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Effect of washing treatments on the removal of pesticide residues, bioactive compounds, and post-harvest quality of sweet cherries (*Prunus avium* L.)

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Abstract

Background Pesticide residues on harvested fruits and vegetables pose significant public health concerns. While consumers commonly use home-type washing treatments to remove these residues, their effectiveness requires scientific validation. This study investigates the effects of pre-harvest pesticide applications and post-harvest washing methods on pesticide residue removal, physicochemical quality parameters, and storage behavior of sweet cherry fruits (*Prunus avium* L.) during 28 days of cold storage at 1 °C.

Results Pre-harvest application of commonly used pesticides (malathion, boscalid + pyraclostrobin) followed by post-harvest washing treatments (distilled water, 5% vinegar, and 5% sodium bicarbonate) significantly influenced residue levels and quality of sweet cherries during storage. Distilled water was the most effective method for reducing pesticide residues, followed by sodium bicarbonate (NaHCO₃) and vinegar. However, NaHCO₃ treatments resulted in greater mass loss and negatively impacted fruit firmness. Pesticide treatments increased soluble solids content but generally reduced titratable acidity and antioxidant capacity by the end of storage. Pesticide and carbonate treatments contributed to undesirable changes in overall fruit quality.

Conclusions Washing treatments, especially with distilled water, effectively reduced pesticide residues from cherries, promoting safer consumption. Washing treatments involving distilled water and vinegar had a positive impact on the preservation of fruit quality. Nevertheless, some treatments had a negative impact on storage quality. These findings highlight the need for further research to identify optimal combinations of washing agents and storage strategies tailored to different pesticides and fruit types.

Keywords Pesticide residues, Sweet cherry, Postharvest washing, Fruit quality, Bioactive compounds

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Introduction

Cherries are rich in vitamins C, K, and A, as well as magnesium, potassium, and bioactive compounds; therefore, they have a positive impact on human health [1]. With unique color, taste, and aroma components, cherries are among the most desired fruits. Early ripening and marketing are critical economic issues in cherry cultivation [2]. According to the FAO (Food and Agriculture Organization) [3], Türkiye is the world's leading cherry producer with an annual production of 689,834 tons. However, it ranks third among countries that export cherries. The significant difference between production and export is primarily attributed to post-harvest losses, packaging and marketing issues, distance to consumer countries, fruit quality, and levels of pesticide residues.

Pests and diseases encountered throughout different growth stages result in serious losses in cherry cultivation. These pests and diseases include Armillaria root rot (*Armillaria mellea*), ruit monilia (*Monilinia fructigena*), Phytophthora root and crown rot (*Phytophthora* spp.), flower and shoot monilia (*Monilinia laxa*), cherry leaf spot (*Blumeriella jaapi*), bacterial cancer (*Pseudomonas syringae*), leaf borer (*Stigmia carpophila*), and root gall (*Agrobacterium tumefaciens*) [4]. Several methods and cultural practices, physical, biological, biotechnical, chemical, and integrated management methods are employed to control pests and diseases. As it is worldwide, chemical disease control treatments are also widely used in Türkiye, as they have proven effective in a short time and are easy to use. In 2020, the pesticide groups used in Türkiye agricultural sector were fungicides (38.4%), herbicides (27.49%), and insecticides (23%) [5].

Producers often use pesticides to achieve higher yields and improve quality traits [6–8]. Unconscious use of pesticides, repeated applications, and overdoses result in residue levels on foodstuffs above the maximum residue limit (MRL). Repeated consumption of foods containing high levels of pesticide residues may lead to acute or chronic health effects, depending on the level and duration of exposure [9]. The levels of pesticide residues on food seriously threaten human health, and may cause complications such as nausea, mild headaches, skin rashes, blindness, blurred vision, paralysis, neurological disorders, and even death [10]. It was also recorded that they cause diseases such as cancer, reproductive damage, and endocrine disruption [11–14]. People are exposed to pesticides mainly through the consumption of fresh produce containing high residue levels.

Fresh vegetables and fruits are frequently exposed to pesticides [15]. Several methods are used to remove pesticides, including washing, cooling, cooking, ultrasonic cleaning, and ozone treatment [16–18]. Washing is the most common method used to remove pesticide residues. Essentially, tap water and aqueous solutions

containing various chemicals (such as sodium bicarbonate, oxalic acid, potassium permanganate, acetic acid, and malic acid) are used in washing treatments [7, 19]. Previous researchers have demonstrated that washing treatments are effective in removing pesticide residues from various fruits and vegetables, including apples [19], lettuce [16], strawberries [20], tomatoes [21], potatoes, onions, and cabbage [22].

The objective of this study was to evaluate the effects of pre-harvest disease control practices, post-harvest washing treatments, and storage conditions on pesticide residue removal and the overall quality of sweet cherry fruits (*Prunus avium* L.). Disease control products containing malathion (an insecticide) and boscalid + pyraclostrobin (a fungicide), commonly used to control pests and diseases, were applied to cherries before harvest. After harvest, home-type washing techniques (distilled water, vinegar, and sodium bicarbonate) were used to remove pesticide residues. The effects of these pre- and post-harvest practices on residue reduction and fruit quality during storage were investigated.

Materials and methods

Chemicals and reagents

Boscalid (98.97% purity), malathion (98.33%), and pyraclostrobin (99.57% purity) standards were obtained from Dr. Ehrenstorfer Laboratories GmbH (Augsburg, Germany). Acetonitrile (MeCN > 99% purity), methanol (MeOH > 99% purity), anhydrous magnesium sulphate ($\text{MgSO}_4 \geq 99\%$ purity), sodium acetate ($\text{NaOAc} \geq 99\%$ purity), and acetic acid ($\text{AcOH} > 99\%$ purity) were obtained from Merck (Darmstadt, Germany). Primer secondary amine (PSA, 40 μm particle size) was obtained from Supelco Analytical (Bellefonte, PA, USA).

