

## Article

# Effects of Storage Conditions, Cultivars, and Production Systems on Fruit Decay Incidence of Sour Cherry (*Prunus cerasus* L.) Fruit after Shelf-Life Conditions

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**Abstract:** Sour cherry is a non-climacteric fruit that quickly loses its quality after harvest, so effective storage and packaging are essential to minimize postharvest decay. Our study aimed to (i) evaluate fruit decay incidence during shelf-life for both freshly harvested and six-week-cold-stored sour cherry fruits, comparing normal atmospheric conditions with modified atmosphere packaging across three sour cherry cultivars ('Érdi bőtermő', 'Újfehértói fürtös', and 'Petri'); and (ii) assess postharvest fruit decay incidence across the following three production systems: conventional, integrated pest management (IPM), and reduced IPM, for the cultivar 'Érdi bőtermő'. The results showed that modified atmosphere packaging effectively preserved or slightly increased fruit firmness (ranging from 27.1 to 46%) compared to control fruits across all cultivars. Fruit weight loss (ranging from 1.18 to 26.1%) was also significantly reduced under modified atmosphere packaging compared to normal atmospheric storage. Over a 14-day period, the decay incidence of harvested fruits consistently increased, with major losses from day 6 onward (ranging from 17.7 to 77.0% at shelf-life day 14) across all cultivars and years. After six weeks of normal atmospheric cold storage, decay incidence remained low (ranging from 0 to 9.4%) and was comparable across all cultivars. Both normal atmospheric and modified atmosphere packaging storage maintained sour cherry quality during cold storage, but the shelf-life of the fruits was significantly shorter at room temperature, regardless of the storage methods. Fruit decay incidence at harvest was highest in the reduced IPM system (ranging from 3.2 to 6.4%), significantly exceeding those observed in the conventional and IPM systems. In post-MAP cold storage, decay incidence followed the following order: conventional < IPM < reduced IPM, with significant differences observed only between the conventional and reduced IPM systems. In conclusion, our results suggest that sour cherries produced under conventional or IPM systems and stored in modified atmosphere packaging offer an effective postharvest strategy for preserving fruit quality.

**Keywords:** tart cherry; fruit firmness; weight loss; MAP storage; IPM; conventional production

## 1. Introduction

Sour (tart) cherry (*Prunus cerasus* L.) production has been increasing over the past 20 years. European countries, including Hungary, are the leading producers, accounting for 66.2% (800,116 tons) of the annual production [1,2]. In Hungary, sour cherry is one of the most important fruits, ranking second in orchard area and production volume, following apples. The predominant cultivars are the Hungarian-bred 'Újfehértói fürtös' (syn.: 'Ungarische Traubige', 'BalatonTM') and 'Érdi bőtermő' (syn.: 'DanubeTM') [1,3].

Sour cherry is widely used in the food industry for the production of preserved fruits (frozen, dried, or canned), beverages (juice or alcoholic drink), confectionery items (jam, marmalade, and jelly), and as a natural colorant [4–6]. The acid/sugar ratio is higher in sour cherry as compared to the sweet cherry (*Prunus avium* L.); therefore, many cultivars are considered to have an astringent taste, which limits their fresh consumption. However, Hungarian cultivars (cvs.), such as 'Újfehértói fürtös' and 'Érdi bőtermő', are also excellent for fresh consumption due to their harmonic sugar/acid ratio [7,8]. Moreover, there is an outstanding nutritional content of fresh sour cherry, with high concentrations of vitamins, minerals, and bioactive components (e.g., antioxidants), which can decrease during fruit processing or storage [9–11].

Sour cherry is a non-climacteric stone fruit and can only be stored for up to one week in cold conditions [12]. Sour cherry fruit has low penetration resistance and high rates of respiration [13]; thus, they quickly soften and lose their moisture content. This results in rapid postharvest quality loss [14,15]. The rapid postharvest quality loss exponentially increases with the development of fruit decay during storage and shelf-life [14]. The biggest obstacle to the worldwide growth in fresh consumption of sour cherries is the perishability of the fruits and the limited options for effective storage technologies.

Many preharvest factors play a critical role in enhancing the storability of fruits, including genetics, environmental conditions, and cultural practices. These factors significantly influence both the development and postharvest quality of fruit crops [16–20]. Key preharvest determinants, such as soil composition, environmental variables, nutrition, and varietal selection, affect the fruit quality and storage life significantly [19–22]. Soil properties, in particular, have a profound influence on the compositional and physical quality of harvested produce, which, in turn, affects postharvest outcomes [18]. Nutrient balance is essential for maintaining optimal fruit texture and size; for instance, nitrogen-deficient trees tend to produce smaller, firmer fruits, while excessive nitrogen leads to a rapid decline in firmness and reduced storability. Similarly, potassium deficiency can lead to poor coloration and textural changes in fruits, rendering them small, hard, and inedible due to improper ripening [19,20,23]. Selecting a high-yielding cultivar with desirable qualities and extended shelf-life is a vital preharvest decision that directly impacts the postharvest longevity of fruits [18,24]. Moreover, environmental stresses, such as heavy rainfall, excessive moisture, and heat stress, can exacerbate fruit cracking and water loss, particularly in crops like cherries and apples, leading to significant postharvest quality deterioration [25,26].

Among postharvest strategies, cold storage is one of the most widespread and oldest methods to preserve the fruits following harvest. Cold storage can suppress decay in many fresh stone fruits [27–32] by increasing CO<sub>2</sub> and decreasing O<sub>2</sub> levels in the ambient atmosphere. In the case of sour cherry, Wang and Vestrheim [28] indicated that fruit decay can be greatly reduced in fruits stored for up to 20 days at 2 °C in a controlled atmosphere (CA) consisting of 25% CO<sub>2</sub> + 10% O<sub>2</sub>.

Cold storage can also be combined with other preservation techniques, like modified atmosphere packaging (MAP). MAP is used to supplement low-temperature management to delay senescence, reduce physiological disorders, and suppress decay in many fresh fruit and vegetable products [33]. Although the positive effect of MAP storage on the weight loss and decay of sweet cherries has already been demonstrated in several studies [28,34–40], few MAP studies are available for sour cherry. For example, Lurie and Weksler [14] showed that sour cherry fruit storage is better in modified atmosphere packaging than in regular air storage at 0 °C. Moreover, the weight loss and fruit decay of the sour cherry cultivars, 'Érdi

jubileum' and 'Érdi bőtermő', were significantly reduced by MAP storage compared to regular cold storage conditions [41]. However, fruit decay as well as the subsequent shelf-life conditions of various sour cherry cultivars were not compared between regular cold storage and cold storage with MAP. Moreover, previous studies focused on the postharvest features of cherry fruits under conventional or integrated production systems; however, there is a significant gap in the research regarding the fruit decay of sour cherries under cold storage with MAP and subsequent shelf-life conditions, particularly for fruits originating from various production systems.

The objectives of our study were twofold: First, to evaluate the incidence of fruit decay during shelf-life for both freshly harvested and cold-stored sour cherry fruits under normal atmospheric conditions and MAP for three cvs.: 'Érdi bőtermő', 'Újfehértói fürtös', and 'Petri'. Second, to assess the fruit decay incidence for harvested, cold-stored fruits in combination with MAP and the subsequent shelf-life of cold-stored fruits in combination with MAP across three production systems (conventional, integrated pest management [IPM], and reduced IPM) for the cv. 'Érdi bőtermő'. Additionally, we measured fruit firmness and weight loss for all three cultivars to provide a comprehensive analysis of their general fruit quality characteristics prior to shelf-life evaluation.

