LWT - Food Science and Technology 227 (2025) 117877

Contents lists available at ScienceDirect

LWT

journal homepage: www.elsevier.com/locate/lwt

The postharvest application of biodegradable polymers and a priming agent as a potential tool to enhance phytochemical content, aroma profile and market life of strawberry fruit

Egli C. Georgiadou [a], Carlos Javier Garcia Hernandez Gil [b,1], Anna Maria Taliadorou [a], Eleni D. Myrtsi [a], Gholamreza Gohari [a], Alice Varaldo [c], Sofia Torrado [a], Alessandra Marcon Gasperini [d], Francisco Tomás-Barberán [b], Maarten L.A.T.M. Hertog [e], Vasileios Fotopoulos [a], George A. Manganaris [a,*,1]

[a] Cyprus University of Technology, Department of Agricultural Sciences, Biotechnology & Food Science, 3603, Lemesos, Cyprus
[b] Quality, Safety and Bioactivity of Plant-Derived Foods, Centro de Edafología y Biología Aplicada del Segura-Consejo Superior de Investigaciones Científicas (CEBAS-CSIC), Murcia, 30100, Spain
[c] Department of Agricultural, Food and Forest Sciences, University of Turin, Italy
[d] MycoLab, Clinical, Pharmaceutical and Biological Sciences, School of Life and Medical Sciences, University of Hertfordshire, Hatfield, AL10 9AB, UK
[e] KU Leuven, BIOSYST-MeBioS Postharvest Group, Willem de Croylaan 42, bus 2428, Leuven, B-3001, Belgium

ARTICLE INFO

Keywords:
Fragaria x *ananassa*
Chitosan
Alginate
Phytochemicals
Phenolic acids
Cold storage

ABSTRACT

Strawberry (*Fragaria* x *ananassa* Duch.) is a highly perishable crop with limited market life. The aim of our work was to dissect the efficacy of an array of molecules with potential priming effect on postharvest performance, antioxidant potential and aroma profile of strawberry fruit. Freshly harvested fruit (cv. 'Savana') of uniform size and ripening stage (commercial ripeness >80 % of the surface red color) were subjected to the following postharvest dip treatments: control (untreated), hydro-primed, NOSH-A, chitosan (CTS) and sodium alginate (NaA). NOSH-A is a proprietary priming agent that acts as a donor that releases nitric oxide (NO), hydrogen sulfide (H_2S), and aspirin (acetylsalicylic acid) concurrently. CTS is a biobased, biologically safe and biodegradable polymer that has been exploited as a nanocarrier to efficiently deliver an array of compounds, while NaA is another biodegradable polymer applied in smart nano-delivery systems. Treated fruit were subjected to 4, 8 and 12 d of cold storage (CS, 4 °C, 90 % RH) and additional maintenance at room temperature for 1 d to simulate short, medium and extended refrigerated storage, respectively. Quality attributes and fungal incidence and severity were determined, without any striking differences among the treatments applied. Polyphenolic compounds analysis by HPLC-DAD-ESI-MS/MS showed an increment in an array of phytochemical compounds such as ellagic acid, pelargonidin-3-glucoside, pelargonidin-3-rutinoside, and catechin, particularly after 8 days CS compared to fleshly harvested fruit. Such changes were more evident when the priming agent NOSH-A was applied, being more pronounced in the case of pedunculagin 2 isomer that registered a significant increment. HS-SPME-GC analysis identified 140 unique volatile organic compounds (VOCs) with chitosan-treated strawberries showing the most distinct VOC profile after extended cold storage with higher contents of methyl hexanoate. Results reported herein shed light in the efficacy of an array of agents on parameters linked to secondary metabolism of strawberry fruit at postharvest level.

1. Introduction

Strawberry (*Fragaria x ananassa* Duch.) is a delicate fruit crop with a considerable growth in terms of production volumes, mainly attributed to its appealing appearance and high nutritional profile and phytochemical content (El-Mogy et al., 2019; Manganaris et al., 2014). However, strawberry fruit suffers from limited storage potential leading to spoilage and reduced marketability (Sun et al., 2022). Noteworthy,

* Corresponding author.
E-mail address: george.manganaris@cut.ac.cy (G.A. Manganaris).
[1] Equal contribution as first author.

https://doi.org/10.1016/j.lwt.2025.117877
Received 23 February 2025; Received in revised form 1 May 2025; Accepted 2 May 2025
Available online 5 May 2025
0023-6438/

postharvest losses can reach up to 50 %, exacerbated by fungal diseases and sensitivity to mechanical damage, and thus significantly impacting the economic returns for producers (Moghadas et al., 2025) Towards preservation of strawberry quality and nutritional value after harvest, an array of postharvest strategies including compounds with hormonal activity (i.e. salicylic acid, abscisic acid, methyl jasmonate) has been also tested (Darwish et al., 2021).

Coatings have been reported as cost-effective and environmentally friendly solutions towards preservation of fruit quality (Adiletta et al., 2021; Guimarães et al., 2018); they create a continuous, thin layer of edible substances, such as polysaccharides, lipids and proteins used alone or in blends, on the fruit surface by spraying or dipping them and obtaining single or double layers (Suhag et al., 2020). Such coatings are usually composed of biodegradable and biocompatible materials that are "generally recognized as safe" (GRAS) or recognized as food additives by the Food and Drug Administration (FDA) or the European Union (Ncama et al., 2018). Coatings form a physical protective barrier between the fruit and the environment (Jongsri et al., 2016) and alter respiration and transpiration, thus slowing down the ripening and/or softening process (Maringgal et al., 2020). At the same time, coatings may contribute to the protection against mechanical damages, microbiological infestations, tissue softening and enzymatic browning, with special reference to fresh-cut commodities (Oms-Oliu et al., 2010).

The most commonly used polysaccharides are cellulose derivatives, alginates starches, pectin, pullulan, carrageenan and chitosan. Among them, chitosan (CTS)-based coatings are considered to be the best ECs, with non-toxic, biodegradability, and antimicrobial actions and with a wide use in several horticultural commodities (Petriccione et al., 2014). CTS is a deacetylated derivative of chitin, the second most abundant renewable biopolymer in nature; it is a linear polysaccharide composed of β-(1,4)-linked glucosamine units (2-amino-2--deoxy-β-d-glucopyranose) together with some quantities of N-acetyl-glucosamine units (2-acetamino-2-deoxy-β-d-glucopyranose) and is present in green algae, the exoskeletons of arthropods and the cell walls of fungi and yeasts (De Queiroz Antonino et al., 2017).

Alginate (Alg) is also a linear copolymer, commonly produced by seaweeds (brown algae) and is structured by (1 → 4)-linked-α-L-guluronate and (1 → 4)-linked-β-D-mannuronate moieties (Nair et al., 2020), widely used as an edible coating for the preservation of fruits and vegetables (Gohari et al., 2024). It is known as a hydrophilic biopolymer capable of forming transparent, uniform, water soluble and high-quality films (Mahcene et al., 2020). Sodium alginate (NaA) is the most common salt of alginate, with excellent colloidal properties, characterised by high degree of reactivity with many metal cations that leads to the formation of gels or insoluble polymers (Jiang et al., 2013).

Biodegradable polymers are extensively being tested as a sustainable, alternative to traditional non-biodegradable materials, postharvest treatment on strawberry fruits, showing promising results in maintaining the freshness extending the shelf-life (Bahmani et al., 2024). The nanoencapsulation-based coatings showed promising results in extending the shelf life of fresh produce (Neethirajan & Jayas, 2011). A nano-coating can contain bioactive compounds in the form of nanoparticles, that due to their improved mechanical properties, have greater chemical reactivity and more bioactivity than conventional particles (Neethirajan & Jayas, 2011). In fact, positive effects on shelf-life extension and/or quality maintenance, after the application of CTS nano-coatings enriched with nanomaterials, essential oils, or antimicrobial agents, have been reported in a considerable number of studies dealing with strawberry (Huang et al., 2022; Lin et al., 2020; Nguyen et al., 2020; Robledo et al., 2018). The use of alginate nano-coatings have also shown a positive effect on strawberry (Dhital et al., 2018; Emamifar & Bavaisi, 2020; Liu et al., 2021). However, each polymer type has unique mechanisms and benefits, making them suitable for various applications in the food industry. The selection of polymer depends on the cultivar properties and scope in terms of storage potential (i.e. destined for exportation).

The priming agents have received considerable attention over the recent years in order to ameliorate plant response under adverse conditions with however limited information available when they are directly applied in the fruit. The exploitation of non-toxic synthetic and natural priming agents towards sustainably-sourced and environmentally sound products has recently received considerable attention. In the current study we aimed to dissect the efficacy of a novel priming agent (NOSH-A) at postharvest level. NOSH-A acts as a donor that releases nitric oxide (NO), hydrogen sulfide (H_2S), and aspirin (acetylsalicylic acid) concurrently; it was initially formulated as an anticancer drug but it also displays protective effects against abiotic stress conditions in plants (Antoniou et al. 2020; Gohari et al. 2024). The simultaneous donation of multiple signal/hormonal molecules renders it an attractive candidate of multifunctional priming, whereby multiple benefits can be achieved through the synergistic activity of different agents. However, no data on its use to combat postharvest abiotic conditions as cold storage have been reported. To this end, our study aimed to evaluate the effect of postharvest dip treatments with either NOSH-A along with two biodegreadble polymers (chitosan and sodium alginate) on quality attributes, volatilome fingerprinting and phytochemical properties of strawberry fruit.

2. Materials and methods

2.1. Fruit material and treatment application

Strawberry fruit of cultivar 'Savana' was used for the needs of the current study. 'Savana' is a rustic and highly productive strawberry variety that allows early production that can be marketed for a premium, covering 'low supply' periods. Fruits of uniform size and ripening stage (commercial ripeness >80 % of the surface red color and without any softness symptoms), were hand-harvested and immediately transferred to the laboratory. After removal of defective fruit, they were separated into 15 lots of 60 fruit each. Each three lots were subjected to immersion with the following postharvest treatments: (1) control (untreated), (2) hydro-primed, (3) NOSH-A (50 μmol L^{-1}), (4) chitosan (CTS, 0.1 g 100 mL^{-1}), (5) sodium alginate, (NaA, 0.1 g 100 mL^{-1}). In all cases, solutions were freshly prepared and 0.1 mL 100 mL^{-1} Tween20 was added as surfactant. Fruit were immersed in the treatment solutions for 10 min, then kept for drying for 30 min at room temperature and subsequently transferred to cold storage (4 °C, 90 % RH) with each lot being kept in a covered punnet. Fruit were maintained at cold storage for 4, 8 and 12 d, respectively and were analyzed after additional maintenance at room temperature (20 °C) for an additional day (4 + 1, 8 + 1, 12 + 1). For biological/enzymatic analyses, the fruit were immediately flash frozen in liquid nitrogen, and stored at −80 °C until needed. For the determination of polyphenolic compound analysis, samples were freeze-dried (Freeze Dryer-Christ Alpha 1–4 LD plus).

