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The Influence of Storage Technologies on the Quality and Storability of Blackcurrant (*Ribes nigrum*) Tihope cv.

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Abstract

The objective of this study was to evaluate the changes in the fruit quality of blackcurrant 'Tihope' cv. during storage in regular atmosphere (RA), controlled atmosphere (CA), and in modified atmosphere packaging (MAP). Flesh firmness (elasticity), total soluble solids, titratable acidity, content of vitamin C, polyphenols, sugars, and antioxidant capacity were measured at harvest, after storage, and after shelf life (1 day at 18 °C or 2 days at 10 °C). The incidence of storage disorders and diseases was also monitored. Additionally, the sensory quality of the stored fruit was also analysed. The fruit of the 'Tihope' cultivar can be stored at 0 °C, in a regular atmosphere, up to 20 days without any negative effect on its quality. Storage in a controlled atmosphere or in MAP packaging allows the extension of the storage period of blackcurrants even up to 33 days, thereby delaying the occurrence of fruit damage and loss of firmness. After storage, vitamin C, polyphenols, sugars, and antioxidant activity remained at a high level similar to the harvest period.

Keywords: controlled atmosphere; firmness; health-promoting compounds; MAP; storage

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1. Introduction

Blackcurrant (*Ribes nigrum* L.) is a species commonly cultivated in many temperate-climate countries. Poland is one of the leading producers of blackcurrant fruit and one of its main exporters, also in processed form. According to FAOSTAT data [1] (accessed 15 April 2024), in 2021 and 2022, the production of currants (including blackcurrants) amounted to 152,000 tonnes and 145,800 tonnes, respectively.

Most blackcurrant fruits are processed and consumed as juices, nectars, jams, or purees, but fresh fruit can also be a valuable addition to a healthy diet. Blackcurrants contain, among others, minerals and antioxidant compounds, mostly vitamin C, anthocyanins and flavonols [2–13]. Although the amount of polyphenols and antioxidant activity decreases during processing (drying, juice production, etc.) the final content depends on the parameters of the process. It is also important that side products from the processing industry could be a good source of bioactive compounds. Michalska et al. [14,15] reported that blackcurrant pomace powders are still a valuable source of polyphenolic compounds, among which anthocyanins are the dominant group.

Fresh berry fruits are perishable and have a short postharvest life. Storage allows the extension of the fruit processing period as well as the availability of fresh fruit on the market.

For the fresh fruit market, the fruit must be uniform, with the appropriate colour specific for the cultivar, firm, free of decay and mechanical injury. The berries should be harvested fully mature, but

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not overripe. Fruits intended for storage and then to the fresh market should be picked with the stem, carefully to avoid mechanical damage. Blackcurrants belong to the 'soft fruit', which are characterized by a high metabolic rate and are perishable (the main postharvest disease is grey mould rot - *Botrytis cinerea*) [16]. To reduce metabolic activity and fungal development, it is advisable to quickly cool the fruit after harvesting to the storage temperature. Because blackcurrant fruits are not sensitive to low temperature, the recommended storage temperature is in the range of --0.5 to 0 °C and relative humidity (RH) of 95% [17,18]. Batzer and Helm [19] reported that the storage duration of black currant can be 1.5 weeks while maintaining optimal storage conditions. The use of a controlled atmosphere (CA) makes it possible to extend the storage period to 3 weeks [20,21]. Modified atmosphere packaging (MAP) can be used to extend the postharvest life of fruits in a similar way to controlled atmosphere (CA) storage. The modified atmosphere packaging, using various plastic films limiting gas diffusion, changes the composition of the atmosphere in and around fresh fruit as a result of their respiration. MAP is known to extend storage and shelf life of various berry fruits [22–26]. In the literature, little information can be found on different storage methods and their impact on the quality of blackcurrant fruit.

The objective of the present study was to determine changes in the quality of 'Tihope' blackcurrant fruit during storage in different technologies – regular atmosphere, controlled atmosphere, and modified atmosphere packaging (RA, CA, MAP, respectively).

2. Materials and Methods

The three independent storage experiments were carried out in the years 2021, 2022, and 2023 at the Fruit and Vegetable Storage and Processing Department at the National Institute of Horticultural Research in Skierniewice, Poland.

Plant Material

The fruits of 'Tihope' blackcurrant cultivars were obtained from the commercial plantation located in Ostrowiec near Łowicz (central Poland, 52°09′30″N 20°12′00″E). The plants were grown in a production system using integrated plant protection. Blackcurrants were hand-harvested at the commercial maturity stage based on skin colour and taste.

Experimental Conditions

After harvest, the fruits were cooled to storage temperature (0 °C) using forced air flow (for 3 hours), and then stored in a regular atmosphere, controlled atmosphere (15% CO_2: 2.5% O_2), or in MAP packaging (Xtend bags intended for blueberries, placed in regular atmosphere). The mean values of oxygen and carbon dioxide concentration inside the bags are given in Table 1. The currants were stored for 8 (in 2021), for 13 and 20 days (in 2022), and for 18 and 33 days (in 2023). After removal from storage, the fruits were placed for 1 day at 18 °C or for 2 days at 10 °C to simulate shelf life.

Table 1. The concentration of oxygen, carbon dioxide and ethylene in MAP packaging during storage of blackcurrant fruit of 'Tihope' cv.

