

Article

Changes in the Biochemical Composition and Physicochemical Properties of Apples Stored in Controlled Atmosphere Conditions

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Abstract: Apples are an important component of the diet and are used in the food industry in the production of food products and beverages. The aim of the study was to determine the changes in the biochemical composition and physicochemical properties of apples stored in a controlled atmosphere. We studied the biochemical composition (sugars, ascorbic acid, soluble solids, and titratable acidity) and physicochemical properties (color coordinates, peel, and flesh firmness) in the apple samples before placing them in the controlled atmosphere chambers and at the end of the experiment 8 months later. The total content of sugars and soluble solids was found to increase in the samples of apples stored in I to VIII conditions. The study showed a decrease in titratable acidity in apple samples of all cultivars stored in I to VIII conditions. The values of C*, L*, a*, and b* co-ordinates of apple colors were evaluated. Apple samples stored in VI conditions were the lightest color, and their lightness was close to that of fresh fruit. The firmness of apple peel samples of the ‘Sampion’ cultivar stored in I and III–VI conditions increased. The study is valuable and proves that, under the studied conditions, it is possible to extend the time of the provision of apples to the consumers with minimal changes in their chemical composition and nutritional value.

Keywords: apple peel; apple flesh; postharvest; controlled atmosphere; quality

1. Introduction

Apples are among the most consumed fruits in the world [1], their annual amount grown reaching about 89.33 million tons [2]. ‘Gala’, ‘Delicious’, and ‘Fuji’ red apple cultivars have been found to be the most widely consumed in the world [3]. Apples are an important component of the diet and are used in the food industry in the production of food products and beverages. The market value of apples depends on the entirety of their external (color and size) and internal (taste, texture, smell, and nutritional value) quality parameters [4,5].

Due to the different organoleptic and physical properties of apples, four apple idiotypes are distinguished: “American/European dessert apples” (regular shape, beautiful appearance, solid color, large size, and sweet-and-sour taste), “European refreshing apples” (juicy and with a solid or two-tone skin color), “Asian dessert apples” (very sweet and juicy, with firm flesh and a long shelf life), and “juicy firm and crisp high-quality apples” (juicy and crisp with a high content of sugars and organic acids) [3].

In order to meet the consumers’ needs and to enrich the diet with quality apples with a known chemical composition that ensures the high nutritional value of the apples, it is important to prepare them properly and to choose optimal storage conditions that would minimize changes in the chemical composition, as well as organoleptic and physical

properties of the apples, thus minimizing the reduction of their market value [6]. In the healthy food chain, apples are an important source of biologically active compounds. It has been found that one of the most important biologically active compounds that have an effect on the prevention of various diseases and determine the nutritional value of apples are phenolic [7,8] and triterpene compounds [9]. Apples also contain organic acids (ascorbic, malic, citric, maleic, pyruvic, and shikimic acids), sugars (glucose, fructose, sucrose, and xylitol) [10,11], vitamins [12], macronutrients (K, Na, Mg, Ca, and P) and trace elements (Fe, Zn, Mn, and Cu) [13], and fibrous materials [14].

Recently, in order to minimize changes in the organoleptic and physical properties of apples, to provide the consumers with a quality product, and to prolong the shelf life of the apples, the fruit have been stored under controlled atmospheric conditions [6,15]. Scientific literature describes storage conditions when apples are stored in low oxygen (about 1 kPa) [16] or ultra-low oxygen (ULO) (0.5 and 0.7–0.8 kPa) [17], high carbon dioxide (2–3 kPa) [18], and low temperature (0.5–1.0 °C) and high relative humidity (94–96%) [19] conditions. In fruit stored in ULO and low oxygen conditions, the cells undergo changes in cellular metabolism [18], ethylene production [20], and enzymatic activity [21]. The above-mentioned factors of cellular metabolism affect the resistance of the fruit to diseases caused by various strains of fungi [22], and allow for minimizing changes in the chemical composition and organoleptic and physical properties of the apples, thus ensuring the provision of the consumers with apples that are suitable for consumption and have a high nutritional value and long shelf life [23].

The quality of apples depends on the organoleptic and physical characteristics, which are important in assessing the market value of the fruit. Scientific literature describes a procedure where the quality of the apples is assessed by performing a color co-ordinate analysis [24,25], the determination of the content of soluble solids and sugars [26,27], and the assessment of the values of titratable acidity [16,27] mechanical strength (firmness and elasticity) indices [28]. Color and size are important quality parameters that determine the market value of apples, as well as the consumers' choice [3,29]. Anthocyanins are biologically active compounds that determine the pink hues of the apples and their commercial appearance and primary choice [5,30]. Guan et al. pointed out that the repetitive purchase and consumption of fruit depends on their taste, aroma, and texture [31]. Cichowska and Aprea provided data indicating that the sweet taste of fruit is determined by sugars and soluble solids, while the sour taste depends on the organic acid complex [32,33]. The fruit firmness index is an important quality parameter to assess the texture of apples [34]. The evaluation of quality parameters for the chemical composition and organoleptic characteristics of apples is relevant in order to provide the consumers with quality apples in which changes in the nutritional value have been minimized.

Scientific literature presents only fragmentary research results on changes in physical and organoleptic properties (color co-ordinates, peel, and flesh firmness), and biochemical composition (sugars, ascorbic acid, soluble solids, and titratable acidity) of apples grown in Lithuania when storing them in a controlled atmosphere of various compositions. The physical and organoleptic parameters of apples stored in a controlled atmosphere determined in this study are valuable and prove that the conditions studied allow for providing consumers with apples for a longer period of time, minimizing changes in their chemical composition and nutritional value.

The aim of the study was to determine the changes in the biochemical composition and physicochemical properties of different apple cultivars stored in a controlled atmosphere of different compositions.

2. Materials and Methods

2.1. Plant Materials

In this study, we used 10 different apple cultivars: 'Alva', 'Auksis', 'Connel Red', 'Cortland', 'Ligol', 'Lodel', 'Noris', 'Rubin', 'Sampion', and 'Spartan'. Apples were grown at the Institute of Horticulture (Babtai), a branch of the Lithuanian Research Center for

Agriculture and Forestry (co-ordinates: 55°60' N, 23°48' E) with equal conditions, agrotechnical treatments, soil, fertilization, and disease control measures. The study was conducted during 2019–2020.

2.2. Chemicals and Solvents

All solvents, reagents, and standards used were of analytical grade. Sodium hydroxide and 2,6-dichlorophenolindophenol sodium salt solution were obtained from Sigma-Aldrich Chemie GmbH (Darmstadt, Germany).

2.3. Controlled Atmosphere Conditions during Apple Storage

Apples picked from different locations of the fruit tree crown were used in the study. Apple samples were stored in eight Besseling Systems controlled atmosphere (CA) chambers (Besseling Group, Osterblokker, Netherlands) with different gas compositions for eight months, ensuring a constant set gas composition for all eight months. The stable gas composition was controlled, and the CO₂ released during fruit respiration was adsorbed and maintained at a constant level by the Combi analysis and adsorption system (Besseling CA Systems B.V.) with software CMB-E-2010-v14.x-1. Different controlled concentrations of oxygen, carbon dioxide, and nitrogen, constant temperature, relative humidity, and removal of endogenous ethylene were continually maintained in the controlled atmosphere chambers to prevent further fruit ripening during the storage (Table 1). Ethylene was removed by means of a scrubber-heated catalyst system MINI AD-SORBER (Besseling CA Systems B.V.) where ethylene is oxidized to yield CO₂ and water vapor. The composition of the controlled atmosphere in the chambers was measured every 30 min, and these conditions were accordingly continuously maintained with a maximum gas composition error of 0.3%. One sample consisted of 8 kg of apples. This weight was chosen because more apples would not fit in the chamber (10 varieties * 8 kg = 80 kg per chamber). Prior to and after the 8-month storage, the biochemical changes and physicochemical properties were evaluated in the apple samples.