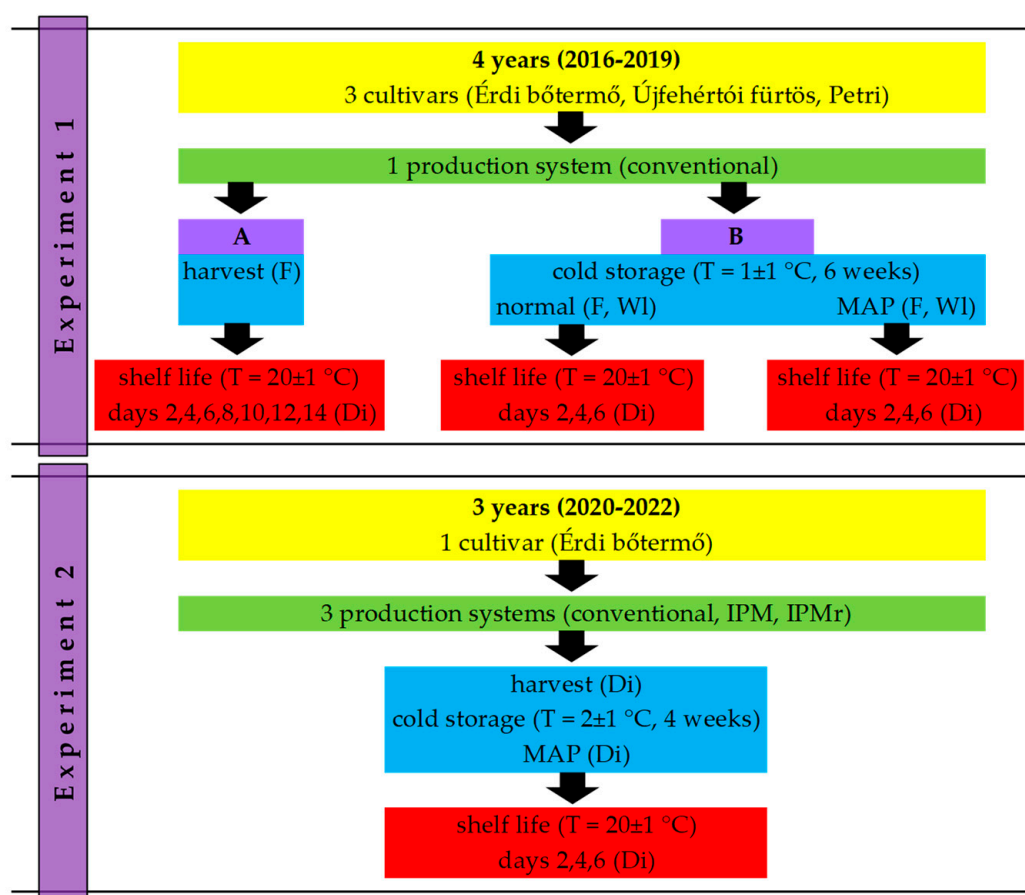
## 2. Materials and Methods

### 2.1. Experimental Orchards, Production Systems, and Sour Cherry Cultivars

In experiment 1, fruits of three Hungarian sour cherry cultivars, 'Érdi bőtermő', 'Újfehértói fürtös', and 'Petri', were collected from the experimental orchards of the Research Institute Újfehértó, Agricultural Research and Educational Farm, University of Debrecen, Újfehértó, Eastern Hungary (E: 47°49.38'; N: 21°40.23') in four consecutive years (2016–2019) (Figure 1). In the experimental site, daily mean temperature from 1 April to 30 July ranged from 5.5 to 27.4 °C, 3.8 to 26.5 °C, 7.4 to 26.1 °C, and 6.2 to 26.8 °C in 2016, 2017, 2018, and 2019, respectively, while rainfall amounts during the same periods were 291.1, 216.4, 133.0, and 374.7 mm, respectively. Conventional plant production and plant protection technology (using approved insecticides and fungicides) was applied for all cultivars. In the orchard, the distance between rows was 5 m, and within the row it was 3 m. Trees were grafted on *Prunus mahaleb* rootstock. The orchard soil type was non-calcareous sandy soil with 1% humus. Bare soil, 0.7 m wide, was maintained in the rows, and grass was grown in the row middles. The orchard was not irrigated. A winter pruning before bud break was carried out each year. Grass in the row middles was cut with an orchard flail mower three times a year (early June, early July, and early September). The orchard relied on annual application of synthetic fertilizers for nutrient supply. Fungicide active ingredients used in the orchard were as follows: copper sulphate, cyprodinil, trifloxistrobin, tebuconazole, elementary sulphur, prochloraz, thiram, mancozeb, and captan. Fruits were harvested with stems, based on the biological ripening of the three cultivars. Cultivar 'Érdi bőtermő' was harvested at 15, 19, 7, and 18 June; 'Újfehértói fürtös' at 1 July as well as 29, 21, and 28 Jun; and 'Petri' at 2 July, 30 June, 25 June, and 1 July, in 2016, 2017, 2018, and 2019, respectively.

In experiment 2, fruits of cultivar 'Érdi bőtermő' were collected from the commercial orchard, Eperjeske, Eastern Hungary (E: 47°49.38'; N: 21°40.23') in three consecutive years (2020–2022) (Figure 1). In the experimental site, daily mean temperature, from 1 April to 30 July, ranged from 4.6 to 27.3 °C, 2.9 to 25.5 °C, 5.2 to 25.1 °C, and 4.7 to 24.6 °C in 2020, 2021, and 2022, respectively, while rainfall amounts during the same periods were 305.6, 217.8, and 101.3 mm, respectively. The orchard consisted of the self-fertile sour cherry cv. 'Érdi bőtermő' with a distance between rows of 5 m and within a row of 3 m. Trees were grafted on *Prunus mahaleb* rootstock. The orchard soil type was brown forest soil with alternating layers of clay substance. Bare soil, 0.7 m wide, was maintained in the rows, and grass was grown in the row middles. The orchards were not irrigated. A winter pruning before bud break was carried out each year. Grass in the row middles was cut with an orchard flail mower three times a year (early June, early July, and early

September). Three plant production/protection systems were applied: conventional (a generally applied conventional growing practice), IPM (a generally used IPM practice in most European countries), and reduced IPM (an advanced integration of known non-chemical practices, accepting most principles of organic farming guidelines), according to the procedure described by the study of Holb et al. [42]. The conventional and IPM orchards relied on annual application of synthetic fertilizers for nutrient supply. In the reduced IPM orchard, stable manure and compost were applied every other year. Fungicide active ingredients used in the conventional and IPM orchards are as follows: copper hydroxide, tebuconazole, mancozeb, prochloraz, penconazole, boscalid + piraclostrobin, captan, and fenhexamid, while those used in the reduced IPM orchards are as follows: copper hydroxide, elementary sulphur, and calcium polysulphide. Fruits were harvested with stem, based on the biological ripening of the cultivar at 14, 16, and 7 June, in 2020, 2021, and 2022, respectively.



**Figure 1.** Experimental design for experiments 1 and 2. Experiment 1A: three sour cherry cultivars were harvested and stored at  $20 \pm 1$  °C (shelf-life) for 14 days. Experiment 1B: three sour cherry cultivars were harvested and stored at  $1 \pm 1$  °C (cold storage) with normal atmosphere (NA) or modified atmosphere packaging (MAP) for 6 weeks. After this, fruits were further stored at  $20 \pm 1$  °C (shelf-life) for 6 days. Experiment 2: one sour cherry cultivar in 3 production systems (conventional; integrated pest management, IPM; and reduced integrated pest management, IPMr) was harvested and stored at  $2 \pm 1$  °C (cold storage) with modified atmosphere packaging for 4 weeks. After this, fruits were further stored at  $20 \pm 1$  °C (shelf-life) for 6 days. Overall decay incidence (Di), fruit firmness (F), and fruit weight loss (WI) were determined where they were indicated in brackets.

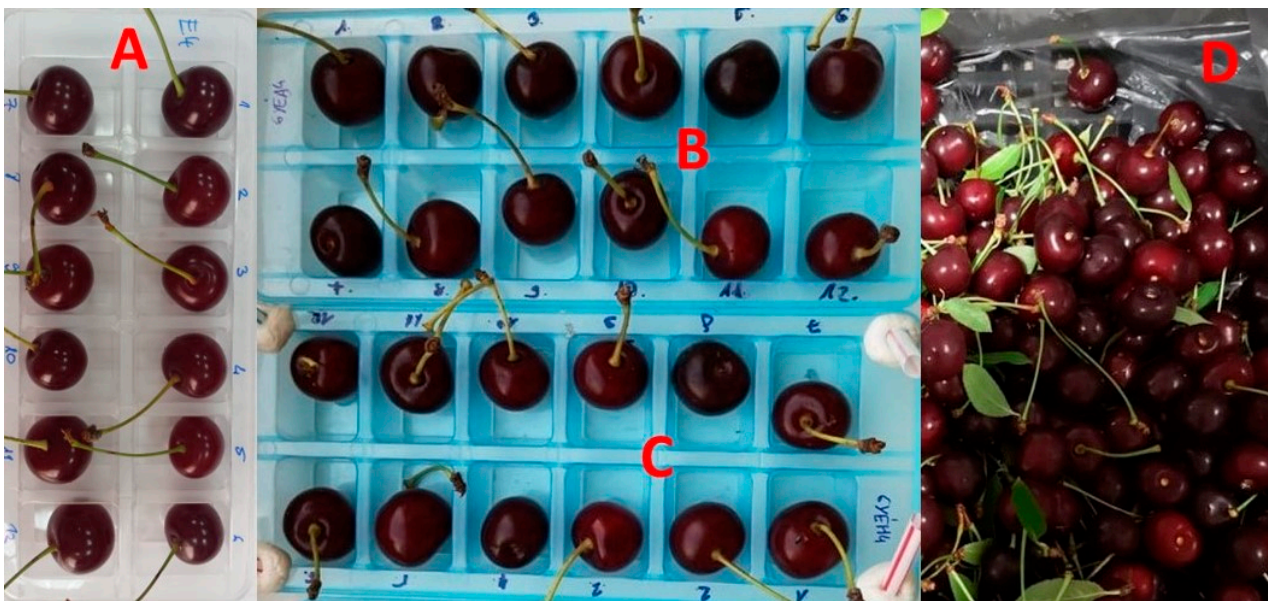
## 2.2. Experimental Setup and Treatments

In both experiments, intact, healthy sour cherry fruits were collected randomly from the whole tree, using disposable medical gloves to minimize surface contamination during

harvest and further handling of the fruits. In both experiments, overall disease incidence (Di), fruit firmness (F), and fruit weight loss (Wl) were determined where they were indicated in brackets in Figure 1, and details of their assessments are given in Section 2.3.