Field treatments

Pesticides were applied to 0900 Ziraat Cherry trees grafted onto Ma X Ma 14 (Mozard-Mahlep) rootstock. Experiments were conducted on experimental fields of Tokat Gaziosmanpaşa University (40° 20' 02" N latitudes, 36° 28' 35" E longitudes, 588 m altitude). Trees were planted at 5 × 3 m spacing (row spacing × on-row tree spacing) in East-West orientation. The field trials were conducted using a randomized complete block design. Selected pesticides were applied to cherry trees with a backpack sprayer at the recommended label dose. Each pesticide was applied to three cherry trees per replicate, with three replicates established for each treatment, totaling nine trees per treatment. Applications were made 3 days before harvest. The active ingredients and doses of the applied pesticides are shown in Table 1. Cherry samples were collected in accordance with the European Commission Directive 2002/63/EC on sampling for the official control of pesticide residues in/on products of

Table 1 Types of pesticides applied to sweet cherries pre-harvest

Trade name	Producer	Active ingredient and ratio	Treatment dose (g/100L water)
Agrofarm Malathion	SAFA TARIM A.Ş.	650 g/l Malathion	100
Signum WG	BASF	26.7% Boscalid + 6.7% Pyraclostrobin	75
Bellis	BASF	25.2% Boscalid + 12.8% Pyraclostrobin	40

EU-MRL: Boscalid; 5 mg/kg, Pyraclostrobin; 3 mg/kg, Malathion: 0.02 mg/kg

plant and animal origin [23]. Cherries were harvested at commercial maturity, and approximately 6 kg of fruit was collected per pesticide treatment for analyses.

Washing treatments and storage conditions

Cherry fruit samples were brought to the laboratory immediately after collection. For the 0900 Ziraat sweet cherry cultivar, harvest was carried out when the average soluble solids content (SSC) reached approximately 14–15%. Fruits selected for the study were free from diseases, pests, and blemishes, and exhibited uniform size. Throughout the storage period, including all treatments and replications, a total of 204 PET crates (each containing 300 g) were used. For day 0 analyses, 12 crates were prepared (4 pre-harvest treatments × 3 replicates). For days 7, 14, 21, and 28, a total of 48 crates were used at each sampling time (4 pre-harvest treatments × 4 post-harvest washing treatments × 3 replicates). Approximately 70 kg of cherries were harvested for the overall storage experiment, of which 61.2 kg were used for the experimental trials. Samples were then immersed in distilled water, 5% vinegar, or 5% carbonated water solutions (at room temperature) for 5 min. Fruit was drained and left to dry on blotting paper at room temperature (22 ± 2 °C) for 30 min, ensuring that internal moisture content was preserved while only surface moisture was removed. Dried fruit samples were placed into individual transparent PET crates (188.5 × 239.7 × 58 mm) with perforated bottoms and sealed lids. Each replicate was assigned to a separate crate, and fruits were loosely placed inside without internal separators or protective padding. The fruits were stored in a cold room at 1 ± 0.5 °C and 85 ± 5% relative humidity [24], with temperature regulated using an Eliwell Coldface control panel (Eliwell, Italy) and RH monitored and adjusted by an HR-DHTC humidification system (Faran Humidification, South Korea). Temperature and humidity values were regularly checked and recorded throughout the storage period to ensure stable conditions. Stored samples were analyzed for pesticide residues after 0 (1 h), 7, 14, 21, and 28 days, following the application of washing

treatments. Approximately 300 g of cherries was used per washing treatment and sampling period. For each pesticide × washing treatment × sampling day combination, approximately 1000 g of cherries was used per replicate (three replicates per treatment).

Pesticide residue analyses

The official QuEChERS AOAC 2007.01 method was employed for extraction and clean-up [25, 26]. Cherry samples from three biological replicates (1 kg of fruit per replicate) were extracted, and each extract was injected into the LC-MS/MS (Shimadzu LC-MS/MS 8050 Shimadzu, Tokyo, Japan) instrument in triplicate. The results were expressed as the mean of the three technical replicates for each biological replicate.

Mass loss

Cherry samples were weighed after 0, 7, 14, 21, and 28 days of storage, and mass loss was calculated as a percentage.

Fruit firmness

Flesh firmness was measured at the widest point on both cheeks of each fruit with a hand-held digital firmness tester (Agrosta®100, 1173XX, Made in France). Measurements were performed on ten fruits per replicate (thirty fruits per treatment in total), and two measurements were taken from each fruit. Firmness was recorded using the Shore A hardness scale (0–100), where 0 = extra soft, 20 = soft, 40 = medium soft, 70 = medium hard, and 90 = hard [27].

Soluble solids content (SSC)

Fruits were homogenized using a commercial blender (Waring Commercial 7011HG 2, USA), and the resulting pulp was filtered through a double-layer muslin cloth to obtain clear juice. Juice soluble solids content (SSC) was measured using a digital refractometer (Atago PAL-1, Japan; Brix 0–53%) and expressed as a percentage.

Titrateable acidity (TA)

Titrateable acidity (TA) was measured using fruit pulp obtained by homogenizing cherries in a commercial blender (Waring Commercial 7011HG 2, USA). For each sample, 5 g of pulp was diluted with 95 mL of distilled water and titrated with 0.1 N sodium hydroxide to a pH of 8.1 [28]. TA was calculated using the equation:

$$TA = \frac{S.N.F.E}{C} \times 100$$

where TA is titrateable acidity (%), S is the volume of sodium hydroxide (ml), N is the normality of sodium hydroxide, F is the sodium hydroxide factor, C is the

sample volume (ml), and E is the acid equivalent (0.067 for malic acid).