Table 1. Composition of controlled atmosphere chambers.

Variant	Amount of Oxygen (O ₂), %	Amount of Carbon Dioxide (CO ₂), %	Amount of Nitrogen (N ₂), %	Relative Humidity, %	Temperature, °C
I	21	0.03	78.97	95 ± 3	+1.5 ± 0.5
II	5	1	94		
III	5	3	92		
IV	5	5	90		
V	5	7	88		
VI	1	3	96		
VII	10	3	87		
VIII	20	3	77		

2.4. The Evaluation of Sugars

The amounts of monosaccharides, sucrose, and total sugars were determined according to the Association of Official Analytical Chemists [35].

2.5. The Determination of Soluble Solids

Soluble solids were quantified with a digital refractometer PR-32 (Atago Co., Ltd., Fukaya, Japan).

2.6. The Evaluation of Titratable Acidity

Titrate acidity was evaluated by titrating with 0.1N NaOH solution to pH 8.2, and was expressed as a percentage of citric acid equivalent [35].

2.7. The Determination of Ascorbic Acid

Ascorbic acid was measured by titration using 2,6-dichlorophenolindophenol sodium salt solution [36].

2.8. The Determination of the Content of Soluble Solids

The content of soluble solids was determined gravimetrically using a moisture analyzer PMB 53 (Adam Equipment Inc., Maidstone Road, Milton Keynes, UK) by drying apple samples to a constant weight at 105 °C temperature, the sensitivity of the change in mass being up to 0.01 g.

2.9. Fruit Color Measurement

The color coordinates of the apple samples in the uniform contrast color space CIE $L^*a^*b^*$ were measured with a MiniScan XE Plus spectrophotometer (Hunter Associates Laboratory, Inc., Reston, VA, USA) as described in [37]. The parameters evaluated during reflected-color measurements were L^* , a^* , and b^* (brightness and red and yellow coordinates according to the CIE $L^*a^*b^*$ scale, respectively), and color saturation (the chroma value) was calculated ($C = (a^{*2} + b^{*2})^{1/2}$) [38]. The values L^* , a^* , b^* , and C^* were measured in NBS units. The NBS unit is a unit of the U.S. National Bureau of Standards and meets one color resolution threshold, i.e., the smallest difference in a color that can be captured by a trained human eye. Prior to each series of measurements, the spectrophotometer was calibrated with a light trap and a white standard with the following color co-ordinates in the XYZ color space: $X = 81.3$, $Y = 86.2$, and $Z = 92.7$. The value of L^* indicated the ratio of white to black, the value of a^* indicated the ratio of red to green, and the value of b^* indicated the ratio of yellow to blue. Five fruits of each cultivar were taken for the analysis. The color co-ordinates were processed by the Universal Software V.4-10.

2.10. Fruit Firmness Measurement

The firmness of apple peel and flesh was evaluated using a texture analyzer TA.XTPlus (Stable Micro Systems, Godalming, UK) and a P/2 probe. Measurements of the firmness of apple peel and flesh began with the probe touching the surface of the sample. Subsequently, when applying a force of 2 g, the probe entered the sample to a depth of 10 mm at the speed of 1 mm/s. Five fruits of each cultivar were taken for the analysis and were measured three times. The data of the fruit firmness analysis were processed using the Texture Exponent software (Stable Micro Systems, Godalming, UK).

2.11. Statistical Analysis

The study of the data was performed by using the software Microsoft Office Excel 121 (Microsoft, Redmond, WA, USA) and SPSS, version 25.0 (SPSS Inc., Chicago, IL, USA). The results of three consecutive test results and standard deviations were presented. Univariate analysis of variance (ANOVA) was applied to determine whether the differences between the compared data were statistically significant. The hypothesis about the equality of variances was verified by applying Levine's test. If the variances of independent variables were found to be equal, Tukey's multiple comparison test was used. The differences were regarded as statistically significant at $p < 0.05$. To find relationships, the Pearson correlation coefficient was calculated.

3. Results and Discussion

3.1. Changes in Chemical Composition Before and after Storage in CA

3.1.1. Variability of the Composition of Sugars, Sucrose, and Ascorbic Acid

The shape, size, color tone, and other characteristics of the quality of apples are important factors of their market value. Apples of attractive color, optimal size, and intact surface are likely to be selected first [34], while their organoleptic properties, such as taste, smell, and texture, determine whether the apples will be bought again [3,31]. The sweet or sour taste of apples is one of the main organoleptic properties that determine the

satisfaction of the consumers' taste and the consumption of these fruit in the diet [31,33]. Cichowska and Aprea argued that the sweet taste of the fruit is determined by the complex of sugars and soluble solids in the apples. The sugars found in apples are sucrose, glucose, fructose, and sorbitol, and the complex of soluble solids consists of sugars and organic acids. These groups of organic substances determine the particularities of sweet or sour flavors of the apples [32,33]. We did not find any published research findings on the organoleptic properties of apples grown in Lithuania that were used in our study. In order to preserve good commercial values and a quality product for a longer period of time, it is important to study the changes in organoleptic properties (sweetness and acidity) in apples stored in a controlled atmosphere of various compositions.

Changes in total sugar and sucrose levels were detected during the experiment. Before the storage, the total sugar content in the samples of different apple cultivars varied from 9.15 to 11.14%, and sucrose content ranged from 2.00 to 3.24% (Table 2). The highest total amount of sugars (11.14%) was found in apple samples of the 'Rubin' cultivar, and the highest sucrose content (3.24%) was found in samples of the 'Sampion' cultivar (Table 2). Similar results for 'Fuji' apples were obtained by Watkins et al. in their study, where they found that the total sugar content in samples of 'Fuji' apples may exceed 20.00% [39].

Table 2. Variability of the total sugar and sucrose content in apple samples before and after storage in CA.

Cultivar	Before Storage		I		II		III		IV		V		VI		VII		VIII	
	TS, %	CS, %	TS, %	CS, %	TS, %	CS, %	TS, %	CS, %	TS, %	CS, %	TS, %	CS, %	TS, %	CS, %	TS, %	CS, %	TS, %	CS, %
'Alva'	10.09	2.75	13.55	3.77	12.63	3.16	12.87	3.59	13.02	3.24	13.02	3.24	13.04	2.98	13.17	3.05	12.78	2.85
'Auksis'	10.31	3.15	13.44	3.32	13.42	3.64	13.00	3.74	12.75	3.24	13.58	3.18	13.45	2.78	12.79	2.52	13.35	2.22
'Connel Red'	10.90	2.43	12.88	3.28	13.99	3.47	13.45	3.20	13.44	2.96	13.03	3.10	14.13	3.19	13.31	2.91	13.62	2.42
'Cortland'	9.42	2.22	13.97	3.72	14.54	3.60	14.16	3.22	13.16	3.29	13.27	3.76	12.80	2.34	13.07	2.40	13.21	2.41
'Ligol'	9.15	2.07	12.04	3.79	12.32	3.74	11.82	2.75	12.46	3.54	12.34	2.96	13.69	3.44	13.50	2.28	13.18	2.91
'Lodel'	10.22	2.68	14.13	3.73	14.55	3.33	14.12	2.99	12.76	3.16	13.18	3.00	13.34	2.40	13.74	2.54	12.82	2.09
'Noris'	10.12	2.00	13.02	3.42	12.94	3.28	13.43	3.18	13.32	2.80	12.75	3.24	12.77	2.99	12.91	2.85	12.62	3.24
'Rubin'	11.14	3.02	12.76	3.16	14.66	3.72	15.07	3.94	14.27	3.05	14.14	2.88	14.25	3.58	13.61	2.61	13.92	2.52
'Sampion'	10.86	3.24	13.83	3.90	12.87	3.61	12.78	2.84	12.47	3.42	12.77	3.11	12.19	2.91	12.70	1.90	13.31	2.85
'Spartan'	10.74	3.00	12.74	3.54	12.72	3.80	12.34	3.42	12.87	3.59	12.45	3.65	12.99	3.82	12.76	3.16	12.79	2.61

Abbreviation: TS—total sugar content; CS—content of sucrose.

