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Preharvest 1-methylcyclopropene and aminoethoxyvinylglycine treatment effects on 'NY2' (RubyFrost®) apple fruit quality and postharvest watercore dissipation at different temperatures

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ABSTRACT

Recent studies have found that dissipation of watercore in apple fruit after harvest can be enhanced by preharvest application of 1-methylcyclopropene (1-MCP). In this study, the effects of plant growth regulators (PGRs) on watercore dissipation have been extended to the use of aminoethoxyvinylglycine (AVG) and the effects of storage at 3 °C, 10 °C, and 20 °C over 30 d. Preharvest 1-methylcyclopropene (1-MCP) and aminoethoxyvinylglycine (AVG) treatments were applied one week before harvest to 'NY2' (RubyFrost®), a cultivar that is prone to development of a stress-associated type of watercore during fruit maturation. Fruit were harvested twice (H1 and H2), 11 d apart. 1-MCP and AVG treatments had more pronounced effects on maturity at H2, with higher I_{AD} values and flesh firmness, respectively, compared with those of fruit harvested at H1. During storage, 1-MCP and AVG treated fruit had lower ethylene production and respiration rates than untreated fruit at H1, but ethylene production in 1-MCP treated fruit increased on day 17 at H2, reaching levels similar to untreated fruit, while remaining low in AVG-treated fruit. IECs were lower in fruit stored at 3 °C than at 10 °C or 20 C. Both treatments maintained low IECs, but more persistently in AVG-treated fruit. Flesh firmness and titratable acidity were higher, and greasiness was lower, in AVG and 1-MCP treated fruit compared with untreated fruit. The PGR treatments had no effect on watercore incidence at H1 as incidence was low in all treated fruit. At H2, 1-MCP reduced watercore incidence at harvest compared with untreated and AVG-treated fruit, which had similar incidences. Watercore dissipation was enhanced by AVG, being more rapid with higher storage temperature. The mechanism by which PGRs can increase watercore dissipation is unknown, but they might alter sorbitol transporter activity and/or cell membrane stability for sorbitol uptake from the intercellular space into the parenchyma cells. Nevertheless, the use of PGRs may be a useful way to decrease the incidences of flesh browning disorders associated with high watercore incidence in fruit at the time of harvest.

1. Introduction

Watercore is a physiological disorder of apples that develops in fruit before harvest and is typically associated with late harvest, orchard management factors such as crop load and nutrition, and climate (Marlow and Loescher, 1984). The disorder develops in the core area first, hence the term 'watercore' and then extends into the cortical tissues, especially the vascular tissues, representing block and radial types, respectively (Harker et al. 1999). However, Carne (1948) described a type of watercore – early or immaturity watercore - that was distinguishable from 'late, radial, or maturity watercore'. This type was further subdivided into speckled watercore that occurs in the cortex and not the core, and surface watercore that is associated with extreme heatwaves (Wilkinson and Fidler, 1973). This variant of watercore has been called early watercore (Yamada et al. 2005; Yamada et al. 2001).

Watercore is usually associated with accumulation of sorbitol in the intercellular spaces as a result of its reduced uptake into parenchyma cells (Marlow and Loescher, 1984; Gao et al. 2005; Yamada et al., 2006a; Liu et al., 2022; Saquet, 2020), but the causal factors of the different watercore variants uncertain. Marlow and Loescher (1984) concluded that both classic and stress induced watercore were related primarily to changes in membrane integrity rather than sorbitol metabolism. However, watercore induced by high preharvest temperatures may occur via a different mechanism from that induced at a lower temperature during

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Table 1
Internal ethylene concentration (IEC), firmness, starch pattern index (SPI), titratable acidity (TA), soluble solids concentration (SSC), difference of absorbance (I_{AD}) values, and watercore incidence and severity of 'NY2' fruit at harvest on October 9 (H1) and October 20 (H2), 2020. Fruit were harvested from trees that were untreated or sprayed with 1-methylcyclopropene (1-MCP) or 1-aminoethoxyvinylglycine (AVG) on October 2, 2020. Means followed by the same letters do not differ at $P < 0.05$.

	H1			H2		
	Control	1-MCP	AVG	Control	1-MCP	AVG
IEC ($\mu L\ L^{-1}$)	0.34 a	0.63 a	0.27 a	0.83 a	1.76 a	0.73 a
I_{AD} value	0.41 b	0.52 a	0.42 b	0.20c	0.40 a	0.27 b
Firmness (N)	95.5 a	93.0 a	98.0 a	88.3 b	89.3 ab	94.2 a
SPI (1−8)	6.1 a	6.1 a	6.0 a	6.5 a	6.7 a	6.3 a
TA (%)	0.84 a	0.83 a	0.77 a	0.81 a	0.79 a	0.78 a
SSC (%)	13.8 a	14.3 a	13.8 a	14.5 a	14.2 a	14.3 a
Watercore (%)	10 a	20 a	10 a	75 a	30 b	75 a
Watercore severity (0−5)	0.3 a	0.6 a	0.4 a	1.6 a	0.6 b	1.8 a

maturation (Yamada et al. 1994), perhaps as a result of increased fruit temperatures and water relations in the fruit affected by evapotranspiration from the fruit surface as well as sorbitol accumulation (Yamada et al. 2006a; Yamada et al. 2006b). Stress-induced watercore has been increasingly observed in several important commercial cultivars including 'Jonagold' and 'NY2' (Algul et al. 2021; Sazo and Cheng, 2017).