Total phenolics content (TP)

Total phenolics were determined using the Singleton and Rossi [29] method with absorbance measured at 750 nm using a UV-vis spectrophotometer (Model T60U, PG Instruments). Results were expressed as µg gallic acid equivalent (GAE) per g fresh weight (fw).

Total antioxidant activity (TAA)

Total antioxidant activity was measured according to Ozgen et al. [30], with absorbance recorded at 734 nm. Results were expressed as µmol Trolox equivalent (TE) per g fresh weight (fw).

Statistical analysis

Experiments were conducted in a randomized plot design with three replications. Data were analyzed using ANOVA (SAS 9.3, SAS Institute Inc., Cary, NC, USA), and significant means were compared using Duncan's multiple range test at $p < 0.05$.

Results and discussion

Mass loss

In terms of mass loss throughout storage, both pesticide and washing treatments had statistically significant

effects (Fig. 1). Among the pesticide treatments, the highest mass loss was observed in fruits treated with Malathion. In terms of washing methods, fruits washed with NaHCO₃ exhibited significantly greater mass loss compared to other treatments. Mass loss increased progressively throughout the storage period. On both day 7 and day 28, the combination of Malathion and NaHCO₃ resulted in the highest level of mass loss. Sodium bicarbonate may have increased the rate of water loss by deteriorating the structure of fruit skin and cuticle of cherries, especially the amount and quality of cuticular wax [31]. Thusly, present observations revealed partial burns in NaHCO₃-treated fruits. Unlike the current findings, Antunes et al. [32] observed lower mass loss in figs treated with sodium bicarbonate (1%) or acetic acid (0.5–1.5%) compared to the control group. Such a discrepancy may be due to the present solution containing 5% NaHCO₃. In another study, parallel to the present findings, Nikos et al. [33] reported similar mass loss ratios of tomatoes for vinegar (Commercial product (~5% acetic acid); 16 ml/l) and control treatments.

Fruit firmness

Fruit firmness and crispness are often associated with freshness. Hardness is a critical quality trait in cherry, and considerable efforts are made to ensure that the fruit remains firm throughout the cold chain [34]. In

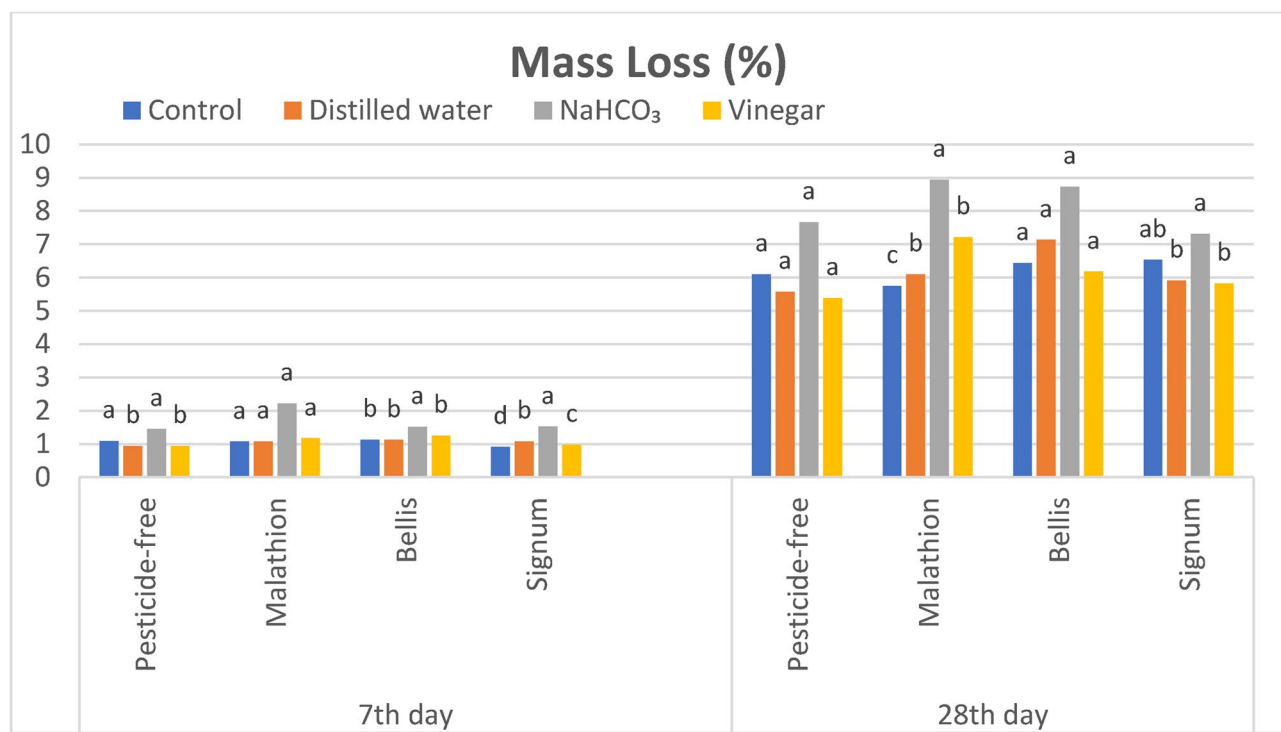


Fig. 1 Mass loss (%) of sweet cherry fruits subjected to different pesticide treatments (Pesticide-free, Malathion, Bellis, Signum) and postharvest washing solutions (Control, Distilled water, NaHCO₃, Vinegar). The data presented correspond to 7 and 28 days after cold storage. Different letters indicate significant differences according to Duncan's multiple range test at $p \leq 0.05$

our study, the results indicated that, on day 0, the effect of pesticide applications on fruit firmness was insignificant (Fig. 2). However, pesticides had a negative impact on fruit firmness throughout the storage period. On day 7, softening was more pronounced in fruits treated with Malathion, while by day 28, the loss of firmness was particularly evident in the Bellis-treated group. Regarding the washing treatments, in pesticide-free fruits, vinegar washing generally preserved fruit firmness better on day 7. However, by day 28, in the same group, the loss of firmness was more pronounced in fruits washed with NaHCO₃. The softening effect of sodium bicarbonate on fruit tissue has also been reported by other researchers [35, 36]. NaHCO₃ applications may create an alkaline environment in the tissue, which can enhance the activity of cell wall-degrading enzymes such as pectin methyl-esterase, leading to the breakdown of pectin structures and resulting in softening [36, 37]. As the storage period progressed, an overall decrease in fruit firmness was observed. However, compared to day 0, an unexpected increase in firmness was recorded across all groups on day 7. This phenomenon may be associated with a transient metabolic response of fruit tissues to cold storage conditions [38, 39].