Length of Fruit Storage in MAP	O_2 (%)	CO_2 (%)	Ethylene (ppm)
	2021		
8 days of storage		8.17 ±0.670	0.144 ±0.0101
	2022		
13 days of storage	12.9 ±1.15	9.70 ±1.054	0.065 ±0.0070
20 days of storage	13.4 ±0.35	9.50 ±0.495	0.049 ±0.0070
	2023		
18 days of storage	14.4 ±0.01	7.9 ±1.280	0.038 ±0.0035
33 days of storage	14.4 ±0.01	8.6 ±0.490	0.028 ±0.0007

Measurements and Analyses

At harvest, after storage, and after shelf life (SL), the following parameters were determined: flesh firmness (FF), total soluble solids (TSS), titratable acidity (TA), content of sugars (sucrose, glucose, and fructose), total polyphenols, vitamin C (L-ascorbic acid), antioxidant activity (ABTS), and sensory quality.

The firmness of the fruits (elasticity) was assessed on fruits from the medial part of the clusters by the penetrometric method using a Zwick Roell Z010 (Germany) instrument, equipped with a flat plunger of 12,7 mm diameter. The results are expressed in N as the force required for deforming the fruit by 10%. Measurements were made in three replicates of ten fruits each.

The percentage of TSS was measured in the freshly prepared fruit pulp using the Atago PR-101 (Japan) electronic refractometer. TA was measured with the potentiometric method by titration of an aqueous solution of fruit pulp with 0.1 N NaOH to the end point pH 8.1, using Mettler Toledo DL 21 (Swiss) automatic titrator. Acidity was expressed as an equivalent percentage of citric acid. The TSS/acid ratio was also calculated. For the determination of TSS and TA, three replicates were used on each analysis date.

Sugar analysis: sucrose, glucose, and fructose were determined by high-performance liquid chromatography methods according to European Standard EN 12630. Separation of sugars was conducted using Aminex HPX-87C column (300 mm x 7.5 mm) with a pre-column on the Agilent 1200 HPLC system, equipped with a differential refractometric detector. The sugars were quantified by a calibration curve for saccharose, glucose, and fructose, and the results were expressed as $g{\cdot}kg^{-1}$ f.m.

The content of L-ascorbic acid was determined by high-performance liquid chromatography (Agilent 1200 HPLC system, equipped with a DAD detector). Analysis was performed using a Supelco LC-18 column (250 mm x 4.6 mm; 5 μm), and the detection of L-ascorbic acid was by absorbance at 244 nm. The results were expressed as $mg{\cdot}100g^{-1}$ f.m., and quantified by a calibration curve for the L-ascorbic acid standard.

The total polyphenols content (TPC) was measured by a modified spectrophotometric method [27] using Folin–Ciocalteu phenol reagent. The absorbance was read against the prepared blank at 765 nm (UviLine 9400 spectrophotometer, SI Analytics, Germany). The polyphenols content was expressed as mg of gallic acid equivalents in $mg{\cdot}100g^{-1}$ f.m. of the analysed sample.

The antioxidant activity was determined using the method described by Re et al. [28], using ABTS●+ radical cation. The detailed measurement procedure was according to Oszmiański and Wojdyło [29]. The absorbance of the reaction mixture was measured at 734 nm using a Cary 3E UV-Visible spectrophotometer (Varian). The linear regression method was used to calculate the concentration of extract, leading to a 50% decrease in the absorbance of the ABTS●+ solution, which was recalculated to mg of Trolox equivalents per gram of fruit sample.

For the respiration rate (carbon dioxide released by fruit) and ethylene production, the samples of fruits (approximately 50 g) were enclosed in gas-tight containers for 1 hour. After the incubation period at 18 °C, gas samples of 1 ml each were taken from the upper space of the containers (headspace). The amount of ethylene was measured using a gas chromatograph HP 5890 II ,(Hewlett Packard, USA). The carbon dioxide was determined using the CheckMate II device (Dansensor, Denmark).

Analyses of sensory quality were performed using the scaling-profiling method. The fruits were evaluated by 7-10 trained people recruited from staff from the National Institute of Horticulture Research. Fruit samples were served in individual plastic containers covered with a lid and the following features were evaluated: appearance (colour, shine, size), aroma (currant, off), hardness, taste (currant, sweet, sour, astringent, bitter), and on the end, the overall quality, that was defined as the sensory impression of the balance and harmony of all attributes and their interactions. The results are presented on a scale from 0 to 10 units, where "0" indicates low quality and "10" denotes high quality of the fruit.

Data Processing and Statistical Methods

Data were statistically analyzed using STATISTICA 13.1 software package [30]. Data are presented as a means ± standard deviation (SD) or compared using one factor ANOVA by post-hoc Tukey test.

3. Results and Discussion

Berries, including blackcurrants, are delicate and perishable fruits. The main problems during storage and commodity turnover are rotting and loss of fruit quality (mainly softening) [16,31]. The durability of berries after harvest and the possibility of storing them depend on many factors, and one of the most important is the proper choice of the storage technology. Storage experiments with the use of 3 different technologies (RA, CA, MAP) were carried out on the 'Tihope' fruits due to their good storability and suitability as a dessert variety. The results presented by Pluta et al. [32], and Pluta and Żurawicz [33] indicated that the fruits of 'Tihope' cultivars, in addition to processing, are also recommended for fresh consumption.

