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The effect of green synthesized nanoparticles on organic acids in strawberry and sweet cherry during storage

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Abstract: This study investigated the effects of boron-, copper-, and chitosan-based nanoparticles (synthesized by the green synthesis method) on organic acid contents of strawberries and sweet cherries during storage. The fruits were dipped in nanoparticle solutions for 2 minutes and stored under cold conditions (0 ± 0.5 °C for sweet cherries, 1 ± 0.5 °C for strawberries) at 90 ± 5% relative humidity. Malic, citric, and oxalic acid levels were evaluated. In strawberries, the Boron1 treatment (500 ppm boron nanoparticle) was the most effective in preserving organic acids, particularly citric acid, which remained at 2431.5 mg kg^{-1} fw by the end of storage compared to 1702.5 mg kg^{-1} fw in the control group. In sweet cherries, Chitosan (1% nanochitosan solution) treatment preserved the highest level of malic acid (2256.7 mg kg^{-1} fw), while Boron1 contributed to the retention of citric acid (20.75 mg kg^{-1} fw), exceeding even the initial harvest value. Oxalic acid degradation was slowed in the treated groups compared to the control in both fruits. The results suggest that nanoparticle-assisted edible coatings may offer a promising strategy for extending shelf life and partially preserving phytochemical content. Moreover, it was observed that the dominant organic acid varied by fruit species, i.e., citric acid in strawberries and malic acid in sweet cherries. These findings support the view that nanoparticle applications should be tailored to fruit type and may contribute to the development of more sustainable postharvest preservation approaches.

Keywords: Coating, nanoparticle, organic acid, storage, sustainable agriculture

Yeşil sentez yöntemiyle elde edilen nanopartiküllerin çilek ve kirazda depolama süresince organik asitler üzerine etkisi

Öz: Bu çalışma, yeşil sentez yöntemiyle elde edilen bor, bakır ve kitosan temelli nanopartiküllerin, çilek ve kiraz meyvelerinin depolama süresince organik asit içerikleri üzerindeki etkilerini araştırmaktadır. Meyveler, 2 dakika boyunca nanopartikül çözeltilerine daldırılmış ve soğuk koşullarda (kirazlar için 0 ± 0.5 °C, çilekler için 1 ± 0.5 °C) %90 ± 5 bağıl nem ortamında muhafaza edilmiştir. Çalışma kapsamında malik, sitrik ve okzalik asit düzeyleri değerlendirilmiştir. Çilekte, Boron1 uygulaması (500 ppm bor nanopartikülü) organik asitlerin korunmasında en etkili yöntem olmuş; özellikle sitrik asit, depolama sonunda 2431.5 mg kg^{-1} t.a. düzeyinde korunarak kontrol grubundaki 1702.5 mg kg^{-1} t.a. seviyesinin üzerinde kalmıştır. Kirazda ise, Kitosan uygulaması (%1 nanochitosan çözeltisi) malik asidin en yüksek düzeyde korunmasını sağlamış (2256.7 mg kg^{-1} t.a.), Boron1 uygulaması ise sitrik asidin korunmasına katkı sağlamış ve bu bileşik, hasat değerini aşarak 20.75 mg kg^{-1} t.a. düzeyine ulaşmıştır. Her iki meyvede de, okzalik asit bozunumu uygulama gruplarında kontrol grubuna göre daha yavaş gerçekleşmiştir. Elde edilen sonuçlar, nanopartikül destekli yenilebilir kaplama uygulamalarının raf ömrünü uzatmada ve fitokimyasal içeriği kısmen korumada umut verici bir yaklaşım olabileceğini göstermektedir. Ayrıca, baskın organik asit içeriğinin meyve türüne göre değiştiği; çilekte sitrik asidin, kirazda ise malik asidin öne çıktığı belirlenmiştir. Bu bulgular, nanopartikül uygulamalarının meyve türüne özel olarak planlanması gerektiğini ve sürdürülebilir hasat sonrası koruma tekniklerinin geliştirilmesine katkı sağlayabileceğini ortaya koymaktadır.