2.2. Quality attributes

Fruit weight was measured using 20 fruit per treatment and storage condition applied and accordingly weight loss was determined. Soluble solid content (SSC) and titratable acidity (TA) were measured in fruit juice isolated using a professional juicer. SSC was quantified with a refractometer (Atago, PR-32α, Japan) and results expressed as °Brix. TA was determined with the use of an automatic multiple positions titrator (862 Compact Titrosampler, Metrohm AG, Switzerland). Briefly for each measurement, 5 mL of diluted juice in 45 mL distilled H_2O was used for titrating 0.1 mol L^{-1} NaOH to a pH end point of 8.1. Results were expressed as g citric acid 100 mL^{-1}. Ripening index (RI) was calculated as the SSC/TA ratio. Strawberry samples (0.3 g) were extracted with 10 mL of 80 % v/v ethanol and sugars [total soluble sugars (TSS), sucrose, glucose, and fructose] were determined spectrophotometrically as described elsewhere (Hadjipieri et al., 2020).

2.3. Aroma profile

The volatilome fingerprinting of juiced strawberry samples using using HS-SPME-GC-MS was adapted from Vandendriessche et al. (2013). In short, fruit were cut and blended with 1.0 M NaCl (0.5 mL: 1 g), snap-frozen in liquid N_2 and stored at −80 °C until needed. After overnight thawing at 4 °C, 5 g of the juice mixture was transferred into a 20 mL headspace (HS) vial (Filter Service, Belgium). Prior to solid phase micro extraction (SPME), the samples were incubated for 35 min at 40 °C on a heated tray to populate the headspace with VOCs. The volatiles were extracted by exposing an SPME fiber (DVB/CAR/PDMS, 50/30 mm film thickness; Supelco Inc., USA) to the headspace for 30 min at 40 °C. After extraction, aroma compounds were thermally desorbed into the injector set to 250 °C and equipped with an SPME liner (0.75 i.d., Supelco Inc., USA). Separation was conducted on a 30 m × 250 μm x 0.250 μm HP-5MS column (Agilent Technologies), using helium as carrier gas. The data were evaluated using MassHunter Workstation (Unknowns Analysis v10.1, Agilent Technologies) and the volatile compounds listed in Supplementary Table 1 were identified with the NIST 2020 database (NIST20, USA). Analyses were performed on three biological replicates per treatment.

2.4. Phytochemical analysis

Phenolic compounds were extracted following the procedure of Shehata et al. (2020) and spectrophotometrically determined at 765 nm. Analysis were conducted in triplicate and the results were expressed as mg gallic acid equivalents (GAE) 100 g^{-1} of fresh weight (FW).

Total anthocyanin content was extracted from the samples following the procedure of Bal and Ürün (2020) and its concentration was calculated as pelargonidin equivalents and expressed on a fresh weight base as mg 100 g^{-1}. Total flavonoid content was estimated from the samples following the procedure of Meyers et al. (2003) and results were expressed on a fresh weight base as mg 100 g^{-1} quercetin equivalents. Ascorbic acid (AsA) assay was performed as described by Georgiadou et al. (2018) and results expressed as mg 100 g^{-1} FW.

The polyphenolic compound analysis by HPLC-DAD-ESI-MS/MS was performed according to Salazar-Orbea et al. (2022). One hundred mg of lyophilized samples were extracted with 1 mL of methanol/water/acetic acid (70:29:1, v/v/v). The samples were homogenized in a vortex for 1 min and then sonicated for 30 min at room temperature. Samples were then centrifuged for 15 min at 20000 g at 10 °C (Thermo Scientific ™ Sorvall™ ST 16, Germany). The supernatant was filtered through a 0.22 μm PVDF filter and analyzed by triplicate. Phenolics identification and quantification were carried out on an Agilent 1100 HPLC system equipped with a photodiode array detector (G1315D) and coupled in series to an HCT Ultra Bruker Daltonics ion trap mass spectrometer through an electrospray ionization (ESI) interface HPLC-DAD-ESI-MS/MS. The chromatographic separation was performed using a Poroshell 120 EC column (3 × 100 mm, 2.7 μm) from Agilent Technologies (Waldbronn, Germany). Phenolic compounds were identified by their UV spectra, retention time, molecular weight, and MS/MS fragmentation pattern. Phenolic compounds quantification was performed using the authentic standards of castalagin (280 nm), catechin (280 nm) *p*-coumaric acid (320 nm), pelargonidin (520 nm), ellagic acid (360 nm) and quercetin (360 nm) to quantify ellagitannins, flavan-3-ols, hydroxycinnamic acids, anthocyanins, ellagic acid conjugates and flavonols respectively.

2.5. Polyamine content

The levels of free putrescine (Put), spermidine (Spd) and spermine (Spm) were determined by high-performance liquid chromatography (HPLC) separation of dansyl derivatives, as analytically described in Marcé et al. (1995). Analyses were performed on three biological replicates per treatment.

2.6. Polyphenol oxidase (PPO) activity

PPO extraction was based on the methodology described in Alegria et al. (2016) with slight modifications. In brief, PPO was extracted from strawberry tissues (0.4 g) adding 1.5 mL of cold phosphate buffer (0.1 mol L^{-1}, pH 6.5) and 0.04 g of polyvinylpyrrolidone. Next, samples were vortexed for 1 min and centrifuged at 20.000×*g* for 30 min at 4 °C. During the entire process, samples were kept in an ice-bath to prevent protein denaturation. PPO activity was assayed spectrophotometrically measuring the catechol oxidation rate at 420 nm for 1 min (TECAN, Infinite 200® PRO). The reaction mixture was adapted to 96-well microplate with 10 μL of enzymatic extract and 290 μL of catechol (0.05 M). Results were expressed as U mg^{-1} fresh weight (FW).

2.7. Cellular damage indicators

Malondialdehyde (MDA) content resulting from the thiobarbituric acid (TBA) reaction was estimated to determine lipid peroxidation (Filippou et al., 2011). The MDA content was measured at 532 and 600 nm and was estimated using the Lambert-Beer law, with extinction coefficient of 155 $mmol^{-1}$ L cm^{-1} and expressed as nmol g^{-1} fresh weight (FW).

Hydrogen peroxide (H_2O_2) content was calculated spectrophotometrically based on the oxidation of iodide (I-1) to iodine (I), after its reaction with potassium iodide (KI), using the procedure described by Loreto and Velikova (2001). The content of H_2O_2 was measured at 390 nm and was estimated based on a standard curve of known concentrations of H_2O_2 (μmol g^{-1} FW).

2.8. Severity index and fungal incidence of strawberry fruit

Fungal incidence due to *Bortytis cinerea* infection was determined by the percentage of strawberries exhibiting visible signs of fungal contamination relative to the total number (n = 24) of fruit in each treatment after 12 d of cold storage and additional maintenance at room temperature for 1 d and 4 d, respectively. The infection severity was determined by a diagrammatic scale (Fig. 1) that was developed in accordance with a relevant study by Filippi et al. (2021) with scores from 0 (no visible infection) to 7 (rotten). The scores from all fruit in each treatment were summed to generate the cumulative severity index. Higher cumulative scores reflected to more severe fungal contamination across the sample set.

2.9. Statistical analysis

Statistical analysis was carried out for quality attributes using the software package SPSS v25.0 (SPSS Inc., Chicago, IL, United States). The comparison of averages of each treatment was carried out using One-way Anova analysis followed by Duncan's multiple range test at significance level 5 % ($p \leq 0.05$). For biochemical and phytochemical analysis, both statistical analysis (one-way ANOVA analysis was conducted including Tukey's-HSD post hoc test ($p \leq 0.05$) and figures were conducted using GraphPad version 10.4.1 (GraphPad Software, San Diego, CA, USA).

For the VOC-data, multivariate statistical analysis, PCA, PLS and variable selection using Jack-knifing, was conducted using the Unscrambler X (CAMO, Norway). Specific VOCs one-way ANOVA analysis was conducted including Tukey's-HSD post hoc test ($p \leq 0.05$) using JMP-Pro (v17, SAS Institute Inc., Cary, NC).

With reference to severity index of fungal diseases, a non-parametric test (Kruskal-Wallis; $p \leq 0.05$) was performed to assess differences in infection severity among the treatment groups followed by pairwise Mann-Whitney *U* test ($p \leq 0.05$) comparing each treatment against the untreated group.

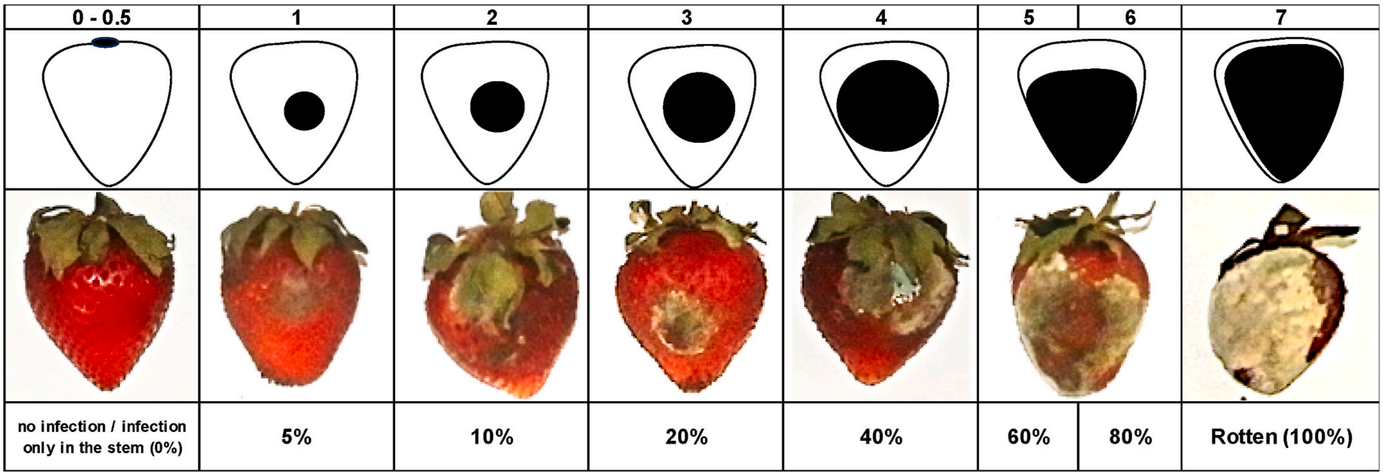

Fig. 1. Diagrammatic scale for the severity of infection (0–7) of fungal spoilage in strawberry fruits and the corresponding percentage (%) of coverage. The scale was developed based on a relevant study by Filippi et al. (2021).