The rate of respiration (CO_2 production) and ethylene production of blackcurrant fruits of 'Tihope' cv. at harvest are seasonal depending and varied from 27 μlCO_2/g*h to above 49 μlCO_2/g*h and from 0.2 μlC_2H_4/kg*h to 0.5 μlC_2H_4/kg*h, respectively (Tables 2a, 2b and 2c). However, ethylene production was not detectable very often. It corresponds well with the data presented by Gross et al. [17]. There was no clear effect of storage conditions on respiration rate and ethylene production.

Table 2a. The effect of storage conditions on CO_2 and ethylene production by 'Tihope' fruits. Season 2021.

Term of analyses	Storage technology	CO_2 (μl/g h)	Ethylene (μl/kg h)
Harvest	-	27.01 ±0.26*	0.02 ±0.001
8 days of storage	RA	26.96 ±0.47	Not detectable
	CA	30.13 ±4.77	Not detectable
	MAP	34.81 ±0.52	Not detectable
8 days of storage + 1 day at 18 °C	RA	27.58 ±0.55	Not detectable
	CA	28.59 ±0.75	Not detectable
	MAP	25.98 ±5.60	Not detectable
8 days of storage + 2 days at 10 °C	RA	32.73 ±4.23	0.07 ±0.012
	CA	36.18 ±0.90	0.03 ±0.033
	MAP	27.86 ±1.64	0.03 ±0.018

* The data are expressed as mean ± SD.

Table 2b. The effect of storage conditions on CO_2 and ethylene production by 'Tihope' fruits. Season 2022.

Term of analyses	Storage technology	CO_2 (μl/g h)	Ethylene (μl/kg h)
Harvest	-	49.37 ±1.80	0.05 ±0.022
13 days of storage	RA	37.80 ±1.08	0.04 ±0.017
	CA	33.27 ±4.85	0.02 ±0.005
	MAP	34.51 ±0.60	0.05 ±0.010
13 days of storage + 1 day at 18 °C	RA	29.51 ±4.41	0.04 ±0.018
	CA	32.49 ±4.46	0.05 ±0.022
	MAP	37.44 ±1.75	0.07 ±0.035
13 days of storage + 2 days at 10 °C	RA	27.76 ±0.26	0.05 ±0.029
	CA	37.67 ±5.00	0.06 ±0.019
	MAP	26.15 ±0.74	0.04 ±0.004
20 days of storage	RA	34.25 ±0.67	0.10 ±0.048
	CA	26.63 ±0.81	0.04 ±0.013

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	MAP	33.37 ±4.36	0.08 ±0.020
20 days of storage + 1 day at 18 °C	RA	25.69 ±0.51	0.11 ±0.054
	CA	26.63 ±0.81	0.11 ±0.029
	MAP	27.02 ±2.32	0.07 ±0.057
20 days of storage + 2 days at 10 °C	RA	31.71 ±5.11	0.13 ±0.046
	CA	28.45 ±0.86	0.07 ±0.038
	MAP	37.62 ±6.71	0.11 ±0.015

* The data are expressed as mean ± SD.

Table 2c. The effect of storage conditions on CO_2 and ethylene production by 'Tihope' fruits. Season 2023.

Term of analyses	**Storage technology**	**CO_2 (µl/g h)**	**Ethylene (µl/kg h)**
Harvest	-	42.31 ±0.81	0.04 ±0.010
18 days of storage	RA	38.53 ±0.57	Not detectable
	CA	39.37 ±3.25	Not detectable
	MAP	46.28 ±1.92	Not detectable
18 days of storage + 1 day at 18 °C	RA	28.90 ±0.43	0.06 ±0.036
	CA	30.24 ±3.64	0.03 ±0.026
	MAP	39.97 ±3.64	0.04 ±0.022
18 days of storage + 2 days at 10 °C	RA	41.80 ±5.13	0.04 ±0.010
	CA	35.80 ±0.90	0.01 ±0.015
	MAP	39.30 ±5.44	0.09 ±0.051
33 days of storage	RA	34.67 ±0.30	0.06 ±0.018
	CA	43.24 ±0.62	0.02 ±0.008
	MAP	43.93 ±0.49	0.03 ±0.001
33 days of storage + 1 day at 18 °C	RA	28.90 ±5.01	0.10 ±0.009
	CA	31.75 ±5.40	0.09 ±0.014
	MAP	35.14 ±0.39	0.16 ±0.039
33 days of storage + 2 days at 10 °C	RA	-	-
	CA	35.75 ±1.08	0.04 ±0.013
	MAP	41.93 ±6.21	0.14 ±0.022

* The data are expressed as mean ± SD.

Tables 3a, 3b and 3c present results of the firmness, total soluble solids content (TSS), titratable acidity (TA) measurements, and a calculated ratio of TSS/TA in the fruits from seasons 2021, 2022, and 2023. All those parameters were seasonally dependent.

Table 3a. The effect of storage conditions on fruit quality of 'Tihope' cultivar. Season 2021.