Soluble solids content (SSC)

The soluble solids content (SSC) values of the experimental treatments throughout storage are shown in Fig. 3. At harvest time (0 day), the soluble solid content (SSC) of fruits treated with Malathion and Signum was found to be higher compared to those with no pesticide treatment and those treated with Bellis. A similar trend was observed on day 28 as well. Malathion appeared to have a more pronounced effect on this increase. The observed increase in SSC may be attributed to the breakdown of carbohydrates into soluble sugars such as glucose, fructose, and sucrose [40]. During this process, the increased activity of enzymes such as sucrose synthase, invertase, and amylase facilitates the hydrolysis of starch [41]. In this context, the applied pesticides may have indirectly influenced the activity of these enzymes, thereby accelerating the conversion of starch into simple sugars. However, further analyses targeting enzyme activity are required to confirm this effect. On the other hand, washing treatments had a significant impact on fruits treated with Signum on day 28. In this case, the SSC content of fruits washed with NaHCO₃ and vinegar was found to be lower. SSC is a practical criterion for determining the optimal harvest timing of cherries, plums, peaches, apricots, sour cherries, and grapes. Most of these substances are composed of sugars. Therefore, they are related to sweetness, and their quantities increase with the progress

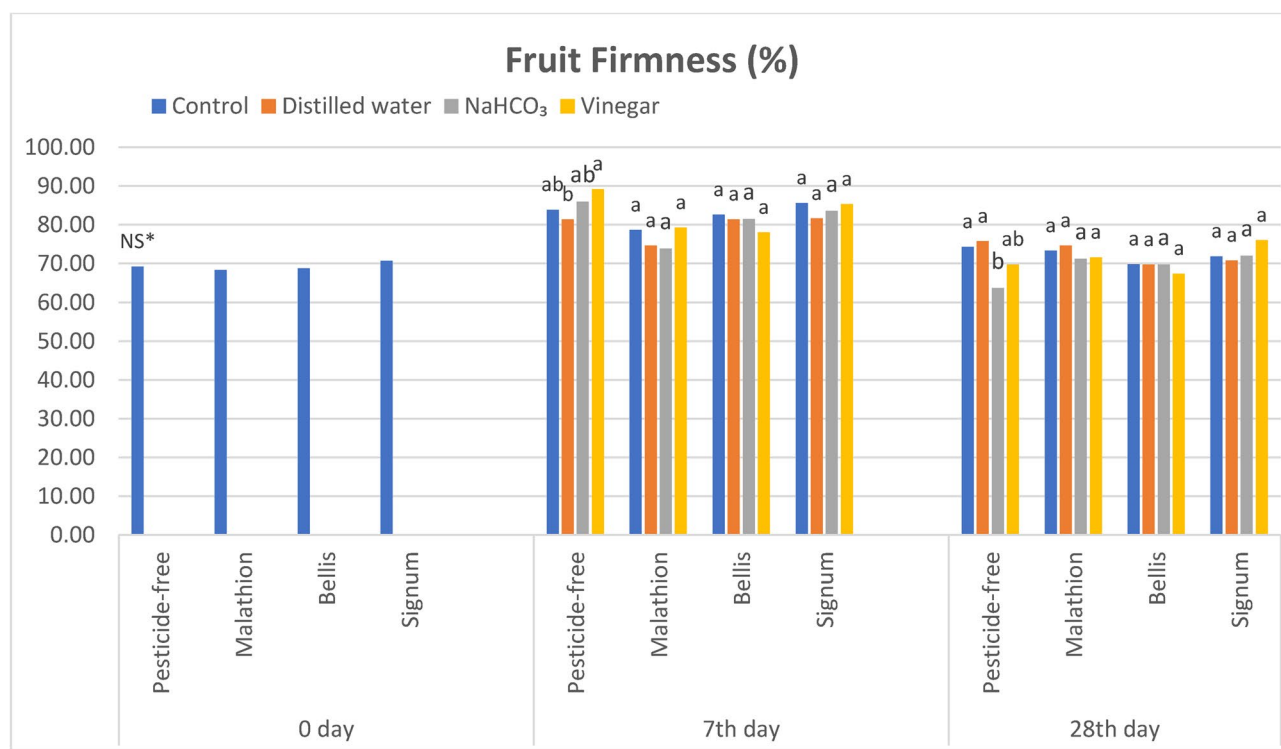


Fig. 2 Fruit firmness (%) of sweet cherry fruits subjected to different pesticide treatments (Pesticide-free, Malathion, Bellis, Signum) and postharvest washing solutions (Control, Distilled water, NaHCO₃, Vinegar). The data presented correspond to 0, 7, and 28 days after cold storage. Different letters indicate significant differences according to Duncan’s multiple range test at $p \leq 0.05$. NS: Non-significant (Duncan’s test, $p \leq 0.05$)

