Postharvest Biology and Technology 195 (2023) 112134

Contents lists available at ScienceDirect

Postharvest Biology and Technology

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

Cultivar, maturity at harvest and postharvest treatments influence softening of apricots

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ARTICLE INFO

Keywords:
Apricots
1-MCP
Ethylene
Softening
Texture

ABSTRACT

Apricots are characterised by a rapid softening after harvest, resulting in a high susceptibility to mechanical damage and decay risk. Postharvest tools that accelerate or slow ripening can improve fruit quality to meet consumer preferences without impairing the supply chain. This study aimed to evaluate the effect of 1.0 μL L^{-1} 1-methylcyclopropene (1-MCP) and 1000 μL L^{-1} ethylene treatment on 'Bergarouge®', 'Farely' and 'Swired' apricots. The influence of maturity at harvest was also investigated, focusing on softening and the texture change. The results showed that 1-MCP reduced softening of the three cultivars, independent of the maturity stage. Ethylene, applied during the shelf life, accelerated softening of 'Bergarouge®' and 'Farely', but it did not influence the firmness of 'Swired'. Both treatments had little or no influence on other quality parameters, such as the total soluble solids, titratable acidity and skin colour. The textural properties of the flesh and skin changed in a cultivar-dependent manner. Further, 1-MCP and ethylene treatments influenced these parameters differently according to the cultivar and maturity stage. Taken together, these results demonstrate that the cultivar is the most important factor in the effectiveness of 1-MCP and ethylene treatments to slow down or accelerate apricot softening after harvest. Texturometry enabled a better understanding of how the maturity stage and postharvest treatments influence the softening of apricots in a cultivar-specific manner.

1. Introduction

Tree-ripened apricots (*Prunus armeniaca* L.) are highly appreciated by consumers for their taste, flavour and sweetness (Azodanlou et al., 2003; Rossier et al., 2006). Unfortunately, such fruit have a short postharvest life due to rapid softening, leading to a higher susceptibility to mechanical damages and decay development. Therefore, ripe apricots must be distributed to local markets to avoid high fruit losses along the whole supply chain. Harvesting apricots at an early maturity stage allows for better quality assurance through the different postharvest processes (Mencarelli et al., 2006), and it is recommended when long commercial distances are targeted. In addition, the increasing danger of losses in Europe caused by new pests, such as *Drosophila suzukii*, which infests ripe apricots (Mazzetto et al., 2015), forces producers to pick fruit at an early maturity stage, despite the risk the fruit quality attributes will not meet consumer preferences (Bruhn et al., 1991). Indeed, as the apricot maturity stage at harvest determines consumer sensory appreciation and the fruit resistance to postharvest handling, timely harvesting is challenging. The fruit undergo several physiological changes during the ripening phase, such as softening, colour changes, an increase in sweetness and volatile production (Aubert et al., 2010; Bureau et al., 2006). Apricot softening is a crucial parameter along the whole postharvest supply chain, one that is highly influenced by the cultivar (Hajnal et al., 2012), storage conditions and duration (Stanley et al., 2009), as well as the maturity at harvest (Stanley et al., 2013). A series of modifications to the polysaccharide components of the primary cell wall and middle lamella are involved in softening during ripening, weakening the structure (Brummell, 2006). Polygalacturonase and pectin methylesterase may play crucial roles in the development of apricot softening during cold storage (Hou et al., 2019).

As apricots are a climacteric fruit, ripening is induced following increased ethylene biosynthesis and respiration (Chahine et al., 1999). The role of ethylene in fruit maturation has not been fully elucidated yet, and conflicting results illustrate the complexity of the biochemical processes acting during fruit ripening (Botondi et al., 2003; Bureau et al., 2006; Chahine et al., 1999). The application of ethylene to apricots was shown to accelerate flesh softening (Pech et al., 2002). However, in a recent study, although apricots treated with ethylene showed higher

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https://doi.org/10.1016/j.postharvbio.2022.112134
Received 16 May 2022; Received in revised form 25 September 2022; Accepted 25 September 2022
Available online 7 October 2022

ethylene production than the control fruit, the rate of firmness loss was similar between both the treated and untreated fruit (Fan et al., 2018). These results highlight that ethylene-dependent and independent biochemical and molecular processes are involved in the maturation of climacteric fruit (Tucker et al., 2017).

The ethylene receptor ligand 1-methylcyclopropene (1-MCP) blocks the action of ethylene (Sisler and Serek, 1997) and thereby delays the ripening of various fruit (Blankenship and Dole, 2003), including apricots (Botondi et al., 2003; De Martino et al., 2006; Fan et al., 2000; Fan et al., 2018). 1-MCP treatment of apricots suppresses the expression of pectin-related genes, including polygalacturonase, β-galactosidase and pectin methylesterase (Fan et al., 2018; Hou et al., 2019), but this effect may be cultivar-dependent (Botondi et al., 2003).

Besides the molecular understanding of softening mechanisms, new methods are needed to improve the characterisation of apricot texture along the supply chain. Sensory analyses conducted using a trained panel of assessors are optimal for describing fruit sensory attributes, such as hardness, juiciness or elasticity (Barrett et al., 2010). However, this approach is time-consuming, needs frequent training of the panel and is costly to implement. A rapid, simple, affordable, precise and accurate method allowing an objective assessment of textural parameters is therefore desired. Most commercial instruments to measure apricot firmness are based on the force required to push a cylindrical probe into the flesh up to a defined depth. These methods only give a single-dimensional value (e.g. hardness) at a single point on the fruit. Motorised instruments, such as the Texture Analyser, can be equipped with different probes to perform various types of tests, such as compression or puncture, offering different textural parameters extracted from force-displacement curves. Many studies have been conducted with such instruments to evaluate the textural properties of various fruit, such as apples (Camps et al., 2005; Poles et al., 2020; Varela et al., 2007), pears (Rizzolo et al., 2015), plums (Qiu et al., 2021), peaches and nectarines (Contador et al., 2015), but rarely apricots. Some studies evaluated the impact of heat treatments on the texture of apricots (Ayour et al., 2017; Ella Missang et al., 2012, 2011). A multi-parameter approach to measuring apricot texture allows deciphering the storage conditions that influence fruit softening (Gabioud Rebeaud et al., 2019).

Postharvest methods regulating apricot ripening are much needed to offer consumers consistently high-quality apricots at the point of sale while reducing fruit losses after harvest along the supply chain. This study aimed to evaluate the response of three apricot cultivars to 1-MCP and ethylene treatment on quality and textural parameters, as well as the influence of fruit maturity. A better understanding of the impact and relationship among the cultivar, maturity stage and postharvest treatments on the texture changes during storage will improve postharvest management and thereby reduce losses along the supply chain, while also offering consumers apricots meeting their quality expectations.

2. Material and methods

2.1. Fruit

Apricots of the 'Bergarouge®', 'Farely' and 'Swired' cultivars harvested in 2018 at Agroscope Research Center in Valais in Switzerland (latitude 46.2°N, longitude 7.3°E, elevation 520 m, average annual rainfall ~600 mm) were used for this study. Immediately after harvest, the fruit were sorted according to their Index of Absorbance Difference (DA Index) in two maturity classes using a sorting machine equipped with a DA-Meter® (Agrimat-Sinteleia Srl, Bologna, Italy). Fruit with a DA Index from 0.8 to 1.2 were classified in the pre-commercial maturity stage (M1), while fruit with a DA Index from 0.0 to 0.7 were defined as commercially mature (M2). For each cultivar, approximately 280 fruit per maturity stage were used for the study.

2.2. Postharvest treatments and storage conditions

Immediately after sorting, 40 fruit for each maturity category were randomly selected for quality control and texture measurements at harvest. The remaining fruit were randomly divided into two groups of approximately 120 fruit, which were stored at 8 °C and 90 % relative humidity for (1) 2 d and (2) 7 d, followed by storage at 20 °C with a relative humidity of 90–95 % for 2 d (Fig. 1). In each group, the fruit were randomly divided into three treatments with approximately 40 fruit each: (1) 1-MCP performed after 24 h of cooling at 8 °C in sealed containers with 1.0 μL L^{-1} released from SmartFresh™ powder (0.14 %, AgroFresh, Spring House, PA, USA) for 24 h; (2) ethylene, whereby after cold storage, apricots were placed for 2 d at 20 °C with a relative humidity of 90–95 % and an ethylene concentration of 1000 μL L^{-1} (Banarg®, Pangas, Dagmersellen, Switzerland); and (3) the control fruit, stored under similar temperature and relative humidity conditions, but without 1-MCP or ethylene treatment. At each measurement (at harvest and after storage) and for each maturity stage, 40 fruit per treatment were taken for assessment of the quality parameters and texture analyses and were randomly divided into two groups: (1) 20 fruit for quality parameter measurements and puncture tests and (2) 20 fruit for compression tests.