Term of analyses	**Storage technology**	**Firmness (N)**	**TSS (%)**	**TA (%)**	**TSS/TA**
Harvest	-	1.43	16.43	3.72	4.42
8 days of storage	RA	1.41 a	15.17 a	3.86 a	3.93 a
	CA	1.47 a	15.03 a	3.90 a	3.85 a
	MAP	1.41 a	15.17 a	3.76 a	4.03 a
8 days of storage + 1 day at 18 °C	RA	1.11 a	15.83 b	3.84 a	4.12 b
	CA	1.34 b	14.70 a	3.83 a	3.84 a
	MAP	1.31 b	16.20 b	3.75 a	4.32 b
8 days of storage + 2 days at 10 °C	RA	1.12 a	13.93 a	3.91 a	3.56 a
	CA	1.43 b	14.73 ab	3.90 a	3.78 ab
	MAP	1.19 a	15.10 b	3.81 a	3.97 b
14 days of storage	RA	0.93 a	16.10 b	3.75 a	4.29 b
	CA	1.71 c	14.47 a	3.73 a	3.88 a

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	MAP	1.29 b	14.83 a	3.83 a	3.87 a
14 days of storage + 1 day at 18 °C	RA	1.15 a	14.87 a	3.78 a	3.93 a
	CA	1.57 b	14.33 a	3.82 a	3.75 a
	MAP	1.20 a	16.53 b	3.68 a	4.49 b
14 days of storage + 2 days at 10 °C	RA	1.20 a	15.33 b	3.74 a	4.10 a
	CA	1.64 b	13.87 a	3.96 a	3.50 a
	MAP	1.13 a	14.37 ab	3.96 a	3.64 a

* Means followed by the same letter are not significantly different at p=0.05 according to Tuckey's test (separately for each analysed term).

Table 3b. The effect of storage conditions on fruit quality of 'Tihope' cultivar. Season 2022.

Term of analyses	Storage technology	Firmness (N)	TSS (%)	TA (%)	TSS/TA
Harvest	-	1.87	13.47	3.65	3.69
13 days of storage	RA	1.19 a	15.70 a	3.31 a	4.74 b
	CA	1.71 c	15.23 a	3.55 b	4.29 a
	MAP	1.51 b	14.90 a	3.63 b	4.10 a
13 days of storage + 1 day at 18 °C	RA	1.08 a	16.17 b	3.63 a	4.46 b
	CA	1.68 b	13.87 a	3.62 a	3.83 a
	MAP	1.01 a	14.10 a	3.97 b	3.55 a
13 days of storage + 2 days at 10 °C	RA	1.04 a	14.07 a	3.70 ab	3.80 a
	CA	1.36 b	15.30 b	3.77 b	4.06 b
	MAP	1.24 b	15.40 b	3.64 a	4.23 c
20 days of storage	RA	0.99 a	15.40 a	3.72 a	4.14 b
	CA	1.58 b	13.80 a	3.84 b	3.59 a
	MAP	1.10 a	15.17 a	3.71 a	4.09 b
20 days of storage + 1 day at 18 °C	RA	0.93 a	15.60 a	3.70 b	4.22 a
	CA	1.17 b	16.23 a	3.46 a	4.69 b
	MAP	0.95 a	15.63 a	3.70 b	4.22 a
20 days of storage + 2 days at 10 °C	RA	0.84 a	16.33 b	3.29 a	4.96 c
	CA	1.44 b	15.70 b	3.56 b	4.41 b
	MAP	0.92 a	14.77 a	3.74 c	3.95 a

* Means followed by the same letter are not significantly different at p=0.05 according to Tuckey's test (separately for each analysed term).

Table 3c. The effect of storage conditions on fruit quality of 'Tihope' cultivar. Season 2023.

Term of analyses	Storage technology	Firmness (N)	TSS (%)	TA (%)	TSS/TA
Harvest	-	1.50	14.03	4.09	3.43
18 days of storage	RA	0.78 a	13.90 a	3.90 a	3.56 a
	CA	1.53 c	14.60 b	3.95 a	3.69 b
	MAP	1.19 b	14.80 b	3.95 a	3.75 b
18 days of storage + 1 day at 18 °C	RA	0.90 a	14.50 a	3.83 a	3.79 a
	CA	1.67 c	14.03 a	3.87 a	3.63 a
	MAP	1.26 b	14.10 a	3.89 a	3.63 a
18 days of storage + 2 days at 10 °C	RA	0.85 a	14.27 b	3.93 a	3.63 a
	CA	1.39 c	14.60 b	4.11 b	3.56 a
	MAP	1.10 b	13.77 a	3.96 ab	3.48 a
33 days of storage	RA	0.54 a	14.40 a	3.89 b	3.70 a
	CA	1.32 b	15.27 b	3.68 a	4.15 b
	MAP	1.41 b	14.07 a	3.87 b	3.64 a

33 days of storage + 1 day at 18 °C	RA	0.49 a	14.73 c	3.89 a	3.79 b
	CA	1.19 c	14.30 b	3.77 a	3.79 b
	MAP	0.84 b	13.23 a	3.80 a	3.48 a
33 days of storage + 2 days at 10 °C	RA	-**	-	-	-
	CA	1.06 b	14.33 b	3.96 b	3.62 a
	MAP	0.78 a	13.47 a	3.78 a	3.57 a

* Means followed by the same letter are not significantly different at p=0.05 according to Tuckey's test (separately for each analysed term); ** no fruits.

