Acta Sci. Pol. Hortorum Cultus, online first, 1–12

https://czasopisma.up.lublin.pl/index.php/asphc ISSN 1644-0692 e-ISSN 2545-1405 https://doi.org/10.24326/asphc.2026.5730

RESEARCH PAPER

Received: 15.06.2026
Accepted: 22.10.2026
Online first: 24.11.2026

POSTHARVEST QUALITY OF FLAT- AND ROUND-SHAPED NECTARINE CULTIVARS UNDER SIMULATED TRANSPORT VIBRATION AND 1-METHYLCYCLOPROPENE TREATMENT: A PRELIMINARY STUDY

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ABSTRACT

Flat-shaped nectarine cultivars represent a growing segment of European stone fruit production, yet their postharvest behaviour under transport and refrigerated handling conditions remains less characterised than that of conventional round-shaped cultivars. This preliminary study evaluated quality changes in two nectarine cultivars, flat-shaped Flateryna and round-shaped Red Gold, subjected to simulated transport vibration and 1-methylcyclopropene (1-MCP) treatment during short-term refrigerated handling. Fruit obtained from a single commercial harvest batch in west-central Poland were assigned to four treatment combinations involving vibration and/or 1-MCP application, with pre-treatment measurements performed on day 0 and subsequent assessments on day 1 and day 7 of storage at 6 °C. Fruit mass differed between cultivars but showed no significant main effects of vibration or 1-MCP treatment, whereas the firmness response to vibration during storage differed between cultivars. Decay incidence was significantly affected by vibration and 1-MCP treatment, with the highest incidence observed in vibrated fruit without 1-MCP treatment in both cultivars. Cultivar and storage day significantly affected pH, titratable acidity, TSS, TPC, and AA, while responses to 1-MCP and vibration varied among quality parameters. The study provides preliminary information on the postharvest behaviour of the two nectarine cultivars under simulated transport and refrigerated handling conditions and supports further investigation of morphology under replicated multi-season conditions.

Keywords: stone fruits, cultivar-specific response, postharvest handling, transport vibration, refrigerated storage, 1-methylcyclopropene

INTRODUCTION

Flat-shaped nectarine cultivars have become an increasingly important segment of European stone fruit production due to their distinctive appearance and growing consumer acceptance. Compared with conventional round-shaped nectarines, flat-shaped cultivars differ in fruit morphology, including fruit profile and contact surface characteristics, which may influence their susceptibility to mechanical stress during postharvest handling and transport. However, published information regarding the postharvest behaviour of flat-shaped nectarines under transport-related mechanical stress remains limited.

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Nectarines are valued for their sensory quality and content of bioactive compounds such as flavonoids and phenolic acids [Zhang et al. 2019, Petruccelli et al. 2023]. Global peach and nectarine production exceeded 27.9 million tons in 2024, with China as the leading producer [FAO 2025]. In Europe, the primary producers are Spain, Italy, Greece, and France [Petruccelli et al. 2023, FAO 2025]. As climacteric fruit, nectarines are highly perishable and susceptible to quality deterioration during transport and refrigerated storage [Zhang et al. 2020b].

During transport and handling, fruit are exposed to mechanical stresses including vibration, compression, and impact, which may contribute to bruising, firmness loss, and accelerated quality deterioration [La Scalia et al. 2016, Zhou et al. 2016, Jung et al. 2018, Vilhena et al. 2023, Zhao et al. 2024]. Transport-related vibration has been identified as an important source of postharvest stress in the fruit supply chain, and previous studies in apples, kiwifruit, and grapes demonstrated that vibration may accelerate quality changes during subsequent storage [Zhou et al. 2016, Dias et al. 2021, Małachowska and Tomala 2023, Wang et al. 2025].

1-Methylcyclopropene (1-MCP) is widely applied as a postharvest crop quality management tool in climacteric fruit to delay ripening-related changes during storage and distribution [Zhao et al. 2024]. Previous studies demonstrated that 1-MCP treatment may contribute to reduced softening and improved quality retention in stone fruits under refrigerated conditions [Vilhena et al. 2023, Zhao et al. 2024, Wang et al. 2025]. However, limited information is available regarding cultivar-specific postharvest responses of nectarines subjected to transport-related vibration in combination with 1-MCP treatment [Zhang et al. 2020a, Dias et al. 2021].

An insufficiently investigated aspect of nectarine postharvest handling concerns the influence of fruit morphology on susceptibility to transport-related mechanical stress. Fruit geometry may contribute to differences in susceptibility to transport-related mechanical stress, and has previously been associated with bruise susceptibility under mechanical loading in other stone fruit [Ahmadi et al. 2010].

To address this issue, two nectarine cultivars differing in fruit morphology, the round-shaped Red Gold and the flat-shaped Flateryna, were selected for comparison. This preliminary study aimed to evaluate postharvest quality changes in nectarine cultivars subjected to simulated transport vibration and 1-MCP treatment during short-term refrigerated handling, with particular attention to fruit mass, firmness, pH, total soluble solids, titratable acidity, total polyphenol content, antioxidant activity, and storage-related decay. The study was conducted using a single commercial harvest batch from west-central Poland; accordingly, results are considered preliminary and intended to provide observations on the two cultivars to support the design of future replicated studies.