Anahtar kelimeler: Kaplama, nanopartikül, organik asit, depolama, sürdürülebilir tarım

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1. Introduction

Strawberry (*Fragaria × ananassa*) and sweet cherry (*Prunus avium* L.) are among the fruits highly appreciated by consumers of all age groups due to their distinctive flavors and rich aroma profiles. The appeal is further enhanced by their richness in bioactive compounds such as vitamin C, polyphenols, and anthocyanins, which contribute to their nutritional and functional value (Alnıak et al., 2025; Xing et al., 2025). Both fruits also hold significant economic importance in global horticultural markets. According to 2023 data from the Food and Agriculture Organization (FAO), Türkiye produced ~676,818 tons of strawberries, ranking 4th globally, and led global sweet cherry production with 736,791 tons, securing the first position globally. These fruits are primarily cultivated in the Mediterranean and Central Anatolian regions and are valuable not only for domestic consumption but also as key export commodities.

Despite their nutritional and commercial significance, strawberries and cherries are highly susceptible to physiological deterioration and mechanical injury due to their soft textures and high respiration rates (Chiabrando et al., 2019; Ozturk et al., 2022). Consequently, considerable postharvest losses may occur, leading to reduced quality and financial returns. Therefore, the development and implementation of effective, sustainable postharvest preservation strategies are essential to extend shelf life, maintain quality, and minimize economic loss throughout the supply chain.

A variety of traditional and modern preservation techniques such as low-temperature storage, modified atmosphere packaging, irradiation, and coating are widely utilized to maintain food quality for extended periods and prevent spoilage (Ocalan et al., 2023; Çezik et al., 2024). Edible coatings offer safe and environmentally friendly alternatives among these methods. These coatings reduce moisture loss and microbial decay by forming a protective barrier on the surface of the fruit, thereby preserving quality and extending shelf life (Gidado et al., 2025). Chitosan, a natural polysaccharide obtained by the deacetylation of chitin, is one of the edible coating materials. The effects of chitosan on the storage of fruits and vegetables have been extensively studied, both alone (Emadifar et al., 2025; Jongsri et al., 2016; Parvin et al., 2023) and in combination with various other components (Iñiguez & González, 2025; Isvand et al., 2024; Kumar et al., 2021). Nanotechnology is an innovative approach that offers significant advantages in food preservation. Applications of nanotechnology in edible films involve the integration of nanomaterials into the film in a way that forms a thin layer and enables production at the nanoscale, with the aim of imparting specific functionalities to the films (Şen & Güner, 2023). Edible films enriched with nanocomposite materials exhibit superior thermal, mechanical, and biological properties compared to conventional composites (Ananda et al., 2017; Korkmaz, 2020; Korkmaz et al., 2024). Considering the positive effects of nanomaterials, researchers are currently investigating the impact of both pure nanomaterials and diverse nanocomposite structures on the preservation efficacy of fruits and vegetables. Numerous studies have been conducted using chitosan/zein nanocellulose in mango (Xiao et al., 2021), nano-SiO_2 and nano-TiO_2 in blueberries (Li et al., 2021), nano-SiO_2 in melon (Sami et al., 2021), and SeNp/nano-chitosan in strawberries (Tayel et al., 2025). The common findings of these studies indicate that edible coating materials enriched with nanoparticles positively preserve the physical properties and phytochemical components of fruits during storage.

Organic acids, which are among the key quality parameters of fruits, play a crucial role in taste profile, microbial resistance, and physiological deterioration processes (Zhang et al., 2023). Changes in the levels of these acids during storage are critical for the freshness and shelf life of fruits. Maintaining their concentrations supports flavor balance by regulating sweetness-to-acidity ratios, and enhances microbial stability by lowering tissue pH. Moreover, organic acids such as oxalic acid have been shown to delay senescence and reduce postharvest physiological disorders by modulating stress-related pathways (Hasan et al., 2023). The compartmentalization of these acids, particularly within vacuoles, is also closely linked to fruit biochemical stability and sensory quality during storage (Liu et al., 2023).