Tolerance for watercore in the industry is low (USDA, 2024) because of its association with watercore breakdown (Park et al. 2024; Argenta et al. 2002; Marlow and Loescher, 1984). Watercore can dissipate after harvest, and therefore management strategies can be employed to minimize the potential of fruit with high incidences and severity of watercore to develop flesh browning disorders. These include storage temperatures, conditioning temperatures and delayed application of controlled atmosphere (CA) and modifications of the CA regimes that are applied (Argenta et al. 2000, 2002; Kweon et al. 2013; Neuwald et al. 2010; Watkins and Mattheis, 2019). Conditioning temperatures can also affect watercore dissipation, with rates being faster with higher temperatures when 1, 3, 6 and 10 °C are compared (Neuwald et al. 2010).

Normal watercore is affected by fruit maturation and therefore the effects of the preharvest plant growth regulators (PGRs) ReTain™ (aminoethoxyvinylglycine; AVG) and Harvista® (1-methylcyclopropene;1-MCP) on fruit disorders has been of interest. AVG and 1-MCP inhibit ethylene production and ethylene perception, respectively (Boller et al. 1979; Sisler, 2006) and where registered for use, e.g. North America, both PGRs are applied to apple cultivars to manage the harvest by delaying fruit maturation, allowing fruit size to increase, widening the picking window of specific cultivars and extending the time between harvests of multiple-pick cultivars (Arseneault and Cline, 2016). The effects of the PGRS are variable however, with preharvest 1-MCP and AVG inhibiting watercore development in some (Amarante et al. 2010; Yuan and Li, 2008) but not all cases (Algul et al. 2021; Elfving et al. 2007; Park et al. 2024), and can be affected by timing of application (Lee et al. 2019).

Interestingly, while preharvest 1-MCP did not consistently affect watercore incidence and severity of 'Fuji' and 'Jonagold' apples, the rate of watercore dissipation after harvest was more rapid in treated than in untreated fruit (Algul et al. 2021; Lee et al. 2019). The study of Lee et al. (2019) compared postharvest temperatures of 0.5 and 20 °C, while that of Algul et al. (2021) was limited to 20 °C. The objective of this study was to study the effects of both preharvest 1-MCP and AVG on fruit quality and stress watercore of 'NY2', and the effects of the PGRs on watercore dissipation at 3, 10 and 20 °C over a 30 d storage period.

