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Cost-Benefit Analysis of Apple Scab Sanitation Practices for ULO-Stored Apple Fruit in Integrated and Organic Production Systems

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ABSTRACT

The economic viability of orchard sanitation practices, is crucial for sustainable apple production. However, our knowledge in this area is limited, particularly after the fruit is stored in the high-energy-consuming ultra-low oxygen (ULO) storage system. The objective of this 3-year study was to investigate the cost-benefit ratios of five sanitation treatments (lime sulfur-Lime-S, leaf collection-Collect-L, mulching-Mulch-C, lime sulfur + leaf collection, leaf collection + mulching) in integrated and organic apple orchards, considering the sale of apples after 6-month ULO storage. Cost-benefit analyses determined cost, total revenue, revenue for class 1 fruit (fruits without scab infection) and income surplus. Costs of ULO storage were twice higher in the integrated orchard (mean 3,064 EUR ha^{-1}) than in the organic one (mean 1,512 EUR ha^{-1}). Direct costs of the two combined sanitation treatments were significantly higher than the Lime-S and Collect-L treatments across all years and orchard systems. Analysis of variance for total revenue, revenue for class 1 fruit and income surplus revealed significant differences among years, sanitation treatments, and orchard systems. The total revenue and revenue for class 1 fruit were significantly higher in the integrated orchard (10,787 and 10,557 EUR ha^{-1}, respectively) than in the organic one (8,713 and 7,742 EUR ha^{-1}, respectively). The lowest total revenue and revenue for class 1 fruit were obtained in the non-sanitized control, while highest were recorded in the Collect-L or Collect-L + Mulch-C treatments. Collect-L and Collect-L + Mulch-C treatments provided the highest income surplus in all years and orchard systems. Kernel density estimations and frequency distributions indicated the widest variability for total revenue and revenue for class 1 fruit in the integrated orchard system. Correlation and linear regression analyses revealed significant relationship between total revenue and revenue for class 1 fruit in both orchard systems. In conclusion, our study demonstrates that Collect-L and Collect-L + Mulch-C treatments offer the greatest economic benefit after 6-month ULO storage regardless of the orchard system employed.

KEYWORDS
Environmentally benign production; leaf collection; lime sulfur; *Malus domestica*; mulch cover; income surplus; ultra low oxygen (ULO) storage

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Introduction

Apple (*Malus x domestica* Borkh.) stands out as one of the most prevalent fruit species in Europe, with primary producers including Poland, Italy, Germany, and France (European Commission sources, 2024a). In the majority of European apple-producing regions, a substantial portion of the harvested apples is stored until the subsequent spring (Büchele et al., 2024; Shewa et al., 2022; Watkins, 2017). Qualitative attributes of apples, such as structure and firmness, generally undergo changes during storage, which are part of the normal metabolic processes of the fruit (Tijskens and Polderdijk, 1996; Watkins, 2017). Among various storage methods, several previous studies have highlighted the advantages of the ultra-low oxygen (ULO) storage system (Korićanac et al., 2019; Matejicek et al., 2015; Radenkovs and Juhnevica-Radenkova, 2018). Storage of apples in the ULO system maintains higher flesh firmness and reduces physiological disorders (Korićanac et al., 2019; Sabban-Amin et al., 2011; Zanella, 2003), flesh breakdown, and mealiness (Bílková et al., 2020; Weber et al., 2011), making it one of the most commonly used storage techniques (Radenkovs and Juhnevica-Radenkova, 2018). Typically, apples are held in ULO storage for 6–8 months (Awad and De Jager, 2000; Bílková et al., 2020). This method involves storage in a warehouse with ultra-low oxygen levels (<1%), along with high humidity, low temperature, and controlled levels of carbon dioxide, to slow down the fruit ripening process and minimize fruit loss while maintaining fruit quality (Bílková et al., 2020; Büchele et al., 2024). However, the initial cooling of harvested fruit and subsequent maintenance of low temperatures require significant energy inputs, thus making cost-effective long-term storage conditions are a major economic concern (Boschiero et al., 2019; Büchele et al., 2024; East et al., 2013). Nevertheless, the ULO system remains one of the prevailing storage methods globally. Following a 6-month period in ULO storage infrastructure, the fruit is brought to market with minimal storage losses (3–5%) and warrants a higher price compared to fruit sold at harvest (Büchele et al., 2024; Korićanac et al., 2019; Matejicek et al., 2015).

In temperate fruit production, pesticides play a major role in fruit disease and pest management (Jackson et al., 2011; Tromp et al., 2005). In apple orchards, plant protection cost constitutes 18–35% of the total production expenses, thereby representing the major cost of apple production (Akdemir et al., 2012; Glover et al., 2002; Goossens et al., 2017; Taylor and Granatstein, 2013). Over recent decades, global emphasis on environmental and food safety principles become strategic concepts due to the increasing demand for healthy and sustainable food production (European Commission sources, 2024b; Reganold et al., 2001). The principles has greatly encouraged the use of biological control options and/or non-chemical control methods in crop protection. This led to a notable increase in integrated and organic apple production than the conventional one. Nowadays, a substantial portion of apple production in Europe adheres to sustainable production practices, encompassing both integrated and organic fruit production systems (European Commission sources, 2024b; Ekinci et al., 2020; Liang et al., 2021). In both sustainable production systems, a major plant protection element is the apple scab management, especially in high-humidity areas where severe scab epidemics can occur (Ekinci et al., 2020; Holb, 2009; Orpet et al., 2020). In many apple-growing areas, inadequate management of apple scab can result in economic losses ranging from 70% to 100% (Biggs and Stensvand, 2014; Holb et al., 2017; MacHardy, 1993, 1996). The production costs of apples are primarily contingent on the intensification level of production technology (extensive, intensive, super intensive), orchard size and orchard system (conventional, integrated, organic) (Beresford and Manktelow, 1994; Ekinci et al., 2020; Ellis et al., 1998; Glover et al., 2002; Taylor and Granatstein, 2013; Wani et al., 2021; Zhang et al., 2017). In the organic orchard system, spray costs against fungal diseases can comprise up to half of the total production expenses (Holb, 2008). Furthermore, many pesticides are prohibited in organic farming, and those permitted are often less effective against diseases compared to chemical fungicides. Consequently, the importance and economic value of alternative defense strategies are crucial in organic production (Holb, 2009; Holb et al., 2017; Taylor and Granatstein, 2013). Several studies focused on comparative economic analyses of apple disease management, considering costs of fungicides, spraying equipment, application rates, cultivars and orchard sizes (Beresford and Manktelow, 1994; Ellis et al., 1998; Funt, 1990; Liang et al., 2021; Sedlar et al., 2013; Sotirov et al., 2018; Yilmaz et al., 2015). However, economic benefit of specific non-chemical control methods have been rarely considered (Antal et al., 2024).