3. Results and discussion

3.1. Quality attributes

A gradual increase of weight loss in all treatments applied, being higher than the threshold of 5 % after 6–8 d of cold storage, was monitored. The treatment of strawberries with water (hydroprimed) prior to storage showed a negative effect compared with control, while none of the agents applied showed any striking difference in terms of controlling weight losses (Supplementary Figure 1). Weight loss is a key parameter that defines both quantitative and qualitative (i.e shrivelling) losses of strawberry fruit during cold storage. As a non-climacteric fruit, strawberries must be harvested at the fully mature stage to obtain the best visual and nutritional quality, resulting in high fruit losses during refrigerated storage. Chitosan-based coatings have been reported to prolong the shelf-life of several fruits and fresh-cut commmodities (Adiletta et al., 2021), including strawberries (Robledo et al., 2018) by slowing down the weight loss and at the same time safeguarding vitamin content (i.e. ascorbic acid) and antioxidant capacity during cold storage (Pagliarulo et al., 2016). Results reported herein showed that weight losses were not reduced when the agents tested were applied. Among the formulations examined, a reduction in weight loss in CTS-treated strawberries as compared with NOSH-A- and NaA-treated fruits was registered. Higher losses in hydroprimed versus untreated strawberries was also monitored, indicating a negative effect due to immersion.

Harvested strawberries had an average SSC content of 8.3 % that is considered well above the threshold that defines a strawberry as of high quality in terms of taste (Table 1). The SSC contents after removal from cold storage and additional maintenance at room temperature for 1 day was in the range 7.6–8.6 % for all storage treatments and durations applied. Cold storage generally leads to a decrease in the soluble solids content of strawberries, although the extent of this decrease can vary based on factors such as cultivar, storage conditions, and specific treatments applied. In the current study, lower values after 12 d CS were not statistically signifcant. On the other hand, titratable acidity showed some alterations among different storage treatments, yet no specific

Table 1
Effect of storage duration[a] and postharvest treatment[b] applied on the soluble solids content (SSC), titratable acidity (TA), and ripening index (RI=SSC/TA) of strawberry fruits.

Storage	SSC (°Brix) (%)				
	Untreated	Hydroprimed	NOSH-A	CTS	NaA
Harvest	8.33 ± 0.11				
4 d CL + 1 d SL	8.10 ± 0.23 a	8.43 ± 0.35 a	8.57 ± 0.42 a	8.25 ± 0.33 a	8.37 ± 0.20 a
8 d CL + 1 d SL	8.50 ± 0.06 a	8.22 ± 0.12 ab	7.98 ± 0.21 b	8.08 ± 0.16 ab	8.43 ± 0.15 ab
12 d CL + 1 d SL	8.37 ± 0.29 a	7.85 ± 0.20 a	7.98 ± 0.19 a	7.58 ± 0.32 a	7.60 ± 0.26 a
Storage	TA (g citric acid 100 mL^{-1})				
	Untreated	Hydroprimed	NOSH-A	CTS	NaA
Harvest	0.97 ± 0.03				
4 d CL + 1 d SL	0.98 ± 0.07 ab	1.12 ± 0.07 a	0.80 ± 0.07 b	1.05 ± 0.07 a	0.99 ± 0.06 ab
8 d CL + 1 d SL	0.94 ± 0.04 a	0.93 ± 0.09 a	0.98 ± 0.03 a	0.90 ± 0.02 a	0.99 ± 0.05 a
12 d CL + 1 d SL	0.82 ± 0.02 a	1.05 ± 0.13 a	0.92 ± 0.10 a	0.99 ± 0.04 a	0.96 ± 0.05 a
Storage	RI (SSC/TA) (%)				
	Untreated	Hydroprimed	NOSH-A	CTS	NaA
Harvest	8.60 ± 0.21				
4 d CL + 1 d SL	8.30 ± 0.58 b	7.55 ± 0.51 b	10.84 ± 0.50 a	7.88 ± 0.51 b	8.51 ± 0.66 b
8 d CL + 1 d SL	9.04 ± 0.38 a	9.00 ± 0.83 a	8.18 ± 0.37 a	8.97 ± 0.07 a	8.54 ± 0.37 a
12 d CL + 1 d SL	10.21 ± 0.55 a	7.74 ± 0.95 a	8.81 ± 0.79 a	7.75 ± 0.63 a	8.02 ± 0.73 a

[a] Cold storage (4 °C, 90 % RH) duration was 4, 8 and 12 d followed by an additional day maintenance at room temperature for (20 °C, 90 % RH).
[b] Fruits were subjected to the following postharvest treatments: (1) control (untreated), (2) hydro-primed, (3) NOSH-A (50 μmol L^{-1} μM), (4) chitosan (CTS, 0.1 g 100 mL^{-1}), (5) sodium alginate, (NaA, 0.1 g 100 mL^{-1}). Values within each row (day of shelf-life) followed by the same letter are not statistically significant according to Duncan's multiple range test at significance level $P \leq 0.05$.

pattern was recorded. Elevated acidity levels were monitored for the treatments after 12 d cold storage plus one day shelf-life resulting in higher ripening index for untreated fruit, potentially due to an advanced senescencing processes. In general, coatings have been reported to enhance quality attributes and sensorial properties (**Maringgal et al., 2020**), yet this cannot be validated by the results reported herein.

The contents of sucrose, glucose and fructose, as well as the total soluble sugars were additionally determined; in line with the SSC results, no statistically significant differences were observed among storage treatments and durations applied (Fig. 2). Glucose is the predominant sugar in strawberries, often found in higher concentrations than fructose and sucrose (Basson et al., 2010). Although fructose is a major sugar in strawberries, it is generally less prevalent than glucose (Lee et al., 2018). However, in the current study, fructose registered the highest contents as also elsewhere indicated (Simkova et al., 2024). Therefore, sugar contents appear to be a cultivar specific characteristic, while our data confirm that sucrose is present in strawberries in lower concentrations.

3.2. Volatile organic compounds

Using HS-SPME-GC-MS, 140 unique volatile organic compounds (VOCs) were identified among samples from the various treatments and storage durations (Supplementary Table 1). The compounds listed are in line with what has been observed by other groups (reviewed in Ulrich et al., 2018). While all fruit were harvested at a fully red ripe stage, over

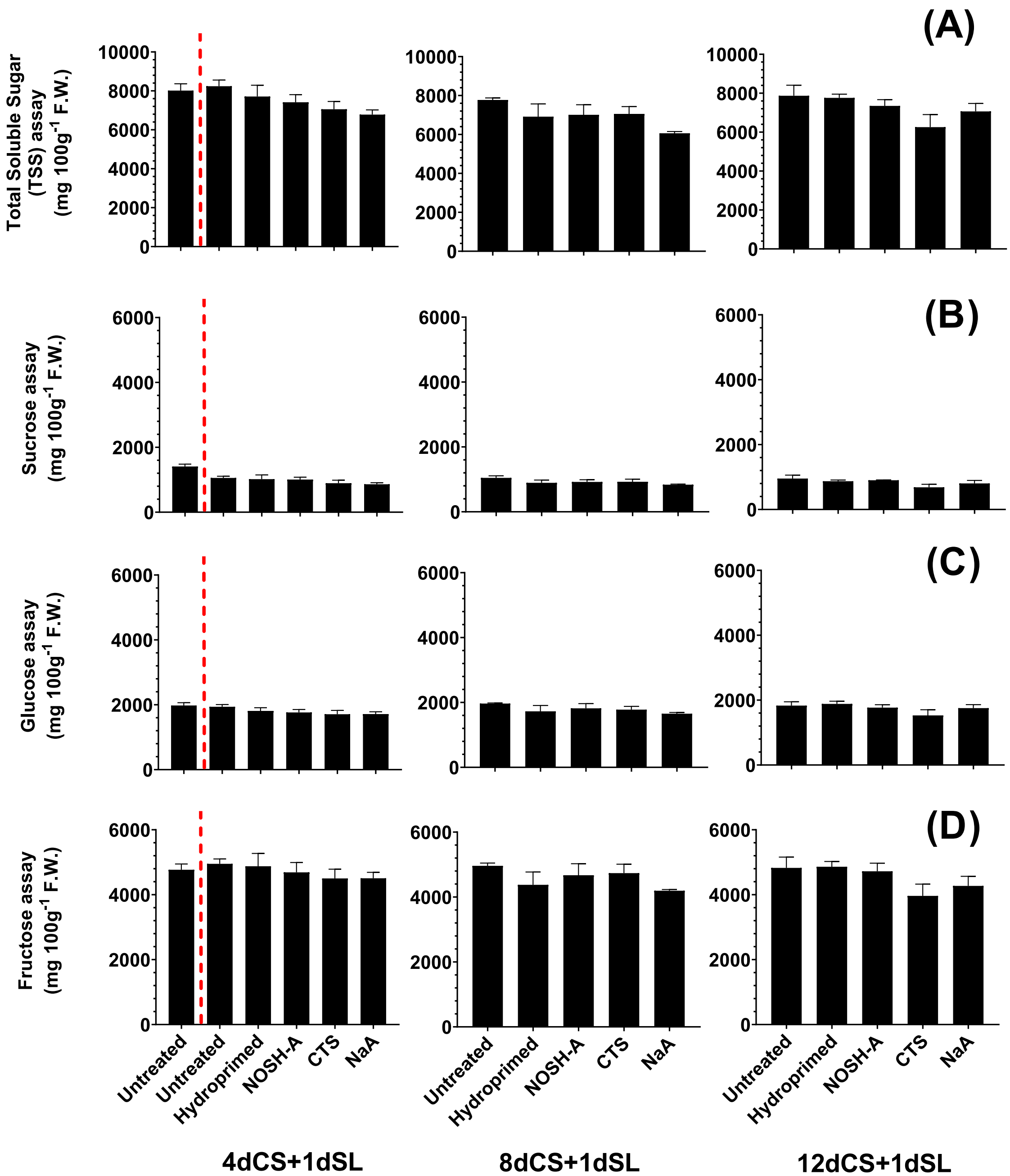

Fig. 2. Effect of storage duration and postharvest treatment applied on the contents of total soluble solids and individual sugars (sucrose, glucose, fructose) in strawberry fruits (ns = p > 0.05, * = p ≤ 0.05, ** = p ≤ 0.01, *** = p ≤ 0.001, **** = p ≤ 0.0001.) Fruits were subjected to the following postharvest treatments: (1) control (untreated), (2) hydro-primed, (3) NOSH-A (50 50 μmol L^{-1}), (4) chitosan (CTS, 0.1 g 100 mL^{-1}), (5) sodium alginate, (NaA, 0.1 g 100 mL^{-1}). Storage duration was 4, 8 and 12 days at 4 °C, 90 % RH) and maintenance for an additional day at room temperature (20 °C).

time the VOC profile still changed as can be observed from the principal component analysis (PCA). Score plot of PCA visualising the shift in VOC composition of the fruit's aroma profiles within the first to principal components sumarised 43 % of the VOC variation (Fig. 3A). The scoreplot showed that the untreated fruit presented the largest changes with time as represented by their arrow trajectories. Fruit treated with CTS remained closest to their starting position indicating their VOC profiles changed the least. The hydro-, NOSH-A and NaA-primed fruit took intermediate positions, showing large overlap between their replicate samples. In spite of these differences large similarities are still present. Using a PLS on time, a total of 47 volatiles were identified as being statistically significant contributors to explain time related changes in common between all treatments (Supplementary Table 1) with a crossvalidation R^2 of 92 % (data not shown).