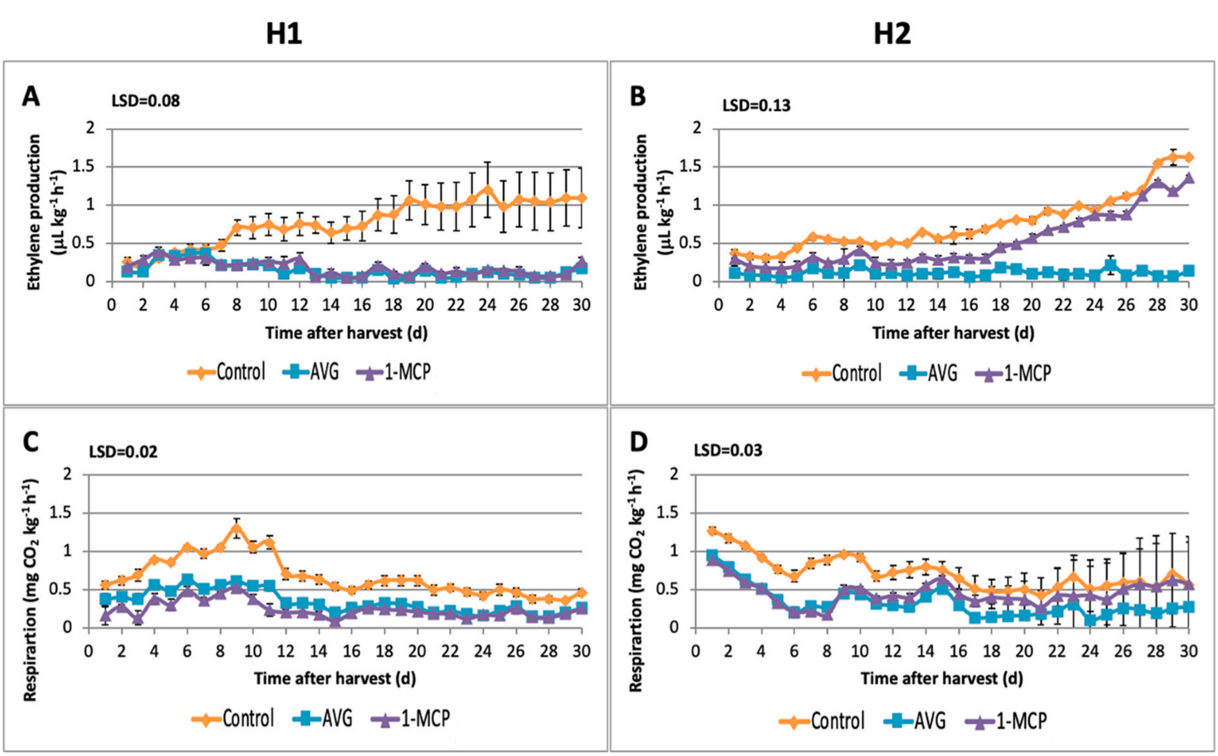

Fig. 1. Ethylene production ($\mu L\ kg^{-1}\ h^{-1}$) and respiration rates (mg CO_2 $kg^{-1}\ h^{-1}$) of untreated, 1- methylcyclopropene (1-MCP) treated or 1-aminoethoxyvinylglycine (AVG) treated 'NY2' fruit harvested on October 9 (H1; A, C)) and October 20 (H2; B, D), 2020 and kept at 20 °C for 30 d. Data are presented as means ± standard error (SE) where larger than the symbol. (n=5 individual fruit).

Table 2
ANOVA for internal ethylene concentration (IEC), firmness, soluble solids concentration (SSC), titratable acidity (TA), difference of absorbance (IAD) values, SPI, stress watercore incidence, stress watercore rating and greasiness of untreated, preharvest 1- methylcyclopropene (1-MCP) treated or 1-aminoethoxyvinylglycine (AVG) treated 'NY2' fruit on October 9 (H1) and October 20 (H2), 2020, and kept at 3 ℃, 10 ℃, and 20 ℃ for up to 30 d.

Harvest	Temperature	Factor	IEC	Flesh firmness	SSC	TA	I_{AD} value	SPI	Stress watercore	Stress watercore ranking	Greasiness
H1	3 ℃	Treatment	<0.0001	0.0007	0.288	0.0002	0.0002	0.263	0.351	0.182	1.00
		Time	<0.0001	<0.0001	0.141	0.484	<0.0001	<0.0001	0.959	0.504	0.018
		Treatment*Time	<0.0001	0.0150	0.222	0.129	0.9372	0.550	0.711	0.729	1.00
	10 ℃	Treatment	<0.0001	<0.0001	0.096	<0.0001	<0.0001	0.276	0.123	0.142	0.0180
		Time	<0.0001	<0.0001	0.063	0.0002	<0.0001	<0.0001	0.0004	0.0004	0.0078
		Treatment*Time	<0.0001	<0.0001	0.213	0.0543	0.719	0.461	0.082	0.202	0.0032
	20 ℃	Treatment	<0.0001	<0.0001	0.292	<0.0001	<0.0001	0.194	0.725	<0.0001	0.266
		Time	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.104	<0.0001	0.031
		Treatment*Time	<0.0001	0.0001	0.775	0.038	0.121	0.959	0.660	<0.0001	0.459
H1	3 ℃–10 ℃–20 ℃	Treatment * Temperature	<0.0001	0.0004	0.0082	0.162	<0.0001	0.136	0.882	0.004	<0.0001
		Treatment * Temperature*Time	<0.0001	0.0083	0.303	0.316	0.574	0.747	0.923	<0.0001	<0.0001
H2	3 ℃	Treatment	<0.0001	0.001	0.0030	0.0004	<0.0001	0.279	<0.0001	0.0015	0.089
		Time	0.0002	0.0003	0.0005	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
		Treatment * Time	<0.0001	0.0050	0.986	0.358	0.143	0.387	0.135	0.210	0.0025
	10 ℃	Treatment	<0.0001	<0.0001	0.251	0.004	<0.0001	0.267	<0.0001	0.0002	<0.0001
		Time	<0.0001	<0.0001	0.005	<0.0001	0.0005	<0.0001	<0.0001	<0.0001	<0.0001
		Treatment*Time	<0.0001	<0.0001	0.577	0.482	0.832	0.058	0.110	0.120	0.134
	20 ℃	Treatment	<0.0001	<0.0001	0.666	<0.0001	<0.0001	0.0343	0.0005	0.0094	<0.0001
		Time	<0.0001	<0.0001	0.0036	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
		Treatment*Time	<0.0001	<0.0001	0.924	0.022	0.0156	0.103	0.034	0.174	<0.0001
H2	3 ℃–10 ℃–20 ℃	Treatment * Temperature	<0.0001	<0.0001	0.224	0.001	0.004	0.915	0.043	0.249	<0.0001
		Treatment * Temperature*Time	<0.0001	0.0004	0.897	0.721	0.312	0.626	0.768	0.712	<0.0001
H1-H2	3 ℃–10 ℃–20 ℃	Harvest	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.957	<0.0001
		Harvest * Treatment	0.0025	<0.0001	0.174	0.609	0.0097	0.168	<0.0001	0.0027	<0.0001
		Harvest*Temperature*Treatment	<0.0001	0.492	0.0729	0.494	0.0019	0.532	0.095	0.0049	0.0019