In recent years, nanoparticle-based postharvest applications have predominantly focused on delaying senescence, reducing microbial spoilage, and enhancing antioxidant defense mechanisms in various fruit commodities. For instance, Bahmani et al. (2024a) investigated the effects of chitosan–putrescine nanoparticles on postharvest decay and reactive oxygen species (ROS) scavenging activity. Similarly, Bahmani et al. (2024b) evaluated chitosan and glycine betaine nanoparticle coatings with regard to firmness, respiration rate, and antioxidant capacity. Taha et al. (2022) reported that starch-based coatings embedded with silver nanoparticles extended storage time by reducing microbial load and decay. These studies primarily focus on external quality attributes and oxidative metabolism-related parameters.

However, there remains a critical gap in the literature concerning the impact of nanoparticle treatments—particularly those involving boron and copper—on internal biochemical quality factors such as organic acid profiles. To date, no published studies have directly examined how these specific nanoparticles affect malic, citric, or oxalic acid contents in soft fruits during cold storage. This study aims to fill this significant research gap by evaluating the effects of boron- and copper-based nanoparticles, alone and in combination with chitosan, on the organic acid metabolism of strawberry and sweet cherry fruits. The results are expected to contribute novel insights into the biochemical mechanisms underlying fruit preservation and support the advancement of sustainable postharvest practices.

2. Materials and Methods

2.1. Fruit materials and harvesting

In the present study, *Fragaria* × *ananassa* 'Monterey' strawberries and *Prunus avium* '0900 Ziraat' sweet cherries were utilized as experimental materials. The strawberries were procured from a commercial production enterprise (Çok Çilek) located along the Tokat–Turhal highway, while the sweet cherries were harvested from the orchards of Tokat Gaziosmanpaşa University Application and Research Center. All fruits were collected at commercially mature stages, based on standard horticultural maturity indicators. Strawberries were harvested when approximately two-thirds of the fruit surface had developed red coloration, indicating commercial ripeness. Sweet cherries were picked at full skin coloration when the soluble solids content (SSC) was around 15 °Brix, consistent with optimum harvest maturity for the cultivar. Immediately after harvest, all fruits were subjected to a precooling treatment at 4 °C for 6 hours to remove field heat, and then promptly transported under controlled conditions to the laboratory for further analysis.

2.2. Nanoparticles

Copper (Copper1 and Copper2) and boron (Boron1 and Boron2) based nanoparticles, as well as nanochitosan (Chitosan), were used in this study. These nanoparticles were synthesized within the scope of the TÜBİTAK-supported project numbered "222O604". In addition, composite formulations were prepared by combining each nanoparticle type with chitosan, resulting in copper-chitosan (Copper1 + Chitosan, Copper2 + Chitosan) and boron-chitosan (Boron1 + Chitosan, Boron2 + Chitosan) treatments.

All nanoparticles were synthesized via a green synthesis method using aqueous extracts obtained from sweet cherry tree pruning waste leaves. These extracts acted as natural reducing and stabilizing agents during synthesis. The use of plant-based materials eliminated the need for toxic chemicals and complied with environmentally sustainable practices (Korkmaz et al., 2025). Characterization of the synthesized nanoparticles was performed using UV–Vis spectrophotometry, X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDX) to confirm structural integrity and composition.

Table 1. Doses and abbreviations of the nanoparticles used in the study

Application Abbreviation	Doses	Applications
Control	–	Control (untreated fruits)
Chitosan	1%	Nanochitosan
Copper1	1000 ppm	Copper Oxide Nanoparticle
Copper2	2000 ppm	Copper Oxide Nanoparticle
Copper1+Chitosan	1000 ppm + 1%	Copper Oxide Nanoparticle + Nanochitosan
Copper2+Chitosan	2000 ppm + 1%	Copper Oxide Nanoparticle + Nanochitosan
Boron1	500 ppm	Boron Nanoparticle
Boron2	1000 ppm	Boron Nanoparticle
Boron1+Chitosan	500 ppm + 1%	Boron Nanoparticle + Nanochitosan
Boron2+Chitosan	1000 ppm + 1%	Boron Nanoparticle + Nanochitosan