The samples of the studied apple cultivars stored for 8 months in the conditions of chambers I–VIII demonstrated a general upward trend of sugar content (Table 2). The largest increase in total sugar content (from 9.42% to 14.16%) was found in apple samples of the 'Cortland' cultivar stored in chamber III conditions (Table 2). The smallest change in total sugar content (from 10.74 to 12.19%) was found in apple samples of the 'Sampion' cultivar stored in chamber VI conditions (Table 2). Studies by Jan and Rab showed that the total sugar content in apple samples increased during storage and ranged from 9.67 to 12.47% [40]. The increase in the total sugar content in apple samples during storage is explained by the ripening process of the fruit and the hydrolysis of starch molecules [40].

An upward trend of sucrose content was found in apple samples of the studied cultivars stored in the conditions of chambers I, II, and IV (Table 2). The largest increase in sucrose content (from 2.07 to 3.74%) was observed in apple samples of the 'Ligol' cultivar stored in chamber II conditions (Table 2). Significant reductions in sucrose content were observed in apple samples of 'Auksis', 'Connel Red', 'Lodel', 'Rubin', 'Sampion', and 'Spartan' cultivars stored in chamber VIII conditions (Table 2). Zhu et al. stated that the sucrose content in apple samples decreases during storage because sucrose decomposes into fructose and glucose, which explains the upward trend in sugar content during apple storage [41].

Ascorbic acid found in apple samples has strong antioxidant properties. Ascorbic acid, as a powerful antioxidant, protects DNA, proteins, lipids, and other macromolecular structures from the damaging effects of free radicals [42]. Ascorbic acid found in apple samples is used not only for the prevention of various chronic diseases, such as cancer [42], but also for assessing the quality of apples [40]. In our study, we determined the variability of ascorbic acid content in apple samples stored under controlled atmosphere conditions.

The amount of ascorbic acid was found to vary from 7.20 mg/100 g to 8.80 mg/100 g in apple samples before storage (Table 3). The maximum content of ascorbic acid was 8.80 mg/100 g in apple samples of the ‘Sampion’ cultivar (Table 3). Jan and Rab stated that the ascorbic acid content in apple samples ranged from 12.80 mg/100 g to 14.20 mg/100 g [40].

Table 3. Variability of the quantitative composition of ascorbic acid in apple samples before and after storage in CA.

	Before Storage	I	II	III	IV	V	VI	VII	VIII
Cultivar				mg/100 g					
‘Alva’	7.20	6.40	6.40	6.00	6.40	6.00	6.00	6.40	6.40
‘Auksis’	7.20	6.40	6.00	6.00	6.40	6.00	5.60	6.00	6.00
‘Connel Red’	8.00	7.20	7.20	6.00	5.60	6.40	6.40	6.40	6.40
‘Cortlend’	7.20	6.00	6.00	5.60	6.00	6.40	6.00	6.40	6.00
‘Ligol’	7.20	6.40	6.40	6.40	6.80	6.40	6.40	6.00	6.80
‘Lodel’	8.00	6.40	7.20	6.40	7.20	6.40	6.40	6.80	6.40
‘Noris’	8.00	5.60	6.00	6.00	6.00	5.60	6.40	6.80	6.40
‘Rubin’	7.20	6.40	6.00	6.00	6.00	6.00	6.40	6.00	6.40
‘Sampion’	8.80	8.00	8.00	8.00	6.40	7.20	7.20	7.20	8.00
‘Spartan’	8.00	6.80	6.40	6.40	6.40	6.80	6.00	6.40	7.20

We found that the content of ascorbic acid decreased in apple samples of all the studied cultivars stored in the conditions of chambers I–VIII (Table 3). The smallest change in the content of ascorbic acid (from 8.80 mg/100 g to 8.00 mg/100 g) was observed in apple samples of the ‘Sampion’ cultivar stored in the conditions of chambers I–III and VIII (Table 3). A significant reduction in ascorbic acid content (from 8.00 mg/100 g to 5.60 mg/100 g) was found in apple samples of ‘Connel Red’ and ‘Noris’ cultivars stored in chamber IV and V conditions, respectively (Table 3). Jan and Rab, in their studies, found that ascorbic acid levels in apple samples decreased during storage and ranged from 14.18 mg/100 g to 8.68 mg/100 g [40]. Oyetade et al., in their study, also found that ascorbic acid content decreased in apple samples during their storage, which confirms the results of our study [43].

3.1.2. Evaluation of Soluble Solids and Titratable Acidity

The content of soluble solids and titratable acidity are some of the most important indicators of apple quality [27]. The acidity of apples is an important indicator of organoleptic properties that influence the perception of fruit taste. The sour taste of apples depends on the complex of organic acids (malic, citric, tartaric, etc.) [3], while the sweet taste of apples depends on the content of soluble solids [33]. The evaluation of the content of soluble solids and the qualitative indicators of titratable acidity allow for assessing the quality and commercial value of apples.

Our study showed that the content of soluble solids in apple samples before storage varied from 12.40 to 14.00%, and titratable acidity ranged from 0.24 to 0.61% (Table 4). The highest content of soluble solids (14.00%) was found in apple samples of the ‘Rubin’ cultivar, and the highest titratable acidity (0.61%) was found in apple samples of ‘Cortlend’ and ‘Noris’ cultivars (Table 4). Łysiak et al. pointed out that the content of soluble solids in the samples of apples grown in Italy, the Netherlands, and Poland was 12.08%, 12.11%, and 14.69 to 14.74%, respectively [44]. In a study by Jan and Rab, the highest titratable acidity of 0.56% was found in apple samples of ‘Mondial Gala’ and ‘Royal Gala’ cultivars [40].

Table 4. Variability of the content of soluble solids and titratable acidity in apple samples before and after storage in CA.

Cultivar	Before Storage		I		II		III		IV		V		VI		VII		VIII	
	SS, %	TA, %	SS, %	TA, %	SS, %	TA, %	SS, %	TA, %	SS, %	TA, %	SS, %	TA, %	SS, %	TA, %	SS, %	TA, %	SS, %	TA, %
‘Alva’	13.00	0.50	15.00	0.37	14.20	0.37	14.00	0.37	14.50	0.34	14.40	0.41	14.50	0.37	14.60	0.34	14.00	0.37
‘Auksis’	13.00	0.50	14.80	0.40	15.00	0.42	14.40	0.42	14.00	0.37	14.80	0.40	14.80	0.37	14.00	0.34	14.80	0.33
‘Connel Red’	13.60	0.24	14.60	0.21	16.00	0.20	14.80	0.17	15.20	0.18	14.40	0.21	15.50	0.18	14.60	0.17	15.40	0.21
‘Cortland’	13.50	0.61	15.40	0.45	15.80	0.40	16.00	0.42	15.80	0.46	14.60	0.50	14.60	0.48	15.00	0.45	15.00	0.48
‘Ligol’	12.40	0.32	13.50	0.18	14.00	0.18	14.30	0.18	14.00	0.21	14.20	0.18	15.00	0.16	14.80	0.20	15.00	0.16
‘Lodel’	13.20	0.45	15.60	0.34	16.80	0.36	16.00	0.36	14.40	0.34	15.20	0.37	15.00	0.34	17.20	0.32	15.20	0.34
‘Noris’	13.50	0.61	14.60	0.50	14.70	0.45	15.20	0.45	16.00	0.48	14.00	0.52	14.20	0.48	14.20	0.45	14.20	0.49
‘Rubin’	14.00	0.50	15.00	0.40	17.60	0.37	16.60	0.40	16.20	0.37	16.60	0.42	16.00	0.37	16.80	0.36	16.50	0.34
‘Sampion’	12.60	0.27	15.00	0.16	14.70	0.18	13.80	0.18	13.80	0.16	14.00	0.21	14.00	0.18	14.00	0.17	14.40	0.18
‘Spartan’	12.80	0.48	14.00	0.37	14.20	0.34	13.60	0.42	14.00	0.34	14.00	0.37	14.40	0.34	14.00	0.37	14.00	0.33

Abbreviation: SS—content of soluble solids; TA—titratable acidity.