### 2.2.1. Experiment 1A

In experiment 1A, the experimental design was a split plot, with the 4 years as blocks, the 7 shelf-life days as main plots, and the 3 cultivars as subplots. The three harvested sour cherry cultivars were stored under shelf-life conditions from 2016 to 2019 (Figure 1). During the shelf-life conditions, 96 healthy fruits for each cultivar were stored separately in trays at  $20 \pm 1$  °C in dark. Eight repetitions ( $8 \times 12 = 96$  fruits) were used for each cultivar, each storage condition, and each year. One tray with 12 fruits was regarded as one repetition (Figure 2A–C). In each tray, fruit decay incidence was recoded on all fruits every second shelf-life day (days 2, 4, 6, 8, 10, 12, and 14).



**Figure 2.** Twelve fruits (one repetition) in each of the three trays for shelf-life conditions (A–C) and fruits in modified atmosphere packaging (MAP) bag after 6-week cold storage (D) for sour cherry cv. ‘Érdi bőtermő’.

### 2.2.2. Experiment 1B

In experiment 1B, the experimental design was a split-split plot with the 4 years as blocks, the 2 cold storage types (NA and MAP) as main plots, the 3 cultivars as subplots, and the 3 shelf-life days as sub-subplots. Intact harvested fruits of the three sour cherry cultivars were stored (cold storage) for 6 weeks with a normal ambient atmosphere (NA) and with a modified atmosphere packaging (MAP) from 2016 to 2019 (Figure 1). During cold storage, harvested fruits were stored for six weeks at  $1 \pm 1$  °C temperature in normal ambient atmosphere and in MAP using Xtend Cherry (StePac LA Ltd., Tefen, Israel) plastic bags (Figure 2D). In the case of MAP samples, a passive MA was reached through the natural respiration of the fruits, as the packaging foil inhibited gas exchange, while the microperforation of the plastic bag prevented water vapor condensation. Each plastic bag was filled with 5.0 kg of fruit. Appropriate weight was set using a scale. Five replicates were set for each cultivar, in each treatment, and each year. At this point (after 6 weeks of storage), fruit firmness and weight loss were determined. Following this, fruits were further stored under shelf-life conditions as described in experiment 1A, and decay incidence was recoded on all fruits every second shelf-life day (days 2, 4, and 6).

### 2.2.3. Experiment 2

In experiment 2, the experiment design was a split plot with the 3 years as blocks, the 3 production systems as main plots, and the 4 storage treatments as subplots. The fruits of sour cherry cultivar 'Érdi bőtermő' were harvested in 3 production systems (conventional, IPM, and reduced IPM) and cold stored with MAP from 2020 to 2022 (Figure 1). During cold storage, harvested fruits were stored for 4 weeks at  $2 \pm 1$  °C temperature in MAP using the same Xtend Cherry plastic bags as in experiment 1B. For organic production, a reduction in energy consumption was aimed at during storage, and therefore, we increased the cold storage temperature from 1 °C to 2 °C in experiment 2 compared to experiment 1. As we increased the cold storage temperature from 1 °C to 2 °C, we assumed that the health status for the sour cherry would be worse; therefore, we decreased storage period from 6 weeks to 4 weeks in experiment 2. Five replicates were set for each production system and each year. After this, fruits were further stored under shelf-life conditions. During the shelf-life conditions, 100 healthy fruits were stored separately in trays at  $20 \pm 1$  °C in dark. One tray with 10 fruits was regarded as one repetition. In each tray, fruit decay incidence was recorded on all fruit at shelf-life days 2 and 6.

## 2.3. Measured Parameters

### 2.3.1. Fruit Firmness

Fruit firmness value was provided as a general fruit quality feature before shelf-life conditions. Fruit firmness was determined using an A100D combined instrument (Agrosta SARL, Serqueux, France), equipped with a measuring head developed for soft fruits without destruction (sensor head type: A100-25, diameter 10 mm). Its values were given in Durofel Index (Durofel index—scale 0–100%), where a higher value indicated higher fruit firmness. Fruit firmness was measured at harvest date, at 6 weeks after normal atmosphere cold storage (NA-CS6w), and at 6 weeks after modified atmosphere package cold storage (MAP-CS6w) (Figure 1). Firmness was measured on all healthy fruits, and mean Durofel index was calculated for each cultivar and each year.

### 2.3.2. Weight Loss

Weight loss value was provided as a general fruit quality feature before shelf-life conditions. The weight of stored samples was measured with the same scale used in experiment 1B. Weight loss was measured using 5 kg fruit packages; samples were measured before and after 6 weeks of cold storage in order to calculate the weight loss percentage for NA and MAP treatments for each cultivar and each year.

### 2.3.3. Fruit Decay Incidence

A fruit was considered decayed if at least one visible symptom of biotic or abiotic disorders was present on the fruit. Finally, fruit decay incidence was calculated as percentage of decayed fruits. Fruit decay was assessed on all fruits in all replications under shelf-life conditions in both experiments, as described in the subsections of Section 2.2 (Figure 1).

## 2.4. Statistical Analysis

Fruit firmness and weight loss percentage values were analyzed by split-plot analysis of variance in order to determine the effect of years, storage treatments, and cultivars. Fruit decay incidence values were analyzed by split-plot analysis of variance for experiment 1A and experiment 2, while a split-split-plot analysis was used for experiment 1B. Subsequently, significant F tests ( $p < 0.05$ ) were followed by a least significant difference (LSD) test for each year, storage treatment, and cultivar or production systems in order to compare the means of all parameters using  $LSD_{0.05}$  values. Prior to the analyses, fruit decay incidence values were arcsine-square root transformed.

The relationships among the years (2016–2019) for fruit firmness and weight loss were analyzed using Pearson correlation. The relationships for fruit decay incidence were also analyzed using Pearson correlation, determining the relationships among the years (2016–2019)

and cultivars combined with storage methods (NA ‘Érdi bőtermő’, NA ‘Újfehértói fürtös’, NA ‘Petri’, MAP ‘Érdi bőtermő’, MAP ‘Újfehértói fürtös’, and MAP ‘Petri’) in experiment 1; and among the years (2020–2022) and management systems (conventional, IPM, and reduced IPM) in experiment 2. Correlation coefficients ( $r$ ) were provided for each correlation pair.

All analyses were performed with Statistical Analysis System v. 8.1 (SAS Institute, Cary, NC, USA).

### 3. Results

#### 3.1. Fruit Firmness and Weight Loss in Experiment 1

The analysis of variance on the parameters of fruit firmness and weight loss showed significant ( $p < 0.05$ ) effects for years, storage treatments, and cultivars (Table 1). Interactions for the treatment effects were non-significant for all treatments.

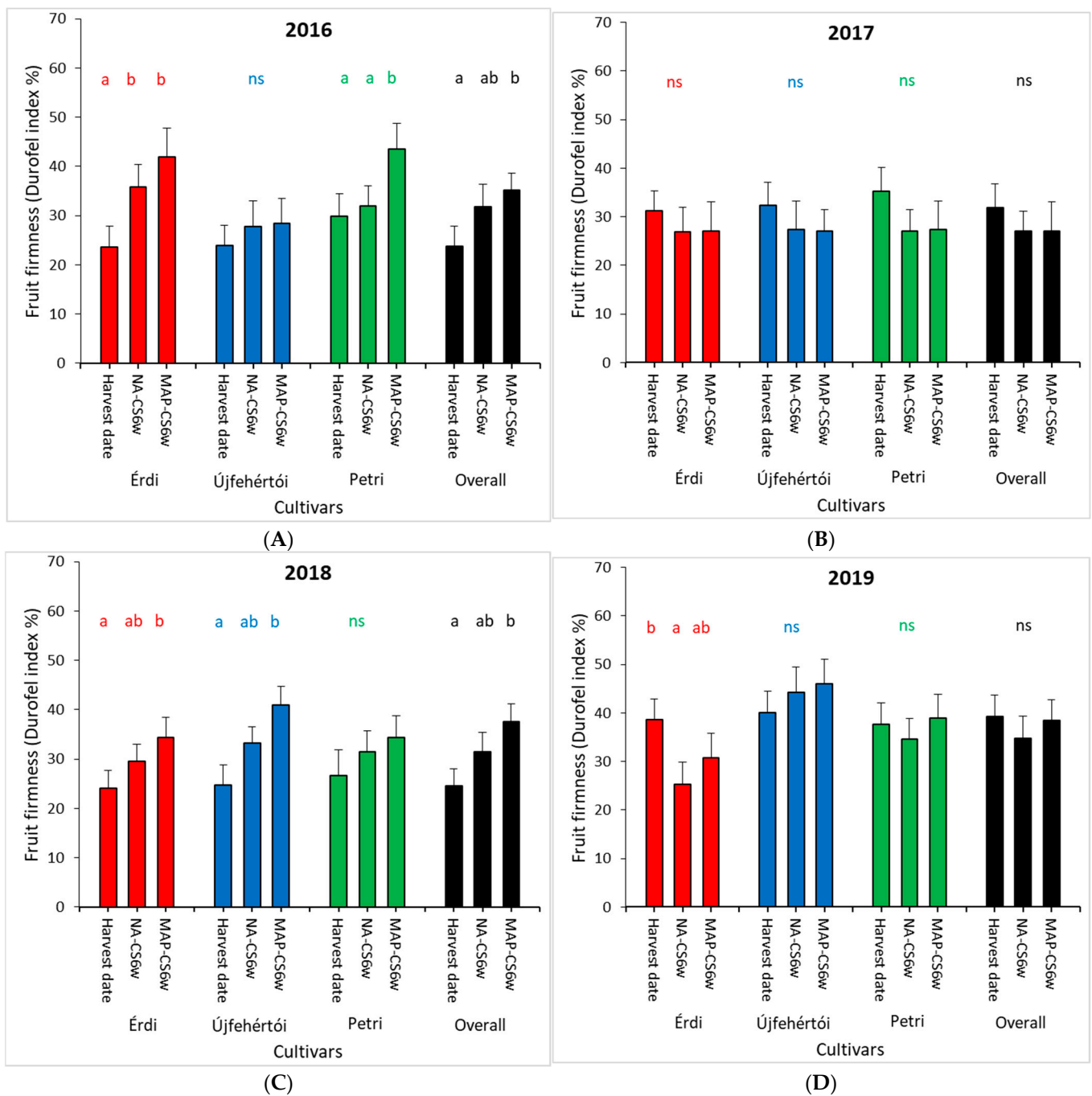
**Table 1.** Split-plot analysis of variance for the effects of years (2016–2019), storage treatments (for fruit firmness: Control-harvest date, NA-CS6w, and MAP-CS6w; for weight loss: NA-CS6w and MAP-CS6w), and sour cherry cultivars (‘Érdi bőtermő’, ‘Újfehértói fürtös’, and ‘Petri’) on fruit firmness and fruit weight loss. Significant values ( $p < 0.05$ ) are indicated with bold figures.