2.3. Quality parameters measurements

A CM-600d spectrophotometer (Konica Minolta, Tokyo, Japan) was used to measure the fruit skin colour in CIE L*a*b* colour space with a D65 light. The Hue angle (H°) was calculated as $\tan^{-1}$(b*/a*), while the DA Index (I_{AD}) was determined on the greener side of each fruit with a DA-Meter® (TR Turoni Srl, Forli, Italy). Firmness measurements were achieved on two opposite sides of each apricot using a Durofel device equipped with a 0.10 cm^2 probe (SETOP Giraud Technologie, Cavaillon, France). Results were expressed using the Durofel Index (DI) on a scale from 0 (very soft) to 100 (very hard). The juice obtained from batches of 5 fruit per treatment was then extracted to determine total soluble solids (TSS, %), measured with an electronic refractometer (PAL-1, Atago, Tokyo, Japan) and titratable acidity (TA, g citric acid kg^{-1}), determined by titration (Titrator DL67, Mettler Toledo, Greifensee, Switzerland) with 0.1 M NaOH to the endpoint of pH 8.1.

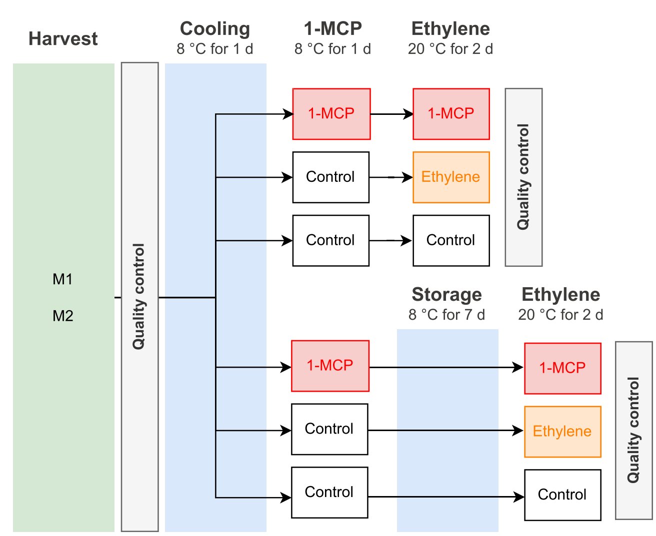

Fig. 1. Experimental design: apricots were harvested and sorted into two categories of maturity (pre-commercial [M1] and commercial [M2]). For each category, fruit were stored for 2 and 7 d at 8 °C and then for 2 d at 20 °C. The 1-MCP treatment were performed after 24 h of cooling at 8 °C for 24 supplementary hours. Ethylene treatments were done after cold storage for 2 d at 20 °C. Fruit quality was determined at harvest and after storage (2 and 7 d at 8 °C followed by 2 d at 20 °C).

2.4. Texture measurements

Compression and puncture tests were performed using a TA-XTplus Texture Analyzer (Stable Micro Systems, Godalming, United Kingdom) fitted with different probes.

2.4.1. Compression tests

The firmness of the whole fruit was determined by compression tests on 20 individual fruit using a flat 75-mm-diameter probe moved at a speed of 2 mm s^{-1} to a maximal deformation corresponding to 5% of the fruit calibre. The applied force was recorded for every step of the displacement, and six parameters were computed from the force-deformation curves using the Exponent software (Version 6, Stable Micro Systems). In the first phase, called 'compression', parameter F_c represents the hardness, which is the maximal force required to push the flat probe until fruit deformation reaches 5% of the calibre. E_c is the slope from the origin to F_c, and it gives information about fruit stiffness. The mechanical work required to compress the fruit is represented by W_c^1 and is the area under the curve (AUC) going from the origin to F_c. In the second phase, called 'decompression', when the probe moves backwards to its origin, W_c^2 represents the AUC, while D_c is the deformation that remains after decompression, which is related to the plastic behaviour of the fruit. W_c^1-W_c^2 is the area between the compression and decompression curves.

2.4.2. Puncture tests of the skin

The textural properties of the skin and the first layers of the flesh were then measured by puncturing 20 apricots on two opposite sides using a 2-mm-diameter needle probe moved at a speed of 20 mm s^{-1} to a final depth of 3 mm. The force was recorded for every step of displacement, and 10 parameters were extracted from the force-displacement curves obtained for each measurement using the Exponent software. The force achieved at skin rupture is called F_p^1, while D_p^1 is the displacement of the probe at the rupture point and E_p^1 is the slope measured from the beginning of the measurement to F_p^1. The mechanical work required to puncture the skin is represented by W_p^1, and it is the AUC from the origin to F_p^1. After skin rupturing, the minimal force was recorded (F_p^2), as well as the parameter D_p^2, which is the distance measured at F_p^2. The needle was then moved into apricot flesh until a depth of 3 mm. The maximal force required to puncture the flesh until this depth (F_p^3) and the distance measured at this point (D_p^3) were recorded. The slope between the minimal and maximal forces measured after skin rupturing (E_p^3) and the mechanical work (W_p^3) needed to move the probe through the flesh were also assessed.

2.4.3. Puncture tests of the flesh

Fruit were then cut in half longitudinally, and each slice of about 1.5 mm thick was punctured on two opposite sides using a 2-mm-diameter stainless steel probe moved at a speed of 10 mm s^{-1} to a final depth of 8 mm. The force was recorded for every step of displacement, and eight parameters were extracted from the force-displacement curves using the Exponent software. The force measured at the first rupture point is represented by the parameter F_p^1. The slope from the origin to F_p^1 was recorded as E_p^1 and the AUC (W_p^1) represents the mechanical work required to reach this first rupture point. D_p^1 is the distance measured at F_p^1, while F_p^{max} is the maximal force required to push the cylindrical probe into the flesh until a maximal depth of 8 mm. D_p^{max} is the displacement of the probe at F_p^{max}. The mean force measured between F_p1 and F_p^{max} (F_p^{mean}) and the mechanical work needed to move the probe until 8 mm (W_p^2) were also assessed.

2.5. Statistical analyses

Student's *t*-tests and analyses of variance (ANOVAs) were used to compare means at $P \leq 0.05$, which were calculated using the XLSTAT software (Version 2021.1.1). Multiple means were compared with the Tukey HSD test and considered significantly different if $P \leq 0.05$. Principal component analyses (PCAs) were calculated using the R software (Version 4.2.1) to explore the variability in the quality and textural parameters as a function of the cultivar, fruit maturity and postharvest treatments.

3. Results

3.1. Influence of cultivar and maturity on quality and textural parameters at harvest

PCA was first performed to explore the effects of the cultivar and maturity stage on the quality and textural parameters measured at harvest. Principal components (PC) 1 and 2 accounted for 60.9% of the total variation (Fig. 2). PC1 discriminated between the two maturity stages of the three tested cultivars and was mainly correlated with the textural parameters obtained by compression tests, the DA Index and TSS. M1 fruit were positively correlated with PC1 and exhibited a higher DA Index, as well as higher hardness (Fc), stiffness (Ec) and mechanical work values (W_c^1, W_c^2, W_c^1-W_c^2) compared to M2 fruit, which were negatively correlated with this PC. The plastic deformation (D_c) and TSS were particularly high for the 'Farely' and 'Bergarouge®' apricots of the commercial maturity stage (M2). PC2 was mainly correlated with textural parameters from puncture tests of the skin (D_p^1, D_p^2, W_p^1, E_p^1) and of the flesh (E_p^1).

Apricots classified in two maturity classes (M1 and M2) had different DA Index values (Table 1). The firmness (Durofel Index) of M1 'Bergarouge®' and 'Farely' apricots was higher than that of M2 fruit (Table 1), but this was not the case for the cultivar 'Swired', which exhibited similar firmness values for both maturity stages, despite different DA Index values (Table 1). The three cultivars harvested at a pre-commercial maturity stage (M1) were less sweet and were greener compared to M2 fruit (Table 1). The TA was higher in M1 'Bergarouge®' and 'Farely' apricots, and as for firmness, the 'Swired' apricots displayed similar values for both maturity stages (Table 1).

Fruit maturity influenced the hardness (F_c) and stiffness (E_c) parameters extracted from force/deformation curves obtained by compression tests (Table 2). M1 'Bergarouge®' and 'Farely' fruit displayed higher values for mechanical work measured during the compression and decompression phases (W_c^1 and W_c^2) and for plastic deformation (D_c), while no effect of maturity was observed on these parameters for 'Swired'. An effect of maturity was nevertheless observed for this cultivar on the textural properties of the skin, as M1 fruit required more force and mechanical work to puncture the skin (F_p^1 and W_p^1) and the flesh (F_p^3, and W_p^3) than M2 fruit (Table 3). However, the skin textural properties of 'Bergarouge®' and 'Farely' were not different according to harvest maturity (Table 3). Differences between both ripening stages of these two cultivars were nevertheless observed for the parameters F_p^3 and W_p^3, related to the flesh texture (Table 3). Finally, the puncture tests performed with a cylindrical probe showed an influence of harvest maturity on the textural properties of 'Farely' apricot flesh, with higher values of forces (F_p^1, F_p^{mean} and F_p^{max}) and mechanical work (W_p^1 and W_p^2) required to push the probe to a depth of 8 mm (Table 4). 'Bergarouge®' and 'Swired' fruit exhibited similar textural properties of the flesh independent of the maturity stage at harvest (Table 4).