An upward trend in the content of soluble solids was observed in apple samples stored in the conditions of chambers I–VIII (Table 4). The greatest increase in the content of soluble solids was observed in apple samples of ‘Lodel’ and ‘Rubin’ cultivars stored in chamber II conditions (from 13.20 to 16.80% and from 14.00 to 17.60%, respectively) (Table 4). Riveria et al., in their study, found that the content of soluble solids in apple samples during storage increased from 9.93 to 13.08%, which confirms the results of our study [45]. Jan and Rab determined that the amount of soluble solids increased during apple storage because starch or other polysaccharides in cell walls were hydrolyzed as the amount of water in the cells decreased [40]. Scientific literature provides data on the decreasing trend of the content of soluble solids during storage of fruit samples. The downward trend can be explained by the biosynthesis of anthocyanins in apple skin. During anthocyanin biosynthesis, sugars in apples are used in the anthocyanidin glycosidation processes, which results in a decrease in the total content of soluble solids [46].

A decreasing trend of titratable acidity was observed in apple samples stored in chambers I to VIII (Table 4). The greatest decrease in titratable acidity (from 0.61 to 0.40%) was observed in apple samples of the ‘Cortland’ cultivar stored in chamber II conditions (Table 4). Data from scientific literature indicating that the titratable acidity in apple samples decreased during storage and varied from 0.69 to 0.37% confirm the results of our study [40]. During the storage of apple samples, the decrease in titratable acidity is influenced by metabolic processes, especially respiration. Organic acids are important components of metabolic processes [47,48]. Musacchi et al. indicated that the percentage of titratable acidity can vary from 1.00% in samples of fresh apples to 0.40% during storage [3]. Sudheeran et al., in their studies, found that elevated levels of sugars and decreased amounts of organic acids positively correlated with a better fruit quality and taste [49].

3.2. Changes in Organoleptic Characteristics of Apple before and after Storage in CA

3.2.1. Changes in Apple Peel Color

Color is an important indicator of the appearance of apples and partly determines the choice of the consumers. Therefore, it is important to determine the particularities of the storage conditions that would minimize color changes and changes in the quality of the apples [4,50]. Consequently, it is expedient to assess color changes of apple samples under controlled atmosphere storage conditions with the aim of keeping the fruit suitable for consumption and of an attractive commercial appearance for as long as possible. To determine color changes in apple samples under controlled atmosphere storage conditions, we performed the analysis of color co-ordinates using the CIE L*a*b* scale.

The composition of the controlled atmosphere was found to influence the color changes of the apples. The highest values of the red co-ordinate (a*) were found for

apple samples of 'Alva' (40.93 NBS), 'Lodel' (40.45 NBS), and 'Sampion' (42.32 NBS) cultivars stored in chamber VII conditions, and they did not differ statistically significantly from the values of the red co-ordinate before storage (Figure 1, Panel a). The study showed that the rich yellow color remained in apple samples of 'Auksis' (16.51 NBS), 'Connel Red' (17.82 NBS), 'Ligol' (13.73 NBS), and 'Rubin' (19.72 NBS) cultivars stored in chamber VI conditions (Figure 1, Panel b).

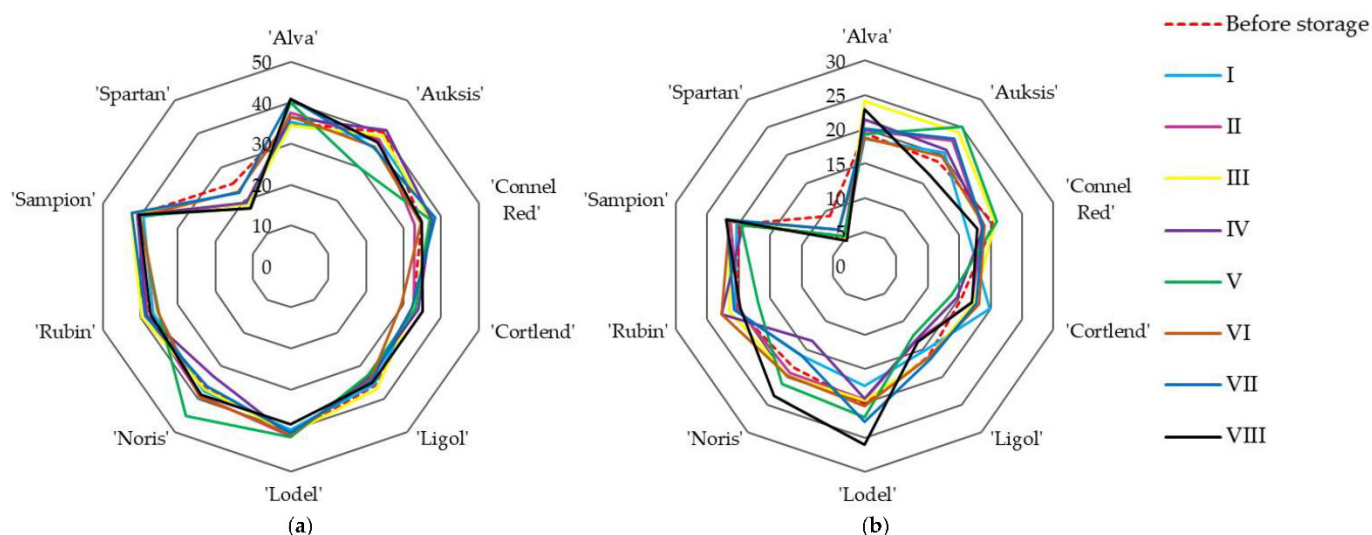


Figure 1. Variability of co-ordinates measured in NBS units in apple peel before and after storage in CA: (a) redness (a^*) co-ordinate; (b) yellowness (b^*) co-ordinate.

Dobrzański 2002 et al. found that, after 5 months of storage in controlled atmosphere chambers, the red co-ordinate (a^*) in 'Sampion' apple peel varied from 10 NBS to 53 NBS, and the yellow co-ordinate (b^*) from 5 NBS to 43 NBS, which confirms the results obtained in our study [50]. Telias et al. pointed out that, recently, consumers tend to choose light red apples more often, while dark red apples are becoming less popular [51]. Researchers studied color changes in apples, which are determined by the pigments in the apple skin. Sethi and Deun found that the color of apple skin is determined by the ratio of the qualitative and quantitative composition of anthocyanins and flavonols. When anthocyanins predominate, apple skin tends to have pink hues, while the predominance of flavonols gives apple skin yellowish shades [52,53]. The dark red color of apples is determined by the ratio of the quantitative composition of anthocyanins to chlorophyll. Apples with a higher content of chlorophyll than anthocyanins in the skin have a dark red color, while a light red color of the apple skin means that the content of anthocyanins is higher than that of chlorophyll [30]. In a study conducted in 2008, Iglesias et al. found that anthocyanin content strongly correlated with red (a^*) and yellow (b^*) co-ordinate values [5]. Bars-Cortina et al., in their study, found that red-fleshed apple samples expressed higher levels of MdMYB10 promoters responsible for anthocyanin synthesis than white-fleshed apple samples did [54].