Apple scab (*Venturia inaequalis*) can be effectively controlled with fungicides, but the frequency of fungicide applications may increase by up to 25% annually depending on various factors such as weather conditions, cultivar susceptibility, growing regions and management approaches (Chatzidimopoulos et al., 2020; Holb, 2008, 2009; Holb et al., 2017, 2022). To address this issue, several non-chemical control approaches, including cultural, physical, sanitation and biological methods, have been developed to either replace or reduce fungicide applications against apple scab (Caffi et al., 2017; Carisse and Dewdney, 2002; Didelot et al., 2016; Holb, 2006; Sutton et al., 2000; Vincent et al., 2004). Among these non-chemical control methods, sanitation practices have proven to be highly effective in reducing scab disease development. Common sanitation practices include leaf shredding, leaf collecting, orchard floor covering (e.g. with mulch). These sanitation practices have significantly suppressed the development of the fungus and reduced the incidence of scab symptoms by 23–92% during the primary infection season (Holb, 2006; MacHardy, 1993; Sutton et al., 2000; Vincent et al., 2004; von Diest et al., 2016). The biological effectiveness of sanitation options has been demonstrated both integrated and organic commercial apple orchards, across various apple cultivars with differing scab susceptibility (e.g. Didelot et al., 2016; Holb et al., 2017). However, cost and economic benefit of sanitation practices have only been investigated in one previous research conducted at fruit harvest (Antal et al., 2024). The authors demonstrated that leaf collection sanitation practices resulted in lower fruit scab incidence, along with better fruit quality, and yielded a surplus economic benefit at harvest. Since the fruit quality of harvested fruit determines the quality during storage, preharvest sanitation methods may have economic benefits on fruit quality after storage, especially considering that apple scab does not develop under ULO storage conditions. Nevertheless, this previous study did not evaluate whether sanitation practices can confer benefits when apples are stored for 6 months under ULO storage conditions. Additionally, it remains unclear whether the benefits of ULO storage can be realized for fruit produced in both sustainable productions systems or exclusively for either integrated or organic system.

In this study, we posited two hypotheses: i) that specific sanitation practices lead to economic advantages in apple production subsequent to ULO storage, and ii) that the magnitude of these advantages differs between integrated and organic production systems. Aligned with these hypotheses, the objective of this 3-year study was to evaluate the cost-benefit ratios of five sanitation treatments (lime sulfur, leaf collection, mulching, lime sulfur + leaf collection, leaf collection + mulching) in integrated and organic commercial apple orchards, considering the sale of apples after 6-month ULO storage. The cost-benefits analyses were based on determining economic indicators including costs, revenues and the income surplus or deficit.

Materials and methods

Experimental orchards, plant material, sanitation treatments, and fruit yield assessment

Sanitation experiments were prepared from 2017 to 2019 in an organic apple orchard (15 ha, Eperjeske, Eastern-Hungary) and in an integrated apple orchard (20 ha, Nagykálló, Eastern Hungary, 89 km from the organic one). The orchards were established in 1996 with a slender spindle training system (4 × 1.5 m and 5 × 2 m distances) in Nagykálló and Eperjeske, respectively. Hungarian Integrated Fruit Production (IFP) guidelines according to the international IFP standards and Hungarian Organic Guidelines according to the International Federation of Organic Agriculture Movements (IFOAM) standards were applied in Nagykálló and Eperjeske, respectively. Fungicide active ingredients used against apple scab provided in supplementary Table 1. In both locations, trees were grafted on M.26 rootstocks and economic analyses were made on the scab susceptible apple cultivar Jonagold.

Table 1. Calculated prices of dessert apples (class 1) excluding VAT in EUR kg^{-1} in case of the sale period of March–April in integrated and organic orchards (nagykálló and Eperjeske, Hungary, 2017–2019).

Years	*Integrated orchard*	*Organic orchard*
2017	0.54	0.78
2018	0.30	0.43
2019	0.45	0.66

[a]Based on average monthly production price of Hungarian Governmental sources (2024b) and convert to EUR by Hungarian Governmental sources (2024a).
[b]Prices were calculated by 145% of dessert apples of integrated apple orchard.

Five treatments in four replicates were prepared in a completely randomized block design: i) lime sulfur spray: one in October and an additional one in November, Lime-S; ii) fallen leaf collection in November, Collect-L; iii) orchard floor mulching in February, Mulch-C; iv) treatments i) + iii), i.e. lime sulfur application followed by mulching, Lime-S + Mulch-C; v) treatments ii) + iii), i.e. leaf collection followed by mulching, Collect-L + Mulch-C; vi) Non-sanitized control. Tiosol (2% with an active ingredient of 29% calcium polysulfide, Tiosol Ltd., Hungary) was used to treat leaves on the trees in Lime-S and Lime-S + Mulch-C treatments in October, and then fallen leaves on the orchard floor received an additional 4% Tiosol in November in both management systems and across the three years. A John Deere F-725 flail mower (Deere and Company, Moline, Illinois, USA) was used to collect leaves from the orchard floor in Collect-L and Collect-L + Mulch-C treatments in both systems and in all years. A 10-cm layer of winter wheat straw mulch was used to cover the orchard floor in Mulch-C and Collect-L + Mulch-C treatments before bud break in February.

The total fruit yield at harvest was measured in all the three years. Ten trees per plot were selected for each sanitation treatment in both management systems and all fruits per trees were weighted. Based on fruit scab incidences, two fruit quality classes were created: i) class 1 fruit (dessert apple fruits without scab) and ii) the remaining fruits as class 2 fruit (fruits infected with scab). In this study, total fruit yield and class 1 fruit were used for calculating total annual revenues (Rtotal) and revenues for the fruit quality category of class 1 (Rclass1), respectively.