3.2. Influence of cultivar, maturity and postharvest treatments on quality and textural parameters after storage

PCA was performed on the quality and textural parameters after 4 and 9 d of storage to explore the influence of the cultivar and postharvest treatment on these parameters. Data from both maturity categories (M1 and M2) were not distinguished in these analyses. PCA performed after 2 d at 8 °C followed by 2 d at 20 °C showed that PC1 and PC2 accounted for 69.7% of the total variation (Fig. 3A). PC1 discriminated between 1-MCP- and ethylene-treated fruit and was positively related to most of the

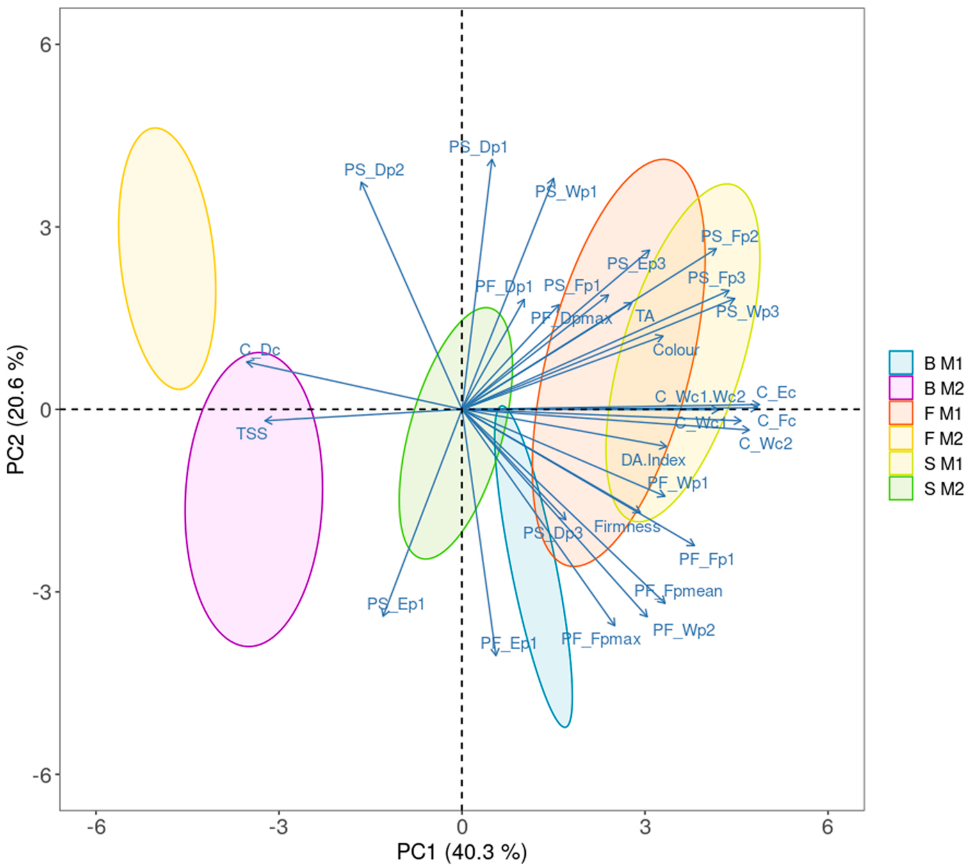

Fig. 2. Principal component analysis (PCA) performed on the quality parameters (DA Index, firmness [Durofel Index], total soluble solids [TSS], acidity [TA] and colour) and textural parameters obtained by compression tests (C), puncture tests of the skin (PS) and puncture tests of the flesh (PF) measured at harvest on 'Bergarouge®' (B), 'Farely' (F) and 'Swired' (S) apricots harvested at the pre-commercial (M1) and commercial (M2) maturity stages. Circles represent the confidence ellipses for the data of each group.

Table 1
Influence of maturity at harvest (pre-commercial [M1] and commercial [M2]) on the DA Index, firmness (Durofel Index), total soluble solids (TSS), titratable acidity (TA) and colour values of 'Bergarouge®', 'Farely' and 'Swired' apricots. The DA Index, firmness and colour values are means of samples of 20 fruit, while the TSS and TA values are means of four samples of five fruit. P-values from Student's t-tests.

Cultivar	Maturity	DA Index [I_{AD}]	Firmness [DI]	TSS [%]	TA [g kg^{-1}]	Colour [H°]
Bergarouge®	M1	0.98	72.4	11.5	8.0	64.5
	M2	0.30	66.0	12.9	7.3	59.8
	P-value	*< 0.0001*	*0.000*	*0.006*	*0.000*	*< 0.0001*
Farely	M1	0.92	73.0	11.3	11.5	71.5
	M2	0.32	65.9	12.8	10.2	62.5
	P-value	*< 0.0001*	*0.003*	*0.000*	*0.001*	*< 0.0001*
Swired	M1	0.82	75.9	11.1	15.7	66.7
	M2	0.15	77.6	13.8	14.2	59.9
	P-value	*< 0.0001*	*0.238*	*0.01*	*0.149*	*< 0.0001*

Table 2
Influence of maturity at harvest (pre-commercial [M1] and commercial [M2]) on the parameters extracted from the force/deformation curves obtained by compression tests on 'Bergarouge®', 'Farely' and 'Swired' apricots. Values are means of samples of 20 fruit. P-values from Student's *t*-tests.

Cultivar	Maturity	F_c [N]	W_c^1 [N mm]	W_c^2 [N mm]	W_c^1-W_c^2 [N mm]	E_c [N mm^{-1}]	D_c [%]
Bergarouge®	M1	23.2	24.0	11.4	12.6	1.4	10.7
	M2	15.3	15.8	6.6	9.2	1.7	7.0
	P-value	*< 0.0001*	*0.001*	*0.000*	*0.008*	*< 0.0001*	*0.001*
Farely	M1	26.4	26.6	13.3	13.2	1.3	12.0
	M2	15.8	16.5	6.7	9.8	1.7	7.2
	P-value	*0.000*	*0.005*	*0.000*	*0.066*	*< 0.0001*	*< 0.0001*
Swired	M1	27.3	27.0	12.7	14.3	1.4	12.9
	M2	22.3	23.5	10.9	12.5	1.5	9.9
	P-value	*0.028*	*0.206*	*0.226*	*0.227*	*0.004*	*0.642*

Table 3
Influence of maturity at harvest (pre-commercial [M1] and commercial [M2]) on the parameters extracted from the force/displacement curves obtained by puncture tests of the skin of 'Bergarouge®', 'Farely' and 'Swired' apricots. Values are the means of 20 fruit samples. P-values from Student's *t*-tests.

Cultivar	Maturity	F_p^1 [N]	E_p^1 [N mm^{-1}]	W_p^1 [N mm]	D_p^1 [mm]	F_p^2 [N]	D_p^2 [mm]	F_p^3 [N]	D_p^3 [mm]	E_p^3 [N mm^{-1}]	W_p^3 [N mm]
Bergarouge®	M1	0.80	1.61	0.10	0.21	0.48	0.54	1.18	2.62	0.35	2.44
	M2	0.82	1.70	0.11	0.24	0.40	0.63	0.96	2.58	0.30	2.01
	P-value	*0.573*	*0.610*	*0.682*	*0.542*	*0.001*	*0.112*	*0.000*	*0.529*	*0.055*	*< 0.0001*
Farely	M1	0.82	1.35	0.17	0.30	0.58	0.53	1.30	2.61	0.35	2.68
	M2	0.81	1.48	0.14	0.32	0.45	0.73	0.94	2.56	0.29	2.02
	P-value	*0.868*	*0.374*	*0.640*	*0.876*	*0.001*	*0.039*	*< 0.0001*	*0.407*	*0.027*	*< 0.0001*
Swired	M1	0.93	1.43	0.17	0.31	0.67	0.62	1.62	2.68	0.47	3.27
	M2	0.87	1.76	0.09	0.16	0.52	0.61	1.17	2.57	0.34	2.51
	P-value	*0.056*	*0.029*	*0.000*	*0.000*	*< 0.0001*	*0.879*	*< 0.0001*	*0.029*	*< 0.0001*	*< 0.0001*

Table 4
Influence of maturity at harvest (pre-commercial [M1] and commercial [M2]) on the parameters extracted from the force/displacement curves obtained by puncture tests of the flesh of 'Bergarouge®', 'Farely' and 'Swired' apricots. Values are means of 20 fruit samples. P-values from Student's *t*-tests.