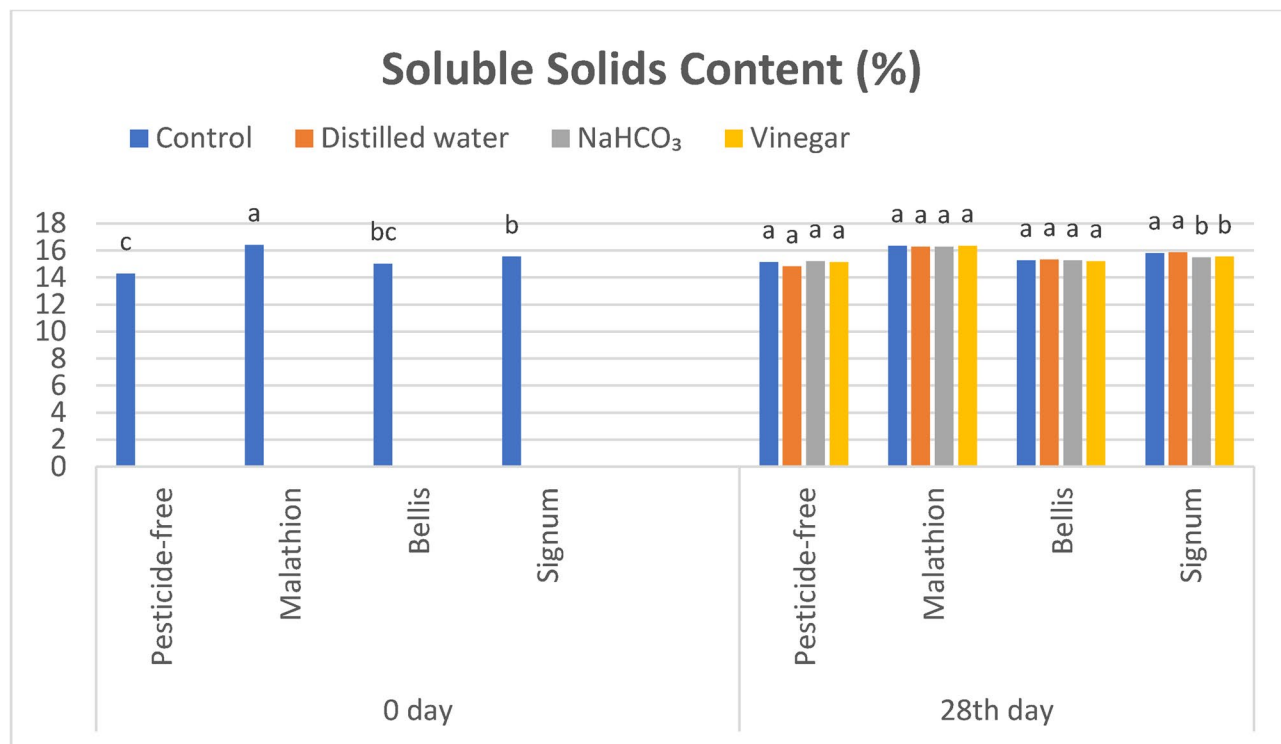


Fig. 3 Soluble solids content (%) of sweet cherry fruits subjected to different pesticide treatments (Pesticide-free, Malathion, Bellis, Signum) and post-harvest washing solutions (Control, Distilled water, NaHCO₃, Vinegar). The data presented correspond to 0 and 28 days after cold storage. Different letters indicate significant differences according to Duncan’s multiple range test at $p \leq 0.05$

of maturity [31]. In this sense, pesticide applications, particularly Malathion and Signum, may have contributed to an apparent earlier maturity of the fruits, potentially leading to earlier harvest. Previous studies reported that pre-harvest treatments with arginine [42] and calcium nitrate [43] increased fruit SSC values, while MeJA [44] treatments resulted in decreased SSC values.

Titrateable acidity (TA)

Significant differences in TA were observed among pesticide treatments at both the initial (day 0) and final (day 28) storage periods (Fig. 4). On day 0, cherries that received no pesticide treatment exhibited higher TA levels. In contrast, those treated with Signum showed a noticeable reduction in TA content. By the end of the storage period, a substantial decrease in TA was particularly evident in fruits treated with Bellis. Regarding the washing treatments (day 28), in the untreated (control) group, cherries washed with vinegar showed higher TA levels. Within the Signum-treated group, the highest TA content was observed in fruits washed with NaHCO₃, while the lowest was found in fruits washed with vinegar. Similarly, Nikos et al. [33] reported the highest TA levels at the end of a two-week storage period in tomato fruit treated with vinegar solutions. Generally, the amount of free acids in fruits and vegetables tends to decrease as growth and ripening progress. In some products, such

as apples, pears, and tomatoes, this decline may continue even after harvest, as free acids are involved in respiration, cation neutralization, and occasionally sugar synthesis, and may crystallize into salts within the cell [45]. Consistent with previous reports on cherries [42, 44, 46, 47], the present study also demonstrated a gradual decrease in TA content during storage.

Total phenolics content (TPC)

Total phenolic content (TPC) of cherries is presented in Fig. 5. At harvest (day 0), although pesticide treatments appeared to increase TPC levels slightly, the effect was not statistically significant. Similarly, by the end of the storage period, neither pesticide applications nor washing treatments had a significant impact on the phenolic content. Total phenolics did not decrease or increase gradually during storage; instead, they followed a fluctuating trend. On the other hand, some researchers reported a gradual increase [24, 48–50] or decrease [Zhang et al. 51] in total phenolics of cherries throughout storage. It was also reported that the total phenolics of cherries harvested late, one week apart, were higher than those of cherries harvested at the normal time [52]. Total phenolics of cherries are strongly dependent on both pre-harvest and post-harvest treatments, as well as harvest date, cultivar, and ecological conditions.