Methods of economic analyses: cost-benefit analyses

Cost calculations of sanitation treatments

In order to determine the direct cost associated with each sanitation treatment, various types of expenses were gathered from 2017 to 2019. These costs encompassed materials, mechanical operations, depreciation, labor, and other miscellaneous expenses (Table S2). All costs, exclusive of VAT, were denominated in EUR per fruit tons and were calculated based on the monthly average exchange rates provided by Hungarian Governmental sources (2024a) for each respective year.

For the Lime-S treatment, material costs were determined by considering the annual prices of Tiosol and the annual fungicide price index (Hungarian Governmental sources, 2024b). This calculation was conducted separately for applications using 2% Tiosol in October and 4% Tiosol in November, in each year and under both orchard systems.

The cost of the 10-cm mulch layer of winter wheat straw (approximately 13 t ha^{-1}) was used as the material cost for the Mulch-C treatment. This was calculated based on the annual average prices of cereal straw (Hungarian Governmental sources, 2024b).

There were no material costs associated with the Collect-L treatment. However, costs related to composting were computed, taking into account open prismatic composting expenses (rotation, sifting) depending on the quantity of leaves collected from orchards (approximately 30 m^3 leaves ha^{-1}). The resulting compost quantities were 16.5 m^3 in integrated orchards and 13.5 m^3 in organic orchards per hectare annually. These produced composts served as a nutritional supply in the Collect-L treatment in both orchard systems. Consequently, they were valued as the active ingredient equivalent of NPK fertilizers, determined by the NPK content of apple leaves (N: 2.0%, P: 0.15%, K: 1.5%). The annual prices of NPK fertilizers, including Nitrosol (30% N content), Superphosphate (20% P content), and Potassium chloride granules (60% K content), were sourced from Hungarian Governmental sources (2024b). The cost of the produced compost, quantified as the NPK fertilizer's active ingredient equivalent, was incorporated into our calculations as additional revenue in the case of leaf collection treatments.

Within each sanitation treatment, mechanical, depreciation, and labor costs were derived from the annual expenses of agricultural machinery provided by National Agricultural Research and Innovation Center, Hungary (Hungarian Governmental sources, 2024c). In the mechanical and depreciation cost category, the costs attributed to the tractor were based on the performance of a 41–75 kW tractor equipped with specific machinery for the respective treatment. In Lime-S treatment, costs attributed to tractor with axial blower spray machine; in the Collect-L treatment, costs attributed to tractor and trailer with leaf collector vacuum sweeper; and in Mulch-C treatment, costs attributed to tractor and trailer with bale shredder and spreader, after with swathers.

For combined treatments, such as Lime-S + Mulch-C and Collect-L + Mulch-C, costs were determined by summing the individual components of each treatment. For instance, the cost of the combined Lime-S + Mulch-C treatment was calculated as the cost of the Lime-S treatment plus the cost of the Mulch-C treatment.

Calculation of apple fruit prices

For price calculations of stored fruits during the sales period of March to April, the average monthly production price (excluding VAT) of class I was obtained from Hungarian Governmental sources (2024b) for the integrated orchard. Prices of fruits per kilogram in the organic orchard were determined as 145% of the prices of dessert apples in the integrated orchard, based on the monthly average prices in EUR (Table 1). All values were converted to EUR using the monthly average exchange rates provided by Hungarian Governmental sources (2024a).

Calculation of ULO Storage Costs

The costs associated with ULO storage were determined through postharvest calculations following the methodology outlined by Szabó (2015). These calculations were performed considering the maximum yield capacities of the investigated orchards. Additionally, ULO costs were converted to EUR using the annual mean exchange rates provided by Hungarian Governmental sources (2024a). Furthermore, we conducted an assessment of storage losses in ULO facilities for dessert apples, specifically during the March–April sales period. This assessment entailed a reduction in the quantity of harvested fruits by 3% in integrated production and 6% in organic production.

Calculation of annual revenues and income surplus or deficit

Depending on the orchards, treatments, and sales periods, the annual revenues (Rtotal and Rclass1) for the five sanitation treatments and the non-sanitized control were calculated by multiplying appropriate yields and prices. The annual revenues of sanitation treatments including the control treatment were subtracted by the costs of ULO storage and storage losses during the March–April sales period. Annual revenues were adjusted with additional revenue from leaf collection treatments, i.e. revenues from compost in the Collect-L and Collect-L + Mulch-C treatments were added to obtain the values of corrected revenues.

The net-returns – income surplus or deficit (EUR ha^{-1}) – for each sanitation treatment was also determined for each year and orchard system. This was done by subtracting the cost of the sanitation treatment and the revenue of the non-sanitized control from the corrected revenues of the sanitation treatments.

Data Analyses

Analysis of Variance

Analysis of variance (Statistical Analysis System v. 8.1; SAS Institute Inc., Cary, NC) was performed in order to determine the effect of year, sanitation treatment, orchard system, and their interactions. Significant F tests ($p = .05$) were followed by an LSD test for comparison using $LSD_{0.05}$ values in order to determine the possible significant differences among year, sanitation treatment and orchard system for the parameters of total annual revenue, revenue for yield class 1 and income surplus/deficit.

A separate LSD test was performed to compare the data of the two orchard systems (integrated versus organic) for each year (overall treatments) and for the three years together (overall years). Significant F tests ($p = .05$) were followed by an LSD test for the comparison, using $LSD_{0.05}$ values to determine the possible significant differences between integrated and organic orchard systems for the parameters of total annual revenue, revenue for yield class 1, and income surplus/deficit.

Correlation analyses among parameters with descriptive statistics

The relationships among the three parameters (total annual revenue, revenue for yield class 1, and income surplus/deficit) were determined through Pearson correlation analyses. Correlation coefficients (r) and their associated significance levels ($p \leq .05$) were separately analyzed for integrated and organic orchard systems. Multiple testing correction was applied in the correlation analyses using the Bonferroni correction (Sedgwick, 2012). Descriptive statistics were prepared with boxplots [1.5×IQR (interquartile range), LQ (lower quartile), median, UQ (upper quartile), 1.5×IQR and outliers], density plots (Kernel density estimation), data plotting for correlation pairs and frequency distribution by orchard systems for the three parameters. The statistical package of R package GGally (Schloerke et al., 2021) was utilized for preparing the descriptive statistics.