Cultivar	Maturity	F_p^1 [N]	D_p^1 [mm]	E_p^1 [N mm^{-1}]	W_p^1 [N mm]	F_p^{mean} [N]	W_p^2 [N mm]	F_p^{max} [N]	D_p^{max} [mm]
Bergarouge®	M1	2.02	1.78	0.62	10.18	2.30	16.07	3.13	5.73
	M2	1.80	2.04	0.57	8.60	2.00	13.82	2.75	5.63
	P-value	*0.345*	*0.232*	*0.589*	*0.21*	*0.086*	*0.067*	*0.178*	*0.864*
Farely	M1	1.97	2.68	0.43	9.29	1.95	13.27	2.36	5.99
	M2	1.32	2.44	0.35	5.30	1.24	8.67	1.55	5.41
	P-value	*0.000*	*0.210*	*0.184*	*0.001*	*< 0.0001*	*< 0.0001*	*0.000*	*0.333*
Swired	M1	2.08	2.81	0.45	10.55	2.19	14.61	2.71	6.40
	M2	1.91	3.60	0.44	8.86	1.93	12.62	2.51	6.29
	P-value	*0.346*	*0.073*	*0.752*	*0.081*	*0.106*	*0.076*	*0.354*	*0.787*

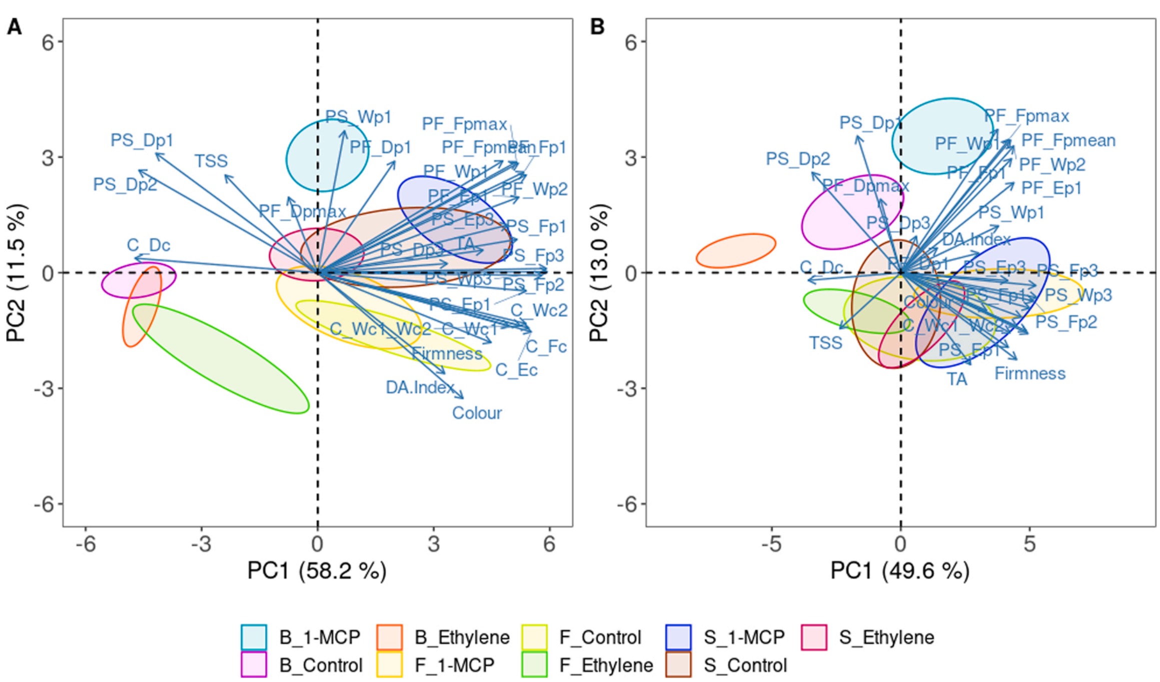

Fig. 3. PCA performed on quality parameters (DA Index, firmness [Durofel Index], total soluble solids [TSS], acidity [TA] and colour) and textural parameters obtained by compression tests (C), puncture tests of the skin (PS) and puncture tests of the flesh (PF) measured after storage of **A**: 2 d and **B**: 7 d at 8 °C followed by 2 d at 20 °C on 'Bergarouge®' (B), 'Farely' (F) and 'Swired' (S) apricots harvested at the pre-commercial (M1) and commercial (M2) maturity stages and treated with 1-MCP, ethylene or nothing (Control). Circles represent the confidence ellipses for the data of each group.

textural parameters obtained by puncture tests of the skin (F_p^1, F_p^2, F_p^3, E_p^1 and W_p^3) and negatively correlated with plastic deformation measured by compression (D_c, Fig. 3A). This indicates that 1-MCP-treated apricots required more force to puncture the skin and flesh with a needle and displayed lower plastic deformation than ethylene-treated fruit. PC2 was principally related to the mechanical work needed to puncture the skin with a needle (W_p^1), and it discriminated 'Farely' from 'Swired' apricots. Further, 1-MCP-treated 'Bergarouge®' fruit, which were also positively correlated on PC2, required more mechanical work to puncture the skin (W_p^1) compared to ethylene-treated and untreated fruit (Fig. 3A). After 7 d at 8 °C and 2 d at 20 °C, groups were less clearly discriminated based on PC1 and PC2, except for the cultivar 'Bergarouge®' which was discriminated from 'Farely' and 'Swired' on PC2 and which displayed clearly different textural properties according to postharvest treatment (mainly for the parameters F_p^3 and D_c on PC1, Fig. 3B).

3.2.1. Quality parameters

The cultivar, maturity at harvest, storage duration and postharvest treatments influenced most of the measured quality parameters (Table 5). 'Bergarouge®' exhibited the lowest firmness (Durofel Index) and TA after storage, whereas 'Farely' displayed the highest firmness, DA Index and colour values. Apricots picked at a pre-commercial maturity stage (M1) showed higher firmness, DA Index, colour and TA values but a lower TSS than M2 fruit. All quality parameters decreased with storage duration, except TSS which slightly increased. Further, 1-MCP treatment delayed softening of fruit during storage for up to 9 d (Fig. 4). This effect was particularly visible on M2 'Bergarouge®' apricots. 'Farely' were more susceptible to ethylene treatments at both maturity stages, whereas the treatment did not influence softening of 'Swired' fruit. The 1-MCP treatment did, however, delay softening of this cultivar. TSS was not influenced by 1-MCP or ethylene treatments, although 1-MCP did slow down the DA Index, TA and hue angle decreases (Table 5). Ethylene-treated fruit showed similar DA Index and TA values compared to control fruit (Table 5). Colour was not affected by the 1-MCP treatment.

3.2.2. Compression tests

An ANOVA was performed on the textural parameters issued from compression tests, showing a cultivar influence on all parameters, as the 'Farely' and 'Swired' apricots displayed higher values than 'Bergarouge®' (Table 6). M2 fruit required less force to push the probe until fruit deformation reached 5% of the calibre (F_c) and had a higher plastic deformation (D_c) compared to M1 fruit. All parameters decreased with storage duration except D_c. 1-MCP treated fruit were firmer in terms of compression and exhibited a lower plastic deformation than non-treated fruit. In contrast, ethylene treatment led to a strong decrease of all textural parameters, except D_c.

Hardness (F_c) and plastic deformation (D_c) provided good differentiation between the treatments and cultivars in the PCA performed on data obtained after 4 and 9 d of storage (Fig. 3) and were therefore further investigated. F_c showed a strong decrease for all cultivars during the first 4 d of storage (Fig. 5A). Ethylene treatment slightly accelerated this loss, while 1-MCP limited it. This effect was more pronounced on 'Farely' apricots, particularly M1 fruit. Parameter D_c slightly increased during storage and was influenced by 1-MCP treatment (Fig. 5B), as 1-MCP-treated fruit exhibited lower values compared to ethylene-treated and untreated fruit. This effect tended to disappear after 9 d of storage.

3.2.3. Puncture tests of the skin

'Swired' apricots required a higher force to puncture the skin (F_p^1) and the first layers of the flesh (F_p^2 and F_p^3) compared to 'Farely' and 'Bergarouge®' apricots (Table 7), where the latter displayed the lowest values for most of the textural parameters. In general, M2 fruit and a storage duration of 9 d resulted in lower forces and mechanical work compared to M1, respectively, with a storage of 4 d. The force needed to puncture the skin (F_p^1) and the skin stiffness (E_p^1) decreased with the storage duration (Table 7). Parameters related to the textural properties of the flesh, such as the maximal force and mechanical work needed to push the needle (F_p^3 and W_p^3), also decreased during the nine storage days. 1-MCP-treated fruit exhibited the highest values for most textural parameters related to the skin and the first layers of the flesh. In contrast, the lowest values were measured for ethylene-treated fruit.