2.3. Coating and storage procedures

Harvested fruits were transported to the laboratory after the precooling process. Following physical inspections, the fruits were dipped into solutions prepared with Copper1, Copper2, Boron1, Boron2, and Chitosan. Each compound was first dispersed in distilled water and homogenized using an ultrasonic processor (Bioevopeak, China) for 30 minutes to ensure uniform nanoparticle dispersion. In addition, composite coatings of Copper1+Chitosan, Copper2+Chitosan, Boron1+Chitosan, and Boron2+Chitosan were prepared and applied using the same method. The dipping process lasted for 2 minutes, in accordance with previous studies where this immersion time was found to be sufficient for achieving a uniform and effective coating layer on fruit surfaces (Ali et al., 2022). After dipping, the fruits were air-dried at room temperature and placed into transparent, lidded trays. Each treatment group consisted of 3 replicates, and each replicate included 20 fruits, totaling 60 fruits per treatment. The coated fruits were stored at 0 ± 0.5 °C for sweet cherries and 1 ± 0.5 °C for strawberries under 90 ± 5% relative humidity. Sweet cherries were stored for 35 days and strawberries for 20 days, with quality analyses performed at predetermined intervals.

2.4. Organic acids

In this study, oxalic acid, malic acid, and citric acid were measured. The measurements were performed according to the method described by Bevilacqua and Califano (1989). Five grams of sample were mixed with 20 mL of 0.009 N H_2SO_4 and vortexed for one hour. Afterward, the samples were centrifuged at 19,000 × g for 15 minutes. The supernatant obtained after centrifugation was filtered through a 0.45 μm membrane filter (Millipore, USA) and a Sep-Pak C18 cartridge. The analysis of organic acids was carried out using an Agilent HPLC system (Germany) equipped with a diode array detector (DAD) set at 214 and 280 nm. Separation was performed on an Aminex HPX-87H column (300 × 7.8 mm, Bio-Rad Laboratories, USA) maintained at 30 °C. A 0.009 N H_2SO_4 solution, filtered through a 0.45 μm membrane filter, was used as the mobile phase at a flow rate of 0.6 mL/min. The injection volume was 20 μL, and the total run time for each sample was approximately 25 minutes. Organic acids were identified and quantified by comparing their retention times and peak areas with those of external standards. The results were expressed as mg kg^{-1} fresh weight (fw) (Ozturk et al., 2019).

2.5. Statistical analysis

Experiments were conducted using a randomized complete design with three replications. Each replication consisted of 20 fruits for both strawberry and sweet cherry. The experimental data were subjected to one-way analysis of variance (ANOVA) using SAS 9.3 software (SAS Institute Inc., Cary, NC, USA). Significant differences between treatment means were compared using Duncan's multiple range test at a $p < 0.05$ significance level.

3. Results

Table 2 presents the effects of different treatments on the organic acid contents of strawberry fruits. Regarding oxalic acid values, the lowest content was observed in the control (321.60 mg kg^{-1} fw) at the end of the storage period, whereas the highest value was detected in the Boron2 treatment (466.77 mg kg^{-1} fw). This difference was statistically significant. It appears that the nanoparticle treatments were effective in preserving oxalic acid content compared to the control.

Similarly, , the lowest malic acid levels was recorded in the control (852.90 mg kg^{-1} fw), while the highest value was observed in the Boron1 treatment (1226.80 mg kg^{-1} fw) at the end of the storage period. Except for the 15th day of storage, the differences observed between the groups at all other time points were statistically significant.

Regarding citric acid contents, the lowest value was measured in the control (1702.50 mg kg^{-1} fw), while the highest value was recorded in the Boron1 treatment (2431.50 mg kg^{-1} fw) at the end of the storage period. Overall, it is concluded that Boron1 and Boron2 treatments were effective in preserving the organic acid content of strawberries during storage.

The effects of treatments on organic acid content of sweet cherry fruits are presented in Table 3. The initial value of oxalic acid at harvest was 158.720 mg kg^{-1} fw. The highest oxlic acid level was observed in the Chitosan treatment (128.933 mg kg^{-1} fw) at the end of the storage period. This was followed by the Copper1+Chitosan treatment (107.387 mg kg^{-1} fw). Other treatments showed results similar to the control. Although fluctuations in oxalic acid values were observed during the storage period, a general decreasing trend was detected over time.