There is evidence in scientific literature that apples show a change in color during storage due to browning, which reduces the quality and commercial value of the apples [50]. Based on the color values of lightness (L^*) and chroma (saturation) (C^*) co-ordinates, we evaluated color changes in apple samples under controlled atmosphere storage conditions. The analysis of apple color saturation showed that apple samples of 'Alva' (46.90 NBS), 'Lodel' (47.44 NBS), 'Noris' (45.33 NBS), and 'Sampion' (46.16 NBS) cultivars stored in Chamber VI conditions had statistically significantly the purest color (Figure 2, Panel a). The most mixed color was found in apple samples of 'Ligol' (35.31 NBS), 'Rubin' (38.98 NBS), and 'Spartan' (18.35 NBS) cultivars stored under chamber V conditions (Figure 2, Panel a).

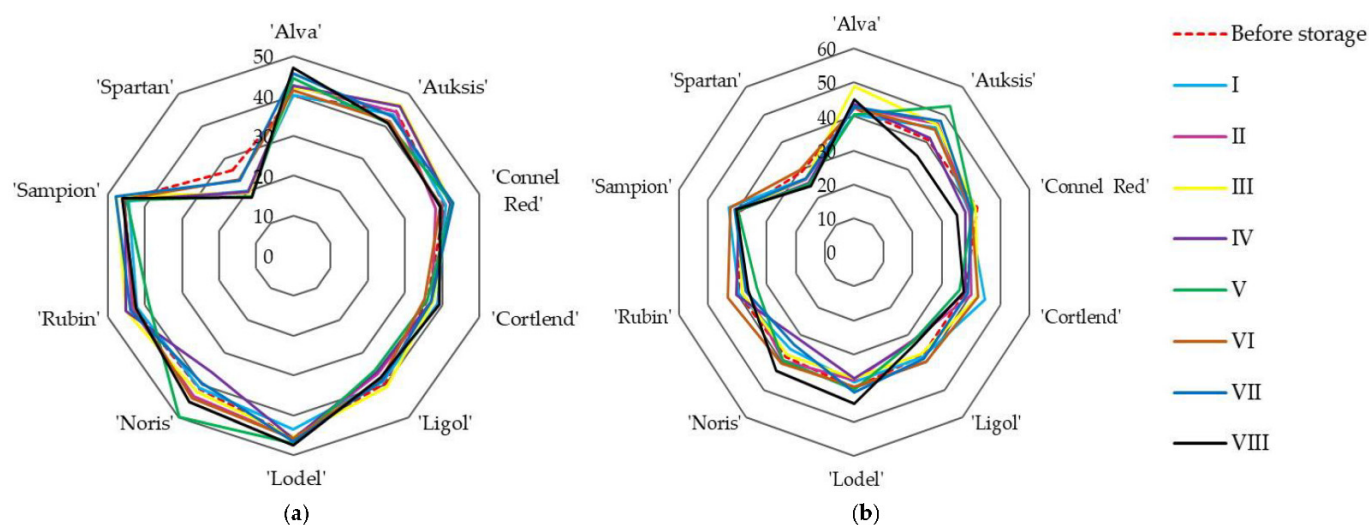


Figure 2. Changes in coordinates measured in NBS units in apple peel before and after storage in CA: (a) color saturation (C*) co-ordinate; (b) lightness (L*) co-ordinate.

The peel color of apple samples of ‘Alva’ (44.92 NBS), ‘Lodel’ (44.47 NBS), and ‘Noris’ (43.09 NBS) cultivars was found to be statistically significantly brightest under chamber VI conditions, and its brightness was close to that of fresh fruit (Figure 2, Panel b). Peel color of apple samples of ‘Ligol’ (32.38 NBS), ‘Rubin’ (33.24 NBS), and ‘Spartan’ (24.95 NBS) cultivars stored under chamber V conditions was the darkest and the furthest away from that of fresh apples (Figure 2, Panel b).

The lightness index (L^*) describes the degree of freshness of the fruit, and the lower the L^* value, the darker the fruit, the more prone they are to turning brown, and the further their condition is from that of the fresh fruit [34]. Dobrzanska 2002 et al. pointed out that apples of the ‘Sampion’ cultivar ranged in brightness (L^*) from 40 to 70 NBS when stored for 5 months in controlled atmosphere chambers, as confirmed by the results obtained in our study [50]. Liu et al. found that the lightness index (L^*) values for ‘Granny Smith’ (56.90 NBS) and ‘Golden Delicious’ (60.42 NBS) cultivars were higher than those for ‘Pink Lady’ (49.02 NBS) and ‘Starkrimon’ (41.54 NBS) cultivars [29]. Our results confirm that non-red apples of different cultivars had higher values of the lightness index (L^*) and lower co-ordinates of redness (a^*) and yellowness (b^*) compared to samples of red apples. In 2012, Iglesias et al. found that the anthocyanin content was inversely proportional to the lightness index (L^*) [55]. Studies have shown that during the browning of apples, the values of the lightness index (L^*) decreased, and the values of the redness (a^*) and yellowness (b^*) co-ordinates increased [4,29].

Determination of the values of apple color co-ordinates C^* , L^* , a^* , and b^* is important in assessing changes in fruit quality indices during storage [34]. Apples tend to brown during storage due to aging of the tissues, resulting in the loss of their original color and commercial appearance [4,53]. The browning of apples is determined by temperature, pH value, changes in the qualitative and quantitative composition of phenolic compounds, and a decrease in the mechanical resistance of apple skin due to damage to the surface of the apples [4]. It has been found that color changes in apple samples can cause changes in apple texture [34], and, thus, it was expedient to perform an analysis of changes in apple peel and flesh firmness under controlled atmosphere conditions.

3.2.2. Changes in Apple Peel and Flesh Firmness

Consumers seek to obtain fruit with good appearance and optimal texture and firmness [39]. Overripe and mechanically damaged fruits soften, and, thus, the fruit firmness index is important as a fruit quality criterion that allows the selection of good quality fruit suitable for consumption [34]. Determining the firmness index of the fruit is important in

assessing the mechanical firmness of apples during both storage and transportation [34]. The values of firmness indices of the peel and flesh of apples of different cultivars were determined at the beginning of the experiment and after 8 months of storage in a controlled atmosphere of various compositions.

The evaluation showed that the firmness of apple peel before storage varied from $165.7 \pm 41.3 \text{ N cm}^{-2}$ to $310.3 \pm 39.8 \text{ N cm}^{-2}$ in different cultivars (Table 5). Apple peel of 'Connel Red' and 'Ligol' cultivars was found to be the firmest, at $310.3 \pm 39.8 \text{ N cm}^{-2}$ and $307.9 \pm 38.4 \text{ N cm}^{-2}$, respectively (Table 5). The evaluation also showed that, before storage, apple samples of the 'Connel Red' cultivar had the firmest flesh ($82.9 \pm 15.9 \text{ N cm}^{-2}$) (Table 5). Watkins et al. pointed out that the firmness of 'Granny Smith' apples varied from 80 N cm^{-2} to 98 N cm^{-2} , while, in apples of the 'Golden Delicious' cultivar, it was up to 53 N cm^{-2} [39].

The peel of 'Spartan' apples kept under chamber VIII conditions was found to have softened by 38.25% (Table 5). Meanwhile, the flesh of 'Spartan' apples stored in chamber I conditions softened by as much as 47.40% (Table 5). Apple peel samples of the 'Sampion' cultivar stored in chamber I and III-VI conditions were found to have increased firmness compared to that before the storage (Table 5). The results of our study were confirmed by Afzadi et al., who found that apple samples may soften by 32.00 to 47.00% during storage, but also presented data showing that the firmness of the apple samples of 'Antonovka Kamenitschka' and 'Antonovka Pamtorutka' cultivars increased, respectively, from 95.1 to 107.9 N cm^{-2} and from 92.2 to 101.0 N cm^{-2} during storage [56].

Jan and Rab pointed out that the firmness of apples during storage depended on the characteristics of the apple cultivar [40]. As fruit shelf-life increases, apples soften due to changes in the pectin content of the cells [57], decreased water content, and intensified respiration [47]. Mechanical damage to carrot roots has been found to increase ethylene production, which intensifies sugar use during the respiration process [58]. During this process, the fruit becomes less sweet and a bitter taste appears. The bitter taste changes the organoleptic properties of the apples and reduces their commercial value.