MATERIAL AND METHODS

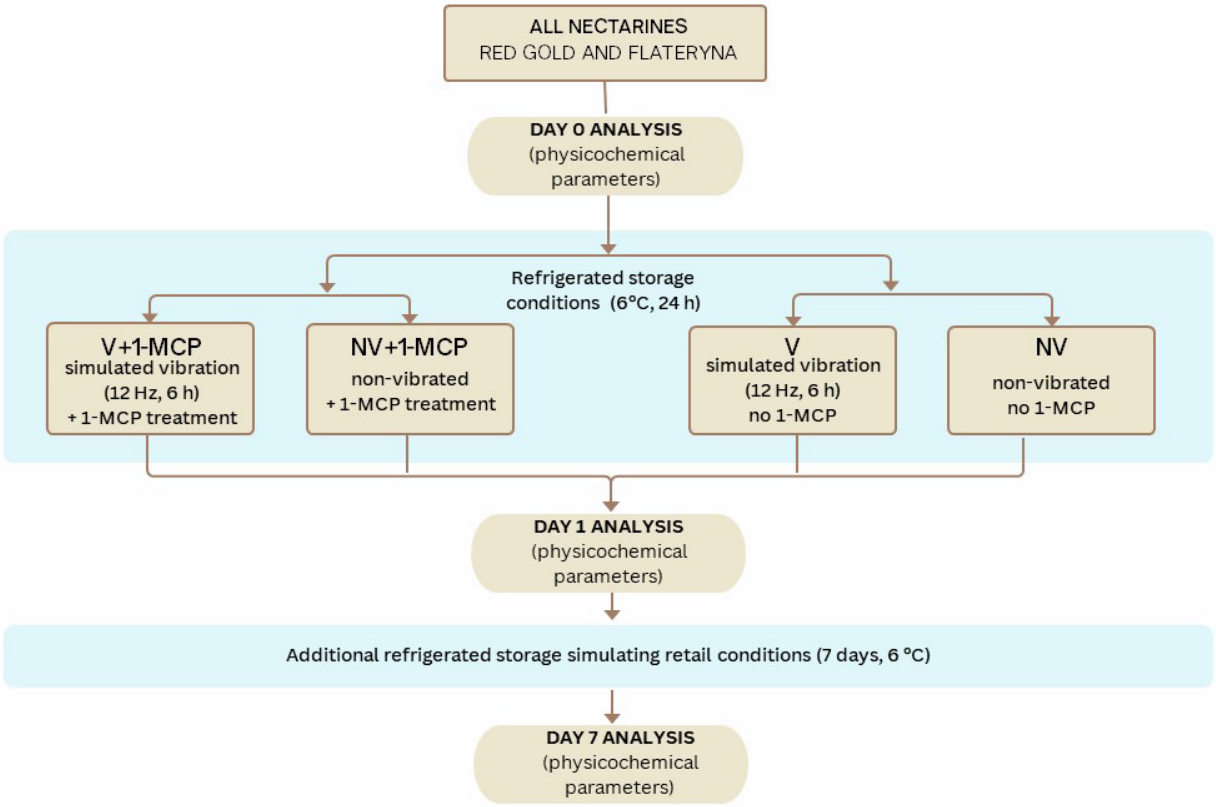
Fruit characteristics and origin

The study was conducted on nectarines of two cultivars: the round-shaped Red Gold and the flat-shaped Flateryna, sourced from the Experimental Horticultural Farm Przybroda, part of the Agricultural Experimental Unit of the Poznań University of Life Sciences (52°31'18.53"N, 16°39'33.59"E). Both cultivars are commercially available in Poland and are suited to temperate growing conditions; Red Gold is an American selection with established cold hardiness, while Flateryna (*Prunus persica* var. *nucipersica*) represents the flat-fruited (platycarpa) nectarine morphotype, characterised by a markedly flattened fruit profile and enlarged equatorial diameter relative to fruit height. The fruits were harvested at commercial maturity, determined based on skin ground colour and flesh firmness assessed with a handheld penetrometer (8 mm probe tip), and harvested when flesh firmness reached the commercially accepted range for each cultivar. Fruits were additionally selected to minimize visible differences in size and external maturity within each cultivar. Only fruits free from visible mechanical damage and disease symptoms were selected. Fruit from both cultivars were harvested on the same date. From the harvested fruit of each cultivar, 40 kg were allocated to the subsequent treatment and storage experiment. These fruits were packed in ventilated plastic crates (5 kg per crate). Additional fruit from the same harvest batch were sampled before treatment application (day 0) to characterise the initial quality of each cultivar. Thirty fruits per cultivar were used for these pre-treatment destructive measurements.