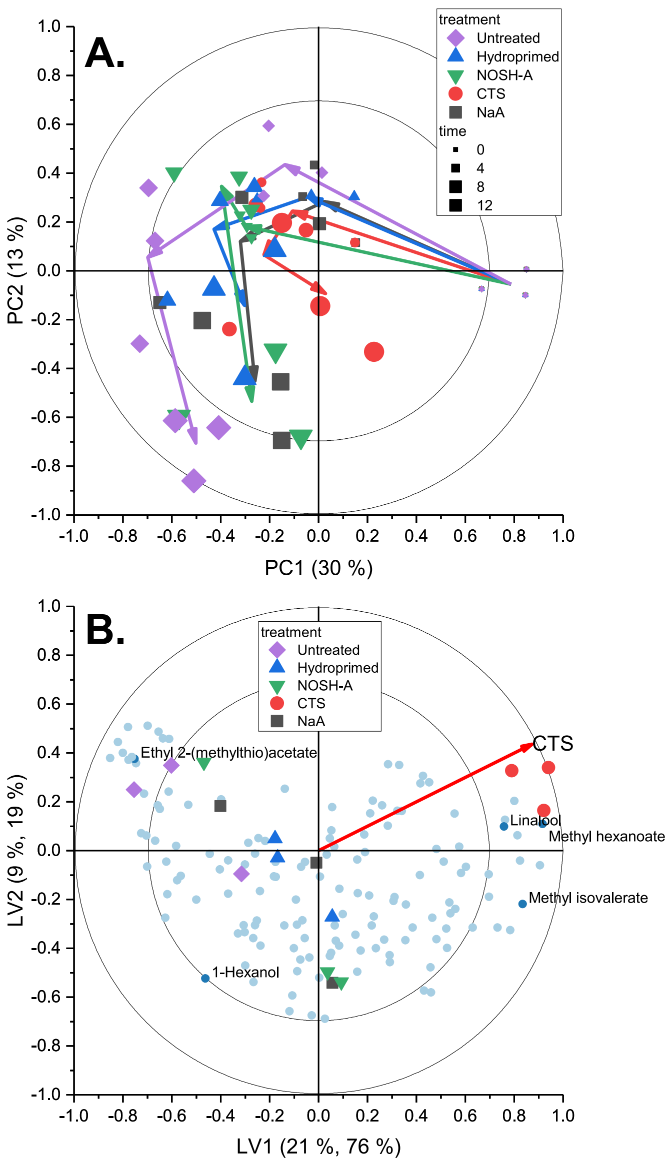

Fig. 3. Multivariate analysis of the VOC patterns of primed strawberry fruit. (A) Score plot of principal component analysis (PCA) visualising the shift in VOC composition of the fruit's aroma profiles. (B) Biplot of a partial least square discriminant analysis (PLS-DA) applied to the data after 12 days cold storage and additional maintenance at room temperature for 1 day to discriminate CTS-treated fruit from the other treatments. The large symbols represent the scores of the triplicate objects per treatment. The small symbols represent the X-loadings of the individual VOCs with the labelled VOCs being the five selected significant contributors to this PLS-DA model. The arrow represents the Y-loading indicating the direction of CTS treated fruit.

Based on the scoreplot from Fig. 3A, the largest differences in the VOC profile can be expected at the end of cold storage (12 d) plus 1 day SL. Therefore, a preliminary PLS-DA regression analysis on the 12 + 1 d data only, revealed that CTS-treated fruit was indeed most different from the other treatments which, amongst them, could not be well separated. Therefore, a final PLS-DA was performed contrasting, at 12 + 1 d, CTS treated fruit against all other treatments (Fig. 3B). This PLS-DA calibration model, based on the first two latent variables (LV), used 30 % of the variation in VOCs (21 % + 9 %) to discriminate with 95 % accuracy CTS treated fruit from the other treatments (76 % + 19 %) and resulted in the selection of five VOCs significantly contributing to this PLS-DA model. In particular, methyl hexanoate (CAS 106-70-7), methyl isovalerate (CAS 556-24-1) and linalool (CAS 78-70-6) were positively correlated to CTS-treated fruit, while ethyl 2-(methylthio)acetate (CAS 4455-13-4) and 1-hexanol (CAS 111-27-3) were negatively correlated. By using only these five VOC's, a stable PLS-DA model was obtained giving a crossvalidation R^2 of 66 % (data not shown). While a good separation could be obtained based on this limited selection of VOCs, only methyl hexanoate showed a statistically significant difference for CTS treated fruit (Supplementary Figure 2).

Esters are the predominant compounds contributing to the characteristic strawberry aroma, with significant contributions from terpenoids, furanones, and sulfur compounds (Abouelenein et al., 2023; Zheng et al., 2023). Methyl hexanoate is one of the most abundant and most frequently identified ester in strawberry (Ulrich et al., 2018) and has been shown, after an initial increase, to decrease during storage of ripe fruits (Li et al. 2021, Yan et al., 2024). Its significantly high value in CTS treated fruit at 12 + 1 d suggests CTS might be inhibiting postharvest fruit senescence-related processes affecting their VOC profile. Interestingly, other relevant studies on strawberry showcased that the application of chitosan coatings can help maintain the aroma profile by enhancing the levels of desirable esters and delaying the buildup of off-flavors (Almenar et al, 2009; Perdones et al., 2016).

Overall, the observed similarities in VOC changing over time were larger than the differences between treatments. Cold storage is used to extend the shelf life of strawberries but can significantly alter their aroma profile. Noteworthy, VOC profile of 'Elsanta' strawberries differed between 4 or 8 °C of cold storage and additionally among fruit harvested in different years, indicating that aroma change at harvest and during storage is highly dependent on environmental factors during growth (Baldwin et al., 2023).

3.3. Phytochemical composition

Total phenols and ascorbic acid content remained unaffected by the agents and the storage duration applied (Fig. 4A and B). Marked differences were visible after 4 d and 8 d of cold storage, for total anthocyanin and total flavonoids contents, respectively. After 4 d CS, NOSH-A-treated strawberries were characteriszed by higher anthocyanin content, while NaA-treated fruits registered the highest flavonoid content (Fig. 4C and D). Polyphenolic compounds analysis by HPLC-DAD-ESI-MS/MS revealed that the strawberry samples contained a characteristic phenolic compound profile, including ellagitannins and ellagic acid conjugates [two pedunculagin (bis-hexahydroxydiphenoyl glucose) isomers, ellagic acid and an ellagic acid pentoside and ellagic acid rhamnoside], anthocyanins (pelargonidin 3-glucoside and 3-rutinoside), flavan 3-ols (catechin) and proanthocyanidins (procyanidin B1), flavonols (quercetin 3-glucuronide and kaempferol 3-glucuronide, 3-glucoside and 3-malonylglucoside), and hydroxycinnamic acid derivatives [p-coumaroyl hexose (2 isomers) and feruloyl hexose] (Fig. 5). Such data are in agreement with previous studies on strawberry phenolic compounds (Buendía et al., 2010).

Noteworthy, polyphenolic compounds analysis by HPLC-DAD-ESI-MS/MS showed an increment in an array of phytochemical

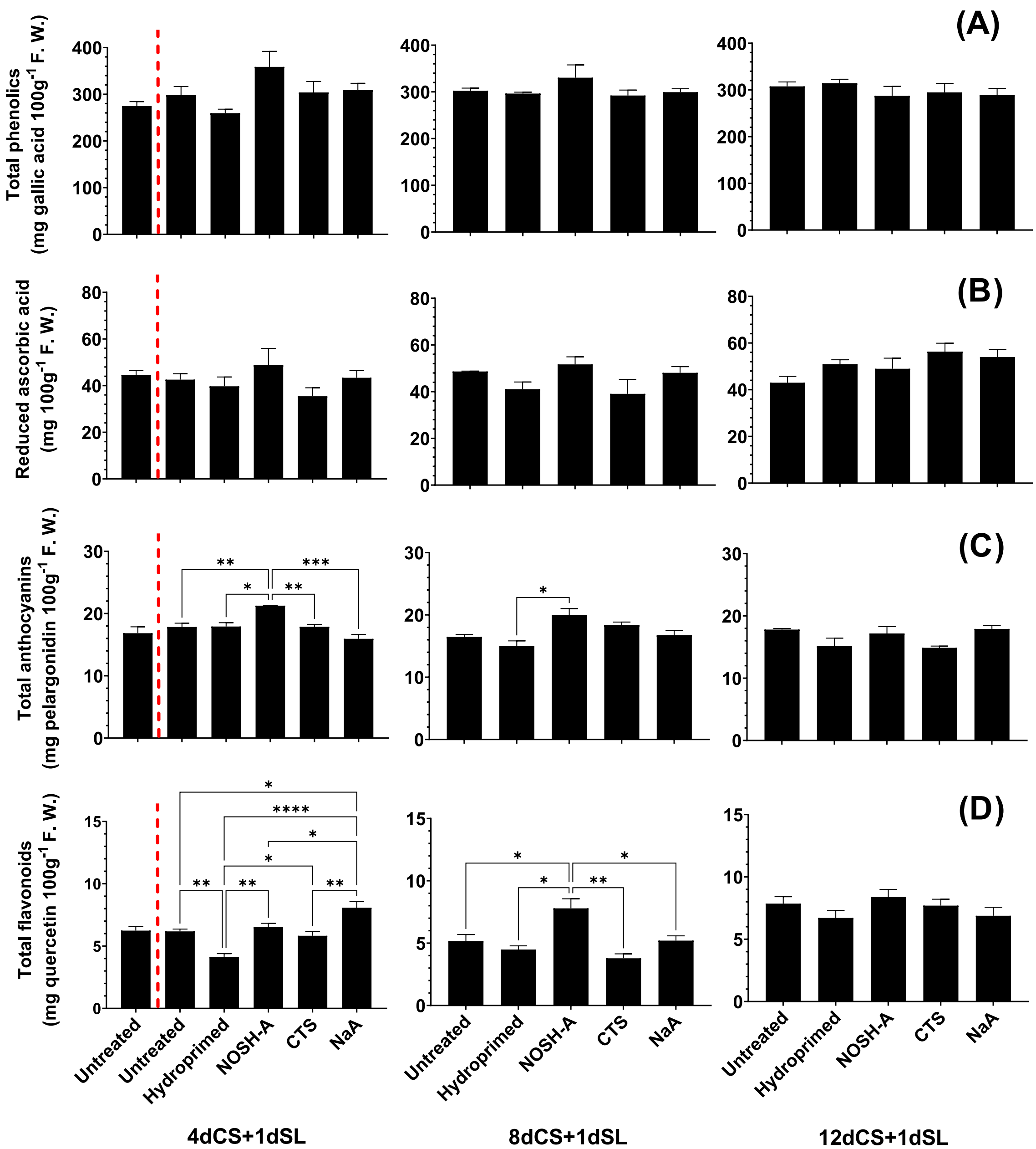

Fig. 4. Effect of storage duration and postharvest treatment applied on the contents of total phenolics, reduced ascorbic acid, anthocyanins and flavonols in strawberry fruits (ns = $p > 0.05$, * = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$, **** = $p \leq 0.0001$.) Storage conditions and postharvest treatments are described in Fig. 2.