Results

Direct cost of sanitation treatments and compost of collecting leaves and ulo storage

Values of the direct costs were significantly higher in the organic orchard system than in the integrated one in 2017, 2018 and the three overall years (Table 2).

In the integrated orchard system, the direct costs were the highest in the Lime-S + Mulch-C treatment ranging form 14.9 to 20.3 EUR t^{-1} (Table 2). The direct costs were the lowest in the Collect-L and in the Lime-S treatments in 2019 (3.7 EUR t^{-1} and 2.8 EUR t^{-1}, respectively). The direct costs of Lime-S + Mulch-C and Collect-L + Mulch-C treatments were significantly higher than the direct costs of Lime-S and Collect-L treatments in all years (Table 2).

In the organic orchard system, the direct costs were the highest again in the Lime-S + Mulch-C treatment ranging form 22.9 to 31.1 EUR t^{-1} (Table 2). The direct costs were the lowest in the Collect-L and in the Lime-S treatments in 2019 (5.6 EUR t^{-1} and 4.5 EUR t^{-1}, respectively). The direct cost of Lime-S treatment was significantly lower than the direct costs of Mulch-C, Lime-S + Mulch-C and Collect-L + Mulch-C treatments in all years. The direct costs of Lime-S + Mulch-C and Collect-L + Mulch-C treatments were significantly higher than the direct costs of Lime-S and Collect-L treatments in all years (Table 2).

The revenue generated from compost in the leaf collection treatments exhibited significantly lower values in the organic orchard system compared to the integrated one (Table 3). The lowest values were observed in 2017 (30.34 and 37.08 EUR ha^{-1}) and the highest one in 2019 (33.30 and 40.7 EUR ha^{-1}) for the organic and integrated orchard systems, respectively (Table 3).

Values of the costs of ULO storage were approximately twice higher in the integrated orchard system than in the organic one and these values were significantly different from each other (Table 3). The lowest values were in 2019 (2939 and 1450 EUR ha^{-1}), while the highest one in 2017 (3127 and 1543 EUR ha^{-1}) in the two orchard systems, respectively (Table 3).

Table 2. Total direct costs (EUR t^{-1} fruit) of six orchard sanitation treatments (lime sulfur -lime-s, leaf collection-collect-l, mulch covering – mulch-c, lime-S + mulch-c, collect-L + mulch-C and non-sanitized control) in two orchard systems (integrated and organic) assessed at the harvest of years from 2017 until 2019 (nagykálló and Eperjeske, Hungary).

Orchard and treatment/year	2017	2018	2019	Overall (year)
Integrated				
Lime-S	4.6b	5.0b	2.8b	4.1b
Collect-L	4.3b	4.6b	3.7b	4.2b
Mulch-C	13.5a	15.8a	11.3a	15.3a
Lime-S + Mulch-C	17.2a	20.3 ba	14.9a	17.5a
Collect-L + Mulch-C	17.0a	19.9a	12.9a	16.6a
$LSD_{0.05}$[b]	4.8	5.5	3.8	4.7
Organic				
Lime-S	7.6c	7.7b	4.5c	6.6c
Collect-L	7.4c	7.1b	5.6c	6.7c
Mulch-C	21.7b	24.2a	17.2b	21.0b
Lime-S + Mulch-C	29.1a	31.1a	22.9a	27.7a
Collect-L + Mulch-C	28.9ab	30.2a	20.9ab	26.7ab
$LSD_{0.05}$	7.3	7.0	5.1	6.4
Overall (treatment)				
Integrated	11.3b	13.1b	9.1	11.2b
Organic	18.94a	20.1a	14.2	17.7a
$LSD_{0.05}$	7.3	6.9	ns	6.4

[a]Values followed by the same letter are not significantly different according to LSD test ($p = .05$).
[b]$LSD_{0.05}$ = least significant differences at $p = .05$ level.

Table 3. Costs of ULO storage and revenues of compost (EUR ha^{-1}) in integrated and organic orchard between 2017 and 2019 (nagykálló and Eperjeske, Hungary, after 6-month ULO storage).

	Cost of ULO storage (EUR ha^{-1})		Revenue of compost (EUR ha^{-1}) [a]	
	Integrated orchard	Organic orchard	Integrated orchard	Organic orchard
2017	3127	1543	37.08	30.34
2018	3126	1542	37.95	31.05
2019	2939	1450	40.70	33.30
Overall years	3064a	1512b	38.58a	31.56b

[a]Calculated by the average prices of Nitrosol 30%, Superphosphate 20%, Potassium chloride granules 60% based on Hungarian Governmental sources (2024c) multiplied the amounts of producible equivalent NPK active ingredient of compost from collecting leaves.

Total revenues and revenue for yield class 1 for sanitation treatments

Analysis of variance for total revenue and revenue for class 1 indicated significant ($p < .05$) differences among years and sanitation treatments in both orchard systems (Table 4). There were no significant interactions among treatment factors. As background information, overall three-years values of apple

Table 4. Analysis of variance for the effects of year (2017, 2018, and 2019), sanitation treatments (lime sulfur, leaf collection, mulch covering, lime sulfur + mulch covering, leaf collection + mulch cover and non-sanitized control), and orchard system (integrated and organic) on total revenue and revenue for class 1 (nagykálló and Eperjeske, Hungary, 2017–2019, after 6-month ULO storage).

		Total revenue		Revenue for class 1	
Source of variation	df	MS	*p*	MS	*p*
Year (Y)	2	87,174,824	<0.001	70,037,1221	<0.001
Treatment (T)	5	12,521,482	0.012	12,532,431	0.008
Main plot error	10	32,934		32,986	
Orchard (O)	1	45,248,281	<0.001	11,352,364	<0.001
T × O	5	27,661	0.476	27,949	0.479
Sub-plot error	29	5,539,295	<0.001	6,103,418	

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

scab incidence on fruit (%), total fruit yield (t ha^{-1}) and fruit yield class 1 (t ha^{-1}) in the six orchard sanitation treatments in two orchard management systems assessed after six months of ULO storage are shown in supplementary Table 3.