Experimental procedure

For each cultivar, the 40 kg of fruit allocated to the treatment and storage experiment were randomly assigned to four treatment combinations of 10 kg each: NV (non-vibrated, no 1-MCP), V (vibrated, no 1-MCP), NV + MCP (non-vibrated, 1-MCP-treated), and V + MCP (vibrated, 1-MCP-treated). Each 10-kg treatment group was distributed between two ventilated plastic crates containing approximately 5 kg of fruit each. Pre-treatment measurements were performed on day 0, before 1-MCP and vibration treatments were applied. Following treatment application, fruit were stored under refrigerated conditions (6 °C) and assessed on days 1 and 7 of storage. An experimental design diagram is shown in Figure 1.

Figure 1. Schematic diagram of the experimental design showing treatment combinations, storage conditions, and sampling time points



1-MCP treatment. For each cultivar, the two 1-MCP treatment combinations (NV + MCP and V + MCP), comprising a total of 20 kg of fruit in four ventilated plastic crates (~5 kg each), were treated simultaneously in a single 200 L airtight plastic container for 24 h at 6 °C. The applied dose was 50 mg of the commercial formulation SmartFresh® 03VP (AgroFresh Inc., USA) per m^3 of nominal container volume. Treatment conditions were selected based on manufacturer recommendations and previous studies on stone fruit storage [Zhang et al. 2023, 2025].

Vibration treatment. For each cultivar, fruit assigned to the vibration treatments (V and V + MCP) were subjected to vibration at 12 Hz for 6 h using a vibration simulation platform. The two crates (~5 kg each) comprising each treatment combination were placed on the platform simultaneously during vibration. The treatment was conducted under refrigerated conditions maintained at 6 °C throughout the treatment period.

The vibration frequency (12 Hz) and RMS acceleration (0.4 $m \cdot s^{-2}$) were selected based on previous measurements conducted during actual road transport of fruit, in which a characteristic frequency around 12.25 Hz was repeatedly identified under different road and vehicle conditions, with RMS acceleration values in this frequency range close to 0.4 $m \cdot s^{-2}$ [Idaszewska and Szymański 2020].

Analytical methods

The analyses included determination of fruit mass, firmness, total soluble solids (TSS), pH, titratable acidity (TA), dry matter content, total polyphenol content (TPC), and antioxidant activity (AA). At day 0, 30 fruits from each cultivar were used for analyses. On days 1 and 7, 30 fruits were used from each treatment combination, comprising 15 fruits sampled from each of the two crates. Firmness was measured on all 30 fruits. Following firmness assessment, the same 30 fruits were used to prepare three composite samples of 10 fruits each for physicochemical analyses. Fruit mass was assessed separately on 15 fruits from each cultivar at day 0 and on 15 fruits from each treatment combination on days 1 and 7. Methanolic extracts prepared from homogenized fruit tissue were used for TPC and AA determination. Fruits were also visually inspected for external decay symptoms after storage.

Fruit mass measurement. At day 0, fruit mass was determined individually on 15 fruits from each cultivar. On days 1 and 7, fruit mass was determined individually on 15 fruits from each treatment combination using a laboratory balance (Radwag WPS 360/C/2, Poland) with an accuracy of 0.01 g. Measurements at each sampling point were performed on separate sets of fruit. Results were expressed in grams (g) as the mean ± standard deviation (SD) of 15 individual fruit measurements.

Firmness measurement. At day 0, firmness was assessed individually on 30 fruits from each cultivar. On days 1 and 7, firmness was assessed individually on 30 fruits from each treatment combination. Measurements were performed using a TA.TX.Plus texture analyzer (Stable Micro Systems Ltd., UK), with one measurement per fruit. After peeling, fruit firmness was measured by penetrating the flesh to a depth of 10 mm using an SMSP/2 cylindrical probe. Results were expressed in newtons (N) as the mean ± standard deviation (SD) of 30 individual fruit measurements.

pH determination. pH was determined potentiometrically according to the Polish standard PN-90/A-75101/06:1990, using a Hanna HI 221 pH meter (Hanna Instruments Inc., USA). Measurements were performed in three independently prepared composite samples per variant, with three technical measurements per sample.

Titratable acidity (TA). Titratable acidity was determined potentiometrically by titrating a diluted juice sample (1 : 4 v/v) with 0.1 M NaOH to pH 8.1, according to EN 12147:1996. Measurements were performed in three independently prepared composite samples per variant, with three technical measurements per sample. Results were expressed in $g \cdot dm^{-3}$ as malic acid equivalents.

Total soluble solids (TSS). TSS content was measured by refractometry using a Hanna HI 96801 refractometer (Hanna Instruments Inc., USA), according to ISO 2173:2003. Measurements were performed in three independently prepared composite samples per variant, with three technical measurements per sample. Results were expressed as a percentage (%).

Dry matter content. Dry matter was determined gravimetrically by drying the samples to constant weight, according to ISO 1026:1982. Results were expressed as $g \cdot 100\ g^{-1}$ dry weight.