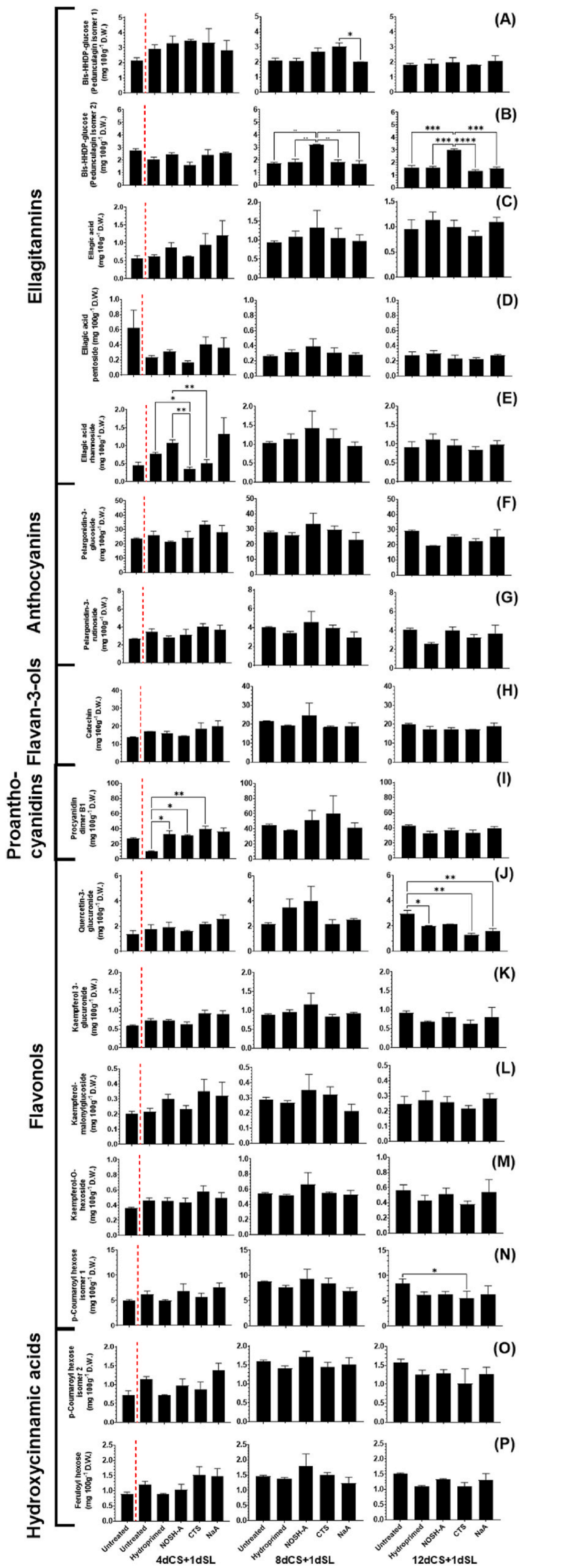

Fig. 5. Content of individual classes (ellagitannins, anthocyanins, flavan-3-ols, proanthocyanidins, flavonols and xydroxycinnamic acids) of phenolic compounds in strawberry fruits (ns = p > 0.05, * = p ≤ 0.05, ** = p ≤ 0.01, *** = p ≤ 0.001, **** = p ≤ 0.0001).

compounds such as ellagic acid, pelargonidin-3-glucoside, pelargonidin-3-rutinoside, and catechin after 8 days CS compared to fleshly harvested fruit. Such changes were more evident when the priming agent NOSH-A was applied, being more pronounced in the case of ellagitannins and pedunculagin 2 isomer in particular that registered a significant increment. However, as a whole, the different agents applied did not show significant changes in an array of key phytochemicals found in strawberry fruit when tested for the same storage conditions with few exceptions. Among agents tested, NOSH-A potential as 'phytochemical enhancer' worths to be further tested in other postharvest experimental set ups.

3.4. PPO activity

PPO activity presented significant changes among the agents applied after 4 and 8 d CS and mainetance at room temperature for 1 d. At 4 + 1 d, PPO activity in untreated-, hydroprimed-, CTS- and NaA-treated strawberries was higher than NOSH-A-treated fruit presented the lowest PPO activity ($p \leq 0.001$) after 4 d CS. A lower PPO activity ($p \leq 0.05$) in NOSH-A-treated fruit compared to CTS- and NaA-treated fruits was also registered after 8 d CS (Fig. 6A). Phenols are secondary metabolites with different roles in plants, primarily displaying antioxidant function that helps plant to cope with oxidative stress induced by ROS (Panahirad et al., 2020). PPO oxidizes phenols and additionaly causes browning in fruits converting polyphenolic substrates to dark pigments in the presence of oxygen (Panahirad et al., 2019). CTS-based coatings have been reported to enhance phenolic content in strawberry (Wang & Gao, 2013) and other crops, being used as nano carrier for delivery of phenylanine (Gohari et al., 2021) and additionally cause reduced PPO activity in litchi (Jiang et al., 2005). Results reported herein provide insights that NOSH-A can be considered as a potential agent that can enhance polyphenolic content at postharvest level (Figs. 5 and 6A).

3.5. Cellular damage indicators

MDA and H_2O_2 contents were not significantly affected neither by the treatments nor the cold storage regimes applied (Fig. 6B and C). MDA and H_2O_2 serve as oxidative stress markers. During postharvest storage of fruits, oxidative stress can lead to an increase in H_2O_2 levels. This, in turn, promotes lipid peroxidation in cellular membranes, resulting in elevated MDA levels (Aghdam & Bodbodak, 2013). Any change in MDA and H_2O_2 over storage time might be a sign of extra stress, i.e. cold storage in our study. In this regard, Bahmani et al. (2024) reported that postharvest cold storage of strawberries at 4 °C for 12 d led to cellular damage, as evidenced by elevated levels of stress markers such as MDA and H_2O_2 with fruit coatings using chitosan-functionalized nanocomposites alleviating such symptoms and thus preserving fruit quality under cold storage conditions. The same study indicated that biodegradable polymers, namely chitosan and chitosan-putrescine nano-composites effectively preserve strawberry fruit by enhancing their antioxidant capacity and scavenging free radicals. However, such effects on CTS-treated strawberries of the current study experimental set up were not observed.

3.6. Polyamine content

Putrescine (Put) contents showed differences after removal from 4 d cold storage; untreated fruit had higher Put content than hydroprimed-, NaA- ($p \leq 0.05$) and CTS- ($p \leq 0.01$) ones; likewise, NOSH-A treatment resulted in higher Put content than CTS treatment in fruit ($p \leq 0.05$). Spm was significantly higher in untreated fruit than NaA ($p \leq 0.05$) after 8 d cold storage. Spd was not significantly affected for all storage durations and treatments applied (Fig. 7).

Polyamines (PAs) are aliphatic nitrogenous bases with low molecular weight, consisting of two or more amino groups and having potential biological activity. The main polyamines in plants, are Put, Spd and Spm

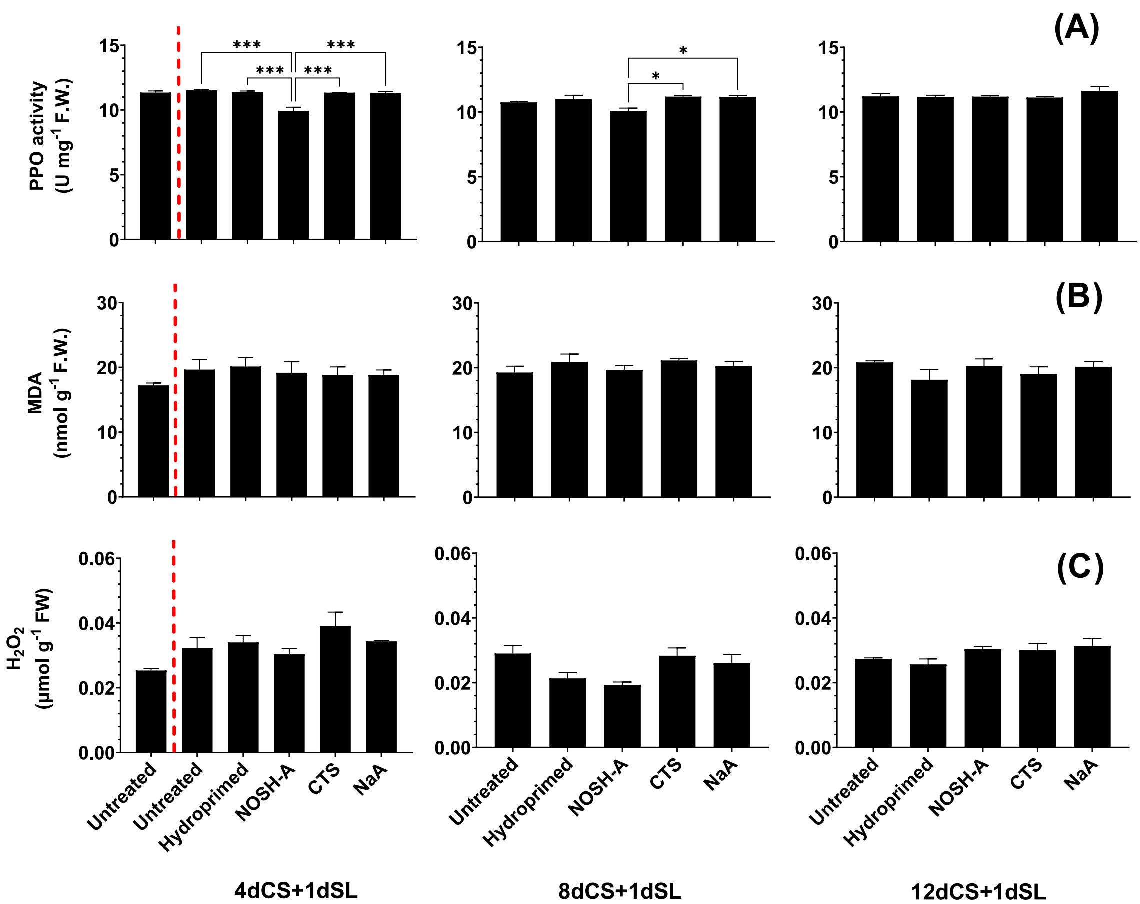

Fig. 6. Effect of storage duration and postharvest treatment applied on polyphenol oxidase (PPO) activity and malondialdehyde (MDA) and hydrogen peroxide (H_2O_2) contents in strawberry fruits (ns = $p > 0.05$, * = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$, **** = $p \leq 0.0001$.). Storage conditions and postharvest treatments are described in Fig. 2.