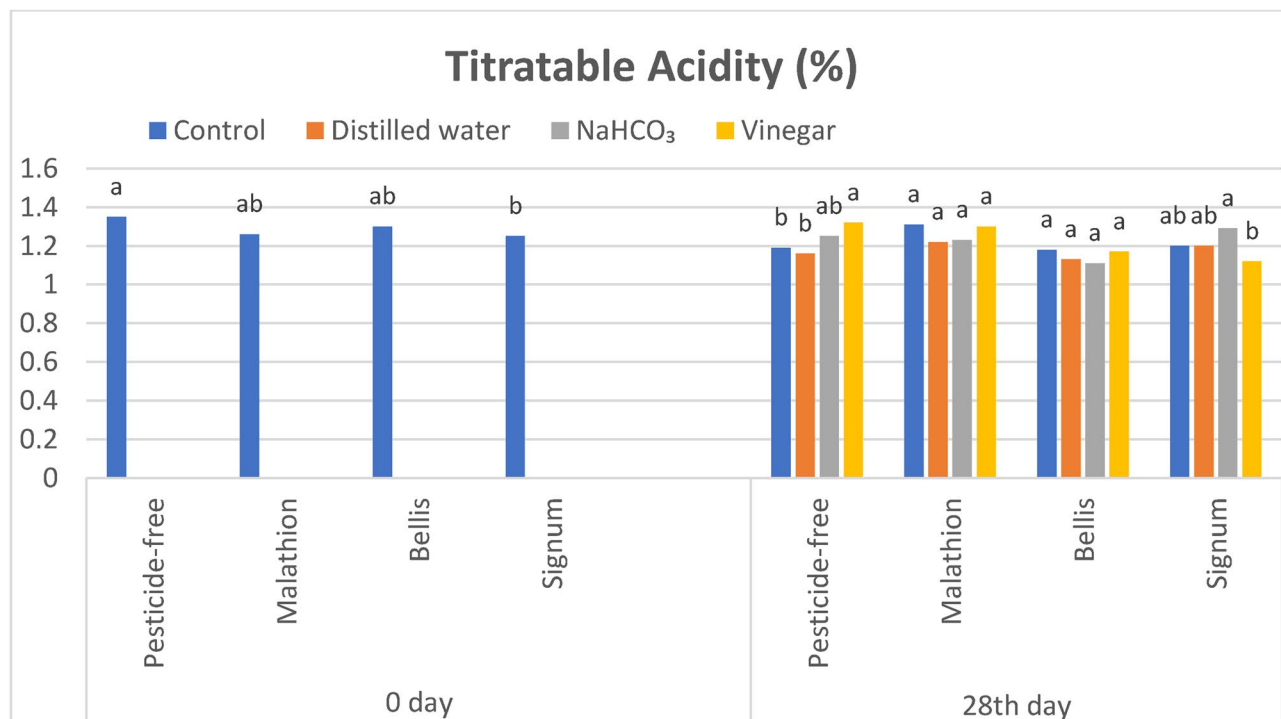


Fig. 4 Titratable acidity (%) of sweet cherry fruits subjected to different pesticide treatments (Pesticide-free, Malathion, Bellis, Signum) and postharvest washing solutions (Control, Distilled water, NaHCO₃, Vinegar). The data presented correspond to 0 and 28 days after cold storage. Different letters indicate significant differences according to Duncan's multiple range test at $p \leq 0.05$