Preparation of methanolic extracts. For each composite sample, extracts were prepared by shaking 5 g of homogenate in 50 mL of 80% methanol for 2 h. After centrifugation, the supernatant was frozen at –20 °C until analysis. These extracts were used to determine total polyphenol content and antioxidant activity.

Total polyphenol content (TPC). TPC was determined spectrophotometrically using the Folin–Ciocalteu reagent [Fang et al. 2006]. Each sample (0.3 mL) was diluted to 1 mL with water, then mixed with 5 mL of 0.2 N Folin reagent and 3 mL of sodium carbonate ($75\ g \cdot L^{-1}$). After 2 h incubation in the dark, absorbance was measured at 765 nm using a Thermo Scientific Helios Epsilon spectrophotometer (Thermo Fisher Scientific Inc., USA). Results were calculated from a calibration curve using chlorogenic acid. Three technical measurements were performed for each of the three independently prepared composite samples, and results were expressed in $mg \cdot 100\ g^{-1}$ dry weight.

Antioxidant activity (AA). AA was assessed using the ABTS + radical cation method [Re et al. 1999]. ABTS + radical cation solution was prepared and diluted to an absorbance of ~0.700 at 734 nm; samples were incubated for 6 min at 30 °C. Antioxidant activity was expressed as $\mu mol\ Trolox \cdot g^{-1}$ dry weight using a Trolox calibration curve. Three technical measurements were performed for each of the three independently prepared composite samples.

Incidence of fruit decay. After 7 days of storage, fruits were visually inspected for visible decay symptoms, including surface lesions and tissue breakdown consistent with storage-related deterioration. Decay incidence was assessed separately for each of the two crates within a treatment combination and expressed as the percentage of affected fruits in each crate

Statistical analysis

Data from days 1 and 7 were analysed using factorial analysis of variance (ANOVA), with cultivar, 1-MCP treatment, vibration treatment, and storage day as fixed factors, including their interactions. Mean comparisons were performed using Tukey's HSD test at $p < 0.05$. Pre-treatment data (day 0) and subsequent treatment combinations were additionally compared using one-way ANOVA followed by Tukey's HSD test at $p < 0.05$. For physicochemical analyses, technical measurements within each composite sample were averaged before statistical analysis. Decay incidence after 7 days was analysed separately using factorial ANOVA with cultivar, 1-MCP treatment, and vibration treatment as fixed factors, including their interactions. Statistical analyses were conducted using Statistica 13.3 software (StatSoft, USA).

RESULTS AND DISCUSSION

Changes in fruit mass and firmness during refrigerated storage

Table 1 presents changes in fruit mass and firmness of nectarines subjected to vibration and/or 1-MCP treatment during refrigerated storage. The results of the factorial ANOVA for all analysed quality parameters are summarized in Table 5.

Fruit mass differed significantly between cultivars ($p < 0.001$), with Red Gold fruit being heavier than Flateryna fruit (Table 1). Fruit mass was numerically lower on day 7 than on day 1 in all treatment combinations, although the main effect of storage day was not significant. No significant main effects of 1-MCP treatment or vibration were found. A significant interaction between 1-MCP treatment and vibration was observed ($p = 0.018$), whereas the remaining interactions were not significant.

Table 1. Changes in fruit mass (g) and firmness (N) (mean ± SD) of nectarines subjected to vibration and 1-MCP treatment during refrigerated storage

		Red Gold		Flateryna	
		Mass (g)	Firmness (N)	Mass (g)	Firmness (N)
Day 0		54.27 ±2.36 C	3.11 ±0.34 DEF	36.78 ±2.69 A	4.12 ±0.61 HI
After 1 day	NV	51.64 ±12.83 C^{d}	2.28 ±0.79 AB^{ab}	33.15 ±9.19 A^{a}	4.16 ±0.94 I^{g}
	V	56.98 ±12.86 C^{d}	3.08 ±0.82 $CDEF^{cde}$	36.50 ±8.97 A^{ab}	4.39 ±0.88 I^{g}
	NV + MCP	52.60 ±13.05 C^{d}	2.71 ±0.90 $ABCD^{abcd}$	37.47 ±7.12 AB^{abcd}	3.44 ±0.61 EGH^{ef}
	V + MCP	52.14 ±8.23 C^{d}	3.10 ±0.74 DEF^{cde}	33.77 ±8.13 A^{a}	2.87 ±0.69 $BCDEF^{bcde}$
After 7 days	NV	49.15 ±12.08 BC^{bcd}	2.11 ±0.87 A^{a}	31.81 ±8.78 A^{a}	3.84 ±0.78 GHI^{fg}
	V	54.17 ±11.19 C^{d}	2.25 ±0.60 AB^{ab}	34.73 ±8.51 A^{a}	2.26 ±0.86 AB^{ab}
	NV + MCP	50.65 ±12.48 C^{d}	2.40 ±0.68 ABC^{abc}	36.34 ±6.88 A^{ab}	3.36 ±0.85 FGH^{def}
	V + MCP	49.92 ±7.52 C^{cd}	2.66 ±0.88 $ABCDE^{abcd}$	32.61 ±7.90 A^{a}	2.61 ±0.69 $ABCD^{abc}$

Uppercase letters indicate homogeneous groups according to Tukey's HSD test following a separate one-way ANOVA including the pre-treatment baseline (day 0) and subsequent treatment combinations. Lowercase superscript letters indicate homogeneous groups according to Tukey's HSD test following the factorial ANOVA performed for days 1 and 7. Mean values sharing at least one letter of the same case do not differ significantly at $p < 0.05$.