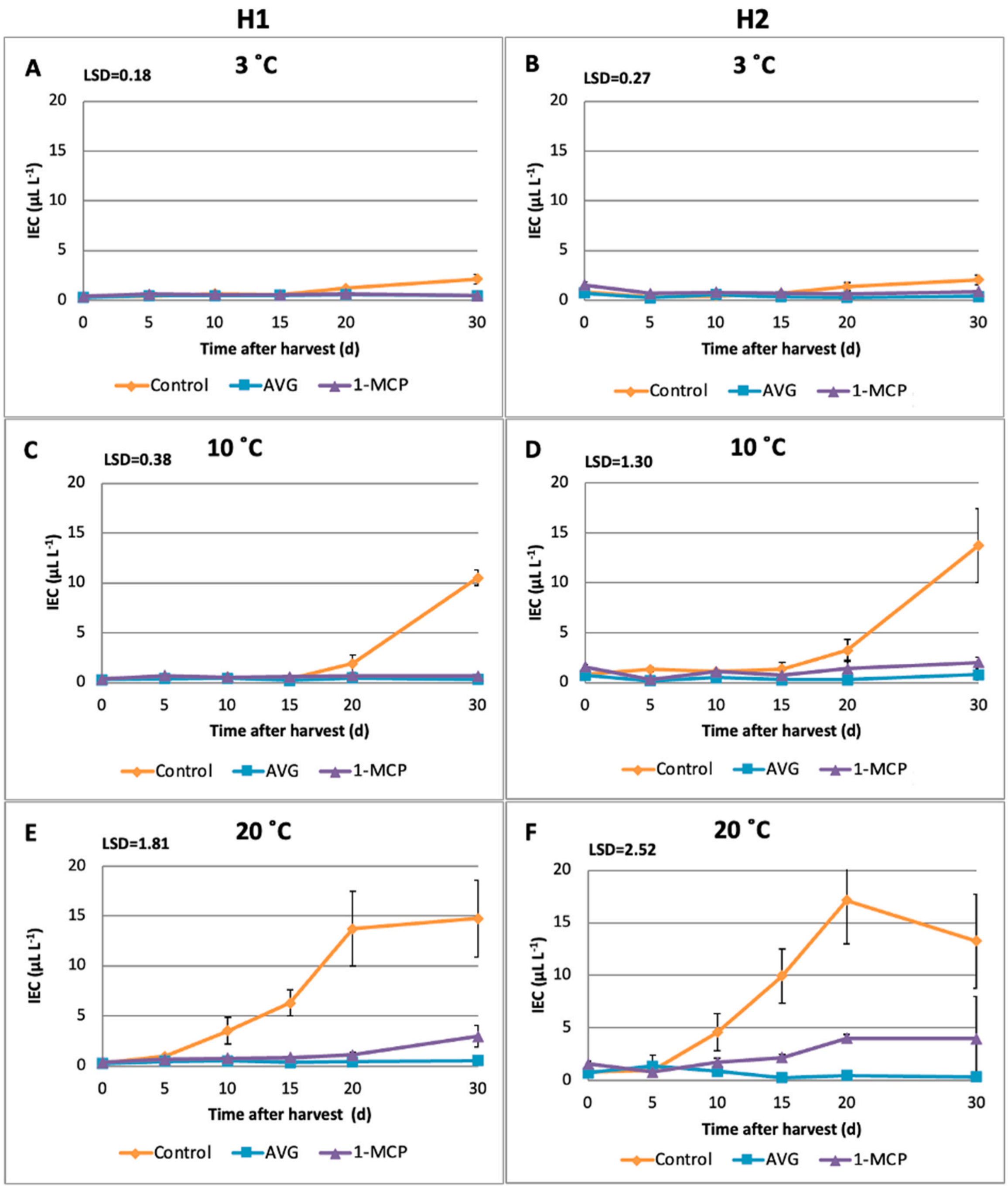

Fig. 2. Internal ethylene concentration (IEC) of untreated, preharvest 1- methylcyclopropene (1-MCP) treated or 1-aminoethoxyvinylglycine (AVG) treated 'NY2' fruit harvested on October 9 (H1) and October 20 (H2), 2020, and kept at 3 °C, 10 °C and 20 °C. Data are presented as means ± standard error (SE) where larger than the symbol. The least significant difference (LSD) is provided at P=0.05.

2. Material and methods

2.1. Fruit material and preharvest PGR treatments

'RubyFrost' (NY2) apples (*Malus domestica* Borkh) were harvested from 5-year-old trees grafted on M9 rootstock, at Cornell University orchard in Ithaca, NY. The study was established as a randomized complete block design with 4 replications of 5 trees. Three trees were used as buffers between treatment plots.

Preharvest 1-MCP (AFxRD-038, 3.8 % a.i.; Harvista™; AgroFresh Inc., Springhouse, PA) was sprayed at a product rate of 6.8 g L^{-1} (870 L ha^{-1}). AVG (ReTainVR; Valent Bio-Science Corporation, Libertyville, IL) was sprayed at a product rate of 0.25 g L^{-1} (410 g ha^{-1}) with 0.1 % v/v Silwet L-77 organosilicon surfactant (Helena Chemical Company, Collierville, TN). Treatments were applied on October 2, 2020 using a CO_2 pressurized backpack sprayer (Bellspray, Opelousas, LA) fitted with a TeeJet 8004VS flat fan nozzle (Spraying Systems, Wheaton, IL). Untreated trees were not sprayed.