In scientific literature, we did not find any research results on the strength of the correlation between changes in the chemical composition of apples and the firmness indices in samples of apples grown in Lithuania, stored in a controlled atmosphere of different compositions. We calculated Pearson's correlation coefficients between changes in the content of soluble solids and the firmness values in apples during storage. The content of soluble solids in apple samples weakly ($r = 0.072$ and $r = 0.291$) and moderately strongly (from $r = 0.300$ to $r = 0.365$) positively correlated with the firmness values of apples before storage (Figure 3).

Table 5. Variability of the firmness indicators in apple peel and flesh samples before and after storage in CA.

	Before Storage		I		II		III		IV		V		VI		VII		VIII	
	Peel, N cm ⁻²	Flesh, N cm ⁻²	Peel, N cm ⁻²	Flesh, N cm ⁻²	Peel, N cm ⁻²	Flesh, N cm ⁻²	Peel, N cm ⁻²	Flesh, N cm ⁻²	Peel, N cm ⁻²	Flesh, N cm ⁻²	Peel, N cm ⁻²	Flesh, N cm ⁻²	Peel, N cm ⁻²	Flesh, N cm ⁻²	Peel, N cm ⁻²	Flesh, N cm ⁻²	Peel, N cm ⁻²	Flesh, N cm ⁻²
Cultivar	Mean ± SD																	
‘Alva’	278.2 ± 22.7	70.3 ± 6.6	229.2 ± 12.3	56.1 ± 4.5	257.8 ± 28.7	59.5 ± 8.8	235.7 ± 16.6	66.7 ± 9.1	247.7 ± 26.5	59.5 ± 6.1	251.7 ± 20.8	61.1 ± 7.7	239.4 ± 32.3	61.5 ± 5.0	263.0 ± 16.0	58.2 ± 7.5	251.8 ± 12.0	58.9 ± 8.8
‘Auksis’	170.0 ± 40.1	47.7 ± 10.2	128.4 ± 19.	40.0 ± 6.8	179.2 ± 12.2	40.4 ± 6.6	150.6 ± 6.8	41.2 ± 2.9	155.8 ± 5.7	40.1 ± 3.6	121.9 ± 31.6	37.3 ± 1.9	162.2 ± 42.3	48.9 ± 11.5	155.5 ± 13.2	39.8 ± 3.5	128.7 ± 10.4	41.5 ± 9.4
‘Connel Red’	310.3 ± 39.8	82.9 ± 15.9	283.1 ± 19.9	79.6 ± 11.2	310.1 ± 36.9	72.7 ± 25.4	280.9 ± 39.7	87.1 ± 25.4	316.8 ± 34.1	78.3 ± 7.3	295.1 ± 54.9	78.7 ± 17.1	302.3 ± 14.7	70.8 ± 13.6	301.8 ± 14.7	79.3 ± 9.3	241.5 ± 22.6	68.6 ± 10.3
‘Cortlend’	215.0 ± 26.9	52.6 ± 2.2	174.5 ± 10.1	39.5 ± 2.5	188.2 ± 19.3	43.5 ± 4.8	190.7 ± 9.7	44.9 ± 4.9	179.1 ± 18.2	45.4 ± 5.9	174.6 ± 9.2	48.4 ± 7.4	170.6 ± 15.2	41.6 ± 3.9	182.5 ± 12.8	38.8 ± 0.9	164.0 ± 31.9	42.6 ± 4.9
‘Ligol’	307.9 ± 38.4	62.2 ± 5.3	275.2 ± 42.4	46.9 ± 2.7	303.1 ± 42.5	57.5 ± 8.4	314.2 ± 34.6	53.8 ± 10.9	295.8 ± 17.6	48.6 ± 2.4	309.5 ± 23.3	52.5 ± 5.2	275.7 ± 25.5	50.4 ± 4.3	291.6 ± 27.7	49.2 ± 4.4	275.5 ± 31.3	47.0 ± 5.9
‘Lodel’	231.4 ± 31.0	44.2 ± 2.9	174.3 ± 21.9	36.8 ± 8.6	235.6 ± 58.5	43.5 ± 13.8	210.8 ± 37.1	45.3 ± 6.8	193.8 ± 18.3	40.7 ± 2.2	192.8 ± 29.6	37.5 ± 2.9	184.9 ± 8.1	33.9 ± 2.7	222.2 ± 44.8	35.3 ± 10.4	170.2 ± 21.2	30.9 ± 2.8
‘Noris’	275.2 ± 35.7	59.9 ± 10.5	223.1 ± 21.3	50.7 ± 4.5	218.3 ± 60.4	59.6 ± 15.7	219.1 ± 33.6	48.3 ± 10.5	235.5 ± 42.3	56.85 ± 6.48	242.0 ± 43.3	56.4 ± 10.5	267.2 ± 44.7	61.4 ± 9.1	234.9 ± 49.1	55.1 ± 8.2	203.9 ± 42.8	46.9 ± 7.1
‘Rubin’	224.4 ± 31.4	63.7 ± 2.9	204.3 ± 12.6	58.8 ± 5.2	229.2 ± 33.4	58.1 ± 7.3	202.9 ± 44.5	56.6 ± 5.0	216.7 ± 27.1	57.9 ± 10.9	210.2 ± 12.5	57.6 ± 5.1	193.0 ± 18.9	54.2 ± 5.9	227.4 ± 14.8	58.8 ± 5.2	210.5 ± 37.9	58.9 ± 8.9
‘Sampion’	165.7 ± 41.3	37.1 ± 6.6	175.5 ± 7.9	32.8 ± 5.1	160.2 ± 24.5	31.4 ± 5.6	175.4 ± 18.8	29.4 ± 5.6	166.6 ± 12.0	28.3 ± 4.2	168.0 ± 28.4	34.9 ± 5.2	173.1 ± 32.8	31.8 ± 7.2	146.5 ± 25.6	26.6 ± 3.4	156.8 ± 21.5	32.1 ± 6.1
‘Spartan’	289.5 ± 51.0	61.6 ± 16.4	217.2 ± 37.8	29.2 ± 7.6	235.2 ± 43.2	36.3 ± 11.3	226.4 ± 44.9	38.5 ± 13.8	225.2 ± 34.8	37.3 ± 8.9	198.9 ± 26.6	36.7 ± 7.5	264.0 ± 51.9	47.8 ± 16.5	234.7 ± 44.8	31.1 ± 5.9	178.8 ± 25.1	47.7 ± 11.6