Fruit firmness decreased during refrigerated storage, although the magnitude of these changes depended on cultivar and treatment combination (Table 1). In vibrated fruit without 1-MCP treatment, firmness decreased significantly from day 1 to day 7 in both cultivars, from 3.08 to 2.25 N in Red Gold and from 4.39 to 2.26 N in Flateryna. No significant decrease over this period was observed in the corresponding

non-vibrated fruit without 1-MCP treatment. The response to vibration during storage differed between cultivars, as shown by a significant cultivar × vibration × storage day interaction ($p = 0.041$). In fruit treated with 1-MCP, no significant decrease in firmness between days 1 and 7 was detected, either with or without vibration. However, some of day-1 values differed from the pre-treatment baseline, including the V + MCP treatment in Flateryna (Table 1).

The cultivar-dependent firmness response to vibration is consistent with previous reports that simulated transport vibration affects the mechanical properties of stone fruit. Dagdelen and Aday [2021] reported vibration-related changes in the physicomechanical properties of peaches, while Cui et al. [2021] linked post-vibration softening in apricots with changes in cell wall polysaccharides. Such changes may contribute to vibration-associated softening in nectarines, although cell wall properties were not examined in the present study. The lack of a significant firmness decline in fruit treated with 1-MCP may also be relevant, given the role of 1-MCP in inhibiting ethylene action and delaying softening in climacteric fruit [Schmidt et al. 2020]. However, a protective effect of 1-MCP against vibration-induced softening cannot be established from the present experiment.

Changes in pH, titratable acidity (TA) and total soluble solids (TSS) during refrigerated storage

The changes in pH, TA, and TSS of nectarines subjected to vibration and 1-MCP treatment are summarized in Table 2.

Table 2. Changes in pH, TA, and TSS (mean ± SD) of nectarines subjected to vibration and 1-MCP during refrigerated storage

		Red Gold			Flateryna		
		pH	TA ($g \cdot dm^{-3}$)	TSS (%)	pH	TA ($g \cdot dm^{-3}$)	TSS (%)
Day 0		3.79 ±0.06 AB	6.45 ±0.31 E	9.39 ± 0.58 AB	3.91 ± 0.17 ABCDEF	5.71 ± 0.18 ABCDE	11.76 ± 0.29 DE
After 1 day	NV	3.79 ±0.05 AB^{ab}	6.43 ±0.13 E^{e}	9.49 ±0.67 AB^{abc}	4.01 ±0.02 $ABCDEF^{bcde}$	5.85 ±0.20 $BCDE^{bcde}$	11.95 ±0.63 E^{f}
	V	3.88 ±0.05 $ABCDE^{abcd}$	6.61 ±0.20 E^{e}	8.98 ±0.60 A^{a}	3.73 ±0.21 A^{a}	5.67 ±0.28 $ABCDE^{abcde}$	11.59 ±0.11 D^{e}
	NV + MCP	3.83 ±0.02 $ABCD^{abc}$	5.94 ±0.20 $BCDE^{bcde}$	10.15 ±0.59 C^{cd}	4.10 ±0.04 DEF^{de}	5.94 ±0.34 $BCDE^{bcde}$	12.06 ±0.37 DE^{ef}
	V + MCP	3.80 ±0.02 ABC^{ab}	6.39 ±0.41 E^{e}	9.20 ±0.26 A^{a}	3.98 ±0.05 $ABCDEF^{abcde}$	5.81 ±0.20 $BCDE^{bcde}$	11.86 ±0.30 DE^{ef}
After 7 days	NV	3.84 ±0.02 $ABCD^{abc}$	6.16 ±0.23 DE^{de}	9.93 ±0.66 BC^{bcd}	4.17 ±0.04 F^{e}	5.14 ±0.41 ABC^{abc}	12.09 ±0.21 DE^{ef}
	V	4.04 ±0.09 $BCDEF^{bcde}$	6.07 ±0.20 CDE^{cde}	9.43 ±0.81 AB^{ab}	4.08 ±0.02 $CDEF^{cde}$	4.78 ±0.34 A^{a}	12.04 ±0.64 DE^{ef}
	NV + MCP	3.85 ±0.04 $ABCD^{abcd}$	5.85 ±0.31 $BCDE^{bcde}$	10.17 ±0.49 C^{d}	4.19 ±0.06 F^{e}	5.27 ±0.20 $ABCD^{abcd}$	12.12 ±0.70 DE^{ef}
	V + MCP	3.88 ±0.08 $ABCDE^{abcd}$	5.94 ±0.43 $BCDE^{bcde}$	9.49 ±0.92 AB^{abc}	4.16 ±0.05 EF^{e}	5.09 ±0.58 AB^{ab}	12.39 ±0.11 E^{f}