The fruit firmness at harvest period varied from 1.43 N (in 2021) to 1.87 N (in 2022), TSS from 13.47% in 2022 to 16.43% in 2021, and TA from 3.65% in 2022 to 4.09% in 2023. Regardless of the season, storage of fruits in CA and MAP bags allowed for maintaining higher fruit firmness compared to regular atmosphere. Firmness of currants decreased after transferring them to the higher temperature (18⁰C, 10⁰C) or after extend the storage time. The fruits stored in CA were characterized by higher firmness compared to the fruits stored in RA. Also, fruits stored in MAP usually had higher firmness compared to fruits stored in RA, but it was not always statistically significant. The different effect of using MAP packaging than CA was probably due to a different concentration of carbon dioxide inside the packaging. In our experiments, we used MAP packaging intended for blueberry storage, where the CO_2 concentration remained at the level of 8-10% (depending on storage time and season) (Table 1) while in CA 15% of CO_2 was kept. As described by the authors in the experiments of Gudkovskii at al. [31], the concentration of CO_2 was 3-7%. Differences in the composition of the atmosphere inside the packages may result from the different permeability of packages to gases and/or the different intensity of respiration of packed fruit. The key element of fruit storage in MAP packaging is the appropriate selection of the type of packaging and the amount of fruit to obtain the optimal CO_2 concentration inside the bags. In the research on blackcurrant storage, Gudkovskii et al. [31] have noticed the beneficial effect of CA application on the preservation of fruit firmness; however, unlike in our research, they found the negative effect of MAP packaging on this quality parameter.

As shown in Tables 3a, 3b and 3c there was no unequivocal effect of the storage technology on the soluble solids content and the titratable acidity of 'Tihope' blackcurrants.

Black currants are rich sources of health-promoting compounds, among others, vitamin C and polyphenols [5,6,10,12,13,31–37]. Our results confirmed these findings. The content of vitamin C, polyphenols, and antioxidant activity of 'Tihope' fruits freshly harvested and stored in RA, CA or MAP are presented in Tables 4a, 4b and 4c, respectively for the years 2021, 2022, and 2023,.

Table 4a. The effect of storage conditions on the content of phenolic compounds, vitamin C, and antioxidant capacity in 'Tihope' blackcurrant fruits after 8 days of storage at RA, CA, and MAP. Season 2021.

Term of analyses	**Storage technology**	**ABTS (mg Trolox/g)**	**TPC (mg/100g)**	**Vitamin C (mg/100g)**
Harvest	-	7.2 ±0,01	330.3 ±5.86	146.2 ±0.83
8 days of storage	RA	8.4 ±0.00	320.4 ±4.77	159.1 ±5.74
	CA	8.0 ±0.07	333.8 ±0.08	158.1 ±2.50
	MAP	5.2 ±0.02	349.7 ±5.82	143.9 ±1.02
8 days of storage + 1 day at 18 °C	RA	8.6 ±0.14	314.4 ±2.31	134.6 ±2.59
	CA	8.9 ±0.10	335.7 ±3.52	142.9 ±3.89
	MAP	9.8 ±0.01	357.2 ±1.02	140.5 ±9.54
8 days of storage + 2 days at 10 °C	RA	8.2 ±0.02	339.0 ±2.07	134.9 ±0.93
	CA	8.7 ±0.06	374.8 ±1.33	147.3 ±1.20
	MAP	8.1 ±0.10	369.8 ±3.24	138.0 ±1.48

* Mean ± SD.

Table 4b. The effect of storage conditions on the content of phenolic compounds, vitamin C, and antioxidant capacity in 'Tihope' blackcurrant fruits after 13 days of storage at RA, CA, and MAP. Season 2022.

Term of analyses	Storage technology	ABTS (mg Trolox/g)	TPC (mg/100g)	Vitamin C (mg/100g)
Harvest	-	9.1 ±0.06	336.5 ±3.14	175.0 ±3.22
13 days of storage	RA	9.4 ±0.07	350.5 ±0.46	181.6 ±0.68
	CA	9.4 ±0.09	330.4 ±4.04	178.7 ±0.49
	MAP	8.8 ±0.10	329.5 ±0.43	171.0 ±1.37
13 days of storage + 1 day at 18 °C	RA	11.0 ±0.08	364.6 ±3.43	187.5 ±2.93
	CA	7.4 ±0.00	300.1 ±0.68	151.0 ±1.76
	MAP	9.7 ±0.03	334.3 ±2.57	175.8 ±0.29
13 days of storage + 2 days at 10 °C	RA	9.7 ±0.03	359.6 ±12.32	181.8 ±1.17
	CA	10.2 ±0.05	368.9 ±0.75	187.8 ±0.88
	MAP	9.9 ±0.04	361.0 ±0.43	178.6 ±1.07

* Mean ± SD.

Table 4c. The effect of storage conditions on the content of phenolic compounds, vitamin C, and antioxidant capacity in 'Tihope' blackcurrant fruits after 33 days of storage at RA, CA, and MAP. Season 2023.

Term of analyses	Storage technology	ABTS (mg Trolox/g)	TPC (mg/100g)	Vitamin C (mg/100g)
Harvest	-	5.7 ±0.03*	287.3 ±0.67	116.7 ±2.69
33 days of storage	RA	6.4 ±0.06	299.0 ±2.25	114.2 ±1.37
	CA	6.7 ±0.06	300.2 ±1.03	135.2 ±3.30
	MAP	7.4 ±0.01	331.1 ±5.10	131.3 ±2.41
33 days of storage + 1 day at 18 °C	RA	7.0 ±0.04	295.9 ±2.06	119.8 ±3.87
	CA	6.3 ±0.03	283.2 ±3.56	108.8 ±1.03
	MAP	7.0 ±0.00	298.2 ±3.32	122.5 ±0.47
33 days of storage + 2 days at 10 °C	RA	-**	-	-
	CA	6.5 ±0.01	283.4 ±4.90	111.1 ±0.13
	MAP	7.1 ±0.00	294.5 ±3.87	114.3 ±0.85

* Mean ± SD; ** no fruits.