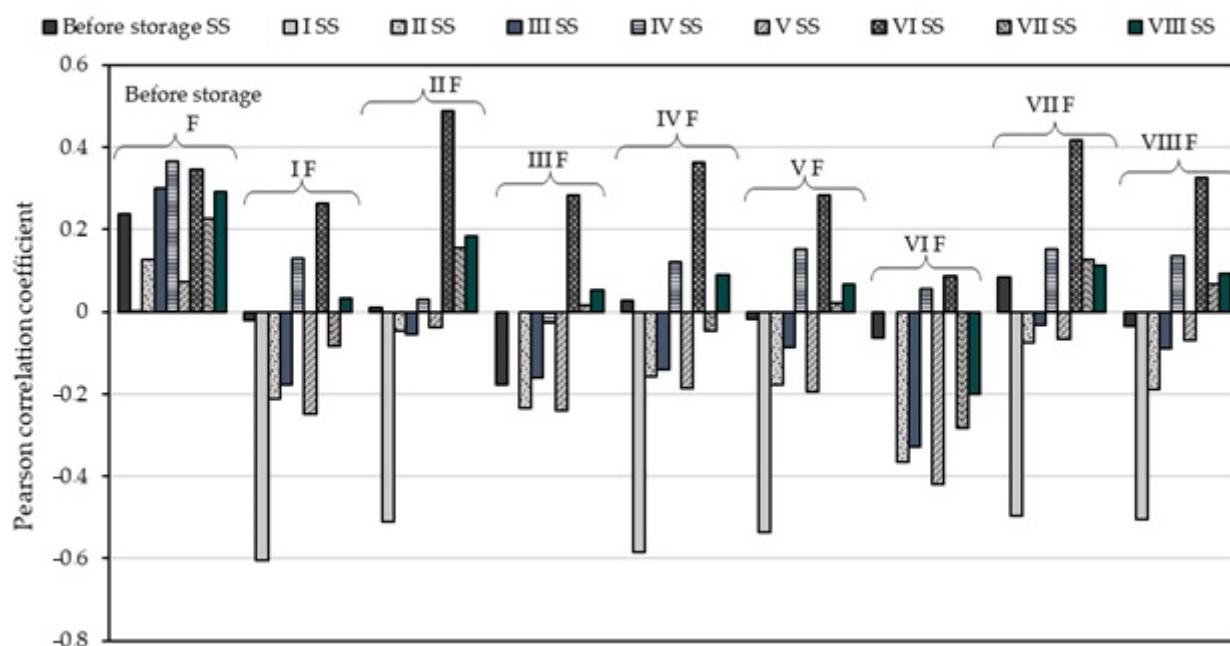


Figure 3. Content of soluble solids (SS) and firmness (F) of apples, Pearson's correlation coefficients. $0 < |r| \leq 0.3$ is a weak correlation; $0.3 < |r| \leq 0.7$ is a moderate correlation; $0.7 < |r| \leq 1$ is a strong correlation [59].

We analyzed the strength of the correlation between the content of soluble solids and the changes in the firmness values in apples stored under chambers I to VIII conditions. The analysis showed that, under chamber I storage conditions, the amount of soluble solids in apple samples moderately strongly (from $r = -0.504$ to $r = -0.689$) negatively correlated with the values of apple firmness registered under the conditions of storage chambers I–VIII (Figure 3). The negative correlation shows that, as the content of soluble solids increased during apple storage, the apple samples softened and their firmness values decreased. The results of the evaluation revealed that the content of soluble solids in apple samples in the conditions of storage chamber VI weakly (from $r = 0.262$ to $r = 0.282$) and moderately strongly (from $r = 0.326$ to $r = 0.418$) positively correlated with apple firmness values registered under chamber I–V and VII–VIII storage conditions (Figure 3). The positive correlation showed that, in apple samples stored in the conditions of chamber VI, the values of the firmness indices increased with the increase of the content of soluble solids. The obtained results are confirmed by the data of other authors' studies, which show that the content of soluble solids positively correlated with the values of the firmness indices of apples [60,61].

3.3. Evaluation of Apple Weight Loss and Quality during Storage

Depending on the apple cultivar, apples differ not only in organoleptic and physical properties or chemical composition, but also in fruit mass [62]. The mass of apples has been found to determine their quality during storage [63]. The postharvest losses are determined by storage conditions, fruit firmness, apple mass, pH, the composition of soluble solids, and other parameters. In our study, we evaluated the weight loss of damaged and depreciated apples during storage in a controlled atmosphere.

The weight loss of apple samples stored in chambers V and VI was the lowest compared to apple samples kept in chambers I–IV and VII–VIII (Table 6). The weight loss of 'Ligol' apples stored in chamber V and VI conditions was found to be the lowest (at 1.60% and 1.40%, respectively) (Table 6). Apple samples of 'Alva' and 'Cortland' cultivars stored in chambers I to II and VIII showed maximum weight losses of 8.30, 8.20, and 8.20%, respectively (Table 6).

Table 6. Variability in quality and weight loss in apples during storage in CA.

	I		II		III		IV		V		VI		VII		VIII	
Cultivar	WL, %	QL, %	WL, %	QL, %	WL, %	QL, %	WL, %	QL, %	WL, %	QL, %	WL, %	QL, %	WL, %	QL, %	WL, %	QL, %
‘Alva’	8.30	17.10	8.20	12.60	3.90	13.00	4.70	13.80	3.40	12.60	3.90	14.50	5.10	10.50	5.20	14.60
‘Auksis’	5.20	35.80	4.70	31.60	5.10	26.20	7.00	37.60	4.10	34.30	4.70	37.90	5.00	33.50	5.00	33.90
‘Connel Red’	6.70	16.60	4.90	16.10	4.40	18.70	4.20	19.40	4.40	28.10	3.60	31.30	8.00	35.30	5.60	39.30
‘Cortland’	7.20	18.70	8.00	12.70	3.20	14.80	3.00	13.30	1.90	3.50	2.50	16.70	6.10	17.60	8.20	12.20
‘Ligol’	5.40	19.90	5.10	16.70	2.40	3.00	2.70	22.70	1.60	5.00	1.40	10.90	3.20	11.00	4.80	11.50
‘Lodel’	6.40	12.30	6.30	11.80	5.30	16.10	7.50	9.30	5.00	9.30	3.60	13.90	5.40	15.30	6.60	15.00
‘Noris’	5.50	25.30	5.30	8.50	3.00	13.90	4.20	16.70	2.30	16.10	2.20	15.70	4.80	15.10	5.20	16.90
‘Rubin’	6.00	16.20	6.50	10.50	2.90	18.40	4.90	18.50	2.50	9.70	2.00	18.20	7.90	19.30	6.30	25.70
‘Sampion’	4.20	13.00	7.50	7.60	3.40	10.40	3.90	8.70	2.20	8.60	2.60	8.50	4.50	8.10	4.90	8.60
‘Spartan’	8.00	8.70	5.60	3.90	4.20	8.30	4.40	4.70	3.50	11.00	3.70	7.20	4.90	7.30	5.10	6.90

Abbreviation: WL—weight loss; QL—quality loss (e.g., the apples rotten, lost their original color, browned).

Studies carried out by Jan and Rab showed that the weight of ‘Red delicious’ apples decreased by at least 2.22% during storage, with a greatest loss of 2.91% detected in apple samples of the ‘Golden Delicious’ cultivar. The researchers found that, with increasing shelf life of apples to 4 months and 5 months, the percent weight loss of apples increased by 4.05 and 4.53%, respectively [40]. In our study, apples were stored for a longer period of 8 months, resulting in twice the loss of apple weight.

Apple samples of ‘Spartan’, ‘Ligol’, and ‘Cortland’ cultivars kept in chambers II, III, and V were found to have the lowest quality losses of 3.90, 3.00, and 3.50%, respectively (Table 6). The largest percentage of apples that sustained quality loss were stored in chamber I and VIII conditions (Table 6). The evaluation showed that, during the storage of apples of the ‘Auksis’ cultivar under the conditions of chambers I to VIII, their quality decreased from 26.20 to 37.90% compared to that of apples of other cultivars (Table 6). The results of the study also showed that the quality of ‘Connel Red’ apples stored in Chamber VIII conditions decreased by as much as 39.30% (Table 6). Shah et al. estimated that, during postharvest operations, the quality of apples decreased by about 17.00% [64]. Ilyas et al. found that during 22-week cold storage, apple quality decreased by 22.00% [65].

Apple weight loss depends on the apple cultivar, apple skin structure, the chemical composition of the wax layer, intensified respiration, and water mass loss [66]. Water loss results in a decrease in turgor pressure in apple tissue cells, and this influences the process of apple softening [47,67]. The softening of the fruit causes changes in the original shape of the fruit and a decrease in quality. Kowitcharoen et al. found that the decrease in cell turgor pressure in tomato (*Lycopersicon esculentum* Mill.) fruit resulted in their softening and weight loss [67].