The "overall (treatment)" for total annual revenues was significantly higher in the integrated orchard system (10,787 EUR ha^{-1}) compared to the organic one (8,713 EUR ha^{-1}, Figure 1). The values of total annual revenue were not affected by sanitation treatments in 2018 in the integrated orchard system (Figure 1). The lowest values of total annual revenue were obtained in the non-sanitized control in 2018 for the organic orchard system (5,639 EUR ha^{-1}), while highest one (16,720 EUR ha^{-1}) were measured in the Collect-L treatment in 2017 in the integrated orchard system. Total annual revenue in the Lime-S or Mulch-C or Lime-S + Mulch-C treatments were not significantly different from the non-sanitized control treatments in all years and in 2019 in the organic and the integrated orchard systems, respectively. In the integrated orchard system, the values of total annual revenues were significantly higher in all sanitation treatments in 2017 than in the non-sanitized control (Figure 1).

The "overall (treatment)" revenues for the fruit quality category of class 1 was significantly higher in the integrated orchard system (10,557 EUR ha^{-1}) compared to the organic one (7,742

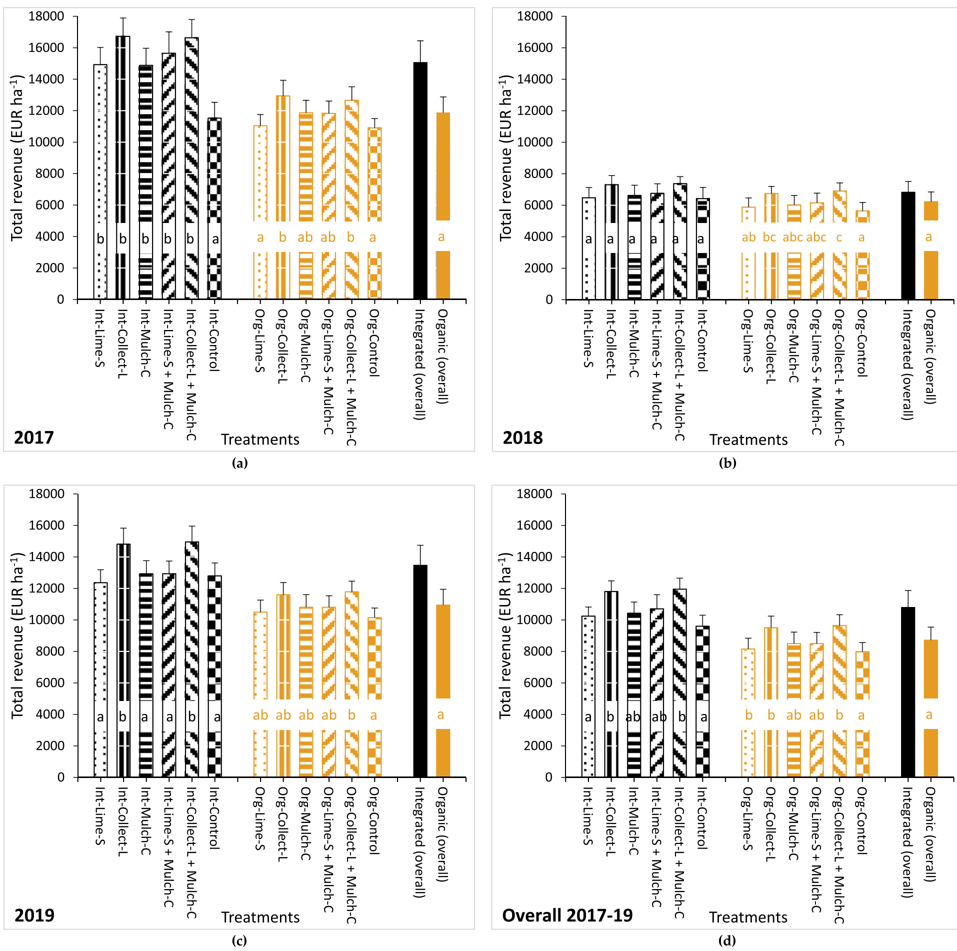

Figure 1. Total annual revenues (rtotal) in EUR ha^{-1} of apple cultivar "jonagold" in six orchard sanitation treatments (lime sulfur-lime -s, leaf collection-collect-l, mulch covering-mulch-c, lime-S + mulch-c, collect-L + mulch-C and non-sanitized control) after 6-month ULO storage (March–April) in integrated (int) and organic (org) orchards between 2017 and 2019 (nagykálló and Eperjeske, Hungary). (a) 2017, (b) 2018, (c) 2019, and (d) overall 2017–2019. Bars above columns represent SD values.