Depending on the season, blackcurrants of 'Tihope' cultivar contained from 287.3 to 336.5 mg/100g FW of polyphenols, from 116.7 to 175.0 mg/100g FW of vitamin C, and from 5.7 to 9.1 mg Trolox/g of antioxidant activity during the harvest period. The seasonal fluctuation of these compounds was also described by Rachtan-Janicka et al. [12], Tian et al. [13] and Pott et al. [38].

The content of sugars (sucrose, glucose, and fructose) in 'Tihope' blackcurrant fruits after 8 days of storage (in 2021), 13 days of storage (in 2022), and 33 days of storage (in 2023) at RA, CA, and MAP are presented in Tables 5a, 5b and 5c.

Table 5a. The content of sugars (sucrose, glucose, and fructose) in 'Tihope' blackcurrant fruits after 8 days of storage at RA, CA, and MAP. Season 2021.

Term of analyses	Storage technology	Sucrose (g/kg)	Glucose (g/kg)	Fructose (g/kg)
Harvest	-	11.2 ±0.23*	22.2 ±0.07	34.8 ±0.11
8 days of storage	RA	10.3 ±0.20	25.7 ±0.08	40.0 ±0.24
	CA	11.4 ±0.12	25.8 ±0.04	40.5 ±0.02
	MAP	15.0 ±0.00	27.7 ±0.06	42.7 ±0.05
8 days of storage + 1 day at 18 °C	RA	12.4 ±0.25	23.6 ±0.21	38.0 ±0.64
	CA	12.4 ±0.24	22.3 ±0.03	39.3 ±0.32
	MAP	11.2 ±0.14	25.4 ±0.14	39.9 ±0.00

8 days of storage + 2 days at 10 °C	RA	10.3 ±0.68	25.9 ±0.06	40.5 ±0.55
	CA	11.6 ±0.07	25.9 ±0.48	40.5 ±0.81
	MAP	11.5 ±0.19	24.9 ±0.80	39.1 ±0.46

* Mean ± SD.

Table 5b. The content of sugars (sucrose, glucose, and fructose) in 'Tihope' blackcurrant fruits after 8 days of storage at RA, CA, and MAP. Season 2022.

Term of analyses	Storage technology	Sucrose (g/kg)	Glucose (g/kg)	Fructose (g/kg)
Harvest	-	15.0 ±0.28*	23.5 ±0.57	37.1 ±0.30
13 days of storage	RA	11.3 ±0.44	25.0 ±0.21	41.4 ±0.33
	CA	11.5 ±0.06	22.7 ±0.14	36.4 ±0.25
	MAP	10.8 ±0.07	21.8 ±0.31	36.3 ±0.07
13 days of storage + 1 day at 18 °C	RA	11.1 ±0.02	24.3 ±0.22	41.3 ±0.28
	CA	7.7 ±0.02	18.3 ±0.39	29.4 ±0.10
	MAP	10.7 ±0.03	21.7 ±0.20	38.0 ±0.18
13 days of storage + 2 days at 10 °C	RA	10.6 ±0.02	21.8 ±0.25	38.0 ±0.25
	CA	13.0 ±0.22	23.9 ±0.33	39.1 ±0.26
	MAP	10.4 ±0.02	22.0 ±0.23	37.5 ±0.23

* Mean ± SD.

Table 5c. The content of sugars (sucrose, glucose, and fructose) in 'Tihope' blackcurrant fruits after 33 days of storage at RA, CA, and MAP. Season 2023.

Term of analyses	Storage technology	Sucrose (g/kg)	Glucose (g/kg)	Fructose (g/kg)
Harvest	-	12.5 ±0.11*	22.6 ±0.18	36.0 ±0.02
33 days of storage	RA	7.5 ±0.03	22.0 ±1.32	37.1 ±0.12
	CA	10.0 ±0.11	25.6 ±0.23	37.9 ±0.85
	MAP	11.9 ±0.05	26.1 ±0.13	42.8 ±0.31
33 days of storage + 1 day at 18 °C	RA	6.5 ±0.02	24.4 ±0.17	43.9 ±0.24
	CA	8.8 ±0.05	22.7 ±0.20	36.0 ±0.34
	MAP	8.6 ±0.02	27.1 ±0.10	43.0 ±0.11
33 days of storage + 2 days at 10 °C	RA	-**	-	-
	CA	8.7 ±0.03	26.1 ±0.21	40.1 ±0.16
	MAP	6.2 ±0.04	25.1 ±0.20	42.0 ±0.25

* Mean ± SD; ** no fruits.

Similar to other quality parameters, the sugar content (sucrose, glucose and fructose) was also seasonally dependent. The sucrose content varied from 11.2 g/kg (in 2021) to 15.0 g/kg (in 2022), and glucose from 22.2 g/kg (in 2021) to 23.5 g/kg (in 2022), and fructose from 34.8 g/kg (in 2021) to 37.1 g/kg (in 2022).

There was no clear effect of any of the applied storage technologies on the content of polyphenols, vitamin C, sugars and antioxidant activity. According to the literature, storage temperature is the main factor influencing the content of some antioxidants. Generally, high temperature promotes their losses (mainly ascorbic acid), and high CO_2 storage decreases polyphenols content and antioxidant capacity [8,39,40]. In our experiments, storage in RA, CA or MAP even up to 33 days at 0 °C (as well as during shelf life at 10 and 18 °C) caused only slight changes in the content of the tested compounds, without reducing their health-promoting value.