The parameters related to the mechanical work needed to puncture the flesh (W_p^3) and the skin (W_p^1) were well correlated with PC1 and PC2, respectively, in the PCA performed after storage (Fig. 3) and were therefore chosen for further analyses. 'Bergarouge®' fruit showed different values for W_p^1, according to the postharvest treatment (Fig. 6A). Further, ethylene-treated fruit required less mechanical work to puncture the skin, whereas 1-MCP-treated apricots exhibited higher values, particularly for more mature fruit. No significant differences were measured for W_p^1 on 'Farely' and 'Swired' apricots 9 days after harvest. All cultivars showed an increase in this parameter with an increased storage duration. The maximal mechanical work needed to puncture the skin and flesh (W_p^3) was highly influenced by 1-MCP treatment during storage for all cultivars (Fig. 6B). 1-MCP-treated fruit required more mechanical work to push the probe until 3 mm of depth, whereas ethylene treatment accelerated apricot flesh softening and required less mechanical work to puncture.

3.2.4. Puncture tests of the flesh

An ANOVA performed on the parameters extracted from the puncture tests showed that 'Swired' was firmer than 'Bergarouge®' and 'Farely' according to all tested conditions (Table 8). Apricots harvested at a pre-commercial maturity stage (M1) exhibited a firmer flesh, whereas storing fruit for up to 9 d decreased the values of most parameters. The flesh of 1-MCP-treated fruit required a higher force to puncture the flesh up to 8 mm (F_p^1, F_p^{mean} and F_p^{max}), whereas ethylene-treated fruit needed less force to push the probe into the flesh.

Most of the parameters obtained by puncture tests of the flesh were correlated in the PCA performed on data after storage (Fig. 3). The

Table 5
Influence of cultivar ('Bergarouge®', 'Farely' and 'Swired'), maturity (pre-commercial (M1) and commercial (M2)), storage duration (4 d (2 d at 8 °C followed by 2 d at 20 °C) and 9 d (7 d at 8 °C followed by 2 d at 20 °C) and postharvest treatment (Control, 1-MCP and Ethylene) on the firmness (Durofel Index), DA Index, total soluble solids (TSS), titratable acidity (TA) and colour of the apricots. Means with the same letters do not differ significantly at $P \leq 0.05$ in the Tukey HSD test.

		Firmness [DI]	DA Index [I_{AD}]	TSS [%]	TA [$g\ kg^{-1}$]	Colour [H°]
Cultivar	Bergarouge®	37.8c	0.30 b	12.6 b	7.2c	59.4c
	Farely	58.7 a	0.44 a	12.3 b	9.2 b	63.3 a
	Swired	54.5 b	0.22c	13.5 a	14.3 a	60.3 b
	P-value	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*
Maturity	M1	54.6 a	0.45 a	11.8 b	10.9 a	63.2 a
	M2	46.0 b	0.19 b	13.8 a	9.5 b	58.8 b
	P-value	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*
Storage duration	4 d[a]	55.3 a	0.40 a	12.7 b	10.6 a	61.9 a
	9 d[b]	45.4 b	0.24 b	12.9 a	10.0 b	60.1 b
	P-value	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*
Treatments	Control	50.2 b	0.30 b	12.9	10.1 b	60.5 b
	1-MCP	57.9 a	0.37 a	12.8	10.7 a	61.4 a
	Ethylene	42.8c	0.28 b	12.8	10.0 b	61.1 a
	P-value	*< 0.0001*	*< 0.0001*	0.755	< 0.0001	*< 0.0001*

[a] 2 d at 8 °C followed by 2 d at 20 °C
[b] 7 d at 8 °C followed by 2 d at 20 °C

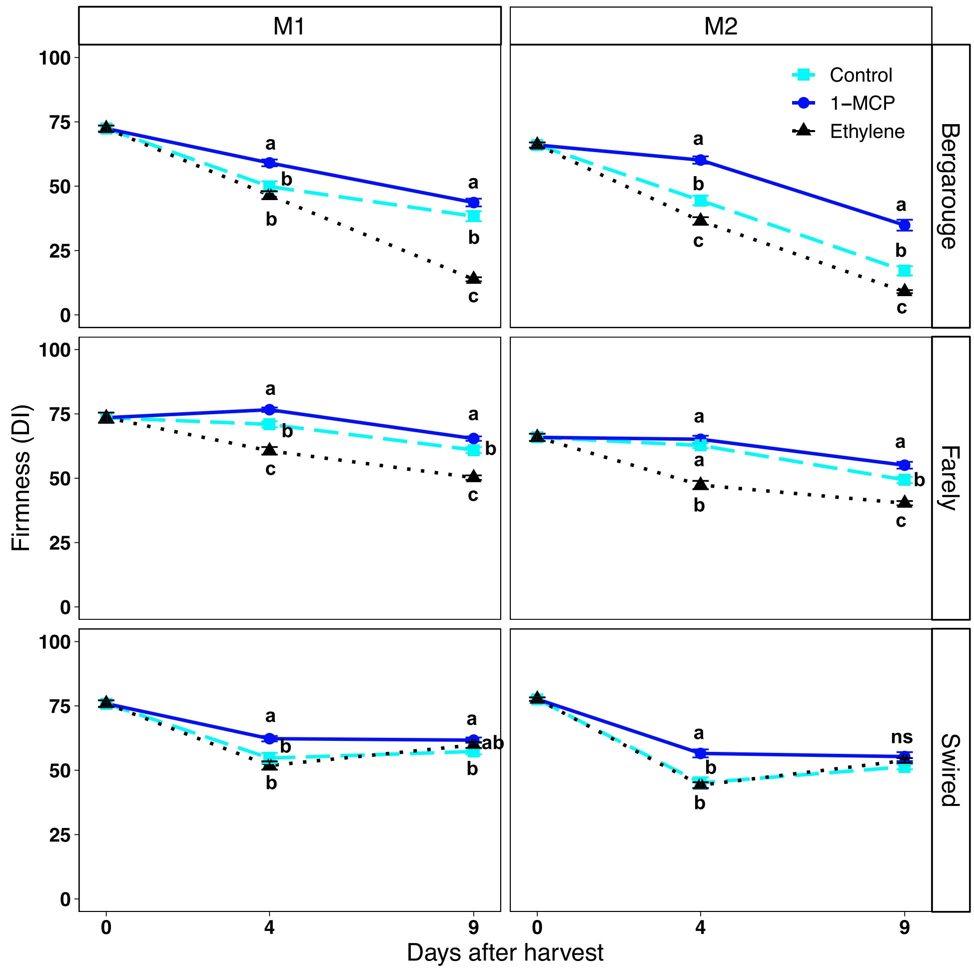

Fig. 4. Influence of 1-MCP and ethylene treatment on the firmness (Durofel Index) of ‘Bergarouge®’, ‘Farely’ and ‘Swired’ apricots harvested at the pre-commercial (M1) and commercial (M2) maturity stages and stored for 4 and 9 d (2 and 7 d at 8 °C followed by 2 d at 20 °C). Values are means ± standard error. Means with the same letters are not significantly different at P ≤ 0.05 in the Tukey HSD test. ns: not significant.

Table 6
Influence of cultivar (‘Bergarouge®’, ‘Farely’ and ‘Swired’), maturity (pre-commercial [M1] and commercial [M2]), storage duration (4 d [2 d at 8 °C followed by 2 d at 20 °C] and 9 d [7 d at 8 °C followed by 2 d at 20 °C]) and postharvest treatment (Control, 1-MCP and Ethylene) on textural parameters extracted from force/deformation curves obtained by compression tests. Means with the same letters do not differ significantly at P ≤ 0.05 in the Tukey HSD test.

		F_c [N]	W_c^1 [N mm]	W_c^2 [N mm]	W_c^1-W_c^2 [N mm]	E_c [N mm^{-1}]	D_c [%]
Cultivar	Bergarouge®	4.87 b	4.72 b	1.92c	2.81 b	2.32 b	1.72 a
	Farely	7.98 a	7.89 a	3.48 a	4.41 a	3.72 a	1.56 b
	Swired	7.92 a	7.54 a	3.15 b	4.39 a	3.80 a	1.68 a
	P-value	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*
Maturity	M1	7.96 a	7.51 a	3.30 a	4.21 a	3.83 a	1.58 b
	M2	5.89 b	5.93 b	2.40 b	3.53 b	2.73 b	1.73 a
	P-value	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*
Storage duration	4 d[(a)]	8.14 a	7.96 a	3.46 a	4.50 a	3.83 a	1.59 b
	9 d[(b)]	5.71 b	5.48 b	2.23 b	3.24 b	2.73 b	1.72 a
	P-value	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*
Treatments	Control	7.00 b	6.83 b	2.86 b	3.96 a	3.30 a	1.67 b
	1-MCP	7.93 a	7.73 a	3.45 a	4.28 a	3.72 a	1.55c
	Ethylene	5.85c	5.60c	2.23c	3.37 b	2.82 b	1.74 a
	P-value	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*