Table 2. Organic acid contents of strawberries

Treatment	Harvest	5 Days	10 Days	15 Days	20 Days
a) Oxalic Acid (mg kg $^{-1}$ fw)					
CONTROL	410.59	415.90 ab	392.24 bc	372.37	321.60 b
Chitosan		471.21 ab	370.69 bc	382.41	463.99 a
Copper1		482.74 ab	370.92 bc	325.10	426.63 ab
Copper2		401.19 b	352.60 c	383.87	452.45 a
Copper1+Chitosan		522.71 a	509.70 a	379.73	405.59 ab
Copper2+Chitosan		460.17 ab	363.57 bc	365.43	419.90 ab
Boron1		426.63 ab	337.51 c	407.73	443.28 a
Boron2		379.82 b	310.21 c	371.22	466.77 a
Boron1+Chitosan		453.73 ab	388.65 bc	425.43	439.09 a
Boron2+Chitosan		466.90 ab	457.18 ab	419.07	461.41 a
b) Malic Acid (mg kg $^{-1}$ fw)					
CONTROL	871.44	861.89 ab	805.53	790.81 bc	852.9 c
Chitosan		700.94 b	852.36	802.67 bc	932.0 bc
Copper1		907.41 a	781.30	826.37 bc	1012.2 abc
Copper2		790.42 ab	881.61	766.15 c	994.5 abc
Copper1+Chitosan		765.95 ab	959.09	864.83 abc	873.9 bc
Copper2+Chitosan		792.41 ab	883.69	725.71 c	1061.0 abc
Boron1		865.23 ab	827.61	924.52 ab	1226.8 a
Boron2		733.55 b	812.57	996.82 a	1129.7 ab
Boron1+Chitosan		793.41 ab	764.80	838.01 bc	987.7 abc
Boron2+Chitosan		796.60 ab	830.20	822.24 bc	902.7 bc
c) Citric Acid (mg kg $^{-1}$ fw)					
CONTROL	1485.76	1450.2 b	1381.1 b	1322.2 d	1702.5 b
Chitosan		1501.6 ab	1471.6 b	1583.0 abcd	1844.3 b
Copper1		1681.3 ab	1404.3 b	1740.3 ab	1813.2 b
Copper2		1605.9 ab	1528.0 b	1361.3 cd	1900.5 ab
Copper1+Chitosan		1558.4 ab	2059.5 a	1592.1 abcd	1950.0 ab
Copper2+Chitosan		1629.6 ab	1543.4 b	1368.7 cd	2000.5 ab
Boron1		1770.6 a	1631.4 ab	1864.4 a	2431.5 a
Boron2		1561.7 ab	1430.0 b	1654.3 abc	2050.1 ab
Boron1+Chitosan		1519.0 ab	1427.1 b	1502.9 bcd	1649.6 b
Boron2+Chitosan		1739.4 ab	1483.4 b	1561.6 abcd	1724.7 b

The groupings indicated by lowercase letters within the columns are based on tests performed within each storage period. Means that do not differ significantly from each other are indicated with the same lowercase letter. ($p < 0,05$).

The initial value of malic acid contents at harvest was 3028.6 mg kg^{-1} fw, and the highest level and at the end of the storage period was noted in Chitosan treatment (2256.7 mg kg^{-1} fw). The lowest malic acid levels were measured in the Copper2 (1015.0 mg kg^{-1} fw), Control (1031.8 mg kg^{-1} fw), and Copper1 (1104.8 mg kg^{-1} fw) treatments, respectively. A general decrease in malic acid levels was observed during the storage period, similar to citric acid, although the Chitosan treatment was more effective in preserving both organic acids. The initial citric acid content at harvest was 18.85 mg kg^{-1} fw, and the highest level at the end of the storage period was recorded in Boron1 treatment (20.75 mg kg^{-1} fw). All other treatments remained similar to the control. By the end of the storage period, citric acid levels were lower compared to harvest in all treatments, except for Boron1, where the citric acid content exceeded the initial harvest value.