The sensory analyses of stored fruits were carried out after 8 days of storage (0 days SL, 1 day SL at 18 °C, and 2 days SL at 10 °C), and after 13 days of storage (0 days SL, 1 day SL at 18 °C, and 2 days SL at 10 °C) in the years 2021 and 2022, respectively. In 2023, the sensory analyses were performed after 18 and 33 days of storage (0 days SL, 1 day SL at 18 °C, and 2 days SL at 10 °C). Data from the sensory analyses are presented in Figures 1a, 1b, 1c and 1d.

Regardless of the season, there was no negative effect of CA and MAP technologies on the sensory quality of currants. The fruits after 8 days of storage and after shelf life at 18 °C or 10 °C in 2021 were scored from 5.2 to 7.1 points at overall sensory quality (Figure 1a). However the fruits stored in MAP were rated the highest, with statistically significant differences found only in the case of currants after an additional 2 days of shelf life at 10 °C. Similar relationships were recorded in 2022 for fruits stored for 13 days (Figure 1b). In 2023, after 18 days of storage plus 2 days at 10 °C, fruits from all storage technologies obtained high scores (close to 7 on a 10-point scale) (Figure 1c). After 33 days of storage, the overall quality of fruits stored under CA or in MAP bags was still scored above 6 on a 10-point scale (Figure 1d).

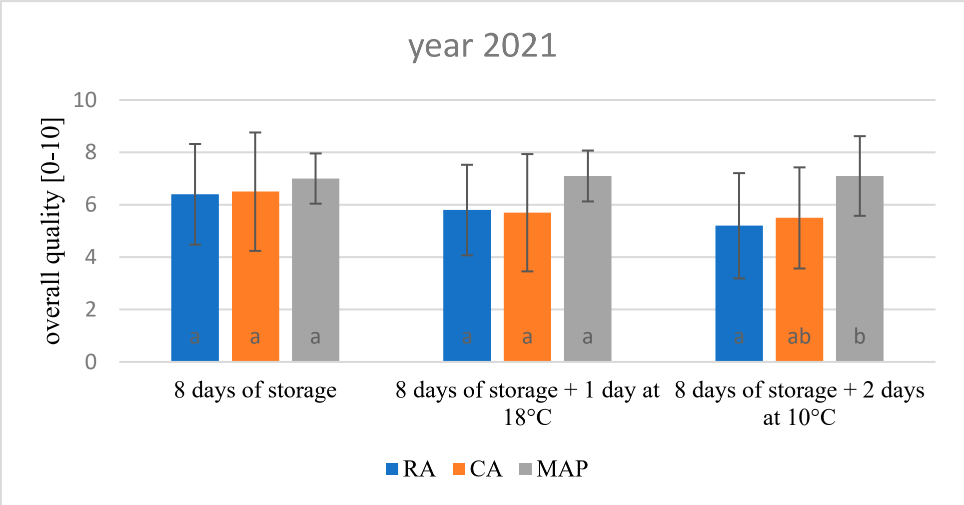

Figure 1a. Sensory quality 'Tihope' blackcurrants after 8 days of storage at RA, CA, and MAP. Season 2021. (Means followed by the same letter are not significantly different at p=0.05 according to Tuckey's test (separately for each analysed term). Vertical bars denote ± SD).

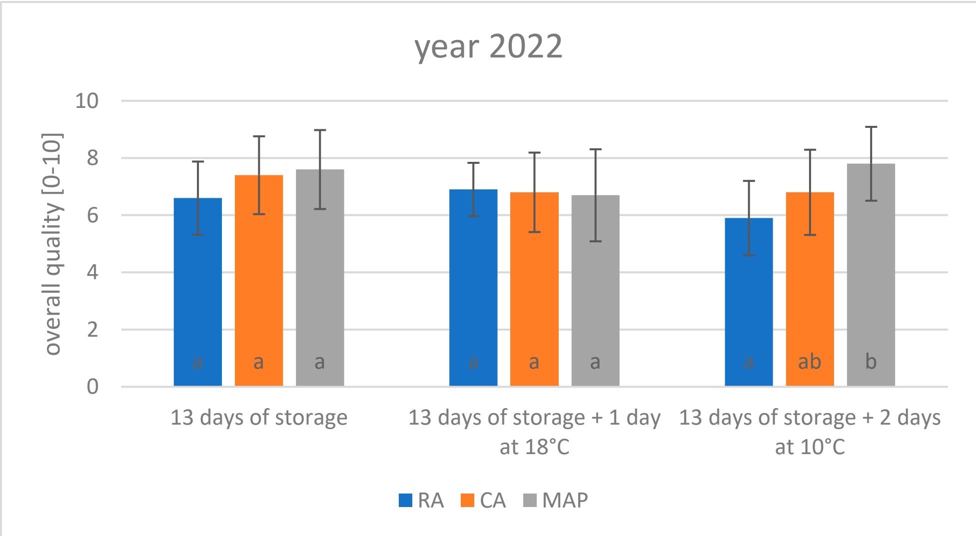

Figure 1b. Sensory quality 'Tihope' blackcurrants after 13 days of storage at RA, CA, and MAP. Season 2022. (Means followed by the same letter are not significantly different at p=0.05 according to Tuckey's test (separately for each analysed term). Vertical bars denote ± SD).