Fruit Firmness			
Source of Variation	df	MS	$p$
Year (Y)	3	337.1	<b>0.003</b>
Storage treatment (S)	2	134.5	<b>0.029</b>
Main plot error	6	376.9	
Cultivar (C)	2	43.9	<b>0.049</b>
S × C	4	16.7	0.112
Subplot error	35	167.2	
Fruit Weight Loss			
Year (Y)	3	614.4	<b>&lt;0.001</b>
Storage treatment (S)	1	127.1	<b>0.002</b>
Main plot error	3	31.9	
Cultivar (C)	2	67.5	<b>0.022</b>
S × C	2	11.0	0.249
Subplot error	23	26.3	

df: degrees of freedom;  $p$ : the probability values associated with the F-tests; MS: mean squares.

During the 4-year period, the fruit firmness (Durofel index, %) value was the lowest for cv. ‘Érdi bőtermő’ in 2016 (23.9%) and the highest for cv. ‘Újfehértói fürtös’ in 2019 (46.0%) (Figure 3). The fruit firmness values of cv. ‘Érdi bőtermő’ were between 23.6 and 41.9%, and the largest variation was detected in 2016. Fruit firmness of cv. ‘Újfehértói fürtös’ was between 23.9 and 46.0%, while the values ranged from 26.7 to 43.5% for cv. ‘Petri’. The ‘overall (year)’ fruit firmness values significantly differed ( $p = 0.05$ ) only for cv. ‘Érdi bőtermő’ among the three storage treatments (Figure 3).

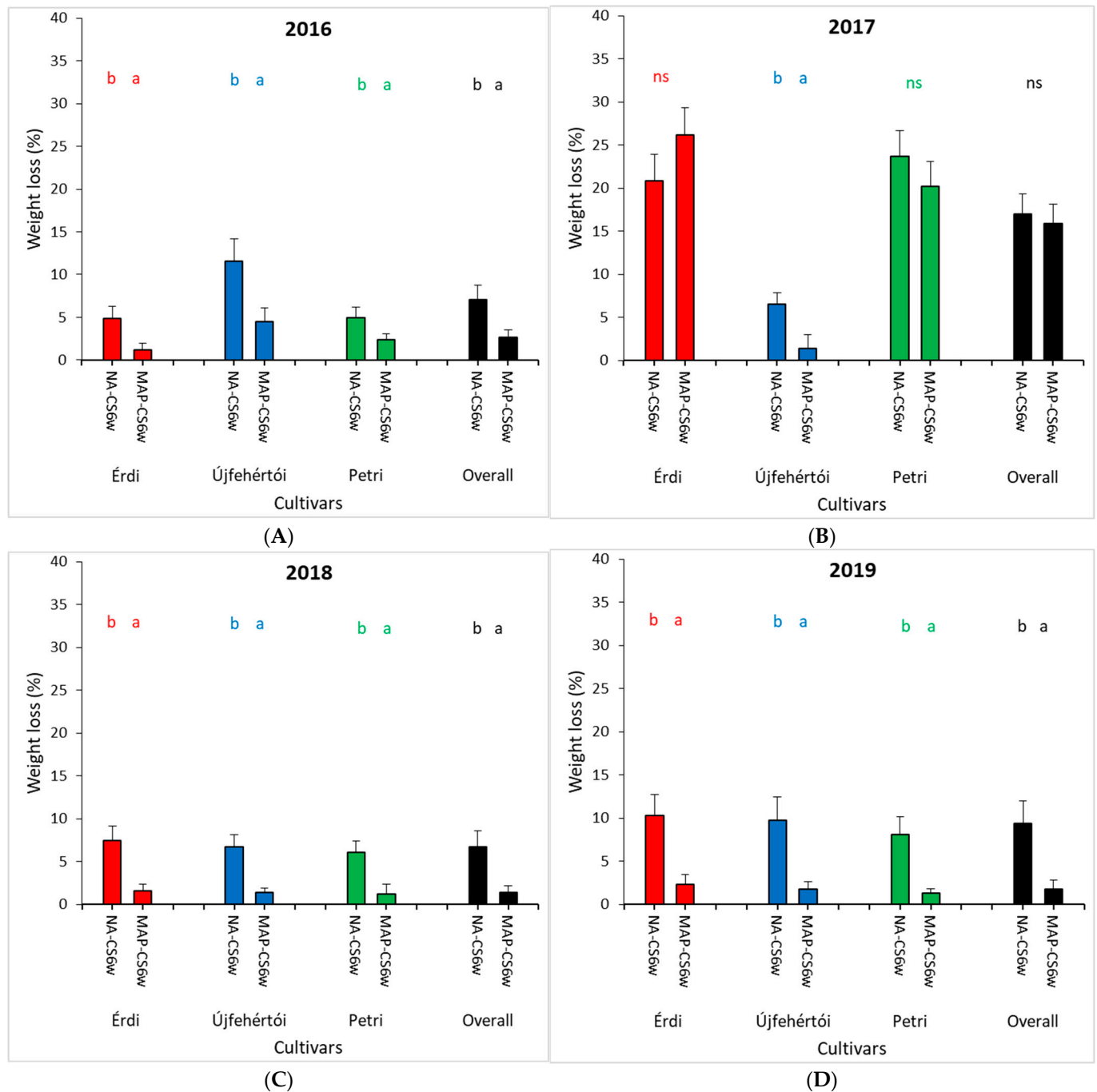
Significant differences in fruit firmness values were found among the three storage treatments for cv. ‘Érdi bőtermő’ in 2016, 2018, and 2019; for cv. ‘Újfehértói fürtös’ in 2018; and for cv. ‘Petri’ in 2016 (Figure 3). The values of the control (harvest date) treatment were significantly different compared to the values of the NA-CS6w treatment for cv. ‘Érdi bőtermő’ in 2016 and 2019, and for the combined data for ‘overall year’ and all cultivars. The values of the control (harvest date) treatment were significantly different compared to the values of the MAP-CS6w treatment for cv. ‘Érdi bőtermő’ in 2016 and 2018, for cv. ‘Újfehértói fürtös’ in 2018, and for cv. ‘Petri’ in 2016, as well as ‘overall (cultivar)’ in 2016 and 2018.



**Figure 3.** Fruit firmness (Durofel index, %) of three sour cherry cultivars (‘Érdi bőtermő’, ‘Újfehértói fűrtös’, and ‘Petri’) after three storage treatments (Control-harvest date, NA-CS6w, and MAP-CS6w) from 2016 to 2019 (A–D) at Újfehértó in Hungary. NA-CS6w: 6 weeks of normal atmosphere cold storage; MAP-CS6w: 6 weeks of modified atmosphere package cold storage. Values above the columns followed by the same letter are not significantly different according to LSD test ( $p = 0.05$ ). ‘ns’: it indicates that there are no significant differences between the treatment values. Érdi: ‘Érdi bőtermő’; Újfehértói: ‘Újfehértói fűrtös’.

During the 4-year period, the weight loss values were the lowest and highest for cv. ‘Érdi bőtermő’ in 2018 (1.18%) and in 2017 (26.1%), respectively (Figure 4). The weight loss values of cv. ‘Érdi bőtermő’ were between 1.18 and 26.1%; cv. ‘Újfehértói fűrtös’ were between 1.36 and 11.5%; while for cv. ‘Petri’, the values ranged from 1.24 to 23.7%. The ‘overall (year)’ weight loss values were significantly higher ( $p = 0.05$ ) in the normal

atmosphere treatment (NA-CS6w) compared to the MAP treatment (MAP-CS6w) for cv. 'Érdi bőtermő' and 'Újfehértói fűrtös' and for 'overall cultivars' (Figure 4).