2.2. Harvest, storage conditions and sampling

Approximately 90 fruit per treatment replicate were harvested on October 9 (H1) and October 20 (H2). The second harvest was chosen based on the extent of development of watercore in fruit. For each

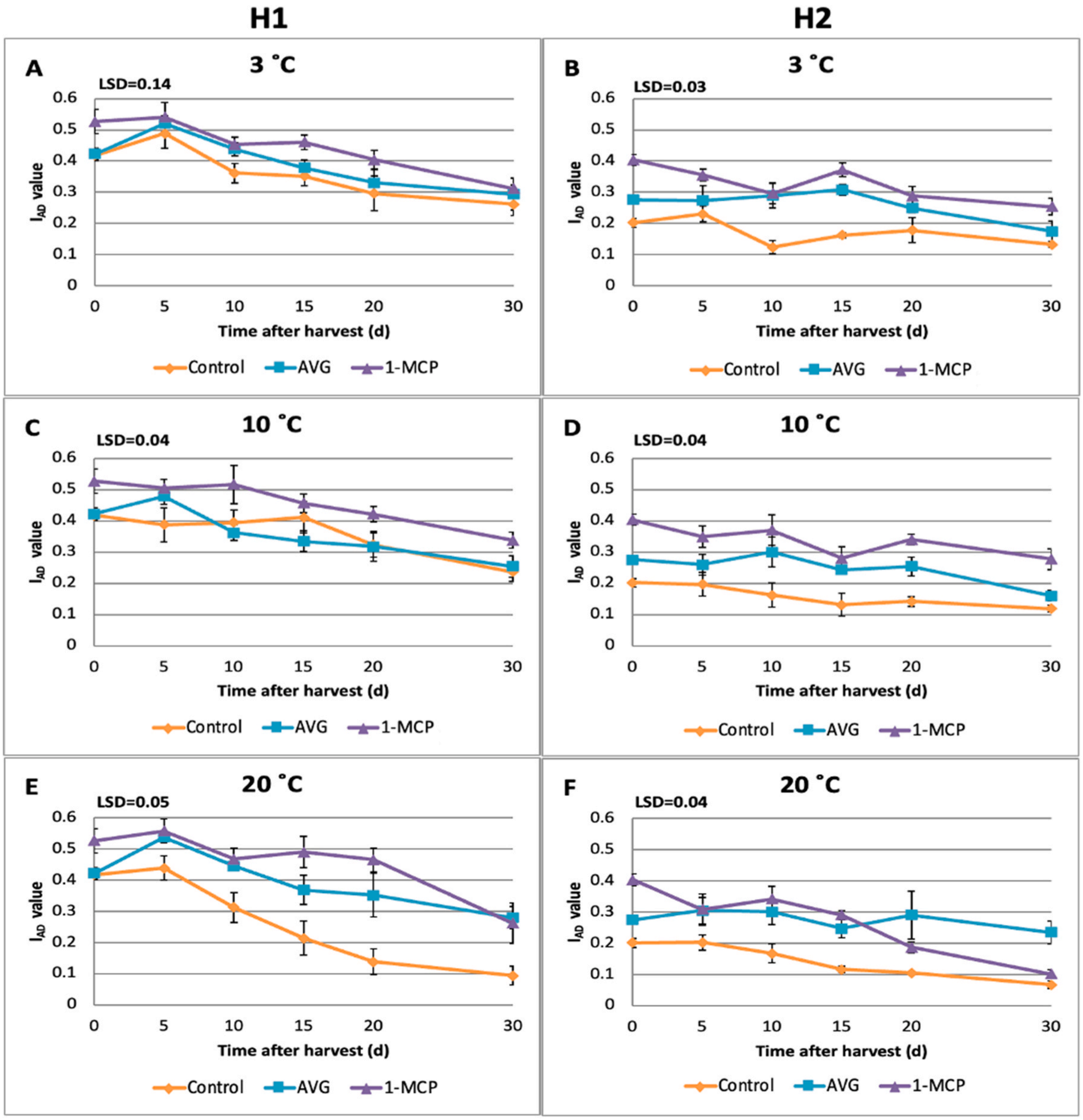

Fig. 3. Difference of absorbance (I_{AD}) value of untreated, preharvest 1- methylcyclopropene (1-MCP) treated or 1-aminoethoxyvinylglycine (AVG) treated 'NY2' fruit harvested a on October 9 (H1) and October 20 (H2), 2020, and kept at 3 °C, 10 °C and 20 °C. Data are presented as means ± standard error (SE) where larger than the symbol. The least significant difference (LSD) is provided at P=0.05.

replicate, ten fruit were used for harvest assessment and the remaining fruit were stored at 3 °C, 10 °C and 20 °C for 30 d. Four replicates of five fruit per treatment were sampled on days 5, 10, 15, 20, and 30. All sampling of each replicate of cold fruit was carried out quickly to avoid warming of the fruit. A further 5 fruit were sampled from each treatment for measurement of ethylene production and respiration rates at 20 °C over 30 d.