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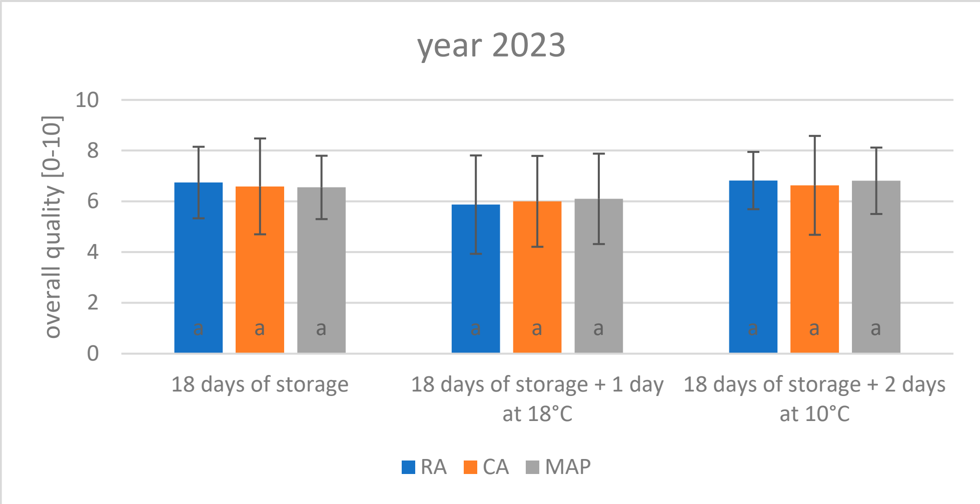

Figure 1c. Sensory quality 'Tihope' blackcurrants after 18 days of storage at RA, CA, and MAP. Season 2023. (Means followed by the same letter are not significantly different at p=0.05 according to Tuckey's test (separately for each analysed term). Vertical bars denote ± SD).

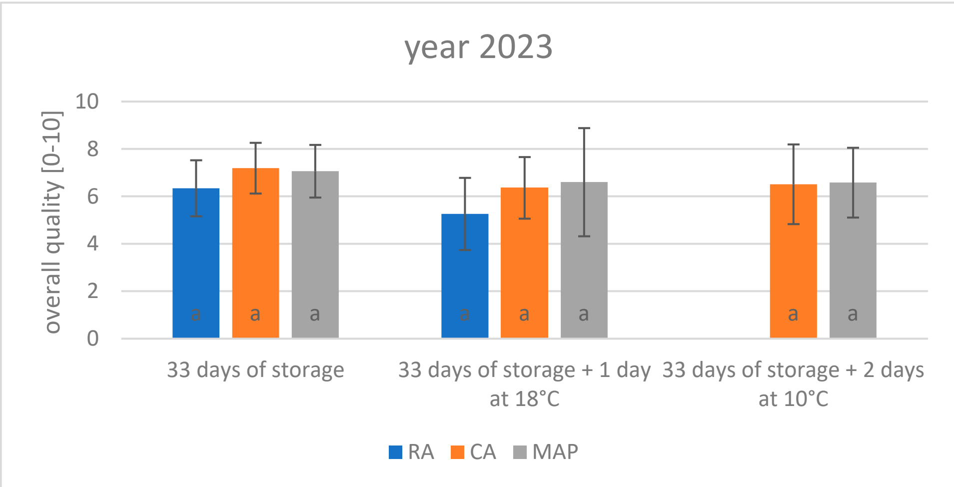

Figure 1d. Sensory quality 'Tihope' blackcurrants after 33 days of storage at RA, CA, and MAP. Season 2023. (Means followed by the same letter are not significantly different at p=0.05 according to Tuckey's test (separately for each analysed term). Vertical bars denote ± SD).

High sensory quality scores for fruit from all storage technologies result from small differences in quality characteristics presented in Tables 3a, 3b and 3c.

Up to 13 days of storage, as well as after the shelf life, no rotting of the fruits was observed in any of the combinations used. Single damaged fruits appeared only after 20 days (in 2022), and after 18 days (in 2023) storage in RA (data not shown). In fruits stored in CA or MAP, no damaged fruits were noted. These results confirm the effect of high CO_2 concentrations on the inhibition of microorganisms' development [20,21,29,41]. Inhibition of the development of grey mold in blackcurrants stored in CA and MA compared to storage in regular atmosphere was also observed by Gudkovskii et al. [31].

5. Conclusions

The obtained results indicate good storability of fruits of the 'Tihope' cultivar. There was no negative impact of storage on the content of health-promoting compounds. After storage, currants still remain a rich source of vitamin C, and polyphenols and retain high antioxidant activity. The fruit

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of the 'Tihope' cultivar can be stored in a regular atmosphere for 20 days without any negative effect on its quality. Storage in a controlled atmosphere or in MAP packaging allows the extension of the storage period of blackcurrants up to 33 days, thereby delaying the occurrence of fruit damage and loss of firmness. Particularly noteworthy is the possibility of using MAP packaging for fruit storage. It is a more reliable method for storing relatively small amounts of fruits (blackcurrants are still a niche product for storing in the fresh market), as it is much cheaper compared to a controlled atmosphere (especially considering the investment cost). It is advisable to conduct further research to optimize this method for currant fruit.

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

Abbreviations

The following abbreviations are used in this manuscript:

RA	Regular atmosphere
CA	Controlled atmosphere
MAP	Modified atmosphere packaging
SL	Shelf life
FF	Flesh firmness
TSS	Total soluble solids
TA	Titratable acidity

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