The widespread consumption of apples in the world is determined by the totality of external (color and size) and internal (taste, texture, smell, and nutritional value) quality parameters of apples [4,5,34]. The sweet or sour taste of apples determines the satisfaction of the consumers’ taste and the consumption of apples in the diet [31,33]. Cichowska and Aprea claimed that the sweet and sour taste of the fruit is determined by the complex of sugars and soluble solids in the apples [32,33]. During storage, the metabolic processes in the apples cause variation in the content of sugars and organic acids, which determines changes in organoleptic properties. Apple samples stored for 8 months in chambers I to VIII showed a general upward trend in the content of sugars and soluble solids, as confirmed by foreign researchers in their studies. Jan and Rab indicated that, during storage, the mass of water in apple tissue cells decreased and starch hydrolysis occurred [40]. Choosing the optimal conditions for the storage of apples in a controlled atmosphere may help affect the increase or decrease in sugar content in the fruit, thus allowing for creating the supply of apples with a lower sugar content and a high nutritional value. A decreasing trend of titratable acidity and ascorbic acid content was observed in apple samples stored in chambers I to VIII. Oyetade et al. found that mechanical damage to apple skin could reduce ascorbic acid content by 8.00 to 25.00% [43]. In order to preserve the maximum ascorbic acid content in apples during storage, optimal storage conditions should be selected, which would minimize changes in ascorbic acid content. Ascorbic acid is an important component

of oxidation–reduction (redox) reactions in the human body, and is needed in the diet to prevent chronic diseases.

Apple color is an important indicator of the commercial appearance of apples, which determines the consumers' choice. In our study, it was important to identify the characteristics of the storage conditions that would minimize color changes during storage. Analysis of CIE $L^*a^*b^*$ color co-ordinates of the samples of different apple cultivars stored in a controlled atmosphere showed that the red co-ordinate predominated in the samples of 'Alva', 'Lodel', and 'Sampion' cultivars stored in chamber VII (10% of O_2 , 3% of CO_2 , and 87% of N_2). Dobrzański et al., indicated that the yellow co-ordinate predominated in apple samples of the 'Sampion' cultivar grown in Poland. Apple color was found to be determined by the cultivar and climatic conditions of its growth [34], the location of the fruit in the fruit tree crown [68–70], and the qualitative and quantitative ratio of the pigments [71,72]. As the light intensity and ambient temperature increase, the amount of carotenoids that determine the yellow color increases in the fruit, while, in lower temperatures and in the acidic medium, apples produce more anthocyanins that produce the red color of the fruit [71]. During storage, apples tend to change color because organic cells release organic acids from the vacuoles in the fruit cells, which interact with enzymes that hydrolyze pigments [24,73]. Dobrzanska and Li found that, during apple storage, apple browning was influenced by temperature, pH value, changes in the qualitative and quantitative composition of phenolic compounds, and a decrease in the mechanical resistance of apple skin [4,50]. Our study showed that the color lightness of the apple samples of 'Alva', 'Lodel', and 'Noris' cultivars kept under low oxygen (1%) and high carbon dioxide (3%) conditions was close to that of fresh fruit. Our study showed that the storage conditions determined the color of the apples, as well as its saturation and intensity, and allowed for maximizing apple storage duration with minimal changes in color and commercial appearance.

Determining the firmness index of fruit is important in assessing the mechanical resistance of apples during both storage and transportation [34]. We investigated the firmness of apple peel and flesh during their storage. We found that the firmness of 'Sampion' apple peel samples stored in chambers I and III–VI increased compared to that recorded before storage. There was also an increase in the firmness of the flesh of apple samples of 'Auksis', 'Noris', 'Connel Red', and 'Lodel' cultivars stored in chamber III and VI conditions. Afzadi et al. found that the firmness of 'Antonovka Kamenitschka' and 'Antonovka Pamtorutka' apple samples during storage increased from 95.1 to 107.9 $N\ cm^{-2}$ and from 92.2 to 101.0 $N\ cm^{-2}$, respectively [56]. Storage conditions affecting the firmness of apple peel and flesh may in part reduce changes in physical properties and prolong the shelf life of apples.

The characteristics of apple cultivars determine not only the organoleptic and physical properties or the chemical composition, but also the mass of the fruit [62]. In our study, we evaluated changes in apple fruit mass during storage. The study showed that apple samples of 'Spartan', 'Ligol', and 'Cortlend' cultivars stored in chamber II (5% of O_2 , 1% of CO_2 , and 94% of N_2), III (5% of O_2 , 3% of CO_2 , and 92% of N_2), and V (5% of O_2 , 7% of CO_2 , and 88% of N_2) conditions were found to have the lowest quality losses of 3.90, 3.00, and 3.50%, respectively. Jan and Rab found that increasing the storage of apples to 4 months or 5 months increased the percent weight loss of apples by 4.05 or 4.53%, respectively [40]. In our studies, apples were stored for a longer period of 8 months, and, thus, twice the loss of apple weight was found. The results also showed that the mass of the apples determined their quality during storage.

During the study, we found that the organoleptic and physical properties, as well as the chemical composition of apples, varied between samples of different cultivars and depended on the composition of the atmosphere used during the storage. By choosing the optimal conditions of a controlled atmosphere, it is possible to minimize changes in the chemical composition and physical and organoleptic properties of the apples, which determine their quality and commercial value.

4. Conclusions

The study showed that the organoleptic and physical properties, as well as the chemical composition, of apple samples stored for 8 months under controlled atmospheric conditions changed. The total content of sugars and soluble solids was found to increase in the samples of apples stored in chamber I to VIII conditions. The highest increase in the total content of sugars was observed in apple samples of the ‘Cortland’ cultivar stored in chamber III (3% of CO₂, 5% of O₂, and 92% of N₂) conditions. The content of soluble solids increased in apple samples of ‘Lodel’ and ‘Rubin’ cultivars stored under chamber II (1% of CO₂, 5% of O₂, and 94% of N₂) conditions. The study also showed a decrease in titratable acidity in apple samples of all cultivars stored in chamber I to VIII conditions.

The values of C*, L*, a*, and b* co-ordinates of apple colors were evaluated. Maximum values of the red co-ordinate (a*) were found in apple samples of ‘Alva’, ‘Lodel’, and ‘Sampion’ cultivars stored in chamber VII (3% of CO₂, 10% of O₂, and 87% of N₂) conditions. Apple samples of ‘Alva’, ‘Lodel’, and ‘Noris’ cultivars stored in chamber VI conditions (3% of CO₂, 1% of O₂, and 96% of N₂) were found to have statistically significantly the lightest color, and their lightness was close to that of fresh fruit. We evaluated the parameters of the firmness of apple peel and flesh, and the changes in these parameters during storage in a controlled atmosphere of various compositions. The firmness of apple peel samples of the ‘Sampion’ cultivar stored in chamber I and III–VI conditions increased compared to that registered before storage. The firmness of the apple flesh of ‘Auksis’, ‘Noris’, ‘Connell Red’, and ‘Lodel’ cultivars also increased during storage in chamber III and VI conditions. We analyzed the strength of the correlation between the content of soluble solids and the changes in the firmness values of apples under storage conditions in chambers I to VIII. The content of soluble solids in apple samples under chamber I storage conditions (0.03% of CO₂, 21% of O₂, and 78.97% of N₂) moderately strongly correlated (from $r = -0.504$ to $r = -0.689$) with the firmness values of apple samples stored under chamber I–VIII conditions. Under chamber VI (3% of CO₂, 10% of O₂, and 87% of N₂) conditions, the content of soluble solids in apple samples weakly (from $r = 0.262$ to $r = 0.282$) or moderately strongly (from $r = 0.326$ to $r = 0.418$) positively correlated with the firmness values of apples under the storage conditions of chambers I–V and VII–VIII.

The physical and organoleptic parameters of apples stored in a controlled atmosphere determined during the study are valuable and prove that under the studied conditions, it is possible to extend the time of the provision of apples to the consumers with minimal changes in their chemical composition and nutritional value.

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