2.3. Harvest indices and fruit quality

The internal ethylene concentration (IEC), flesh firmness, soluble solids concentration (SSC), I_{AD}, starch pattern index (SPI) and greasiness incidence was assessed as described by Algul et al. (2021).

2.4. Ethylene production and respiration rates

Ethylene production and respiration rate were measured using weighed individual fruit with a flow board system for 30 d as described by Cai et al. (2023).

2.5. Evaluation of watercore

Watercore incidence and severity were then determined by cutting each fruit transversely at least 4 times. Disorder incidence was determined as a percentage of fruit with disorders. Watercore was rated by giving a score where 0 = no watercore, 1 = slight to 5 = severe.

2.6. Statistical analysis

All statistical analyses was carried out with JMP Pro 17 software (SAS, Cary, NC, USA). Tukey's honest significant difference (HSD) test was used to compare treatments at P=0.05 after analysis of variance (ANOVA).

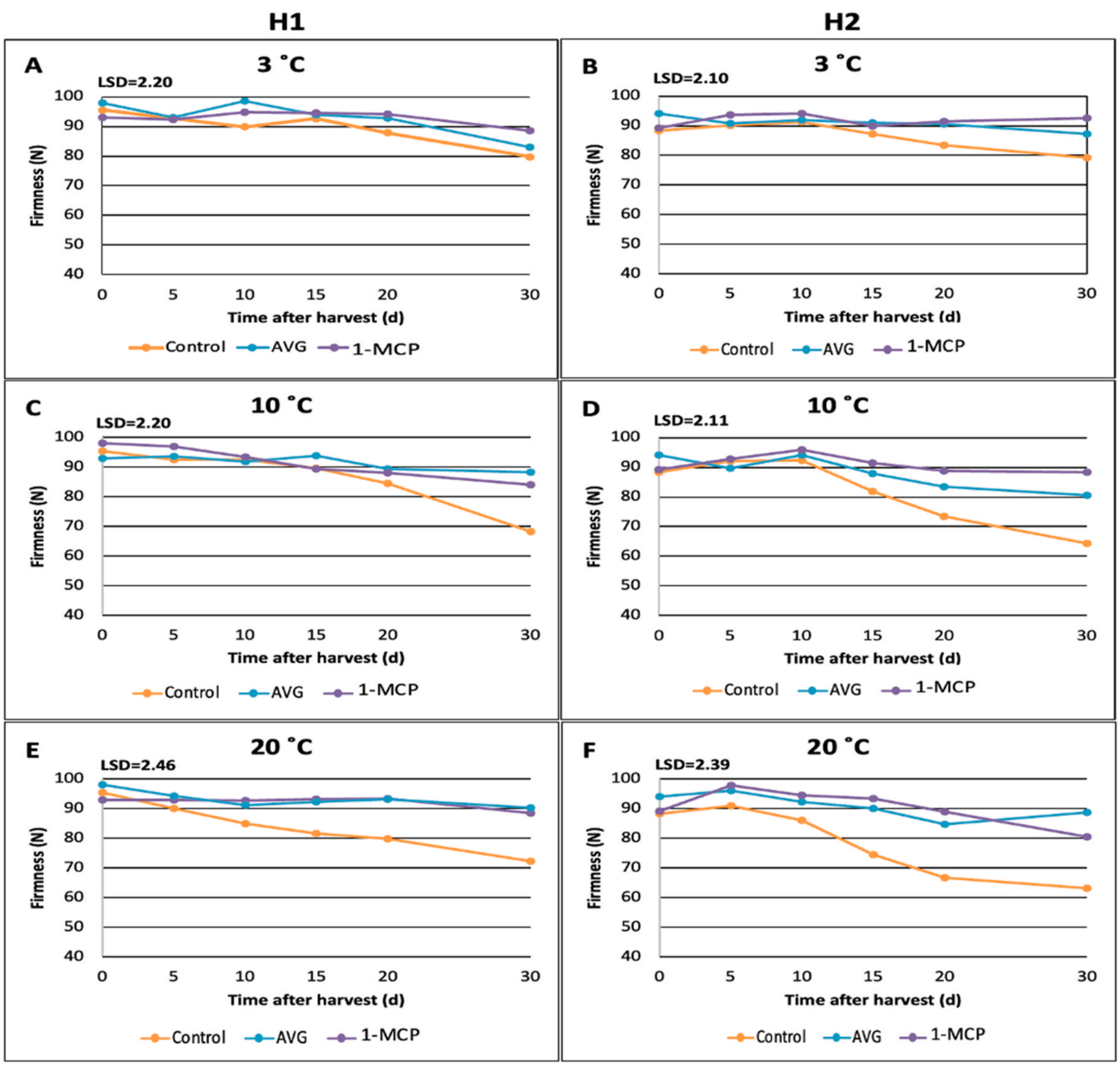

Fig. 4. Flesh firmness of untreated, preharvest 1- methylcyclopropene (1-MCP) treated or 1-aminoethoxyvinylglycine (AVG) treated 'NY2' fruit harvested on October 9 (H1) and October 20 (H2), 2020, and kept at 3 °C, 10 °C and 20 °C. Data are presented as means ± standard error (SE) where larger than the symbol. The least significant difference (LSD) is provided at P=0.05.