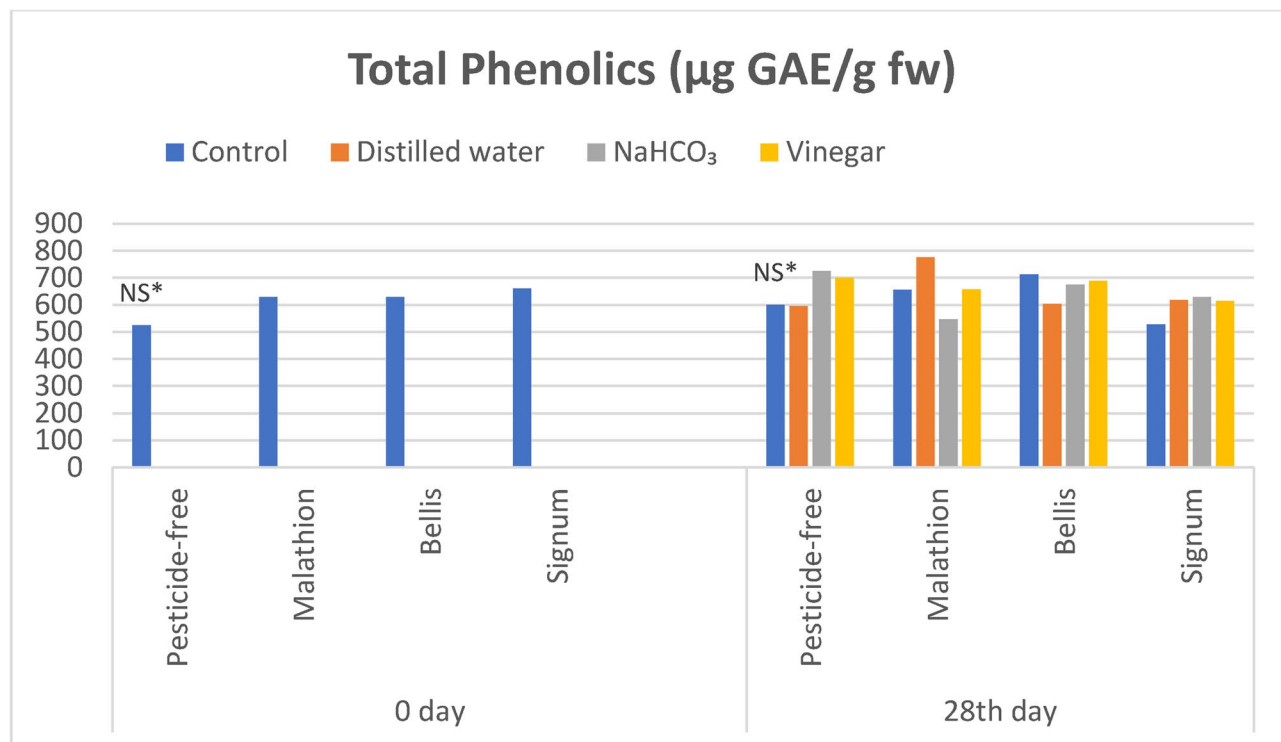


Fig. 5 Total phenolic substance content of sweet cherry fruits subjected to different pesticide treatments (Pesticide-free, Malathion, Bellis, Signum) and postharvest washing solutions (Control, Distilled water, NaHCO₃, Vinegar). The data presented correspond to 0 and 28 days after of cold storage. NS*: Non-significant (Duncan's test, $p \leq 0.05$)

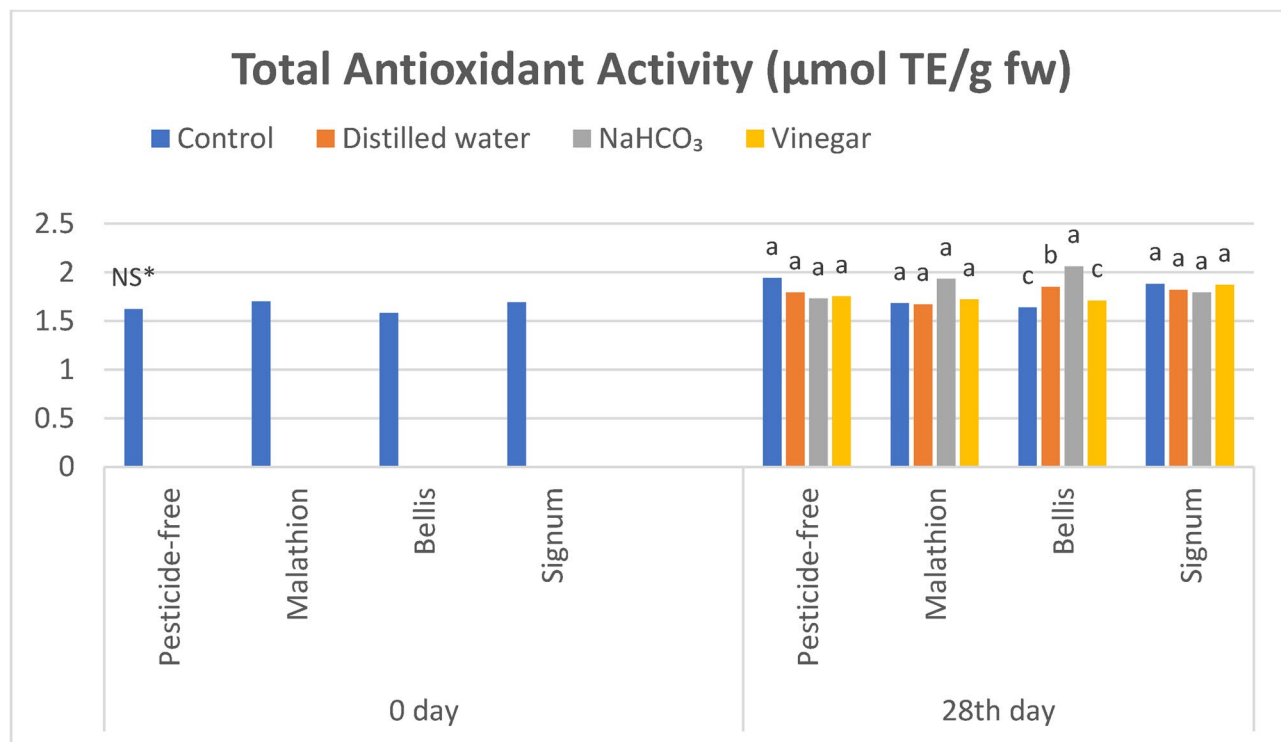


Fig. 6 Total antioxidant activity of sweet cherry fruits subjected to different pesticide treatments (Pesticide-free, Malathion, Bellis, Signum) and postharvest washing solutions (Control, Distilled water, NaHCO₃, Vinegar). The data presented correspond to 0 and 28 days after of cold storage. Different letters indicate significant differences according to Duncan’s multiple range test at $p \leq 0.05$. NS*: Non-significant (Duncan’s test, $p \leq 0.05$)

Table 2 Method verification parameters

Pesticide	Linear regression equation	Correlation coefficient (R ²)	LOD (µg kg ⁻¹)	LOQ (µg kg ⁻¹)	Spiking level (µg kg ⁻¹)	Reatibility Recovery, % (RSD, %)	Reproducibility Recovery, % (RSD, %)	U%
Boscalid	Y=82706.8X –15619.1	0.99994	0.40	1.32	10	95.83 (2.37)	95.53 (2.38)	9.57
					50	96.05 (0.70)	94.06 (2.95)	
					100	97.61 (1.42)	96.77 (3.27)	
Pyraclostrobin	Y=113436X –107,099	0.99939	0.98	3.27	10	101.82 (1.71)	98.90 (2.27)	7.10
					50	96.33 (1.48)	97.07 (1.79)	
					100	101.35 (1.62)	100.02 (2.90)	
Malathion	Y=176888X +41,606	0.99973	0.67	2.23	10	103.04 (1.95)	103.14 (1.85)	28.35
					50	101.15 (1.90)	100.47 (0.99)	
					100	105.75 (1.64)	105.08 (2.12)	

Total antioxidant activity (TAA)

For total antioxidant activity, the effect of pesticide treatments at harvest was not significant (Fig. 6). By the end of the storage period, the highest TAA was detected in the Bellis group in fruits treated with NaHCO₃. Additionally, a trend of increasing TAA values in cherries was observed during the storage period. Similarly, Zhang et al. [50] and Michailidis et al. [49] also reported increasing TAA values in cherries as storage progressed. A study conducted in Iran reported that in cherries (*Prunus avium* L. cv Takd Danehe Mashhad), preharvest arginine treatments increase the activity of antioxidant enzymes [superoxide dismutase (SOD), catalase (CAT),

and ascorbate peroxidase (APX)] during 20 days of cold storage [42]. However, Zhang et al. [51] reported that post-harvest coating treatments decreased TAA values of cherries (Red Agate) throughout the storage. Such differences were mostly attributed to differences in cultivar and growing regions.