**Figure 4.** Weight loss (%) of three sour cherry cultivars ('Érdi bőtermő', 'Újfehértói fűrtös', and 'Petri') after two different storage treatments (NA-CS6w and MAP-CS6w) from 2016 to 2019 (A–D) at Újfehértó in Hungary. NA-CS6w: 6 weeks of normal atmosphere cold storage; MAP-CS6w: 6 weeks of modified atmosphere package cold storage. Values above columns followed by the same letter are not significantly different according to LSD test ( $p = 0.05$ ). 'ns': it indicates that there are no significant differences between the treatment values. Érdi: 'Érdi bőtermő'; Újfehértói: 'Újfehértói fűrtös'.

Significant differences in fruit weight loss values were found among the two storage treatments for all cultivars and years with the exception of 2017, i.e., weight loss of the

normal atmosphere treatment (NA-CS6w) was significantly higher compared to the MAP treatment (MAP-CS6w) (Figure 4).

### 3.2. Fruit Decay Incidence of Harvested Sour Cherry Fruits during Shelf-Life Storage in Experiment 1A

The analysis of variance on disease incidence after the shelf-life of the harvested sour cherry fruits showed significant ( $p < 0.05$ ) effects for years, storage times, and cultivars (Table 2). Interactions for the treatment effects were non-significant for all treatments.

**Table 2.** Split-plot analysis of variance for the effects of years (2016–2019), shelf-life days (days 2, 4, 6, 8, 10, 12, and 14), and sour cherry cultivars (‘Érdi bőtermő’, ‘Újfehértói fürtös’, and ‘Petri’) on fruit decay incidence (Újfehértó, Hungary). Significant values ( $p < 0.05$ ) are indicated with bold figures.

Fruit Decay Incidence-Harvest-Experiment 1A			
Source of Variation	df	MS	<i>p</i>
Year (Y)	3	3438.2	<b>0.001</b>
Shelf-life days (SLD)	2	23,232.8	<b>&lt;0.001</b>
Main plot error	6	2039.4	
Cultivar (C)	2	7580.3	<b>&lt;0.001</b>
SLD × C	4	1736.1	0.054
Subplot error	36	704.5	

df: degrees of freedom; *p*: the probability values associated with the F-tests; MS: mean squares.

The fruit decay incidence value of the harvested sour cherry fruits was the lowest at shelf-life day 2 (ranging from 0.0 to 5.2%), while the highest at shelf-life day 14 (ranging from 17.7 to 77.0%) for all cultivars and years (Table 3). Cultivars showed remarkable differences, as the highest decay incidence values at shelf-life day 14 ranged between 49.5 and 77.0%, 17.7 and 44.8%, and 25.0 and 63.0% for cultivars ‘Érdi bőtermő’, ‘Újfehértói fürtös’, and ‘Petri’, respectively.

**Table 3.** Fruit decay incidence (%) of harvested fruits at shelf-life days 2, 4, 6, 8, 10, 12, and 14 on three sour cherry cultivars (‘Érdi bőtermő’, ‘Újfehértói fürtös’, and ‘Petri’) from 2016 to 2019 (Újfehértó, Hungary). During shelf-life days, fruits were stored at  $20 \pm 1$  °C.

Storage/Cultivar	Érdi bőtermő	Újfehértói fürtös	Petri	Overall (Cultivar)
2016				
day 2	0.0 a <sup>a</sup>	3.1 a	3.0 a	2.0 a
day 4	16.7 b	8.8 a	10.5 a	12.0 a
day 6	36.5 c	26.0 b	35.0 b	32.5 b
day 8	50.0 c	31.2 bc	46.1 bc	42.4 bc
day 10	70.8 d	37.5 cd	57.2 cd	55.2 cd
day 12	76.0 d	47.9 de	59.1 cd	61.0 d
day 14	77.0 d	52.1 e	63.0 d	64.0 d
LSD <sub>0.05</sub> <sup>b</sup>	14.8	10.8	14.2	12.3
2017				
day 2	5.2 a	0.0 a	0.0 a	1.7 a
day 4	23.9 b	3.1 ab	2.1 ab	9.7 a
day 6	43.7 c	8.3 b	8.3 bc	20.1 b
day 8	51.0 de	15.6 c	13.5 cd	26.7 bc
day 10	59.4 ef	16.7 c	16.6 de	30.9 cd
day 12	64.1 ef	18.7 c	20.4 ef	34.4 cd
day 14	68.7 f	17.7 c	25.0 f	37.1 d
LSD <sub>0.05</sub>	13.8	5.7	6.5	8.5

Table 3. Cont.

Storage/Cultivar	Érdi bőtermő	Újfehértói fürtös	Petri	Overall (Cultivar)
2018				
day 2	2.8 a	0.0 a	0.0 a	0.9 a
day 4	20.8 b	2.1 a	5.2 ab	9.4 a
day 6	42.7 c	20.9 b	15.6 b	26.4 b
day 8	54.7 cd	21.9 b	34.4 c	37.0 bc
day 10	61.5 de	29.2 bc	56.2 d	48.9 cd
day 12	63.5 de	33.3 c	58.3 d	51.7 d
day 14	71.9 e	44.8 d	60.4 d	59.0 d
LSD <sub>0.05</sub>	14.9	9.7	12.4	12.2
2019				
day 2	4.2 a	1.0 a	9.4 a	4.9 a
day 4	19.8 bc	7.3 bc	11.4 ab	12.8 ab
day 6	26.0 cd	13.5 c	18.7 bc	19.4 bc
day 8	33.3 de	19.7 d	27.1 cd	26.7 cd
day 10	44.8 ef	19.8 d	34.4 de	33.0 de
day 12	49.0 f	21.9 d	38.5 e	36.5 e
day 14	49.5 f	23.9 d	38.7 e	37.4 e
LSD <sub>0.05</sub>	9.6	5.5	8.9	8.0
Overall (year)				
day 2	3.1 a	1.0 a	3.1 a	2.4 a
day 4	20.3 b	5.3 a	7.3 a	10.9 a
day 6	37.2 cd	17.2 bc	19.4 b	24.6 bc
day 8	47.3 de	22.1 cd	30.3 c	33.2 cd
day 10	59.1 ef	25.8 de	41.1 d	42.0 de
day 12	63.2 f	30.5 ef	44.1 d	45.9 e
day 14	66.8 f	34.6 f	46.8 d	49.4 e
LSD <sub>0.05</sub>	13.1	7.9	10.2	10.1

<sup>a</sup> Values followed by the same letter are not significantly different according to LSD test ( $p = 0.05$ ). <sup>b</sup> LSD<sub>0.05</sub> = least significant differences at  $p = 0.05$  level.

In all years, the fruit decay incidence values of the harvested fruits continuously increased from shelf-life day 2 to day 14 (Table 3). However, differences in fruit decay incidence values at shelf-life days 2 and 4 were nonsignificant for cv. 'Petri' and when the data of all years and all cultivars were combined. After shelf-life day 10, no significant increase in the fruit decay incidence was observed either in years or in the cultivars, with the exceptions of cv. 'Újfehértói fürtös' in 2016 and 2018 and cv. 'Petri' in 2017. The 'overall (year)' decay incidence values were the lowest in all shelf-life days for cv. 'Újfehértói fürtös' compared to the other two cultivars (Table 3).

### 3.3. Fruit Decay Incidence of Cold-Stored Sour Cherry Fruits during Shelf-Life Storage in Experiment 1B

The analysis of variance on disease incidence after the shelf-life of cold-stored sour cherry fruits showed significant ( $p < 0.05$ ) effects for years, storage types, cultivars, and shelf-life days (Table 4). Interactions for the treatment effects were non-significant for all treatments.

In all the years, fruit decay incidence values after normal atmosphere (NA) cold storage continuously increased from shelf-life day 2 to day 6 (Table 5). Fruit decay incidence values were significantly different among all the three shelf-life days for all cultivars in both 'overall (year)' and in 'overall (cultivar)', as well as for cv. 'Érdi bőtermő' in 2016; for cv. 'Petri' in 2019; and for all cultivars in 2018 (Table 5). However, fruit decay incidences between shelf-life days 4 and 6 were nonsignificant for cv. 'Újfehértói fürtös' in 2016, 2017, and 2019; for cv. 'Petri' in 2016 and 2019; and for cv. 'Érdi bőtermő' in 2019 (Table 5). On the other hand, for cv. 'Érdi bőtermő' in 2017, fruit decay incidences between shelf-life days 2 and 4 were nonsignificant (Table 5).

**Table 4.** Split-split-plot analysis of variance for the effects of years (2016–2019), storage type (NA and MAP), sour cherry cultivars (‘Érdi bőtermő’, ‘Újfehértói fürtös’, and ‘Petri’), and shelf-life days (days 2, 4, and 6) on fruit decay incidence (Újfehértó, Hungary). Significant values ( $p < 0.05$ ) are indicated with bold figures.