[a] 2 d at 8 °C followed by 2 d at 20 °C
[b] 7 d at 8 °C followed by 2 d at 20 °C

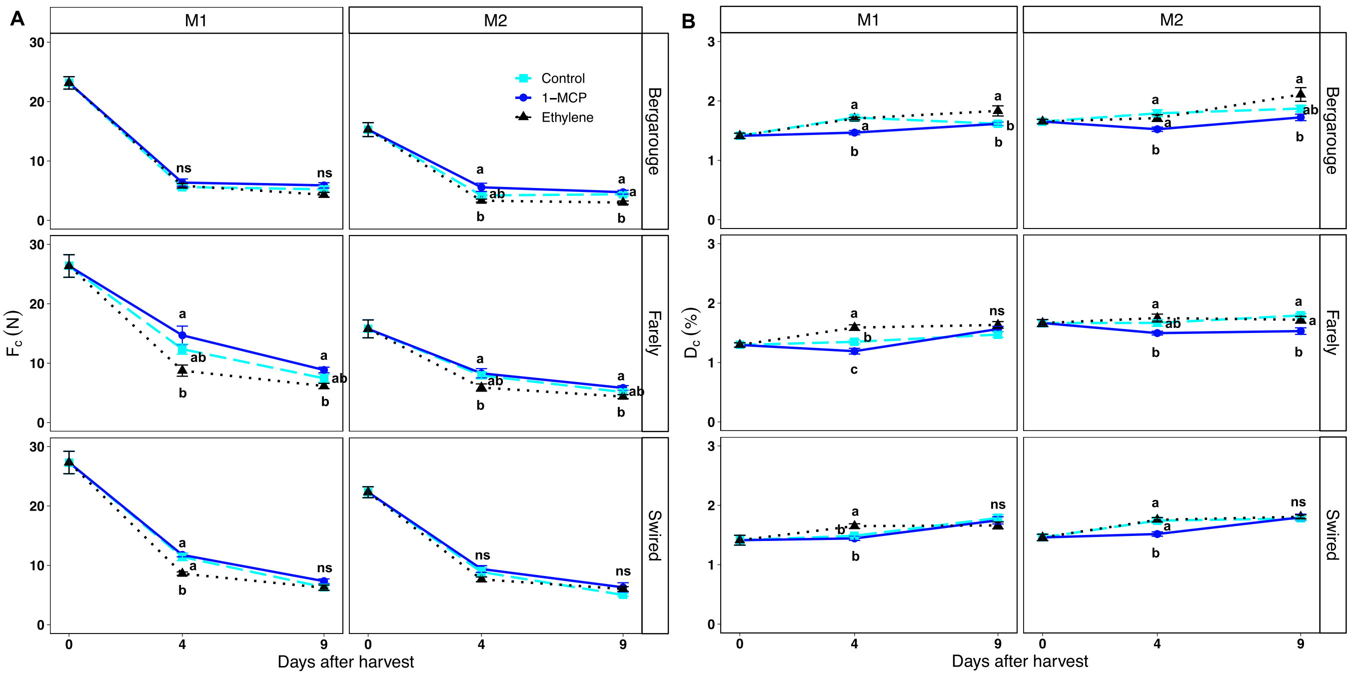

Fig. 5. Influence of 1-MCP and ethylene treatment on **A**: hardness (F_c) and **B**: plastic deformation (D_c) extracted from the force/deformation curves obtained by compression tests on 'Bergarouge®', 'Farely' and 'Swired' apricots harvested at the pre-commercial (M1) and commercial (M2) maturity stages and stored for 4 and 9 d (2 and 7 d at 8 °C followed by 2 d at 20 °C). Values are means ± standard error. Means with the same letters are not significantly different at P ≤ 0.05 in the Tukey HSD test. ns: not significant.

Table 7

Influence of cultivar ('Bergarouge®', 'Farely' and 'Swired'), maturity (pre-commercial [M1] and commercial [M2]), storage duration (4 d [2 d at 8 °C followed by 2 d at 20 °C] and 9 d [7 d at 8 °C followed by 2 d at 20 °C]) and postharvest treatment (Control, 1-MCP and Ethylene) on textural parameters extracted from force/displacement curves obtained by puncture tests of the skin. Means with the same letters do not differ significantly at P ≤ 0.05 in the Tukey HSD test.

		F_p^1 [N]	E_p^1 [N mm^{-1}]	W_p^1 [N mm]	D_p^1 [mm]	F_p^2 [N]	D_p^2 [mm]	F_p^3 [N]	D_p^3 [mm]	E_p^3 [N mm^{-1}]	W_p^3 [N mm]
Cultivar	Bergarouge®	0.76c	1.19c	0.19 b	0.54 a	0.32c	0.96 a	0.72c	2.53 b	0.25c	1.56c
	Farely	0.87 b	1.34 b	0.20 ab	0.44 b	0.43 b	0.83 b	0.90 b	2.57 ab	0.28 b	1.98 b
	Swired	0.98 a	1.49 a	0.21 a	0.43 b	0.47 a	0.84 b	1.02 a	2.58 a	0.34 a	2.24 a
	P-value	*< 0.0001*	*< 0.0001*	*0.019*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*0.011*	*< 0.0001*	*< 0.0001*
Maturity	M1	0.93 a	1.40 a	0.21 a	0.46 b	0.45 a	0.84 b	0.91 a	2.58 a	0.32 a	2.15 a
	M2	0.82 b	1.28 b	0.18 b	0.48 a	0.36 b	0.91 a	0.77 b	2.54 b	0.26 a	1.70 b
	P-value	*< 0.0001*	*< 0.0001*	*0.000*	*0.000*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*0.082*	*< 0.0001*	*< 0.0001*
Storage duration	4 d[a]	0.94 a	1.36 a	0.23 a	0.53 b	0.40 a	0.96 b	0.82 a	2.57 a	0.28 a	1.86 a
	9 d[b]	0.84 b	1.11 b	0.23 a	0.62 a	0.31 b	1.06 a	0.62 b	2.50 b	0.24 b	1.43 b
	P-value	*< 0.0001*	*< 0.0001*	*0.521*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*
Treatments	Control	0.89 b	1.24 b	0.22 b	0.56 b	0.35 b	0.99 b	0.72 b	2.52 b	0.26 b	1.63 b
	1-MCP	0.97 a	1.35 a	0.25 a	0.57 b	0.42 a	0.98 b	0.88 a	2.58 a	0.31 a	1.96 a
	Ethylene	0.81c	1.12c	0.22 b	0.60 a	0.29c	1.06 a	0.57c	2.51 b	0.21c	1.35c
	P-value	*< 0.0001*	*< 0.0001*	*< 0.0001*	*0.000*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*0.001*	*< 0.0001*	*< 0.0001*

[a] 2 d at 8 °C followed by 2 d at 20 °C
[b] 7 d at 8 °C followed by 2 d at 20 °C

maximal force needed to push the cylindrical probe through the flesh until 8 mm (F_p^{max}) was selected for further investigation (Fig. 7). 1-MCP slowed the decrease in this parameter, particularly for 'Bergarouge®', whereas ethylene accelerated it, though the latter effect was more pronounced on 'Farely' fruit.

4. Discussion

4.1. Influence of cultivar and maturity on fruit quality and texture at harvest

Fruit growers often have difficulties determining the optimum maturity for harvesting apricots. Skin degreening is one of the common parameters used, but it can be insufficient for cultivars having a deep red-coloured skin (Gouble et al., 2010). Measuring classical quality parameters, such as firmness, sugar or acidity levels, allows the maturity stage of apricots at harvest to be defined more precisely, as shown in our study: commercially mature fruit was softer, sweeter, less green and less acidic than fruit harvested at a pre-commercial maturity stage. This was, however, only observed for 'Bergarouge®' and 'Farely', as 'Swired' apricots showed similar firmness and acidity values at both maturity stages. Measuring these parameters is, however, time-consuming and destructive for the fruit. Using an innovative method to determine maturity at harvest rapidly and non-destructively would improve the postharvest management of apricots by sorting them according to their storage potential. The sorting machine equipped with a DA-Meter® used in our study is based on the DA Index representing the difference in absorbance between two wavelengths near the chlorophyll-a absorption