3. Results

3.1. Harvest indices

The maturity and quality of fruit at H1 were not affected by treatment, with the exception of higher I_{AD} values (higher chlorophyll concentration) in the 1-MCP treated fruit than in untreated and AVG-treated fruit (Table 1). At H2, fruit treated with 1-MCP also had the highest I_{AD} values, however, AVG treated fruit were the most firm, while the 1-MCP treated fruit were intermediate between untreated and 1-MCP treated fruit.

AVG and 1-MCP treatments did not affect watercore incidence or severity at H1 but incidence was lower in the 1-MCP treated fruit than in the untreated and AVG treated fruit at H2 (Table 1).

3.2. Ethylene production and respiration rates

At H1, the ethylene production of untreated fruit was similar to that of AVG and 1-MCP treated fruit until day 7, after which ethylene production of untreated fruit increased, whereas that of treated fruit remained low. (Fig. 1A). For H2 fruit, however, ethylene production of the untreated fruit was similar to that of H1. While production of the AVG treated fruit remained low, that of the 1-MCP treated fruit increased on day 17 to rates similar to that of the untreated fruit (Fig. 1B). The overall ethylene production of fruit of the untreated, AVG and 1-MCP treated fruit was 0.78, 0.15, 0.18 μL kg^{-1} h^{-1} for H1 and 0.76, 0.11 and 0.53 μL kg^{-1} h^{-1} for H2 respectively.

AVG and 1-MCP treated fruit from H1 had consistently lower respiration rates than untreated fruit (Fig. 1C), but at H2, the respiration rates of 1-MCP treated fruit increased, while those of the AVG treated fruit remained low (Fig. 1D). Overall, the average respiration rates of untreated, AVG and preharvest 1-MCP treated fruit were 0.67, 0.34, 0.24 mg CO_2 kg^{-1} h^{-1} for H1 and 0.72, 0.33 and 0.46 mg CO_2 kg^{-1} h^{-1} for H2, respectively.

3.3. IEC and quality of fruit during storage

ANOVA results are shown in Table 2.

The IECs of fruit kept at 3 °C was much lower than that of fruit kept at 10 °C and 20 °C, and presented with a smaller scale of 0–5 μL L^{-1} (Fig. 2 A,B). At 3 °C, the IECs of fruit treated with AVG and 1-MCP were low at H1 (Table 1) and remained low over the storage time, while that of the untreated fruit increased increased markedly by day 30 (Fig. 2A). The IECs of fruit were initially higher at H2 compared with those at H1, the