Pesticide residues

Method verification was conducted following the SANTE guidelines [53, 54]. The method validation parameters for the analyzed pesticides are shown in Table 2. The correlation coefficients (R²) for all pesticides exceeded 0.999, indicating excellent linearity. The limits of quantification

Table 3 Residue amounts in cherries during storage ($\mu\text{g}/\text{kg}$)

Trade name	Pesticide	Dipping	0 day	7th day	14 th day	21 st day	28 th day
Bellis	Boscalid	Control	31.44	29.05	27.38	25.31	< LOQ
		Distilled water	28.02	25.42	24.27	20.97	< LOQ
		NaHCO ₃	37.78	32.11	28.99	23.37	< LOQ
		Vinegar	57.11	43.67	43.25	35.31	< LOQ
	Pyraclostrobin	Control	19.64	16.36	14.20	12.27	< LOQ
		Distilled water	10.83	9.19	6.13	3.91	< LOQ
		NaHCO ₃	16.72	15.04	11.08	8.81	< LOQ
		Vinegar	18.67	12.54	10.18	6.65	< LOQ
Signum	Boscalid	Control	112.66	103.96	95.60	87.51	< LOQ
		Distilled water	39.28	32.90	25.51	14.09	< LOQ
		NaHCO ₃	79.62	47.29	44.86	40.13	< LOQ
		Vinegar	53.49	38.48	33.00	30.34	< LOQ
	Pyraclostrobin	Control	28.86	28.78	19.49	17.43	< LOQ
		Distilled water	13.89	6.82	5.89	4.04	< LOQ
		NaHCO ₃	17.72	11.20	9.28	8.52	< LOQ
		Vinegar	29.98	15.16	11.66	11.49	< LOQ

LOQ Limit of quantification

(LOQ) for boscalid, pyraclostrobin, and malathion were determined as $1.32 \mu\text{g kg}^{-1}$, $3.27 \mu\text{g kg}^{-1}$, and $2.23 \mu\text{g kg}^{-1}$, respectively. Recovery studies were conducted at three spiking levels (10, 50, and $100 \mu\text{g kg}^{-1}$) under repeatability and reproducibility conditions. The recoveries of boscalid ranged between 95.53% and 97.61% with RSD values of 0.70–3.27%. Pyraclostrobin exhibited recoveries between 96.33% and 101.82%, with RSD values ranging from 1.48% to 2.90%. Similarly, malathion demonstrated recoveries within the range of 100.47% to 105.75%, with RSD values between 0.99% and 2.12%. According to the SANTE guidelines, acceptable method performance criteria require recovery values between 70 and 120% and RSD values of $\leq 20\%$. The results confirm that the method meets these performance criteria, ensuring the reliability and accuracy of the analytical approach [53].

Malathion residues were below the LOQ in all samples (Table 3). However, boscalid and pyraclostrobin residues were detected at varying levels throughout the storage period, except on the 28th day, where they fell below the LOQ for all treatments. The degradation rate of these pesticides progressed over time, with residue levels decreasing depending on the washing treatments applied. That is, while all washing treatments contributed to residue reduction, their efficiency varied based on the type of pesticide and storage duration. Compared to the unwashed control group, significant reductions in pesticide residues were observed in samples washed with distilled water, NaHCO₃, and vinegar. Although distilled water was the most effective method in reducing pesticide residues, NaHCO₃ and vinegar also demonstrated significant effects. Compared to other treatments, these washing treatments consistently resulted in lower residue levels on the fruit after 7 days of storage. These findings

highlight distilled water as an easily accessible and chemical-free method suitable for consumer use. The study underscores the importance of washing fruits and vegetables to minimize pesticide residues, emphasizing that thorough rinsing with distilled water is a crucial step in enhancing food safety.

Conclusion

The levels of pesticide residues on cherry fruit declined over storage, with washing treatments promoting further reduction. Distilled water was the most effective washing method, followed by NaHCO₃, and vinegar. By the end of storage, all pesticides were reduced to below detectable levels. Additionally, washing with distilled water and vinegar showed positive effects in preserving fruit quality. Malathion treatment, particularly when combined with NaHCO₃ washing, resulted in the highest mass loss, likely due to cuticle damage and wax degradation. NaHCO₃ also contributed to tissue softening, whereas vinegar washing helped preserve firmness in pesticide-free fruits at early storage stages. Malathion contributed to an increase in SSC throughout storage, potentially accelerating sugar accumulation. Titratable acidity declined over time regardless of the treatment, with the sharpest reduction observed for Bellis-treated fruits. Pesticide and washing treatments had limited influence on total phenolics, while total antioxidant activity generally increased during storage, with the highest values observed for Bellis-treated cherries washed with NaHCO₃.

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Authors' contributions

ONÖ: Writing, editing, laboratory work. TB: Writing, laboratory work, research, editing, general control. ED: Laboratory work, research, editing. MK: Laboratory work, research, editing. FÇ: Laboratory work, research, editing. AAMAS: Laboratory work, research, editing. OS: Translation, editing, general control.

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Competing interests

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