mentioned above. There is a lack of information in the literature on the effect of advanced storage technologies on this fruit quality indicator. From the point of view of the value of fruit consumers, the content of antioxidants from the group of polyphenols is an important criterion for the health-promoting nature of food. In many publications, the authors point out the differences in the content of the compounds between the peel and the pulp in favour of the former [52,57,58]. The antioxidant content of apples is determined by many factors, from the varietal factor [14,59] or the degree of ripeness [30]. In our own experiment, the apple peel was characterised by up to four times higher TPC content than apple flesh. The study showed a significant effect of an atmosphere with reduced oxygen content on slowing down the processes leading to the loss of these important compounds. During the first period of storage, up to 3 months, an increase in TPC values was found in comparison with postharvest values, with the increase being higher in NA than in DCA, which resulted in fruits stored in NA having a higher TPC content. Longer storage resulted in lower TPC content, and again this process occurred more strongly in NA than in DCA or ULO. The effect of these changes was a higher TPC content in fruit stored in DCA than in NA or ULO, after 9 months of storage. The results of the study confirm reports by MacLean et al. [60], suggesting that the rate of apple ripening, which is influenced by storage conditions, is responsible for changes in TPC content during storage. Reducing the rate of respiration and ethylene production in a very low-oxygen atmosphere promotes the preservation of valuable components for the consumer [21,27,54]. This is also confirmed by studies on the compound 1-MCP, in which fruit treated with this 'ripening inhibitor' showed higher contents of biologically active compounds after storage than untreated fruit [26,31,61].

In addition, the higher firmness of fruit stored in DCA maintains the semi-permeability of cell walls, making it more difficult to degrade compounds contained in the cells. The varietal factor is a strong determinant of fruit nutritional value. In our study, clone 'JB' stood out in terms of TPC and TFC content, as well as antioxidant capacity. In general, it can be said that antioxidant capacity was determined by the content of TPC and TFC, and the effect of storage conditions on antioxidant capacity was analogous to both groups of compounds. After 3 months of storage, the growth of antioxidant capacity of the tested varieties was faster in apples stored in NA than in ULO or DCA. In contrast, at subsequent analysis dates, the recorded antioxidant capacity loss between 3 and 9 months of storage progressed more slowly if apples were stored in ULO or DCA than in NA.

In the literature, we find a multidirectional description of antioxidant capacity changes during storage. A study by Hoang et al. [61] showed a decrease in the antioxidant capacity of apples. On the other hand, Lu et al. [62] and Yurong et al. [30] found increased antioxidant capacity in apple peel after storage, while Kolniak-Ostek et al. [26] showed no change in the value of the index for apples during storage. Such different results of the work are probably due to the high variability of varietal characteristics, fruit maturity, or the conditions under which the observations were carried out. Continuing them is necessary to develop appropriate apple storage parameters for the ever-emerging new cultivars.

5. Conclusions

The experiment demonstrated the inhibition of apple ripening in low-oxygen storage technology, which had a beneficial effect on their physicochemical properties and the stabilisation of polyphenol and flavonoid levels. The results indicate that the varietal factor is a stronger determinant of apple quality traits than the storage technology. 'Ligol' and 'Idared' apples were characterised by high firmness even after 9 months of cold storage, while 'Šampion' apples were characterised by drastically low firmness already after 6 months. The use of DCA technology enables the long-term storage of 'Ligol', 'Chopin', 'Gala Brookfield', and 'Idared' apples, which are still characterised by acceptable firmness (above 45 N) and high acidity. Limiting the rate of ripening of the apples in an atmosphere with very low oxygen content also favours the retention of valuable components for the consumer, i.e., polyphenols and flavonoids at a high level. The 'JB' clone excels in terms of TPC and TFC content and antioxidant capacity, but it is characterised by very low storability. Among the cultivars, 'Chopin', 'Idared', and 'Gala Brookfield' are characterised by a higher content of biologically active compounds than 'Ligol' or 'Šampion'. The low oxygen content of the DCA technology contributes to slowing down the loss of polyphenols and, in the case of flavonols, no reduction in their content was noted even after 9 months of storage in all varieties. The above-average acidity and high content of polyphenols and flavonoids probably predisposes 'JB' apples as a valuable raw material for processing.

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