Uppercase letters indicate homogeneous groups according to Tukey's HSD test following a separate one-way ANOVA including the pre-treatment baseline (day 0) and subsequent treatment combinations. Lowercase superscript letters indicate homogeneous groups according to Tukey's HSD test following the factorial ANOVA performed for days 1 and 7. Mean values sharing at least one letter of the same case do not differ significantly at $p < 0.05$

After 7 days of refrigerated storage, pH values increased slightly in both cultivars (Table 2) with significant effects of cultivar and storage day ($p < 0.001$). The effect of storage day on pH depended on cultivar and vibration treatment, as indicated by significant cultivar × storage day ($p = 0.029$) and vibration × storage day ($p = 0.032$) interactions. In Flateryna, pH increased significantly from 3.73 to 4.08 in vibrated fruit

without 1-MCP treatment, whereas no significant change between days 1 and 7 was detected in the other treatment combinations (Table 2).

Titratable acidity (TA) was higher in Red Gold than in Flateryna and decreased during refrigerated storage (Table 2), with significant effects of cultivar and storage day ($p < 0.001$). The decrease in TA during storage differed between cultivars, as indicated by a significant cultivar × storage day interaction ($p = 0.029$), with a greater numerical decrease observed in Flateryna. A significant cultivar × 1-MCP treatment interaction was also found ($p = 0.016$), whereas the main effects of 1-MCP treatment and vibration were not significant.

TSS values were higher in Flateryna than in Red Gold and increased during refrigerated storage (Table 2), with significant effects of cultivar, 1-MCP treatment, vibration, and storage day ($p < 0.001$). Significant interactions were also found between cultivar and vibration ($p < 0.001$) and between vibration and storage day ($p = 0.004$), as well as for cultivar × 1-MCP treatment × vibration ($p = 0.026$) and cultivar × 1-MCP treatment × storage day ($p = 0.049$). Despite the overall effect of storage day, no significant differences between days 1 and 7 were detected within individual treatment combinations.

The increase in pH and decrease in TA observed during storage may reflect changes in organic acid metabolism associated with fruit ripening. Organic acids can be utilized as respiratory substrates during postharvest storage, and their decline has been reported in stored nectarines [Eroğul et al. 2023]. Mechanical stress may modify these processes, as simulated transport vibration has been shown to alter respiratory pathways in apricot fruit [Pan et al. 2015] and to affect pH and TSS in peaches [Dagdelen and Aday 2021]. These metabolic responses may contribute to the interactions of vibration with storage day observed for pH and TSS in the present study. The response to 1-MCP was also not uniform: although 1-MCP had no significant main effect on pH or TA, its effect on TA depended on cultivar, while TSS was significantly affected by 1-MCP and showed interactions with cultivar and the other experimental factors. Such variation is physiologically plausible because 1-MCP can modify organic acid metabolism, including pathways involved in malate and citrate synthesis and degradation in peach fruit [Cai et al. 2023]. However, respiration rate, ethylene production, and individual organic acids were not measured in the present study, and these mechanisms therefore remain possible explanations rather than directly demonstrated responses.

Changes in antioxidant-related parameters during refrigerated storage

The changes in TPC and AA of nectarines affected by vibration and 1-MCP treatment are summarized in Table 3.

Table 3. Changes in TPC and AA (mean ± SD) of nectarines subjected to vibration and 1-MCP treatment during refrigerated storage

		Red Gold		Flateryna	
		TPC (mg · 100 g^{-1} d.w.)	AA (µmol T · g^{-1} d.w.)	TPC (mg · 100 g^{-1} d.w.)	AA (µmol T · g^{-1} d.w.)
Day 0		394.5 ±27.87 A	12.69 ±1.78 A	532.25 ±21.05 DEF	28.2 ±2.67 B
After 1 day	NV	423.09 ±17.86 AB^{ab}	14.57 ±2.45 A^{a}	522.20 ±21.94 DE^{de}	28.50 ±1.43 B^{b}
	V	374.23 ±28.24 A^{a}	10.70 ±1.42 A^{a}	537.13 ±46.33 $DEFG^{def}$	26.57 ±2.62 B^{b}
	NV + MCP	388.35 ±49.59 A^{a}	13.73 ±2.22 A^{a}	566.79 ±22.14 EFG^{ef}	31.07 ±0.54 B^{b}
	V + MCP	371.86 ±14.49 A^{a}	12.43 ±0.66 A^{a}	550.97 ±20.34 EFG^{ef}	30.23 ±0.45 B^{b}
After 7 days	NV	453.71 ±30.90 BC^{bc}	17.07 ±3.80 A^{a}	553.22 ±29.37 EFG^{ef}	30.40 ±0.65 B^{b}
	V	494.33 ±37.23 CD^{cd}	15.73 ±2.24 A^{a}	588.12 ±24.98 G^{f}	31.13 ±1.60 B^{b}
	NV + MCP	386.69 ±65.58 A^{a}	15.87 ±2.12 A^{a}	568.40 ±30.41 EFG^{ef}	32.43 ±1.36 B^{b}
	V + MCP	423.24 ±10.53 AB^{ab}	15.10 ±0.36 A^{a}	587.07 ±22.58 FG^{f}	32.23 ±1.13 B^{b}