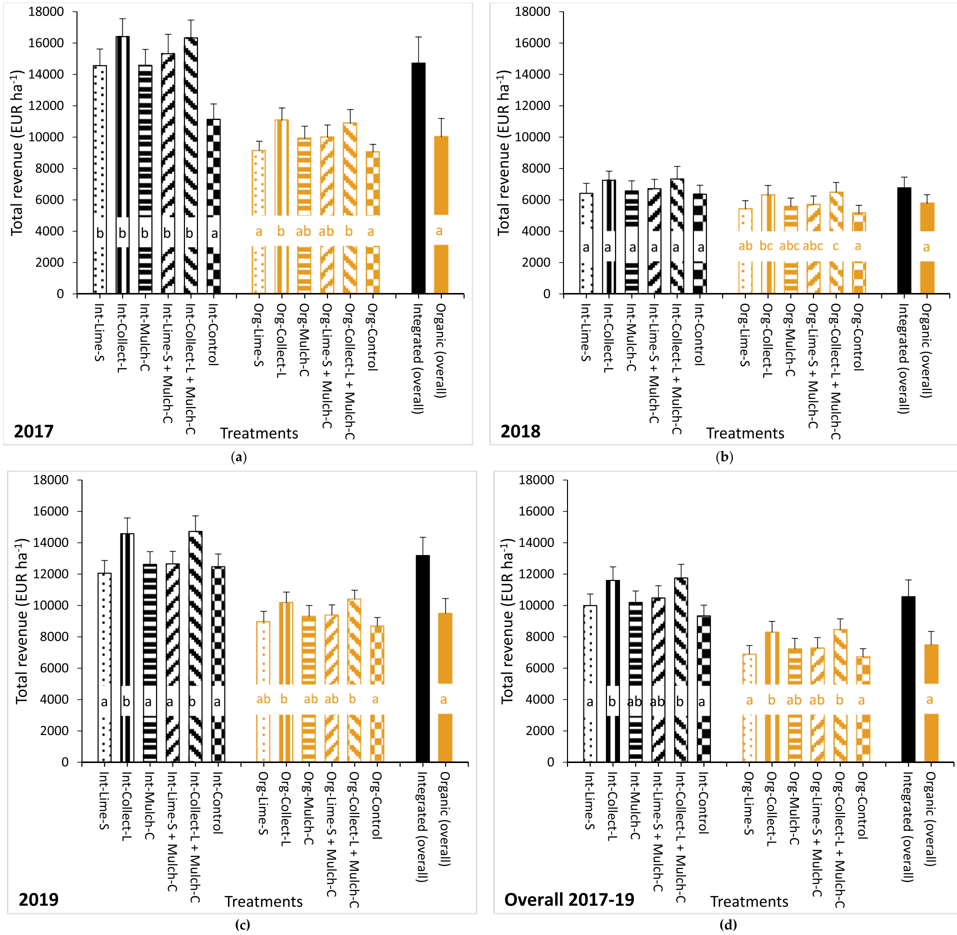

Figure 2. Revenues for fruit quality category of class 1 (Rclass1) in EUR ha^{-1} of apple cultivar "jonagold" in six orchard sanitation treatments (lime sulfur-lime-s, leaf collection-collect-l, mulch covering-mulch-c, lime-S + mulch-c, collect-L + mulch-C and non-sanitized control) after 6-month ULO storage (March–April) in integrated (int) and organic (org) orchards between 2017 and 2019 (nagykálló and Eperjeske, Hungary). (a) 2017, (b) 2018, (c) 2019 and (d) overall 2017–2019. Bars above columns represent SD values.

EUR ha^{-1}) in all years (Figure 2). Similar to total annual revenues, sanitation treatments did not have an impact on the values of revenues for the fruit quality category of class 1 in 2018 within the integrated orchard system (Figure 2). The lowest values of revenues for the fruit quality category of class 1 were obtained in the non-sanitized control in 2018 for the organic orchard system (5,133 EUR ha^{-1}), while highest returns (16,412 EUR ha^{-1}) were recorded in the Collect-L treatment in 2017 within the integrated orchard system. Revenues for the fruit quality category of class 1 in the Lime-S or Mulch-C or Lime-S + Mulch-C treatments did not significantly differ from the non-sanitized control treatments in all years and in 2019, in the organic and the integrated orchard systems, respectively. In the integrated orchard system, the revenues for the fruit quality category of class 1 were significantly higher in all sanitation treatments in 2017 compared to the non-sanitized control (Figure 2).

Table 5. Analysis of variance for the effects of year (2017, 2018, and 2019), sanitation treatments (lime sulfur, leaf collection, mulch covering, lime sulfur + mulch covering, and leaf collection + mulch cover), and orchard system (integrated and organic) on income surplus/deficit in relation to non-sanitized control treatment (nagykálló and Eperjeske, Hungary, 2017–2019, after 6-month ULO storage).

		Suplus income/deficit	
Source of variation	d.f.	MS	*p*
Year (Y)	2	87,174,824	<0.001
Treatment (T)	4	12,521,482	0.012
Main plot error	8	32,934	
Orchard (O)	1	45,248,281	<0.001
T × O	4	27,661	0.476
Sub-plot error	29	5,539,295	<0.001

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

Table 6. Income surplus or deficit (EUR ha^{-1}) of apple cultivar "jonagold" in six orchard sanitation treatments (lime sulfur -lime-s, leaf collection-collect-l, mulch covering-mulch-c, lime-S + mulch-C and Collect-L + mulch-c) after 6-month ULO storage (March–April) in integrated and organic orchards between 2017 and 2019 (nagykálló and Eperjeske, Hungary).

Orchard and treatment/year	2017	2018	2019	Overall (year)
Integrated				
Lime-S	−355a [a]	−107 ba	−589a	−233a
Collect-L	1 450b	730c	1 865b	1346b
Mulch-C	−732a	−361a	−384a	−388a
Lime-S + Mulch-C	−123a	−375a	−539a	−266a
Collect-L + Mulch-C	877b	252b	1 489b	998b
$LSD_{0.05}$ [b]	781	382	811	582
Organic				
Lime-S	−16a	77a	194a	11a
Collect-L	1 882b	943b	1 297b	1371b
Mulch-C	476a	−83a	143a	37a
Lime-S + Mulch-C	275a	−196a	−19a	−140a
Collect-L + Mulch-C	1 111b	557b	968b	1018b
$LSD_{0.05}$	566	432	441	451
Overall (treatment)				
Integrated	223a	28	368	291
Organic	746b	260	517	459
$LSD_{0.05}$	511	ns	ns	ns

[a]Values followed by the same letter are not significantly different according to LSD test ($p = .05$).
[b]$LSD_{0.05}$ = least significant differences at $p = .05$ level.

Income surplus or deficit of sanitations compared to the non-sanitized control

Analysis of variance for income surplus/deficit indicated significant ($p < .05$) differences among years, sanitation treatments and orchard systems (Table 5). There were no significant interactions among treatment factors.

The "overall treatment" income surplus or deficit was significantly lower in 2017 in the integrated orchard system (223 EUR ha^{-1}) compared to the organic one (746 EUR ha^{-1}, Table 6). However, in subsequent years, the two orchard systems did not differ from each other (Table 6).

The highest income surplus (1882 EUR ha^{-1}) was obtained in Collect-L treatment in 2017 within the organic orchard system. Conversely, the highest deficit (−732 EUR ha^{-1}) was recorded in the Mulch-C treatment in 2017 within the integrated orchard system (Table 6). Income surplus was consistently observed in the treatments of Collect-L and Collect-L + Mulch-C in all years and both orchard systems. Moreover, values in these treatments were significantly higher compared to corresponding values of all other treatments in all years and in both orchard systems (Table 6).