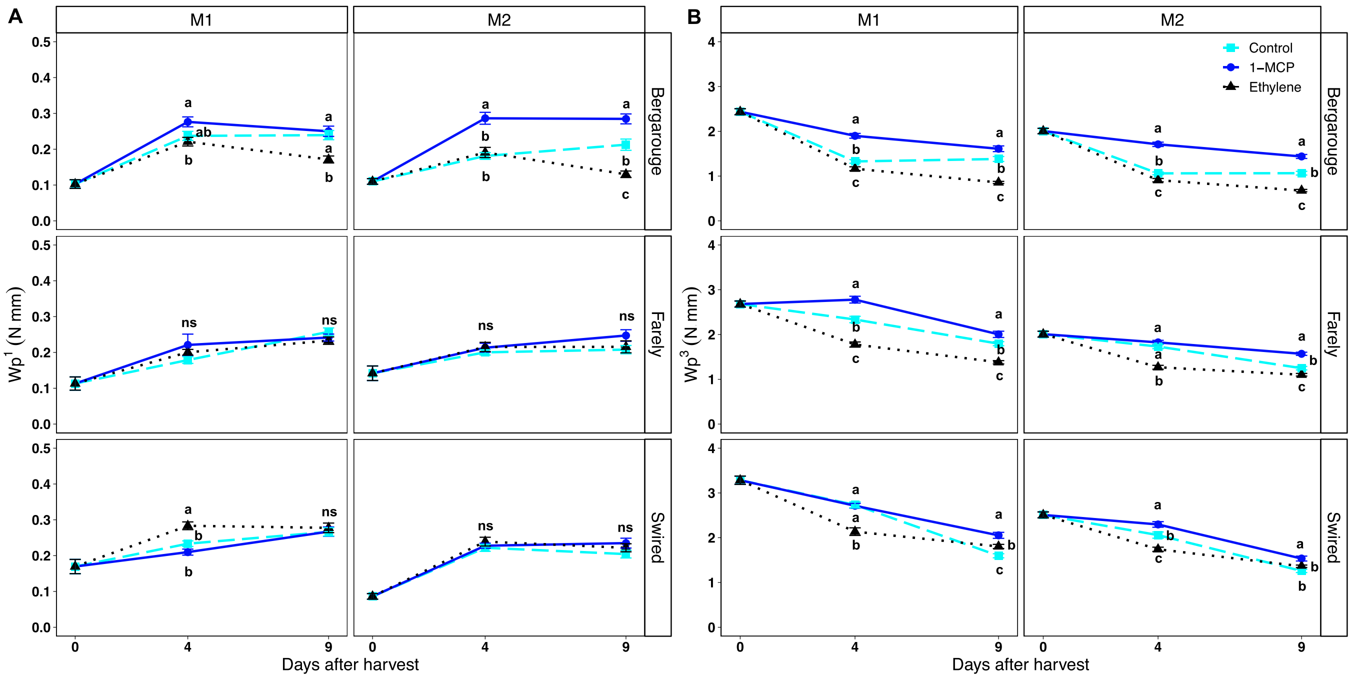

Fig. 6. Influence of 1-MCP and ethylene treatment on **A**: mechanical work to puncture the skin (W_p^1): and **B**: mechanical work to move the probe through the flesh (W_p^3) extracted from the force/deformation curves obtained by a puncture test of the skin on 'Bergarouge®', 'Farely' and 'Swired' apricots harvested at the pre-commercial (M1) and commercial (M2) maturity stages and stored for 4 and 9 d (2 and 7 d at 8 °C followed by 2 d at 20 °C). Values are means ± standard error. Means with the same letters are not significantly different at P ≤ 0.05 in the Tukey HSD test. ns: not significant.

Table 8
Influence of cultivar ('Bergarouge®', 'Farely' and 'Swired'), maturity (pre-commercial [M1] and commercial [M2]), storage duration (4 d [2 d at 8 °C followed by 2 d at 20 °C] and 9 d [7 d at 8 °C followed by 2 d at 20 °C]) and postharvest treatment (Control, 1-MCP and Ethylene) on textural parameters extracted from force/displacement curves obtained by puncture tests of the flesh. Means with the same letters do not differ significantly at P ≤ 0.05 in the Tukey HSD test.

		F_p^1 [N]	D_p^1 [mm]	E_p^1 [N mm^{-1}]	W_p^1 [N mm]	F_p^{mean} [N]	W_p^2 [N mm]	F_p^{max} [N]	D_p^{max} [mm]
Cultivar	Bergarouge®	0.85 b	3.09 a	0.20 b	4.16 b	0.86 b	5.60 b	1.17 b	6.40 a
	Farely	0.87 b	2.92 a	0.22 b	3.84 b	0.82 b	5.61 b	1.12 b	6.02 b
	Swired	1.16 a	3.20 a	0.27 a	4.90 a	1.05 a	7.15 a	1.41 a	5.93 b
	P-value	*< 0.0001*	*0.096*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*0.002*
Maturity	M1	1.13 a	3.06 a	0.27 a	5.05 a	1.07 a	7.21 a	1.43 a	6.03 a
	M2	0.80 b	3.08 a	0.19 b	3.55 b	0.75 b	5.02 b	1.04 b	6.21 a
	P-value	*< 0.0001*	*0.868*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*0.122*
Storage duration	4 d[a]	1.11 a	3.03 a	0.27 a	4.86 a	1.06 a	7.06 a	1.41 a	6.03 a
	9 d[b]	0.82 b	3.11 a	0.20 b	3.74 b	0.77 b	5.18 b	1.06 b	6.21 a
	P-value	*< 0.0001*	*0.470*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*0.135*
Treatments	Control	0.91 b	2.88 b	0.23 b	4.14 b	0.87 b	5.91 b	1.20 b	6.10 a
	1-MCP	1.36 a	3.57 a	0.30 a	5.90 a	1.28 a	8.36 a	1.66 a	6.23 a
	Ethylene	0.62c	2.76 b	0.16c	2.86c	0.59c	4.09c	0.84c	6.02 a
	P-value	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*< 0.0001*	*0.326*

[a] 2 d at 8 °C followed by 2 d at 20 °C
[b] 7 d at 8 °C followed by 2 d at 20 °C

peak (670 and 720 nm, Ziosi et al., 2008). This device allowed discriminating non-destructively ripe from unripe fruit of the three cultivars, which is in line with the results for other cultivars obtained by other authors (Amoriello et al., 2018; Costa et al., 2010).

Interestingly, 'Swired' apricots that showed a highly different DA Index according to maturity had similar firmness values. Fruit picked at a pre-commercial maturity stage, however, better maintained their firmness during storage compared to commercially mature fruit. These results confirmed that the DA Index is an interesting tool to predict the postharvest behaviour of apricots, particularly softening, a key parameter of the fruit supply chain.

Firmness measured using the Durofel device is a classical method applied by growers and retailers in Switzerland along the apricot supply chain. This method consists of measuring the maximal force required to push a flat probe against the fruit. It is easy to use and relatively cheap. The results, however, are based on only one parameter, precluding a detailed description of the skin and flesh influence on the results, as shown previously (Gabioud Rebeaud et al., 2019).

In this study, compression tests performed with a Texture Analyzer showed an influence of maturity stage on the textural properties of 'Bergarouge®' and 'Farely', but not 'Swired'. These results are in line with those obtained by the classical method. Puncturing the skin and the first layers of the flesh until a depth of 3 mm with a needle allowed, however, for discrimination between the maturity stages for the three cultivars. Interestingly, 'Swired' apricots needed a higher force to rupture the skin and push the needle until 3 mm compared to 'Bergarouge®' and 'Farely'. A more resistant epidermis may be favourable for the storage of apricots. Penetrometry tests performed with a