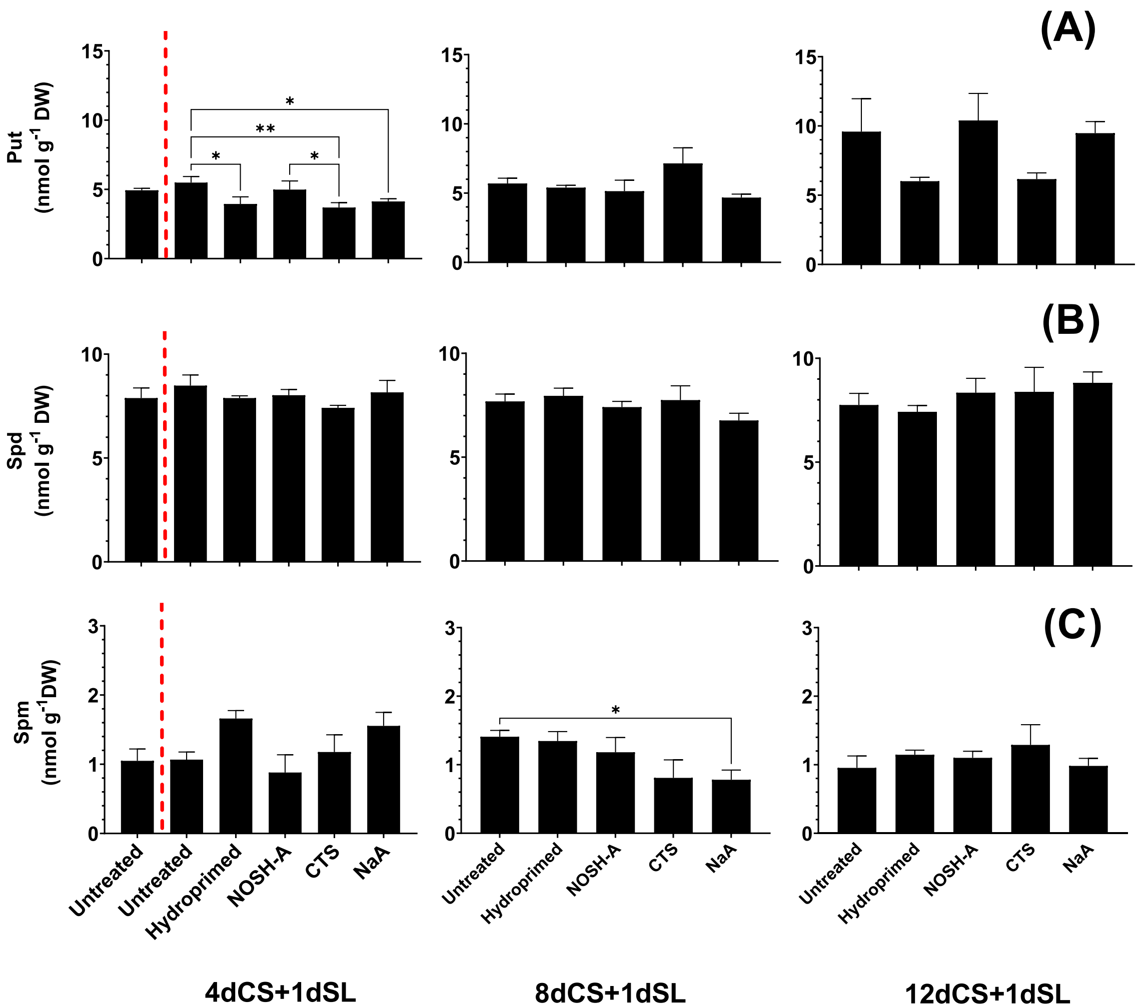

Fig. 7. Effect of storage duration and postharvest treatment applied on the contents of free spermidine, spermine and putrescine contents in strawberry fruits (ns = $p > 0.05$, * = $p \leq 0.05$, ** = 729 $p \leq 0.01$, *** = $p \leq 0.001$, **** = $p \leq 0.0001$)". Storage conditions and postharvest treatments are described in Fig. 2.

which are involved in the regulation of diverse physiological processes (Sequera-Mutiozabal et al. 2017), while they are widely used in postharvest applications to prolong the shelf-life of perishable horticultural crops (Pareek et al. 2018). Polyamines act as anti-senescence agents in fruits by inducing ROS detoxification, leading to reduced colour changes, increased fruit firmness, delayed ethylene and respiration rate emissions, induced mechanical resistance and reduced chilling symptoms (Handa et al., 2018). Several studies have indicated that the exogenous application of polyamines increases storage life and quality attributes of several fruit crops, including strawberry fruit either alone (Khosroshahi et al., 2007) or in combination with CTS (Bal & Ürün, 2020). Increasing polyamine contents enhances the stress tolerance *via* reinforcement of antioxidative properties (Seo et al., 2019). Yet, in our study, results showed that the agents applied had no significant effect on polyamine metabolism; exception for some slight changes in Put and Spd contents monitored afte 4 and 8 d CS, respectively that can be additionally attributed to fruit response to the applied treatments and temperature changes.

3.7. Fungal incidence and severity index

The fungal incidence and severity were monitored on strawberry fruit subjected to extended (12-d) CS. Results indicated that among the priming agents applied, CTS-treated fruit had the lowest incidence and severity (Fig. 8). These data can be linked with the fact that CTS-treated fruit after extended cold storage had a distictive VOC profile that at certain extent can affect postharvest fruit senescence-related processes (Fig. 3). On the other hand, both NOSH-A and NaA, well known for their enhanced performance under abiotic conditions, did not display marked activity against fungal diseases. Interestingly, in another soft fruit crop (blueberry), NaA coatings incorporating cyclolipopeptides from *Bacillus subtilis* demonstrated potent antifungal properties, significantly reducing fungal counts (Xu et al., 2020).

After additional maintenance at room temperature for 4 d, fungal incidence increased across all treatments. The limited effectiveness of NOSH-A and NaA at postharvest level suggests the need to explore the association with other compounds or combinatory approaches with antifungal agents. For instance, while NaA alone may primarily serve as a barrier to moisture and gas exchange, its antifungal properties can be significantly enhanced when combined with natural antimicrobial agents (Janik et al., 2023).

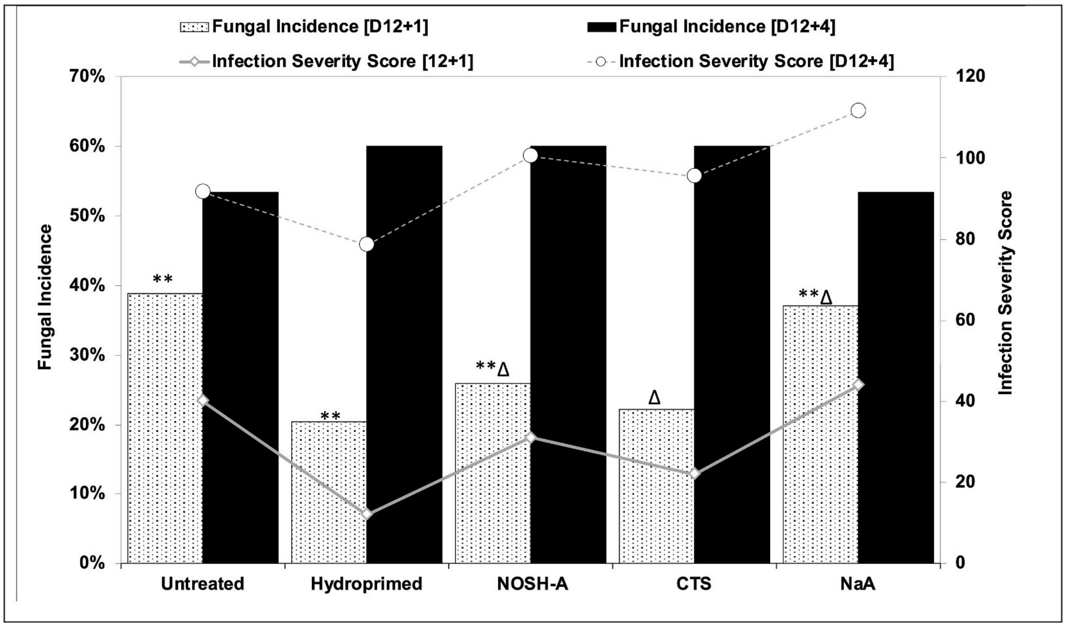

Fig. 8. Fungal incidence (%) and infection severity of strawberry fruits after 12 d of cold storage and additional maintenance at room temperature for 1 [D12 + 1] and 4 [D12 + 4] days, respectively. Same symbol (** or Δ) indicates significant difference for the infection severity between the treatments in the Mann-Whitney *U* test ($p \leq 0.05$) for the D12 + 1.

4. Conclusions

Our aim was to dissect to what extent the use of biocompatible polymers can be considered as an effective postharvest treatment to enhance postharvest quality attributes with special reference to aroma and phytochemical properties. Fruit treated with CTS remain closest to their starting position indicating their VOC profiles changed the least. Methyl hexanoate is one of the most abundant and most frequently identified ester in strawberry; its significantly higher value in CTS-treated fruit after extended cold storage (12 d) suggests that CTS might be inhibiting postharvest fruit senescence-related processes that can affect their VOC profile. HPLC-DAD-ESI-MS/MS showed an increment in an array of phytochemical compounds after cold storage compared to fleshly harvested fruit. Noteworthy, the application of the proprietary priming agent NOSH-A led to enhanced contents for some phytochemical compounds and its potential use as 'antioxidant potency enhancer' at postharvest level can be further dissected in future postharvest experiments. On the other side, no clear beneficial effects in terms of qualitative attributes were observed of the agents applies. Future attention could address whether other specific agents, with known preharvest priming activity to combat abiotic stress conditions such as drought and/or salinity, can be additionally exploited at a postharvest storage level for other stress types, i.e. biotic stress conditions linked to fungal resistance.

CRediT authorship contribution statement

Egli C. Georgiadou: Writing – review & editing, Methodology, Formal analysis, Data curation. **Carlos Javier Garcia Hernandez Gil:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Anna Maria Taliadorou:** Writing – review & editing, Methodology. **Eleni D. Myrtsi:** Methodology, Data curation. **Gholamreza Gohari:** Writing – review & editing, Conceptualization. **Alice Varaldo:** Methodology, Formal analysis. **Sofia Torrado:** Methodology, Formal analysis. **Alessandra Marcon Gasperini:** Writing – review & editing, Methodology, Formal analysis. **Francisco Tomás-Barberán:** Writing – review & editing, Supervision, Methodology, Formal analysis, Data curation. **Maarten L.A.T.M. Hertog:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Vasileios Fotopoulos:** Writing – review & editing, Validation, Methodology, Investigation. **George A. Manganaris:** Writing – review & editing, Writing – original draft, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study has received funding from the European Union's Horizon Europe programme PRIMESOFT under the Grant Agreement No 101079119]. We would like to thank Rubén Alcázar (Faculty of Pharmacy and Food Sciences, University of Barcelona, Barcelona, Spain) for carrying out the polyamine analysis, Stella Gedeon for technical assistance during the experimental procedure and Elfie Dekempeneer for performing the HS-SPME-GC-MS analyses.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lwt.2025.117877.