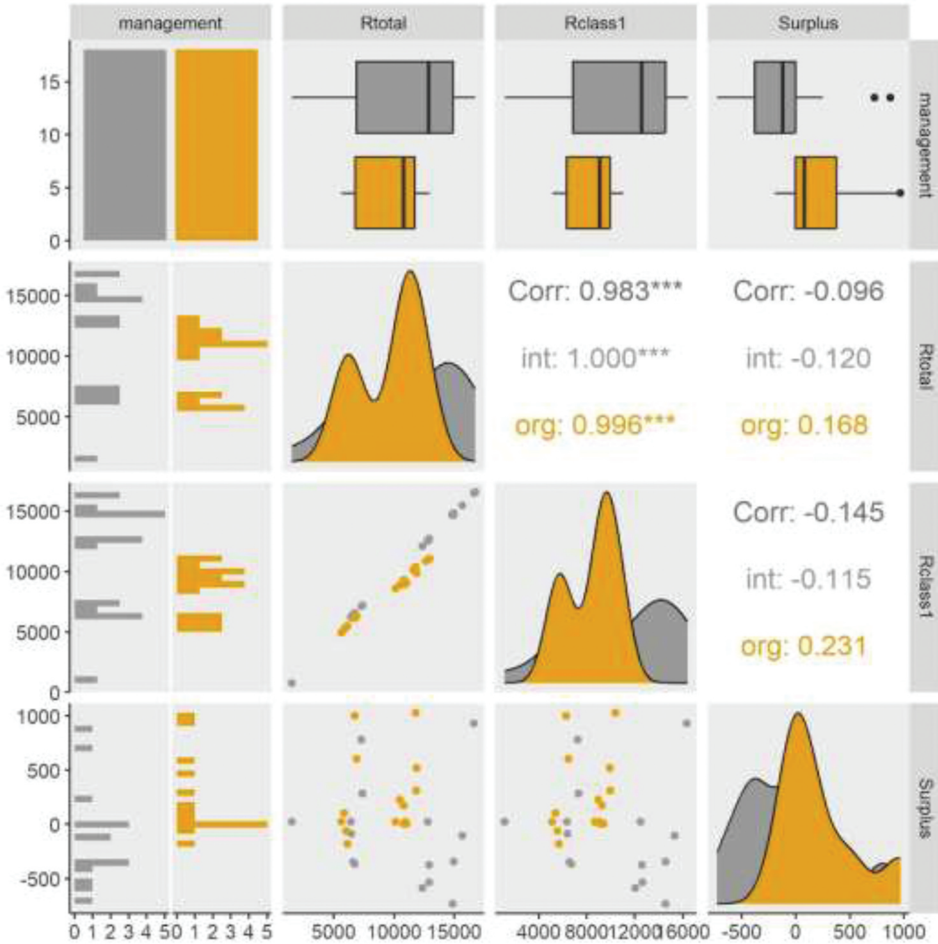

Figure 3. Pearson correlation coefficients (Corr), boxplots (1.5×IQR, LQ, median, UQ, 1.5×IQR and outliers), density plots (kernel density estimation), data plotting for correlation pairs (ocher yellow and gray pints) and frequency distribution by management groups among six orchard sanitation treatments in integrated (int, gray color) and organic (org, ocher yellow color) orchards (nagykálló and Eperjeske, Hungary, 2017–2019, after 6-month ULO storage). *** represent significant correlations at 0.001 levels, respectively. scab: Rtotal: total annual revenue, Rclass1: revenue for yield class 1 and surplus: income surplus/deficit. In the correlation analyses, the Bonferroni correction test was used.

Descriptive statistics and correlation among parameters

Descriptive statistics showed that IQRs, Kernel density estimations and frequency distributions were the widest for the parameters of total revenue and revenue for class 1 in the integrated orchard system (Figure 3). The Pearson correlation coefficient (r) was the highest ($r = 0.999$) between total annual revenue (Rtotal) and revenue for yield class 1 (Rclass1) in the integrated orchard system (Figure 3). The correlation pair of Rtotal vs Rclass1 was significant ($p = .001$) for both the integrated and organic orchard systems (Figure 3). The scatter plot figure revealed a significant ($p = .001$) linear relationship for Rtotal vs Rclass1 in both orchard systems (Figure 3).

Discussion

In this 3-year study, we determined direct costs, annual revenues and income surplus or deficit of five sanitation treatments (Lime-S, Collect-L, Mulch-C, Lime-S + Collect-L, Collect-L + Mulch-C) in integrated and organic orchard systems when the fruit was sold after six months ULO storage. Furthermore, density plots, frequency distributions and correlations were demonstrated among cost-revenue-income parameters for the sanitation practices in both orchard systems.

The ULO storage costs in EUR ha^{-1} in the organic orchard system were approximately half compared to those observed in the integrated orchard system (Table 3). This discrepancy between the two orchard systems arises from the fact that fruit yields per hectare in organic apple orchards are 40–75% lower compared to integrated ones (Holb et al., 2012, 2022; Peck et al., 2006, 2010; Reganold et al., 2001). Furthermore, 10–25% of the harvested organic fruit is unsuitable for ULO storage (Fotirić Akšić et al., 2022; Róth et al., 2007). Although, the storage costs for a ton fruit remain nearly uniform between the organic and integrated orchard systems, the quantity of fruit per hectare amenable to storage in organic orchards is nearly halved compared to the integrated ones. This resulted in an approximate 50% reduction in storage costs per hectare for the organic orchard compared to the integrated one (Table 3).

The costs of each sanitation type per hectare were the same for integrated and organic orchards, as the same machines and materials were used for the sanitation treatments regardless of whether the farming management was integrated or organic. The direct costs of sanitation treatments in EUR t^{-1} were higher in the organic orchard system than in the integrated one (Table 2). This disparity may be attributed to the orchard practices employed in the two types of orchards systems. In the organic orchard system, disease and pest orchard are less effective, and only natural nutrient supplies are permitted, in contrast to the integrated approach (Holb et al., 2017, 2022; Peck et al., 2006; Reganold et al., 2001). These differences in management practices result in reduced fruit yield and size, an increase in fruit damage caused by insects and diseases, thereby reducing the proportion of first-grade fruits in the organic orchard system compared to the integrated one (Holb et al., 2012, 2022). This finding aligns with the results of this study and the study by Antal et al. (2024), where revenue from first-grade fruits is lower in the organic farming compared to integrated one at harvest and after 6 months of ULO storage, respectively. These factors contribute to the increased production cost per ton of fruit in organic orchard system compared to the integrated one (Table 2). Consequently, this indicates that the costs of all sanitation treatments per ton of fruit are likely to be significantly higher in commercial organic orchards compared to commercial integrated ones as well.