Table 3. Organic acid contents of sweet cherries

Treatment	Harvest	7 Days	14 Days	21 Days	28 Days	35 Days
a) Oxalic Acid (mg kg $^{-1}$ fw)						
CONTROL	158.72	186.16 a	109.56 b	140.25 abc	107.52 bc	73.470 c
Chitosan		125.66 cd	185.34 a	163.04 a	134.20 ab	128.933 a
Copper1		125.35 cd	111.48 b	127.69 abcd	140.01 a	83.293 c
Copper2		130.90 cd	117.06 b	112.18 bcd	129.32 ab	82.077 c
Copper1+Chitosan		142.27 abcd	174.62 a	143.81 abc	134.80 ab	71.223 c
Copper2+Chitosan		146.52 abcd	215.48 a	149.17 ab	133.54 ab	107.387 b
Boron1		169.39 abc	219.03 a	131.25abcd	112.36 abc	90.953 bc
Boron2		179.84 ab	193.27 a	144.25 abc	99.35 cd	92.520 bc
Boron1+Chitosan		133.03 bcd	132.44 b	107.14 dc	72.23 de	70.437 c
Boron2+Chitosan		103.45 d	109.56 b	93.65 d	62.33 e	73.180 c
b) Malic Acid						
CONTROL	3028.6	3341.4ab	2202.3 c	2584.1 a	2053.3 bc	1031.8 e
Chitosan		2645.0 c	3295.9 ab	2443.5 ab	2150.2 bc	2256.7 a
Copper1		3092.0 abc	2606.0 bc	2268.9 bc	2553.5 a	1104.8 e
Copper2		2911.1 bc	2925.3 abc	2258.1 bc	2270.5 abc	1015.0 e
Copper1+Chitosan		2835.5 bc	3196.4 ab	2284.9 abc	2362.1 ab	1492.6 d
Copper2+Chitosan		3017.1 bc	3414.8 a	2394.8 ab	2334.0 ab	1872.1 bc
Boron1		2817.1 bc	3542.1 a	2026.8 c	2028.5 bc	1912.0 bc
Boron2		2830.4 bc	2916.2 abc	2051.3 c	2078.0 bc	1759.8 bc
Boron1+Chitosan		3609.1 a	2900.9 abc	2212.2 bc	2140.3 bc	2001.4 b
Boron2+Chitosan		2697.2 c	2574.8 bc	2580.8 a	1943.4 c	1679.7 cd
c) Citric Acid						
CONTROL	18.85	16.10 c	17.97bc	22.73 b	19.29 a	14.41 b
Chitosan		14.13 c	20.78 bc	37.34 a	11.79 cd	12.25 b
Copper1		14.20 c	18.59 bc	16.72 b	12.51 bcd	13.22 b
Copper2		15.58 c	24.37 b	15.52 b	15.94 abc	16.00 b
Copper1+Chitosan		17.31 bc	22.73 bc	19.66 b	11.69 cd	13.71 b
Copper2+Chitosan		16.18 c	34.50 a	20.80 b	10.03 d	11.82 b
Boron1		15.85 c	21.16 bc	20.76 b	17.44 ab	20.75 a
Boron2		22.27 b	20.45 bc	17.82 b	15.62 abc	14.80 b
Boron1+Chitosan		27.96 a	21.16 bc	22.16 b	11.60 cd	12.78 b
Boron2+Chitosan		15.99 c	13.88 c	15.33 b	13.08 bcd	13.03 b

The groupings indicated by lowercase letters within the columns are based on tests performed within each storage period. Means that do not differ significantly from each other are indicated with the same lowercase letter. (p < 0,05).

4. Discussion

Citric acid was identified as the predominant organic acid in strawberry fruits, followed by malic and oxalic acids. This profile is consistent with previous findings reported by Holcroft and Kader (1999), Pelayo et al. (2003), and Ali et al. (2022). The application of boron-based nanoparticles (particularly Boron1 and Boron2) was more effective in preserving all three organic acids throughout the storage period. In contrast, Eroğul et al. (2024), who worked on the Albion cultivar, reported malic acid as the dominant organic acid. These differences may be attributed to genotypic variation among cultivars, growing conditions, and pre-harvest factors.