Data availability

Data will be made available on request.

References

Abouelenein, D., Acquaticci, L., Alessandroni, L., Borsetta, G., Caprioli, G., Mannozzi, C., et al. (2023). Volatile profile of strawberry fruits and influence of different drying methods on their aroma and flavor: A review. *Molecules, 28*, 15. https://doi.org/10.3390/molecules28155810

Adiletta, G., Di Matteo, M., & Petriccione, M. (2021). Multifunctional role of chitosan edible coatings on antioxidant systems in fruit crops: A review. *International Journal of Molecular Sciences, 22*, 2633. https://doi.org/10.3390/ijms22052633

Aghdam, M. S., & Bodbodak, S. (2013). Physiological and biochemical mechanisms regulating chilling tolerance in fruits and vegetables under postharvest salicylates and jasmonates treatments. *Scientia Horticulturae, 156*, 73–85. https://doi.org/10.1016/j.scienta.2013.03.028

Alegria, C., Gonçalves, E. M., Moldão-Martins, M., Cisneros-Zevallos, L., & Abreu, M. (2016). Peel removal improves quality without antioxidant loss, through wound-induced phenolic biosynthesis in shredded carrot. *Postharvest Biology and Technology, 120*, 232–239. https://doi.org/10.1016/j.postharvbio.2016.07.004

Almenar, E., Hernández-Muñoz, P., & Gavara, R. (2009). Evolution of selected volatiles in chitosan-coated strawberries (*Fragaria* x *ananassa*) during refrigerated storage. *Journal of Agricultural and Food Chemistry, 57*, 974–980. https://doi.org/10.1021/jf802319v

Antoniou, C., Xenofontos, R., Chatzimichail, G., Christou, A., Kashfi, K., & Fotopoulos, V. (2020). Exploring the potential of nitric oxide and hydrogen sulfide (NOSH)-releasing synthetic compounds as novel priming agents against drought stress in *Medicago sativa* plants. *Biomolecules, 10*, 120. https://doi.org/10.3390/biom10010120

Bahmani, R., Razavi, F., Mortazavi, S. N., Juárez-Maldonado, A., & Gohari, G. (2024). Chitosan–putrescine nanoparticle coating attenuates postharvest decay and maintains ROS scavenging system activity of strawberry cv. 'Camarosa'during cold storage. *Folia Horticulturae, 36*, 149–160. https://doi.org/10.2478/fhort-2024-0009

Bal, E., & Ürün, B. A. (2020). Effects of chitosan coating with putrescine on bioactive compounds and quality of strawberry cv. San Andreas during cold storage. *Erwerbs-obstbau, 63*, 7–14. https://doi.org/10.1007/s10341-020-00531-9

Baldwin, A., Dhorajiwala, R., Roberts, C., Dimitrova, S., Tu, S., Jones, S., et al. (2023). Storage of halved strawberry fruits affects aroma, phytochemical content and gene expression, and is affected by pre-harvest factors. *Frontiers in Plant Science, 14*. https://doi.org/10.3389/fpls.2023.1165056

Basson, C. E., Groenewald, J. H., Kossmann, J., Cronjé, C., & Bauer, R. (2010). Sugar and acid-related quality attributes and enzyme activities in strawberry fruits: Invertase is the main sucrose hydrolysing enzyme. *Food Chemistry, 121*, 1156–1162. https://doi.org/10.1016/j.foodchem.2010.01.064

Buendía, B., Gil, M. I., Tudela, J. A., Gady, A. L., Medina, J. J., Soria, C., López, J. M., & Tomás-Barberán, F. A. (2010). HPLC-MS Analysis of proanthocyanidin oligomers and other phenolics in 15 strawberry cultivars. *Journal of Agricultural and Food Chemistry, 58*, 3916–3926. https://doi.org/10.1021/jf9030597

Darwish, O. S., Ali, M. R., Khojah, E., Samra, B. N., Ramadan, K. M. A., & El-Mogy, M. M. (2021). Pre-harvest application of salicylic acid, abscisic acid, and methyl jasmonate conserve bioactive compounds of strawberry fruits during refrigerated storage. *Horticulturae, 7*, 568. https://doi.org/10.3390/horticulturae7120568

De Queiroz Antonino, R. S. C. M., Lia Fook, B. R. P., de Oliveira Lima, V. A., de Farias Rached, R.Í., Lima, E. P. N., da Silva Lima, R. J., Peniche Covas, C. A., & Lia Fook, M. V. (2017). Preparation and characterization of chitosan obtained from shells of shrimp (*Litopenaeus vannamei* boone). *Marine Drugs, 15*, 141. https://doi.org/10.1007/s13201-019-0967-z

Dhital, R., Mora, N. B., Watson, D. G., Kohli, P., & Choudhary, R. (2018). Efficacy of limonene nano coatings on post-harvest shelf life of strawberries. *LWT–Food Science and Technology, 97*, 124–134. https://doi.org/10.1016/j.lwt.2018.06.038

El-Mogy, M. M., Ludlow, R. A., Roberts, C., Müller, C. T., & Rogers, H. J. (2019). Postharvest exogenous melatonin treatment of strawberry reduces postharvest spoilage but affects components of the aroma profile. *Journal of Berry Research, 9*, 297–307. https://doi.org/10.3233/JBR-180361

Emamifar, A., & Bavaisi, S. (2020). Nanocomposite coating based on sodium alginate and nano-ZnO for extending the storage life of fresh strawberries (*Fragaria* × *ananassa* Duch.). *Journal of Food Measurement and Characterization, 14*, 1012–1024. https://doi.org/10.1007/s11694-019-00350-x

Filippi, D., Nienow, A. A., Chiomento, J. L. T., et al. (2021). Development and validation of a set of standard area diagrams to assess severity of gray mold in strawberry fruit. *European Journal of Plant Pathology, 160*, 277–286. https://doi.org/10.1007/s10658-021-02238-3

Filippou, P., Antoniou, C., & Fotopoulos, V. (2011). Effect of drought and rewatering onthe cellular status and antioxidant response of *Medicago truncatula* plants. *Plant Signaling & Behavior, 6*, 270–277. https://doi.org/10.4161/psb.6.2.14633

Georgiadou, E. C., Goulas, V., Majak, I., Ioannou, A., Leszczynska, J., & Fotopoulos, V. (2018). Antioxidant potential and phytochemical content of selected fruits and vegetables consumed in Cyprus. *Biotechnology and Food Science, 82*, 3–14. https://doi.org/10.34658/bfs.2018.82.1.3-14

Gohari, G., Jiang, M., Manganaris, G. A., Zhou, J., & Fotopoulos, V. (2024). Next generation chemical priming: With a little help from our nanocarrier friends. *Trends in Plant Science, 29*, 150–166. https://doi.org/10.1016/j.tplants.2023.11.024

Gohari, G., Zareei, E., Kulak, M., Labib, P., Mahmoudi, R., Panahirad, S., Jafari, H., Mahdavinia, G., Juárez-Maldonado, A., & Lorenzo, J. M. (2021). Improving the berry quality and antioxidant potential of flame seedless grapes by foliar application of chitosan–phenylalanine nanocomposites (CS–Phe NCs). *Nanomaterials, 11*(9), 2287. https://doi.org/10.3390/nano11092287

Guimarães, A., Abrunhosa, L., Pastrana, L. M., & Cerqueira, M. A. (2018). Edible films and coatings as carriers of living microorganisms: A new strategy towards biopreservation and healthier foods. *Comprehensive Reviews in Food Science and Food Safety, 17*, 594–614. https://doi.org/10.1111/1541-4337.12345

Hadjipieri, M., Georgiadou, E. C., Costa, F., Fotopoulos, V., & Manganaris, G. A. (2020). Dissection of the incidence and severity of purple spot physiological disorder in loquat fruit through a physiological and molecular approach. *Plant Physiology and Biochemistry, 155*, 980–986. https://doi.org/10.1016/j.plaphy.2020.06.043

Handa, A. K., Fatima, T., & Mattoo, A. K. (2018). Polyamines: Bio-Molecules with diverse functions in plant and human health and disease. *Frontiers in Chemistry, 6*, 10. https://doi.org/10.3389/fchem.2018.00010

Huang, G., Huang, L., Geng, C., Lan, T., Huang, X., Xu, S., Shen, Y., & Bian, H. (2022). Green and multifunctional chitosan-based conformal coating as a controlled release platform for fruit preservation. *International Journal of Biological Macromolecules, 219*, 767–778. https://doi.org/10.1016/j.ijbiomac.2022.08.038

Janik, W., Nowotarski, M., Ledniowska, K., et al. (2023). Modulation of physicochemical properties and antimicrobial activity of sodium alginate films through the use of chestnut extract and plasticizers. *Scientific Reports, 13*, Article 11530. https://doi.org/10.1038/s41598-023-38794-3

Jiang, T., Feng, L., & Wang, Y. (2013). Effect of alginate/nano-Ag coating on microbial and physicochemical characteristics of shiitake mushroom (*Lentinus edodes*) during cold storage. *Food Chemistry, 141*, 954–960. https://doi.org/10.1016/j.foodchem.2013.03.093

Jiang, Y., Lib, J., & Jiang, W. (2005). Effects of chitosan coating on shelf life of cold-stored litchi fruit at ambient temperature. *LWT–Food Science and Technology, 38*, 757–761. https://doi.org/10.1016/j.lwt.2004.09.004

Jongsri, P., Wangsomboondee, T., Rojsitthisak, P., & Seraypheap, K. (2016). Effect of molecular weights of chitosan coating on postharvest quality and physicochemical characteristics of mango fruit. *LWT–Food Science and Technology, 73*, 28–36. https://doi.org/10.1016/j.lwt.2016.05.038

Khosroshahi, M. R. Z., Esna-Ashari, M., & Ershadi, A. (2007). Effect of exogenous putrescine on post-harvest life of strawberry (*Fragaria ananassa* Duch.) fruit, cultivar Selva. *Scientia Horticulturae, 114*, 27–32. https://doi.org/10.1016/j.scienta.2007.05.006

Lee, J., Kim, H. B., Noh, Y. H., Min, S. R., Lee, H. S., Jung, J., et al. (2018). Sugar content and expression of sugar metabolism-related gene in strawberry fruits from various cultivars. *Journal of Plant Biotechnology, 45*, 90–101. https://doi.org/10.5010/JPB.2018.45.2.090

Li, H., Brouwer, B., Oud, N., Verdonk, J. C., Tikunov, Y., Woltering, E., Schouten, R., & Pereira da Silva, F. (2021). Sensory, GC-MS and PTR-ToF-MS profiling of strawberries varying in maturity at harvest with subsequent cold storage. *Postharvest Biology and Technology, 182*, Article 111719. https://doi.org/10.1016/j.foodhyd.2020.105871