Uppercase letters indicate homogeneous groups according to Tukey's HSD test following a separate one-way ANOVA including the pre-treatment baseline (day 0) and subsequent treatment combinations. Lowercase superscript letters indicate homogeneous groups according to Tukey's HSD test following the factorial ANOVA performed for days 1 and 7. Mean values sharing at least one letter of the same case do not differ significantly at $p < 0.05$

TPC was higher in Flateryna than in Red Gold and generally increased during refrigerated storage (Table 3), with significant effects of cultivar and storage day ($p < 0.001$). A significant effect of 1-MCP treatment was also found ($p = 0.027$), although its association with TPC depended on cultivar and storage day, as indicated by significant cultivar × 1-MCP treatment ($p < 0.001$) and 1-MCP treatment × storage day ($p = 0.002$) interactions. Vibration had no significant main effect on TPC, but interacted significantly with storage day ($p < 0.001$). In Red Gold, TPC increased significantly from 374.23 to 494.33 mg · 100 g^{-1} d.w. in vibrated fruit without 1-MCP treatment, whereas no significant changes between days 1 and 7 were detected in the other treatment combinations of either cultivar.

AA was higher in Flateryna than in Red Gold and generally increased during refrigerated storage (Table 3), with significant effects of cultivar and storage day ($p < 0.001$). Neither 1-MCP treatment nor vibration had a significant effect on AA and no significant interactions involving these treatments were detected. Despite the overall effect of storage day, no significant differences between days 1 and 7 were detected within individual treatment combinations.

The increase in TPC and AA during refrigerated storage may reflect changes in antioxidant metabolism occurring during postharvest storage. Mechanical stress can induce changes in phenolic metabolism as part of the plant antioxidant response [Šic Žlabur et al. 2021], which may provide a physiological context for the interaction between vibration and storage day observed for TPC. However, this response was not reflected in AA, for which neither vibration nor its interactions were significant. The response of TPC to 1-MCP was also dependent on cultivar and storage day. Previous work in nectarines has shown that 1-MCP can modify antioxidant metabolism through changes in ROS-related processes [Zhang et al. 2020b], which may be relevant to the cultivar- and storage-dependent response of TPC to 1-MCP observed here. These mechanisms may contribute to the observed changes, although they were not directly examined in the present study.

Incidence of storage-related decay after refrigerated storage

Signs of storage-related decay were observed after 7 days of refrigerated storage (Table 4). Decay incidence was significantly affected by 1-MCP treatment and vibration ($p < 0.001$), whereas the main effect of cultivar was not significant ($p = 0.189$). Significant cultivar × vibration ($p = 0.007$) and 1-MCP treatment × vibration ($p < 0.001$) interactions were also found, indicating that the response to vibration depended on cultivar and 1-MCP treatment. The three-way cultivar × 1-MCP treatment × vibration interaction was not significant. In both cultivars, decay incidence was significantly higher in vibrated fruit without 1-MCP treatment than in the corresponding non-vibrated fruit, increasing from 6.51 to 14.28% in Red Gold and from 8.13 to 13.04% in Flateryna. Decay incidence was also significantly lower in 1-MCP-treated fruit than in the corresponding untreated fruit in three of the four cultivar × vibration combinations; the only exception was non-vibrated Red Gold, for which the difference was not significant. Similar effects of 1-MCP treatment on storage-related decay have been reported previously [Daulagala and Daundasekera 2016, Xia et al. 2021, Xu et al. 2017]. In the absence of 1-MCP, vibration was associated with significantly higher decay incidence in both cultivars, suggesting that mechanical stress may increase fruit susceptibility to storage-related deterioration. These results indicate that the effects of simulated transport vibration and 1-MCP treatment on decay incidence may be relevant to postharvest handling of nectarines.

Table 4. Incidence of storage-related fruit decay (%) after 7 days of storage in Red Gold and Flateryna

Cultivar	Treatment			
	NV	V	NV + MCP	V + MCP
Red Gold	6.51 bcd	14.28 e	4.34 ab	6.98 cd
Flateryna	8.13 d	13.04 e	3.89 a	5.47 abc

NV – non-vibrated, no 1-MCP; V – vibrated, no 1-MCP; NV + MCP – non-vibrated, 1-MCP-treated; V + MCP – vibrated, 1-MCP-treated. Different lowercase letters indicate significant differences according to Tukey's HSD test at $p < 0.05$

Study limitations and future research directions

The present study was conducted using a single commercial harvest batch, without independent replication across harvest batches or seasons, and the results should therefore be interpreted as preliminary observations under the specific conditions applied rather than as broadly generalisable postharvest responses.