Malic acid was the dominant organic acid in sweet cherry fruits, followed by citric and oxalic acids. This distribution aligns with findings reported by Hayaloğlu and Demir (2015), Wang et al. (2016), and Karaat et al.

(2019). However, Çolak et al. (2025) found that succinic acid was dominant in cherries treated with spermidine, highlighting how treatment type, cultivar, and environmental conditions can influence acid composition. In our study, chitosan-based treatments were most effective in preserving malic acid levels in cherry, while boron-based treatments had a noticeable effect on citric acid.

The present study also supports growing evidence that nanoparticle coatings can significantly preserve organic acid profiles in soft fruits. For instance, Bahmani et al. (2022) demonstrated that proline-enriched chitosan nanoparticles slowed citric acid degradation in strawberries under cold storage. Likewise, Sani et al. (2025) found that zinc oxide nanoparticles combined with chitosan helped maintain titratable acidity in strawberries and reduce decay. Ma et al. (2019) observed that nitric oxide-releasing chitosan nanoparticles preserved malic acid content in cherry during cold storage by slowing respiration. Similarly, Yıldız et al. (2025) reported that chitosan–selenium microparticles reduced acid loss in sweet cherries, likely due to their barrier-forming and antioxidant effects.

The collective findings suggest that nanoparticles incorporated into edible coatings form semi-permeable layers that reduce oxygen permeability and suppress respiration rates. Since malic and citric acids are among the primary substrates utilized in the respiratory cycle, slowing their consumption helps delay senescence and maintain quality. Therefore, higher acid retention in nanoparticle-treated fruits in our study further validates the stabilizing role of nanomaterials in fruit storage.

Considering the superior performance of Boron1 and Boron2 treatments, a deeper look at boron's physiological effects is warranted. Boron is known to play essential roles in maintaining cell wall structure, regulating membrane function, and modulating key enzymes in carbon metabolism (Shireen et al., 2018; Pereira et al., 2023). Vera et al. (2024) demonstrated that boron improves antioxidant and osmotic regulation in fruit tissues under stress, which may explain improved acid retention in treated samples. Furthermore, boron may reduce vacuolar leakage, thus protecting organic acid compartments. Michailidis et al. (2023) reported that boron reprograms metabolism in cherry fruits, supporting the retention of citric and malic acids, while Zhang et al. (2024) found similar effects in strawberry through enhanced membrane integrity and cell wall strength.

In summary, the combination of boron and copper nanoparticles, particularly when integrated with chitosan, represents a promising approach for preserving organic acid content and overall quality in strawberries and sweet cherries during cold storage. These findings contribute valuable insight to the limited literature focused on the biochemical impacts of nanotechnology-based treatments on organic acid metabolism in soft fruits.

5. Conclusion

This study evaluated the effects of green-synthesized boron, copper, and chitosan nanoparticles on the organic acid profiles of strawberry and sweet cherry fruits during cold storage. The results demonstrated that nanoparticle-based treatments led to measurable improvements in the retention of key organic acids compared to the untreated control. In strawberries, Boron1 and Boron2 applications were particularly effective in sustaining higher concentrations of citric, malic, and oxalic acids throughout the storage period. In sweet cherries, Chitosan and Boron1 treatments were associated with relatively higher retention of malic and citric acid contents.

Citric acid was identified as the dominant organic acid in strawberries, while malic acid was the primary component in sweet cherries. The use of nanoparticle-enriched edible coatings, particularly those incorporating boron and copper, may contribute to the biochemical stabilization of soft fruits by mitigating oxidative stress and slowing the depletion of organic acids during storage.

Overall, the findings of this study offer useful insights into the application of nanomaterials in postharvest handling of horticultural crops. Future research should focus on optimizing nanoparticle concentrations and composite formulations, and explore their effects across different fruit species and quality parameters. Such efforts will support the development of science-based, sustainable postharvest strategies tailored to improving the storage quality of high-value perishable produce.

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Conflict of interest

The authors declare no conflicts of interest.

Authorship contribution statement

E.D.: Data collection, laboratory work, article writing. O.S.: Planning, editing, article writing. N.K.: Planning, laboratory work, editing, article writing.

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