Fruit Decay Incidence-CS-Experiment 1B			
Source of Variation	df	MS	<i>p</i>
Year (Y)	3	1297.7	<b>0.003</b>
Storage type (ST)	1	596.4	<b>0.008</b>
Main plot error	3	2076.4	
Cultivar (C)	2	12,061.6	<b>&lt;0.001</b>
ST × C	4	305.9	0.055
Subplot error	6	1818.8	
Shelf-life days (SLD)	2	57,937.1	<b>&lt;0.001</b>
ST × SLD	2	523.5	<b>0.048</b>
C × SLD	4	3588.5	<b>0.001</b>
ST × C × SLD	4	1826.2	<b>0.006</b>
Sub-subplot error	24	1728.3	

df: degrees of freedom; *p*: the probability values associated with the F-tests; MS: mean squares.

**Table 5.** Fruit decay incidence (%) after normal atmosphere (NA) cold storage ( $1 \pm 1$  °C) at shelf-life days 2, 4, and 6 on three sour cherry cultivars (‘Érdi bőtermő’, ‘Újfehértói fürtös’, and ‘Petri’) from 2016 to 2019 (Újfehértó, Hungary). During shelf-life days, fruits were stored at  $20 \pm 1$  °C.

Storage/Cultivar	Érdi bőtermő	Újfehértói fürtös	Petri	Overall (Cultivar)
2016				
day 2	1.0 a <sup>a</sup>	6.2 a	11.5 a	6.2 a
day 4	52.1 b	69.8 b	56.2 b	59.4 b
day 6	76.0 c	95.8 b	95.8 b	89.2 c
LSD <sub>0.05</sub> <sup>b</sup>	20.1	30.1	32.1	27.1
2017				
day 2	3.1 a	11.5 a	33.3 a	15.9 a
day 4	11.5 a	33.3 b	61.5 b	35.4 b
day 6	54.2 b	79.2 b	95.8 c	76.4 c
LSD <sub>0.05</sub>	10.4	17.3	25.1	17.6
2018				
day 2	1.0 a	3.1 a	5.2 a	3.1 a
day 4	15.6 b	39.6 b	36.5 b	30.6 b
day 6	45.8 c	77.1 c	87.5 c	70.1 c
LSD <sub>0.05</sub>	13.2	18.3	24.1	17.8
2019				
day 2	7.3 a	9.4 a	9.0 a	8.6 a
day 4	64.5 b	47.9 b	59.1 b	57.2 b
day 6	83.3 b	66.7 b	82.0 b	77.3 c
LSD <sub>0.05</sub>	22.3	19.9	21.1	21.0
Overall (year)				
day 2	3.1 a	7.5 a	14.8 a	8.5 a
day 4	35.9 b	47.6 b	53.4 b	45.6 b
day 6	64.8 c	79.7 c	90.3 c	78.3 c
LSD <sub>0.05</sub>	17.2	21.8	26.7	21.1

<sup>a</sup> Values followed by the same letter are not significantly different according to LSD test ( $p = 0.05$ ). <sup>b</sup> LSD<sub>0.05</sub> = least significant differences at  $p = 0.05$  level.

Fruit decay incidence values after modified atmosphere package (MAP) cold storage were the lowest at shelf-life day 2 (ranging from 3.1 to 22.9%) while the highest at shelf-life day 6 (ranging from 23.9 to 100%) for all cultivars and years (Table 6). Similar to NA treatments, variation in decay incidence values was considerable among cultivars; for example, the highest decay incidence values at shelf-life day 6 ranged between 23.9 and

72.9%, 97.9 and 98.9%, and 95.8 and 100% for cultivars 'Érdi bőtermő', 'Újfehértói fürtös', and 'Petri', respectively, among the four years.

**Table 6.** Fruit decay incidence (%) after modified atmosphere package (MAP) cold storage ( $1 \pm 1$  °C) at shelf-life days 2, 4, and 6 on three sour cherry cultivars ('Érdi bőtermő', 'Újfehértói fürtös', and 'Petri') (2016–2019, Újfehértó, Hungary). During shelf-life days, fruits were stored at  $20 \pm 1$  °C.

Storage/Cultivar	Érdi bőtermő	Újfehértói fürtös	Petri	Overall (Cultivar)
2016				
day 2	7.3 a <sup>a</sup>	21.9 a	11.5 a	13.6 a
day 4	20.8 b	82.3 b	79.2 b	60.8 b
day 6	39.6 c	97.9 b	95.8 b	77.8 c
LSD <sub>0.05</sub> <sup>b</sup>	6.7	18.3	10.5	12.4
2017				
day 2	19.8 a	22.9 a	21.9 a	21.5 a
day 4	39.6 b	89.6 b	77.1 b	68.8 b
day 6	72.9 c	98.9 b	96.9 b	89.6 b
LSD <sub>0.05</sub>	17.9	20.1	20.3	19.5
2018				
day 2	3.1 a	13.5 a	1.0 a	5.9 a
day 4	6.2 a	94.8 b	98.9 b	66.6 b
day 6	29.2 b	98.9 b	100.0 b	76.0 b
LSD <sub>0.05</sub>	3.1	10.5	12.5	12.6
2019				
day 2	3.1 a	4.17 a	6.3 a	4.5 a
day 4	9.4 a	52.1 b	57.3 b	39.6 b
day 6	23.9 b	97.9 c	100.0 c	73.9 c
LSD <sub>0.05</sub>	3.0	14.7	19.3	12.6
Overall (year)				
day 2	8.3 a	15.6 a	10.2 a	11.4 a
day 4	19 a	79.7 b	78.1 b	58.9 b
day 6	41.4 b	98.4 c	98.2 c	79.3 c
LSD <sub>0.05</sub>	12.5	16.3	15.1	14.4

<sup>a</sup> Values followed by the same letter are not significantly different according to LSD test ( $p = 0.05$ ). <sup>b</sup> LSD<sub>0.05</sub> = least significant differences at  $p = 0.05$  level.

In all the years, fruit decay incidence values after modified atmosphere package (MAP) cold storage continuously increased from shelf-life day 2 to day 6 (Table 6). Fruit decay incidences between shelf-life days 2 and 4 were nonsignificant for cv. 'Érdi bőtermő' in 2018, 2019, and in overall (year). Similarly, fruit decay incidences between shelf-life days 4 and 6 were nonsignificant for cvs. 'Újfehértói fürtös' and 'Petri' in 2016, 2017, and 2018, as well as 'overall (cultivar)' in 2017 and 2018 (Table 6). However, fruit decay incidence values were significantly different among all the three shelf-life days for cv. 'Érdi bőtermő' in 2016 and 2017; for cvs. 'Újfehértói fürtös' and 'Petri' in 2019; for cvs. 'Újfehértói fürtös' and 'Petri' in 'overall (year)'; and for 'overall (cultivar)' in 2016 and 2019 (Table 6).

Comparing the decay incidence values of the three cultivars under NA and MAP cold storage treatments, the MAP treatment significantly inhibited fruit deterioration at all shelf-life days only for cv. 'Érdi bőtermő' compared to the corresponding NA treatments (Tables 5 and 6).

### 3.4. Fruit Decay Incidence of Harvested and Stored Sour Cherry Fruits in Three Production Systems in Experiment 2

The analysis of variance on disease incidence after the shelf-life of cold-stored sour cherry fruits in experiment 2 showed significant ( $p < 0.05$ ) effects for years, production systems, and storage treatments (Table 7). Interactions for the treatment effects were non-significant for all treatments.

**Table 7.** Split-plot analysis of variance for the effects of years (2020–2022), production systems (conventional, IPM, and reduced IPM), and storage treatments (Control-harvest date, MAP-CS4w, MAP-CS4w-SL2, and MAP-CS4w-SL6) on fruit decay incidence (‘Érdi bőtermő’, Eperjeske, Hungary). Significant values ( $p < 0.05$ ) are indicated with bold figures.

Fruit Decay Incidence-Production System-Experiment 2			
Source of Variation	df	MS	<i>p</i>
Year (Y)	2	3254.8	<b>&lt;0.001</b>
Production system (PS)	2	307.4	<b>0.049</b>
Main plot error	4	106.2	
Storage treatment (S)	3	16,176.5	<b>&lt;0.001</b>
PS × S	6	87.5	0.1588
Sub-plot error	12	133.3	

df: degrees of freedom; *p*: the probability values associated with the F-tests; MS: mean squares.

Fruit decay incidence values after modified atmosphere package (MAP) cold storage in the three production systems were the lowest at harvest date (ranging from 0 to 6.4%), while the highest at shelf-life day 6 after four weeks of MAP cold storage (ranging from 25.7 to 87.9%) for all years (Table 8).

**Table 8.** Fruit decay incidence (%) at harvest date (control-harvest date); after 4 weeks of modified atmosphere package cold storage (MAP-CS4w); after MAP-CS4w, followed by 2 days of shelf-life (MAP-CS4w-SL2); and after MAP-CS4w, followed by 6 days of shelf-life (MAP-CS4w-SL6) under three production systems (Conventional, IPM, and reduced IPM) (‘Érdi bőtermő’, 2020–2022, Eperjeske, Hungary). During cold storage and shelf-life days, fruits were stored at  $2 \pm 1$  and  $20 \pm 1$  °C, respectively.