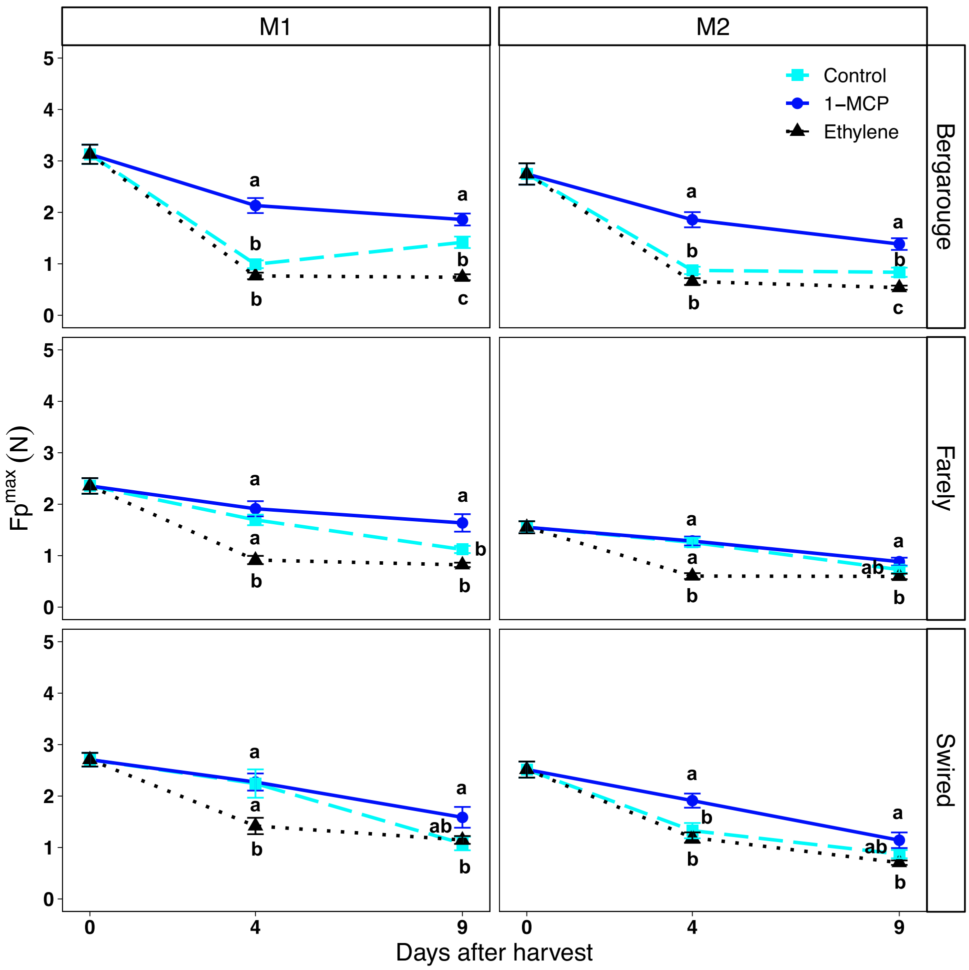

Fig. 7. Influence of 1-MCP and ethylene treatment on the maximal force required to move the probe through the flesh (F_p^{max}) extracted from the force/deformation curves obtained by a puncture test of the flesh of 'Bergarouge®', 'Farely' and 'Swired' apricots harvested at the pre-commercial (M1) and commercial (M2) maturity stages and stored for 4 and 9 d (2 and 7 d at 8 °C followed by 2 d at 20 °C). Values are means ± standard error. Means with the same letters are not significantly different at $P \leq 0.05$ in the Tukey HSD test.

cylindrical probe into the flesh showed very similar values for both maturity stages of 'Bergarouge®' and 'Swired'. 'Farely' exhibited different textural properties according to the maturity: more mature fruit required less force to push the probe into the flesh.

These results showed that the maturity stage influenced the textural properties of the apricots in a cultivar-specific manner, and they offer evidence that despite similar firmness values obtained with a classical method of measurements, such as using the Durofel device, textural properties of the skin and flesh can vary when measured more precisely with a Texture Analyzer. This confirms the previous results obtained with a similar methodology (Gabioud Rebeaud et al., 2019).

4.2. Influence of cultivar, maturity and postharvest treatments on quality parameters after storage

Softening is an essential parameter determining the ability of fresh apricots to withstand postharvest manipulations and to be accepted by consumers. Storage, conditioning, transport and commercialisation at room temperature are among the most essential postharvest steps of the supply chain, though fruit degradation and losses can be caused by softening and decay development. Identifying the most resistant cultivars and optimal postharvest conditions for delivering apricots meeting consumer expectations while limiting losses along the supply chain is key for apricot producers and suppliers.

Our study showed a strong cultivar-specific softening rate. Despite similar firmness values at harvest, 'Bergarouge®' softened faster during storage than 'Farely' and 'Swired', independent of the maturity stage. Therefore, determining the right cultivar in relation to the postharvest itinerary is of utmost importance.

1-MCP reduced softening, loss of TA and green colour. TSS was not influenced by 1-MCP, while the DA Index remained higher than in the absence of treatment, which indicates that chlorophyll degradation was slowed down with the treatment. This corroborates the results obtained by spectrophotometry. The effect of ethylene treatment, applied during shelf life right after harvest or after 7 d of storage at 8 °C, was also cultivar-specific. Ethylene accelerated the softening rate of 'Bergarouge®' and 'Farely' at both maturity stages, but its effect was not observed for 'Swired'. In general, TSS, TA and the DA Index were not impacted by ethylene treatment.

Similar to the observations made on 'Swired', 'Shushanggan' apricots treated with 1-MCP or ethylene after 30 d of storage at a cold temperature showed that 1-MCP effectively slowed down firmness loss during shelf life, but ethylene had no influence on this parameter (Fan et al., 2018). These authors explained this effect by the strong suppression with 1-MCP of the ethylene-induced expression of pectin-related gene encoding for pectin-degrading enzymes. Interestingly, despite the absence of an influence on firmness values, treatments with ethylene increased ethylene production and respiration rates, suggesting the rate of ethylene production is not systematically correlated with a softening rate. Similar results were observed by Christen et al. (2018).

The influence of 1-MCP treatment on delayed apricot softening has been demonstrated in various cultivars (Dong et al., 2002; Egea et al., 2010; Fan et al., 2000; Hou et al., 2019; Palou and Crisosto, 2003). Few studies have, however, reported on ethylene application to improve the quality of apricots for consumers at the point of sale. In the study performed on the 'Shushanggan' cultivar by Fan et al. (2018), ethylene treatment did not influence firmness but could have improved sensory quality; ethylene accelerated TSS accumulation, organic acid degradation and colour changes to apricots, which are related to the sensory scores of sweetness, sourness and visual appearance, leading to the improvement of apricot marketing acceptance. A higher softening of 'Patterson' and 'Castlebrite' apricots, when treated with ethylene during cold storage at 5 °C, has also been reported by Palou et al. (2003), as well as an enhanced softening of apricots with 100 μL L^{-1} ethylene for 48 h at 20 °C (Brecht et al., 1982).

Taken together, these studies indicate that cultivars and application methods influence the efficacy of 1-MCP and ethylene treatment in apricot softening.

4.3. Influence of cultivar, maturity and postharvest treatments on textural parameters after storage

In this study, measurements done with a Texture Analyzer allowed describing more precisely the influence of the tested factors on apricot textural properties and represented a substantial advantage over measurements performed with a manual device, such as Durofel, achieved on a small surface of each fruit. Compression tests that give information on the viscoelastic properties of the apricots showed both postharvest treatments with 1-MCP or ethylene and the maturity stage at harvest influenced these properties. The 1-MCP-treated fruit required higher forces to push the probe until the fruit reached 5% deformation and were more resistant to pressure, as they showed lower plastic deformation. This indicates that 1-MCP-treated fruit may better support postharvest handling requirements, such as transport, which can induce vibration and possible mechanical damages. Pre-commercially harvested fruit also displayed a lower plastic deformation than fruit picked at commercial maturity.

In contrast, ethylene treatment increased plastic deformation and fruit softening, as the force needed to push the probe in the compression test was lower than for untreated fruit. In a previous study, Gabioud Rebeaud et al. (2019) showed that plastic deformation was influenced by temperature in a different manner according to the cultivar. The influence of the cultivar was also observed in this study, but, interestingly, more so on the force applied to push the probe than plastic deformation.

The influence of both 1-MCP and ethylene treatments was observed on the two puncture tests performed in this study, where 1-MCP-treated apricots required a higher force to puncture the skin and flesh. The textural parameters of the skin were also influenced by the cultivar, with 'Swired' showing the highest values, followed by 'Farely' and 'Bergarouge®'. Fruit harvested at a pre-commercial maturity stage and stored for a short period also had higher values for skin texture parameters compared to fruit that were more mature and stored longer. Finally, the influence of postharvest treatments was cultivar-specific: 1-MCP strongly delayed flesh softening for both maturity stages of 'Bergarouge®', and ethylene treatment was particularly effective in accelerating the decrease in mechanical work needed to puncture the flesh of 'Farely' apricots. 'Swired' required the highest forces to puncture the flesh, independently of postharvest treatment. This shows the cultivar has textural properties to support postharvest manipulations.

5. Conclusions

All three cultivars showed reduced fruit softening after postharvest 1-MCP treatment. The softening rate was cultivar-specific, and the maturity stage at harvest had only a moderate influence. 'Bergarouge®' and 'Farely', but not 'Swired', showed increased softening after an ethylene treatment during the shelf life.

This study also demonstrated the benefit of using texturometry to assess fruit response to postharvest treatment and, thus, to evaluate more precisely cultivar influence and the maturity stage on apricot texture. 'Bergarouge® was the most susceptible cultivar to deformation, while 'Swired' required the highest force and mechanical work to puncture the skin and the flesh. 1-MCP treatment increased the ability of the flesh and the skin of 'Bergarouge®' apricots to resist puncture even when fruit was harvested at the commercial maturity stage, while for 'Farely', the influence of ethylene was stronger.

This study highlighted that each cultivar responds differently to postharvest treatment, stressing the need for cultivar-specific recommendations for postharvest management. Texturometry offers new avenues to define the optimal maturity and postharvest strategy (e.g. direct commercialisation or storage).

Author Statement

This manuscript is the authors' original work and has not been published, nor has it been submitted simultaneously elsewhere. This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors.

CRediT authorship contribution statement

Séverine Gabioud Rebeaud: Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft. **Laura Cioli:** Investigation, Data curation. **Pierre-Yves Cotter:** Investigation. **Danilo Christen:** Supervision.

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.

Data Availability

Data will be made available on request.

Acknowledgements

The authors thank Fabien Rebeaud for his support in writing this paper.

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