Table 5. P-values from factorial ANOVA for the effects of cultivar, 1-MCP treatment, vibration treatment, storage day, and their interactions on nectarine quality parameters

Effect	Mass	firmness	pH	TA	TSS	TPC	AA	Decay incidence
Cultivar (C)	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.189
1-MCP (M)	0.804	**0.035**	0.230	0.504	**<0.001**	**0.027**	0.111	**<0.001**
Vibration (V)	0.453	0.072	0.270	0.760	**<0.001**	0.164	0.074	**<0.001**
Storage day (D)	0.164	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	–
C × M	0.319	**<0.001**	**0.003**	**0.016**	0.335	**<0.001**	0.053	0.067
C × V	0.332	**<0.001**	**<0.001**	0.051	**<0.001**	0.376	0.335	**0.007**
M × V	**0.018**	0.684	0.661	0.363	0.983	0.686	0.526	**<0.001**
C × D	0.702	0.076	**0.029**	**0.029**	0.335	0.082	0.630	–
M × D	0.855	**<0.001**	0.081	0.504	0.869	**0.002**	0.265	–
V × D	0.923	**<0.001**	**0.032**	0.251	**0.004**	**<0.001**	0.225	–
C × M × V	0.840	0.597	**0.015**	0.760	**0.026**	0.104	0.568	0.140
C × M × D	0.977	**<0.001**	0.532	0.951	**0.049**	0.220	0.943	–
C × V × D	0.989	**0.041**	0.501	0.584	0.069	0.058	0.964	–
M × V × D	0.967	**<0.001**	0.460	0.951	0.902	0.635	0.439	–
C × M × V × D	0.973	0.059	0.839	0.760	0.287	0.270	1.000	–

C – cultivar; M – 1-MCP treatment; V – vibration treatment; D – storage day. Factorial ANOVA for quality parameters was performed using data from days 1 and 7. Decay incidence was assessed only on day 7 and was therefore analysed without storage day as a factor. Significant effects ($p < 0.05$) are shown in bold. – not applicable

Ethylene production and respiration rates were not measured, and the interpretation of 1-MCP-associated effects is therefore based on the compound's established mode of action as reported in the literature rather than on directly measured physiological responses. Chilling injury assessment was not included in the study design, which focused on quality changes during 7 days of storage at 6 °C. The vibration treatment represented a single simplified mechanical stress regime and does not capture the full variability of mechanical conditions occurring during commercial transport.

These methodological limitations should be considered when interpreting the present findings and indicate the main directions for future research. Future studies should incorporate replicated trials across multiple harvest seasons, a broader range of vibration parameters, direct measurement of ethylene production and respiration, and chilling injury assessment over extended storage periods. Morphological characterisation of flat- and round-shaped cultivars would further help clarify whether fruit morphology contributes to differences in their responses to mechanical stress.

CONCLUSIONS

Within the conditions of this study, fruit mass differed between cultivars and showed no significant main effects of vibration or 1-MCP treatment, although a significant interaction between these two factors was observed. The firmness response during refrigerated storage differed between Flateryna and Red Gold. The effects of 1-MCP varied among quality parameters and depended in part on cultivar and storage

conditions. Cultivar-related differences were also observed in pH, titratable acidity, TSS, TPC, and AA, while storage day significantly affected these parameters. Decay incidence was significantly affected by vibration and 1-MCP treatment, with significant cultivar × vibration and 1-MCP × vibration interactions; the highest incidence was observed in vibrated fruit without 1-MCP treatment in both cultivars.

The findings provide preliminary baseline information on postharvest quality changes in the two nectarine cultivars during short-term refrigerated handling following simulated transport vibration. The observed differences between the two cultivars support further investigation of the possible role of fruit morphology in postharvest responses during supply-chain handling, particularly in replicated multi-season studies.

SOURCE OF RESEARCH FUNDING

The presented research results were funded by grants for education allocated by the Ministry of Higher Education in Poland. The publication was co-financed by the Polish Minister of Science and Higher Education as part of the Strategy of the Poznan University of Life Sciences for 2024–2026 in the field of improving scientific research and development work in priority research areas.

CONFLICT OF INTEREST STATEMENT

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.

DECLARATION OF THE USE OF GENAI TOOLS IN THE PROCESS OF PREPARING THE PAPER

We declare that this work has not been prepared using generative artificial intelligence (genAI) tools.

AUTHOR'S CONTRIBUTION

N.I. and D.W. conceived and designed the study. N.I. carried out the methodology, software development, validation, and data collection. D.W. supervised the study, conducted formal analysis, and provided resources and project administration. M.G. curated the data and contributed to reviewing and editing the manuscript. The original draft was written by N.I., and all authors contributed to reviewing and editing subsequent drafts. Funding was acquired by N.I., D.W., and M.G. All authors approved the final version of the manuscript.

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