Among the sanitation treatments, the Mulch-C treatment emerged as the most economically burdensome method per ton of fruit, being 2.8–3.7 times more expensive compared to either Collect-L or Lime-S treatment, among the three single treatments (Table 2). This cost disparity is attributed to substantial material costs in the Mulch-C treatment compared to the other two ones (unpublished data). The cost per ton of fruit in combined treatments reaches the highest levels, primarily due to the cumulative expenses of individual treatments, with 70–75% of these costs attributed to the utilization of mulch. Consequently, the economic advantages of mulching are questionable, and its role is affirmed exclusively in the Collect L + Mulch-C treatment after 6-month ULO storage (Table 6). This treatment effect was also confirmed at harvest in the previous study of Antal et al. (2024). Furthermore, mulch cover has been shown to present several biological drawbacks, such as its potential to attract pests detrimental to cultivated crops, negatively impact on some soil microbial communities, and increase the severity of apple replant disease (Merwin and Stiles, 1994; Merwin et al., 1999; St Laurent et al., 2008; Yao et al., 2009). However, mulch cover also offers biological advantages, such as providing habitats for natural predators or increasing essential plant nutrients in the soil (Atucha et al., 2011; Marliac et al., 2015; Miñarro and Dapena, 2003; Pfiffner et al., 2019; Teravest et al., 2010; Yan et al., 1997). Due to the aforementioned reasons, mulching is particularly crucial in organic farming, where opportunities for nutrient supply and soil life enhancement are more limited compared to integrated farming (Holb and Nagy, 2009; Peck et al., 2006; Xu et al., 2024). Thus, the application of mulch cover in a combined treatment should be based on both economic and biological benefits, particularly when the harvested apple fruit is planned to be stored in the ULO storage system, which has a high per-hectare cost (Table 3) with continuously increasing energy input costs for ULO storage facility (Boschiero et al., 2019; Büchele et al., 2024; East et al., 2013).

A previous study of Antal et al. (2024) demonstrated that the sanitation treatments of Collect-L and Collect-L + Mulch-C were able to generate income surplus after harvest in both integrated and organic apple orchards. In this study, we hypothesized that these sanitation practices against apple scab can lead to economic advantages not only at harvest but subsequent to ULO storage. This hypothesis was supported by our findings as we observed that income surplus produced by Collect-L and Collect-L + Mulch-C treatments persisted even after six months of storage (Table 6), in spite of the high cost of ULO storage (Boschiero et al., 2019; Büchele et al., 2024), the higher spring selling prices ensured income surplus in the following spring. On the other hand, the sanitation treatments of Lime-S, Mulch-C, Lime-S + Mulch-C resulted in income deficits in most years, especially in the integrated production systems (Table 6). This study also revealed that the magnitude of income surplus of certain sanitation treatments differs between integrated and organic orchards. In most cases, the economic benefit was lower in the integrated orchard than in the organic one in most years, but in one year (2019), the Collect-L and Collect-L + Mulch-C treatments produced more income surplus in the integrated orchard compared to the organic one (Table 6). The reasons of the variability may be that the organic system is more sensitive to environmental and yearly effects in terms of yield and quality than the integrated one (Antal et al., 2024; Goossens et al., 2017; Reganold et al., 2001; Taylor and Granatstein, 2013), even if the fruit prices are higher in the organic system than in the integrated one. Due to higher environmental sensitivity in the organic orchard, the amplitude of income surplus can be higher in the organic system than in the integrated one in one year, while in another year, the income surplus in the organic system can fall below that in the integrated one (Table 6).

This study clearly demonstrated that the Collect-L treatment is one of the most successful sanitation methods economically (Table 6, Figures 1 and 2). This treatment not only provided income surplus but provides nutrient return by composting the collected fallen leaves (Table 3, Ekinci et al., 2021; Holb, 2006). As these leaves originated from the same orchard, the produced organic matter returns to the same area as an environmental friendly nutrient supply, reducing the total nutrient costs of the orchard. These points are especially important in the organic production system, where the balanced nutrient return is challenging, and the leaf collection itself also contributes to disease reduction (Fotirić Akšić et al., 2022; Holb et al., 2017; Taylor and Granatstein, 2013), cost reduction, and income surplus, which can be particularly beneficial for a biologically and economically sensitive production system such as the organic one.

Overall, this work clearly demonstrated that regardless of years and orchard systems, Collect-L and Collect-L + Mulch-C treatments ensured a stable income surplus after 6 months ULO storage under the given fruit price categories and treatment costs (Table 6). Thus, this study showed stable economic benefits for both orchard systems. However, key questions regarding economic benefits arose, such as how the increase in ULO storage energy costs and potential reductions in fruit prices and/or increases in treatment costs could diminish the income surplus of these sanitation practices to zero. Thus, whether the future fruit prices can cope with the unpredictable increase of energy prices as expressed in production and ULO storage costs. Therefore, the stability of income surplus from sanitation practices is influenced by several factors that may warrant further research.

Conclusions

This study demonstrated that orchard sanitation treatments against apple scab influenced the economic parameters of cost, revenue and income after 6 months of ULO storage, indicating their possible benefit both in integrated and organic apple orchard systems.

This study demonstrated that Collect-L and Collect-L + Mulch-C treatments provided the greatest economic benefit after 6-month ULO storage in all years and under both orchard systems. However, it has to note that the combined sanitation treatment is more sensitive to increasing energy costs compared to the treatment applied individually.

From an economic standpoint, other sanitation treatments cannot be recommended for either orchard system after 6-month ULO storage. However, in the organic orchard system, the use of sanitation treatments may be considered even if not economically justified. This is because: i) the positive environmental effects of sanitation treatments may outweigh financial considerations, and ii) due to the limited availability of effective biological control options, sanitation practices can be essential for significantly reducing the severity of apple scab infections in organic orchards.

Disclosure Statement

No potential conflict of interest was reported by the author(s).

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author, IJH, upon reasonable request.

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