Management/Year	2020	2021	2022	Overall (Year)
Conventional				
Control-harvest date	0.0 a <sup>a</sup>	0.0 a	0.0 a	0.0 a
MAP-CS4w	0.6 a	0.4 a	0.7 a	0.6 a
MAP-CS4w-SL2	3.2 a	2.5 a	3.7 a	3.1 a
MAP-CS4w-SL6	31.5 b	25.7 b	38.5 b	31.9 b
LSD <sub>0.05</sub> <sup>b</sup>	4.6	3.7	5.9	5.2
IPM				
Control-harvest date	0.5 a	0.7 a	0.3 a	0.5 a
MAP-CS4w	1.7 a	2.2 a	1.1 a	1.7 a
MAP-CS4w-SL2	5.8 a	6.5 a	4.1 a	5.5 a
MAP-CS4w-SL6	45.1 b	54.3 b	40.1 b	46.5 b
LSD <sub>0.05</sub>	7.6	8.8	7.5	8.1
Reduced IPM				
Control-harvest date	5.6 a	6.4 a	3.2 a	5.1 a
MAP-CS4w	10.1 a	9.8 a	7.2 a	9.0 a
MAP-CS4w-SL2	26.4 b	30.3 b	22.3 b	26.3 b
MAP-CS4w-SL6	84.2 c	87.9 c	78.4 c	83.5 c
LSD <sub>0.05</sub>	10.6	12.9	11.8	11.7
Overall (storage)				
Conventional	8.8 a	7.2 a	10.7 a	8.9 a
IPM	11.8 ab	9.5 a	14.3 ab	11.9 ab
IPM-reduced	17.4 b	14.1 a	21.1 b	17.5 b
LSD <sub>0.05</sub>	8.4	ns	10.3	8.5

<sup>a</sup> Values followed by the same letter are not significantly different according to LSD test ( $p = 0.05$ ). <sup>b</sup> LSD<sub>0.05</sub> = least significant differences at  $p = 0.05$  level.

In all years, fruit decay incidence values after modified atmosphere package (MAP) cold storage continuously increased from harvest date to shelf-life day 6 after four weeks of MAP cold storage (MAP-CS4w-SL6) (Table 8). Fruit decay incidence values increased in the following order: conventional, IPM, and reduced IPM systems. However, significant differences were detected only between conventional and reduced IPM systems in 2020,

2021, and overall (year). Fruit decay incidences at harvest were the highest in the reduced IPM and were significantly higher than conventional and IPM systems.

Fruit decay incidence values between harvest date and 4 weeks of MAP cold storage (MAP-CS4w) were nonsignificant across years and production systems (Table 8). In the cases of conventional and IPM systems, only the fruit decay incidence values of MAP-CS4w-SL6 were significantly higher than all other treatments. While in the case of a reduced IPM system, the fruit decay incidence values of both MAP-CS4w-SL2 and MAP-CS4w-SL6 were significantly higher than the values at harvest date and MAP-CS4w (Table 8).

### 3.5. Pearson Correlation Analysis

Pearson correlation coefficient ( $r$ ) was the highest ( $r = 0.9981$ ) between 2018 and 2019 for weight loss (Table 9B). Twenty-two correlation pairs were significant ( $p = 0.05$ ) among the analyzed relationships; 22 parameter pairs correlated positively and one negatively (Table 9A–E). All correlation pairs were significant for fruit decay incidence among the years (2016, 2017, 2018, and 2019) in experiment 1 (Table 9C). Additionally, all relationships for decay incidence among the years (2020, 2021, and 2022) and management systems (conventional, IPM, and reduced IPM) were significant in experiment 2 (Table 9E,F).

**Table 9.** Pearson’s correlation coefficients ( $r$ ) for fruit firmness, weight loss, and fruit decay incidence for sour cherry postharvest experiments 1 and 2. Relationships among the years (2016, 2017, 2018, and 2019) for fruit firmness (A) and weight loss (B) in experiment 1. Relationships for decay incidence among the years (2016, 2017, 2018, and 2019) (C); cultivars combined with storage methods (MAP ‘Érdi bőtermő’—MAPÉrdi, MAP ‘Újfehértói fürtös’—MAPÚf, MAP ‘Petri’—MAPPetri, NA ‘Érdi bőtermő’—NAÉrdi, NA ‘Újfehértói fürtös’—NAÚf, and NA ‘Petri’—NAPetri) (D) in experiment 1; and among the years (2020, 2021, 2022) (E); and management systems (conventional, IPM, and reduced IPM) (F) in experiment 2. Bold letters represent significant correlation at  $p = 0.05$ .

<b>Fruit Firmness (A)</b>	2016	2017	2018		
2017	−0.5699				
2018	0.5388	<b>−0.7481</b>			
2019	−0.4842	0.1929		0.2020	
<b>Weight loss (B)</b>	2016	2017	2018		
2017	−0.5293				
2018	<b>0.7122</b>	0.0675			
2019	<b>0.7348</b>	0.0463		<b>0.9981</b>	
<b>Decay incidence (C)</b>	2016	2017	2018		
2017	<b>0.7161</b>				
2018	<b>0.7377</b>	<b>0.9610</b>			
2019	<b>0.8188</b>	<b>0.8039</b>		<b>0.8071</b>	
<b>Decay incidence (D)</b>	MAPÉrdi	MAPÚf	MAPPetri	NAÉrdi	NAÚf
MAPÚf	<b>0.8289</b>				
MAPPetri	<b>0.8331</b>	<b>0.9888</b>			
NAÉrdi	0.4408	0.6757	0.6183		
NAÚf	0.5678	0.6323	<b>0.6813</b>	<b>0.8787</b>	
NAPetri	0.5006	0.6764	0.6709	<b>0.8323</b>	<b>0.9379</b>
<b>Decay incidence (E)</b>		2020		2021	
2021		<b>0.9932</b>			
2022		<b>0.9921</b>		<b>0.9732</b>	
<b>Decay incidence (F)</b>		Conventional		IPM	
IPM		<b>0.9402</b>			
Reduced IPM		<b>0.9506</b>		<b>0.9821</b>	

#### 4. Discussion

Our research showed that sour cherry fruit decay incidence was variously dependent on storage temperature conditions (shelf-life vs. cold storage), storage atmosphere conditions (normal atmospheric (NA) vs. modified atmosphere packaging (MAP)), and cultivars' susceptibility ('Érdi bőtermő', 'Újfehértói fürtös', and 'Petri'). In addition, we showed that cold-stored fruits in combination with MAP showed significantly lower fruit decay incidence in the conventional production system as compared to the reduced IPM production system for the cv. 'Érdi bőtermő'.

The fruit firmness was determined for sour cherry in several previous studies, and a significant difference was detected among the various genotypes [6,15,28,41–48]. In this study, sour cherry fruit firmness (Durofel Index) ranged between 23.6% and 41.9%, 23.9% and 46.0%, and 26.7% to 43.5% for cvs. 'Érdi bőtermő', 'Újfehértói fürtös', and 'Petri', respectively, at harvest and under cold storage NA and MAP treatments (Figure 3). These results are similar to those of Desiderio et al. [48], who showed that the fruit firmness of cv. 'Újfehértói fürtös' ranged from 28.4% to 44.5%. There was also a significant difference in fruit firmness among the three studied Hungarian cultivars. The fruits of cv. 'Érdi bőtermő' were the softest, cv. 'Újfehértói fürtös' had higher firmness, and cv. 'Petri' had the highest firmness at harvest. Upon comparisons of Hungarian and other sour cherry cultivars (including cvs. 'Érdi bőtermő', 'Petri', and 'Újfehértói fürtös'), cv. 'Újfehértói fürtös' exhibited high firmness values [41], which were higher compared to the most well-known sour cherry cultivars, including 'Schattenmorelle' and 'Montmorency' [6,44,45]. However, higher firmness was also shown by some Iranian cultivars [15], providing a good option for postharvest storage.

Our study showed that MAP effectively preserved (or even increased, to some extent) the firmness of the samples compared to control fruits for the three tested Hungarian cultivars (Figure 3). In one case, this result corresponds to a previous study by Szabo et al. [47], where authors found no significant differences in firmness values during the storage of control and MAP-treated cv. 'Újfehértói fürtös' (days 0–14). In another case, a similar increase in fruit firmness was reported previously for sour cherry cultivars 'Érdi jubileum' and 'Érdi bőtermő', following six weeks of MAP storage at 0 °C [41,43], and for sour cherry cv. 'English Morello' with 20 days of controlled air storage at 2 °C [28]. The possible reasons for this can be explained by the biochemical processes in fruits, i.e., fruit softening, a biochemical process typically attributed to changes in cell wall composition due to enzymes, such as polygalacturonase, that modify cell walls [49]. Low oxygen and high CO<sub>2</sub> levels inhibit the activity of these enzymes, thus helping to maintain fruit firmness during storage. Moreover, reduced transpiration and water retention provide flexibility to fruit cells [50]. This also means that fruit firmness is highly correlated with the water content of fruits and the corresponding measure of fruit weight loss [41,51].