Lin, M., Fang, S., Zhao, X., Liang, X., & Wu, D. (2020). Natamycin-loaded zein nanoparticles stabilized by carboxymethyl chitosan: Evaluation of colloidal/chemical performance and application in postharvest treatments. *Food Hydrocolloids, 106*, Article 105871. https://doi.org/10.1016/j.foodhyd.2020.105871

Liu, C., Jin, T., Liu, W., Hao, W., Yan, L., & Zheng, L. (2021). Effects of hydroxyethyl cellulose and sodium alginate edible coating containing asparagus waste extract on postharvest quality of strawberry fruit. *LWT–Food Science and Technology, 148*, Article 111770. https://doi.org/10.1016/j.lwt.2021.111770

Loreto, F., & Velikova, V. (2001). Isoprene produced by leaves protects the photosynthetic apparatus against ozone damage, quenches ozone products, and reduces lipid peroxidation of cellular membranes. *Plant Physiology, 127*, 1781–1787. https://doi.org/10.1104/pp.010497

Mahcene, Z., Khelil, A., Hasni, S., Akman, P. K., Bozkurt, F., Birech, K., … Tornuk, F. (2020). Development and characterization of sodium alginate based active edible films incorporated with essential oils of some medicinal plants. *International Journal of Biological Macromolecules, 145*, 124–132. https://doi.org/10.1016/j.ijbiomac.2019.12.093

Manganaris, G. A., Goulas, V., Vicente, A. R., & Terry, L. A. (2014). Berry antioxidants: Small fruits providing large benefits. *Journal of the Science of Food and Agriculture, 94*, 825–833. https://doi.org/10.1002/jsfa.6432

Marcé, M., Brown, D. S., Capell, T., Figueras, X., & Tiburcio, A. F. (1995). Rapid high-performance liquid chromatographic method for the quantitation of polyamines as their dansyl derivatives: Application to plant and animal tissues. *Journal of Chromatography B Biomedical Applications, 666*, 329–335. https://doi.org/10.1016/0378-4347(94)00586-T

Maringgal, B., Hashim, N., Mohamed Amin Tawakkal, I. S., & Muda Mohamed, M. T. (2020). Recent advance in edible coating and its effect on fresh/fresh-cut fruits quality. *Trends in Food Science & Technology, 96*, 253–267. https://doi.org/10.1016/j.tifs.2019.12.024

Meyers, K. J., Watkins, C. B., Pritts, M. P., & Liu, R. H. (2003). Antioxidant and antiproliferative activities of strawberries. *Journal of Agricultural and Food Chemistry, 51*, 6887–6892. https://doi.org/10.1021/jf034506n

Moghadas, H. C., Smith, J. S., & Tahergorabi, R. (2025). Recent advances in the application of edible coatings for shelf-life extension of strawberries: A review. *Food and Bioprocess Technology, 18*, 1079–1103. https://doi.org/10.1007/s11947-024-03517-7

Nair, M. S., Tomar, M., Punia, S., Kukula-Koch, W., & Kumar, M. (2020). Enhancing the functionality of chitosan- and alginate-based active edible coatings/films for the preservation of fruits and vegetables: A review. *International Journal of Biological Macromolecules, 164*, 304–320. https://doi.org/10.1016/j.ijbiomac.2020.07.083

Ncama, K., Magwaza, L. S., Mditshwa, A., & Tesfay, S. Z. (2018). Plant-based edible coatings for managing postharvest quality of fresh horticultural produce: A review. *Food Packaging and Shelf Life, 16*, 157–167. https://doi.org/10.1016/j.fpsl.2018.03.011

Neethirajan, S., & Jayas, D. S. (2011). Nanotechnology for the food and bioprocessing industries. *Food and Bioprocess Technology, 4*, 39–47. https://doi.org/10.1007/s11947-010-0328-2

Nguyen, V. T. B., Nguyen, D. H. H., & Nguyen, H. V. H. (2020). Combination effects of calcium chloride and nano-chitosan on the postharvest quality of strawberry (*Fragaria* × *ananassa* Duch.). *Postharvest Biology and Technology, 162*, Article 111103. https://doi.org/10.1016/j.postharvbio.2019.111103

Oms-Oliu, G., Rojas-Graü, M. A., González, L. A., Varela, P., Soliva-Fortuny, R., Hernando, M. I. H., … Martín-Belloso, O. (2010). Recent approaches using chemical treatments to preserve quality of fresh-cut fruit: A review. *Postharvest Biology and Technology, 57*, 139–148. https://doi.org/10.1016/j.postharvbio.2010.04.001

Pagliarulo, C., Sansone, F., Moccia, S., Russo, G. L., Aquino, R. P., Salvatore, P., … Volpe, M. G. (2016). Preservation of strawberries with an antifungal edible coating using peony extracts in chitosan. *Food and Bioprocess Technology, 9*, 1951–1960. https://doi.org/10.1007/s11947-016-1779-x

Panahirad, S., Naghshiband-Hassani, R., Ghanbarzadeh, B., Zaare-Nahandi, F., & Mahna, N. (2019). Shelf life quality of plum fruits (*Prunus domestica* L.) improves with carboxymethylcellulose-based edible coating. *HortScience, 54*, 505–510. https://doi.org/10.21273/HORTSCI13751-18

Panahirad, S., Naghshiband-Hassani, R., & Mahna, N. (2020). Pectin-based edible coating preserves antioxidative capacity of plum fruit during shelf life. *Food Science and Technology International, 26*, 583–592. https://doi.org/10.1177/1082013220916559

Pareek, S., Sharma, S., Sagar, N., & González-Aguilar, G. A. (2018). Polyamines treatments. In S. Pareek (Ed.), *Novel postharvest treatments of fresh produce* (pp. 79–101). CRC Press.

Perdones, A., Escriche, I., Chiralt, A., & Vargas, M. (2016). Effect of chitosan-lemon essential oil coatings on volatile profile of strawberries during storage. *Food Chemistry, 197*, 979–986. https://doi.org/10.1016/j.foodchem.2015.11.054

Petriccione, M., De Sanctis, F., Pasquariello, M. S., Mastrobuoni, F., Rega, P., Scortichini, M., & Mencarelli, F. (2014). The effect of chitosan coating on the quality and nutraceutical traits of sweet cherry during postharvest life. *Food and Bioprocess Technology, 8*, 394–408. https://doi.org/10.1007/s11947-014-1411-x

Robledo, N., López, L., Bunger, A., Tapia, C., & Abugoch, L. (2018). Effects of antimicrobial edible coating of thymol nanoemulsion/quinoa protein/chitosan on the safety, sensorial properties, and quality of refrigerated strawberries (*Fragaria* × *ananassa*) under commercial storage environment. *Food and Bioprocess Technology, 11*, 1566–1574. https://doi.org/10.1007/s11947-018-2124-3

Salazar-Orbea, G., García-Villalba, R., Sánchez-Siles, L. M., Tomás-Barberán, F. A., & García, C. J. (2022). Untargeted metabolomics reveals new markers of food processing for strawberry and apple purees. *Molecules, 27*, 7275. https://doi.org/10.3390/molecules27217275

Seo, S. Y., Kim, Y. J., & Park, K. Y. (2019). Increasing polyamine contents enhances the stress tolerance *via* reinforcement of antioxidative properties. *Frontiers in Plant Science, 10*, 1331. https://doi.org/10.3389/fpls.2019.01331

Sequera-Mutiozabal, M., Antoniou, C., Tiburcio, A. F., Alcázar, R., & Fotopoulos, V. (2017). Polyamines: Emerging hubs promoting drought and salt stress tolerance in plants. *Current Molecular Biology Reports, 3*, 28–36. https://doi.org/10.1007/s40610-017-0052-z

Shehata, S. A., Abdeldaym, E. A., Ali, M. R., Mohamed, R. M., Bob, R. I., & Abdelgawad, K. F. (2020). Effect of some Citrus essential oils on post-harvest shelf life and physicochemical quality of strawberries during cold storage. *Agronomy, 10*, 1466. https://doi.org/10.3390/agronomy10101466

Simkova, K., Veberic, R., Hudina, M., Grohar, M. C., Pelacci, M., Smrke, T., et al. (2024). Non-destructive and destructive physical measurements as indicators of sugar and organic acid contents in strawberry fruit during ripening. *Scientia Horticulturae, 327*, Article 112843. https://doi.org/10.1016/j.scienta.2024.112843

Suhag, R., Kumar, N., Petkoska, A. T., & Upadhyay, A. (2020). Film formation and deposition methods of edible coating on food products: A review. *Food Research International, 136*, Article 109582. https://doi.org/10.1016/j.foodres.2020.109582, 2020.

Sun, Y., Huang, Y., Wang, X. Y., Wu, Z. Y., & Weng, Y. X. (2022). Kinetic analysis of PGA/PBAT plastic films for strawberry fruit preservation quality and enzyme activity. *Journal of Food Composition and Analysis, 108*. https://doi.org/10.1016/j.jfca.2022.104439

Ulrich, D., Kecke, S., & Olbricht, K. (2018). What do we know about the chemistry of strawberry aroma? *Journal of Agricultural and Food Chemistry, 66*, 3291–3301. https://doi.org/10.1021/acs.jafc.8b01115

Vandendriessche, T., Nicolai, B. M., & Hertog, M. L. A. T. M. (2013). Optimization of HS SPME Fast GC-MS for high-throughput analysis of strawberry aroma. *Food Analytical Methods, 6*, 512–520. https://doi.org/10.1007/s12161-012-9471-x

Wang, S. Y., & Gao, H. (2013). Effect of chitosan-based edible coating on antioxidants, antioxidant enzyme system, and postharvest fruit quality of strawberries (*Fragaria* x *ananassa* Duch.). *LWT–Food Science and Technology, 52*, 71–79. https://doi.org/10.1016/j.lwt.2012.05.003

Xu, L., Zhang, B., Qin, Y., Li, F., Yang, S., Lu, P., et al. (2020). Preparation and characterization of antifungal coating films composed of sodium alginate and cyclolipopeptides produced by *Bacillus subtilis*. *International Journal of Biological Macromolecules, 143*, 602–609. https://doi.org/10.1016/j.ijbiomac.2019.12.051

Yan, B., Wang, Y., Bai, Y., Liu, Z., Liu, H., Chen, X., Shen, Y., & Duan, L. (2024). Insights into the senescent mechanisms of harvested strawberry fruit at the physiological, molecular and metabolic levels. *Fruit Research, 4*, Article e018. https://doi.org/10.48130/frures-0024-0011

Zheng, S., Cai, J., Huang, P., Wang, Y., Yang, Z., & Yu, Y. (2023). Determination of volatile profiles of woodland strawberry (*Fragaria vesca*) during fruit maturation by HS-SPME GC–MS. *Journal of the Science of Food and Agriculture, 103*, 7455–7468. https://doi.org/10.1002/jsfa.12827