Our results showed that, as expected, the fruit weight loss of the three sour cherry cultivars was reduced significantly under MAP storage compared to NA storage (Figure 4). In agreement with our study, many sweet cherry studies have shown a positive effect of MAP storage on fruit weight loss [28,34–40]. However, only a few sour cherry studies [41,47] demonstrated that the weight loss of the sour cherry was significantly reduced by MAP storage. Aryanpooya and Davarynejad [41] showed that the weight loss of the sour cherry cvs. 'Érdi jubileum' and 'Érdi bőtermő' was significantly reduced by MAP storage compared to ambient air packaging. The study by Szabo et al. [47] measured 3.9 and 6.4% fruit weight losses in the control stored samples of cvs. 'Kántorjánosi' and 'Újfehértói fürtös', respectively, while MAP-stored fruits showed 1% weight loss during the 14-day storage. Our results showed larger fruit weight loss (ranging between 1.18 and 26.1%) in the MAP treatment after 6 weeks of storage compared to the previous two sour cherry studies, which was probably due to a longer storage duration in our study as well as differences in cultivars and experimental setup.

Our results showed that in all years, the yield loss of harvested fruits continuously increased over the observed 14 days, causing considerable loss from day 6 in all cultivars

(Table 3). This corroborates previous findings that sour cherry fruits quickly soften and lose moisture and can only be stored for up to one week [12], due to their low penetration resistance and high respiration rates [13]. This leads to rapid postharvest quality loss [14], which exponentially increases with the development of fruit decay during storage [14,15,47,52]. In our study, consistent with these findings, the incidence of fruit decay in harvested fruits significantly increased during shelf-life in all the cultivars (Table 3). However, decay incidence was lowest across all shelf-life days for the harvested cv. 'Újfehértói fürtös' compared to the other two cultivars, 'Érdi bőtermő' and 'Petri'. Soltész et al. [52] also demonstrated that the storage capability of cv. 'Újfehértói fürtös' was similar to that of 'Petri' but better than cv. 'Érdi bőtermő'. The study by Szabo et al. [47] reported a decay incidence of over 50% for cv. 'Újfehértói fürtös' after 12 days of shelf-life, which was considerably higher than in this study. The differences between these studies could be due to different seasons, different plant protection technologies used during growth, and different shelf-life conditions applied to the harvested fruits.

It is important to note that this study aimed to show the incidence of overall disorders in sour cherry fruits, expressed as fruit decay incidence, at harvest and under postharvest treatments. Therefore, the specific types of postharvest fruit decay were not identified in this study. However, it is generally known that more than 80% of fruit decay is caused by fungal pathogens belonging to the genera *Alternaria*, *Penicillium*, *Monilinia*, *Botrytis*, and *Rhizopus*, which is consistent with previous studies on sour cherries under postharvest treatments [14,53,54].

Fruit decay incidence values after 6 weeks of normal atmosphere (NA) cold storage were low (below 20%) and similar for all cultivars (Table 5). In line with our results, Wang and Vestrheim [14] indicated that the decay of sour cherries can be greatly reduced when fruits are stored for up to 20 days at 2 °C in controlled atmosphere storage. However, Soltész et al. [52] showed that postharvest fruit decay incidence was significantly higher for cv. 'Érdi bőtermő' (above 50%) than for cv. 'Újfehértói fürtös' (below 40%) after 6 weeks of cold storage, while cv. 'Újfehértói fürtös' and cv. 'Petri' showed similar postharvest decay incidence after the 6-week cold storage. The possible differences among the studies may be due to the different seasons of the tested cultivars and the fact that CO<sub>2</sub> concentration was higher in our cold storage technology. This aligns with the previous study by Lurie and Weksler [14], who showed that increasing CO<sub>2</sub> concentrations (higher than 5%) had a better fungistatic effect against the development of decay.

Our results for both NA and MAP indicated that six weeks of cold storage was effective for maintaining the quality of sour cherries; however, the shelf-life of the fruits was significantly reduced at room temperature, regardless of the storage method (Tables 5 and 6). Lurie and Weksler [14] also showed that the main fruit loss of sour cherries occurred after cold storage during the shelf-life period. MAP has been previously reported to reduce the decay of cherry fruits during storage, but this effect was maintained only until day 5 of shelf-life at 20 °C [55]. The proportion of decayed fruits was the lowest on the 6th day for cv. 'Érdi bőtermő' following MAP storage. However, the other two cultivars had a significantly higher proportion of decayed fruits, following both NA and MAP storage. This may be the result of inappropriate gas concentration achieved by the applied packaging, leading to anaerobic fermentation during MAP storage. MAP storage can induce anaerobic fermentation if the O<sub>2</sub> concentration drops to a level where aerobic respiration can no longer be maintained or if the CO<sub>2</sub> concentration exceeds an acceptable level [56]. Anaerobic fermentation (an excessive decrease in O<sub>2</sub> levels and an excessive increase in CO<sub>2</sub> levels) can occur when the gas permeability of a MAP sachet does not match the respiration dynamics of the fruits inside it. It has been observed that there is a difference between the respiration intensity of different sweet cherry [57] and sour cherry [47] cultivars. Kappel et al. [58] found that the respiratory intensity of cultivars harvested later was lower compared to earlier ones. Crisosto et al. [59] found in their experiment that sweet cherries with higher respiration intensity had softer fruits. In the case of raspberry cultivars, it was concluded that fruits with higher respiration intensity are more prone to decay [60]. Based on this

information, we can assume that the earlier harvested cv. 'Érdi bőtermő' has a higher respiration intensity than the other two cultivars, as a shorter shelf-life, lower fruit firmness, and a higher degree of decay were observed. Cultivar 'Érdi bőtermő' may have achieved the proper gas composition earlier with the applied MAP bag, which ensured that quality was maintained longer following storage. In the other two cultivars, the perforation of the MAP sachet was presumably inadequate.

Our results showed that fruit decay incidence at harvest was highest in the reduced IPM system and significantly higher than in the conventional and IPM systems (Table 8). This finding aligns with the study by Holb et al. [42], which showed that the incidence of disease in apples at harvest was higher in the reduced IPM system compared to the IPM or conventional systems. The efficacy of disease management in the reduced IPM system is closer to that of organic production systems than to classical IPM systems, where disease management efficacy is lower than in IPM and conventional systems [61–65]. Due to less effective disease and pest management during the season, higher disease occurrence was observed at harvest in the reduced IPM system in our sour cherry study (Table 8). Additionally, some fungal diseases (e.g., *Monilinia laxa*) can cause latent infections by penetrating immature fruits and remaining dormant until conditions become suitable, often manifesting after harvest as postharvest decay [66–68]. Moreover, latent infections in fruits at harvest can also be higher in these systems compared to conventional or classical integrated systems. These latent infections express symptoms during storage, which likely occurred in our experiment with the reduced IPM system.

Fruit decay incidence values after MAP cold storage increased in the order of conventional, IPM, and reduced IPM systems, but significant differences were detected only between the conventional and reduced IPM systems (Table 8). Although previous studies have not compared various production systems for stone fruits under MAP cold storage followed by shelf-life conditions, our results confirm that the health status of sour cherry fruits at harvest influences the longevity of postharvest quality. Additionally, fungicides applied during the growing season may also influence the early stages of storage by preventing postharvest diseases and latent infections [67,69] in sour cherry fruits compared to reduced IPM fruits in our study.

## 5. Conclusions

In this study, we determined the incidence of fruit decay during shelf-life for both freshly harvested and six-week-cold-stored sour cherry fruits, comparing normal atmospheric conditions with modified atmosphere packaging across three sour cherry cultivars, and assessed postharvest fruit decay incidence across three production systems for the cv. 'Érdi bőtermő'. The characteristics of the studied Hungarian sour cherry cvs. 'Érdi bőtermő', 'Újfehértói fürtös', and 'Petri' affected their shelf-life and long-term, cold storage potential. The applied modified atmosphere packaging (Xtend<sup>®</sup> Cherry, StePac LA Ltd.) effectively reduced weight loss, minimized fruit decay, and preserved or even increased the fruit firmness of the sour cherries following the storage at 0 °C for six weeks. The best post-storage shelf-life was observed in the MAP-stored cv. 'Érdi bőtermő'. Our study suggests that cold storage of sour cherries with modified atmosphere packaging can be a viable commercial option. However, cultivar genetics, along with environmental conditions and cultural practices, may greatly influence the successful postharvest storage ability of sour cherry fruits.

Fruit decay incidence was the lowest in the conventional or IPM systems after 4-week cold storage conditions combined with modified atmosphere packaging. Fruit decay incidence at harvest was the highest in the reduced IPM system, significantly exceeding that observed in the conventional and IPM systems. During post-MAP cold storage, fruit decay incidence followed the order of conventional < IPM < reduced IPM, with significant differences observed only between the conventional and reduced IPM systems. Our findings suggest that sour cherries produced under conventional or IPM systems and then cold-stored for four weeks under modified atmosphere packaging conditions may

successfully contribute to the development of an optimal postharvest storage method for sour cherries that can also be applicable for commercial purposes.

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