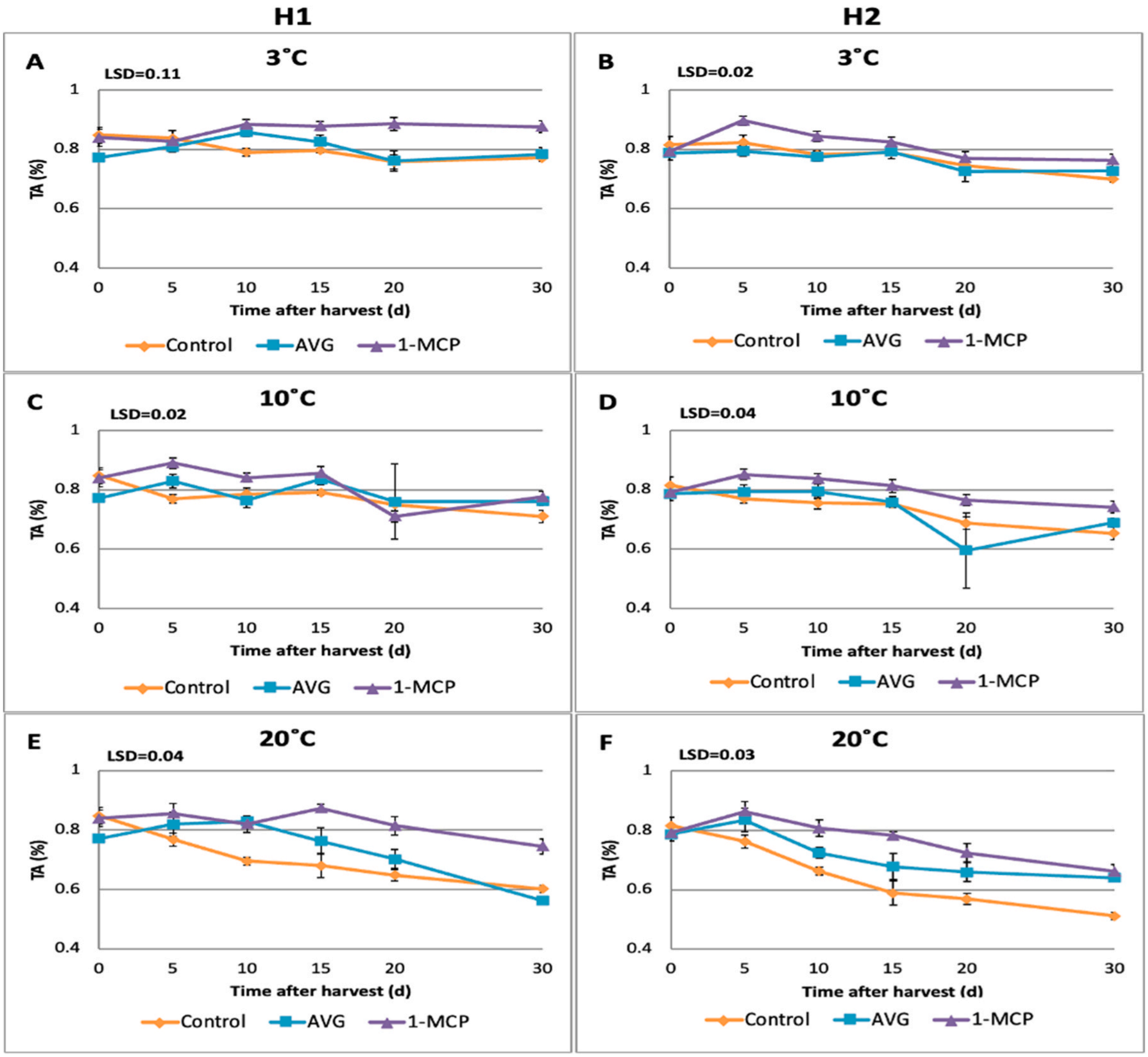

Fig. 5. Titratable acidity (TA) of untreated, preharvest 1- methylcyclopropene (1-MCP) treated or 1-aminoethoxyvinylglycine (AVG) treated 'NY2' fruit harvested on October 9 (H1) and October 20 (H2), 2020, and kept at 3 °C, 10 °C and 20 °C. Data are presented as means ± standard error (SE) where larger than the symbol. The least significant difference (LSD) is provided at P=0.05.

decreases between 0 and 5 d reflecting the effects of cooling (Fig. 2B). At both harvests, the IECs of the untreated fruit increased over time while those of the AVG and 1-MCP fruit remained low.

The effects of treatment were also expressed at 10 °C (Fig. 2 C, D) and 20 °C (Fig. 2 E, F) where overall IECs were higher. The IECs of the untreated fruit increased markedly compared with those of AVG and 1-MCP treated fruit and the effect of AVG on maintaining low IECs was more persistent than that of 1-MCP. The IECs of the untreated fruit increased earlier at 20 °C than at 10 °C. However, there was no effect of harvest date on the timing of the IEC increase, being after day 15 and day 5 for fruit kept at 10 °C and 20 °C, respectively.

I_{AD} values of fruit were lower (less chlorophyll) at H2 than at H1, and they decreased over time and more rapidly at 20 °C than at 3 °C and 10 °C (Fig. 3). Treatment differences were inconsistent for H1 fruit kept at 3 °C and 10 °C (Fig. 3 A, C, E), but at H2 both AVG and 1-MCP maintained higher I_{AD} values regardless of storage temperature (Fig. 3 B, D, F).

The flesh firmness of AVG and 1-MCP treated fruit remained higher than untreated fruit at both harvest times (Fig. 4). Interactions between treatment and time were significant for firmness in both H1 and H2 regardless of storage temperature (Table 2). Treatment differences were detected between untreated and treated fruit earlier in H1 fruit at 20 °C than at 10 °C but there was no effect at 3 °C. Similar, but more pronounced effects of greater softening in untreated than AVG and 1-MCP treated fruit, were found at H2, and a small but significant effect of softening in untreated fruit stored at 3 °C.

While TA was variable across harvests and storage temperatures, 1-MCP treated fruit often had higher values compared with those of untreated and AVG treated fruit over time (Fig. 5). The treatment effects were most pronounced for 1-MCP treated fruit from both H1 and H2 that were stored at 20 °C. The effects of treatment on SSC were variable and not significant except for H2 where contents in AVG and 1-MCP treated fruit were lower than in untreated fruit stored at 3 °C (data not shown). The SPIs were affected by harvest date, but not by AVG or 1-MCP, nor by storage temperature (data not shown).

Greasiness incidence of the fruit was higher at H2 than at H1 at all storage temperatures, except for the unexplained low greasiness on day 30 in H1 fruit kept at 20 °C (Fig. 6). For H2 fruit, incidence was highest at 20 °C and was consistently lower in the AVG and 1-MCP treated fruit than untreated fruit at 20 °C (Fig. 6F).

3.4. Watercore incidence and severity

The observed watercore was the speckled type, where it occurs predominantly in the cortex. Watercore incidence of fruit at H1 was low irrespective of treatment (Table 1) and was little affected by field treatment during storage (Fig. 7A, C, E). Overall, however, watercore

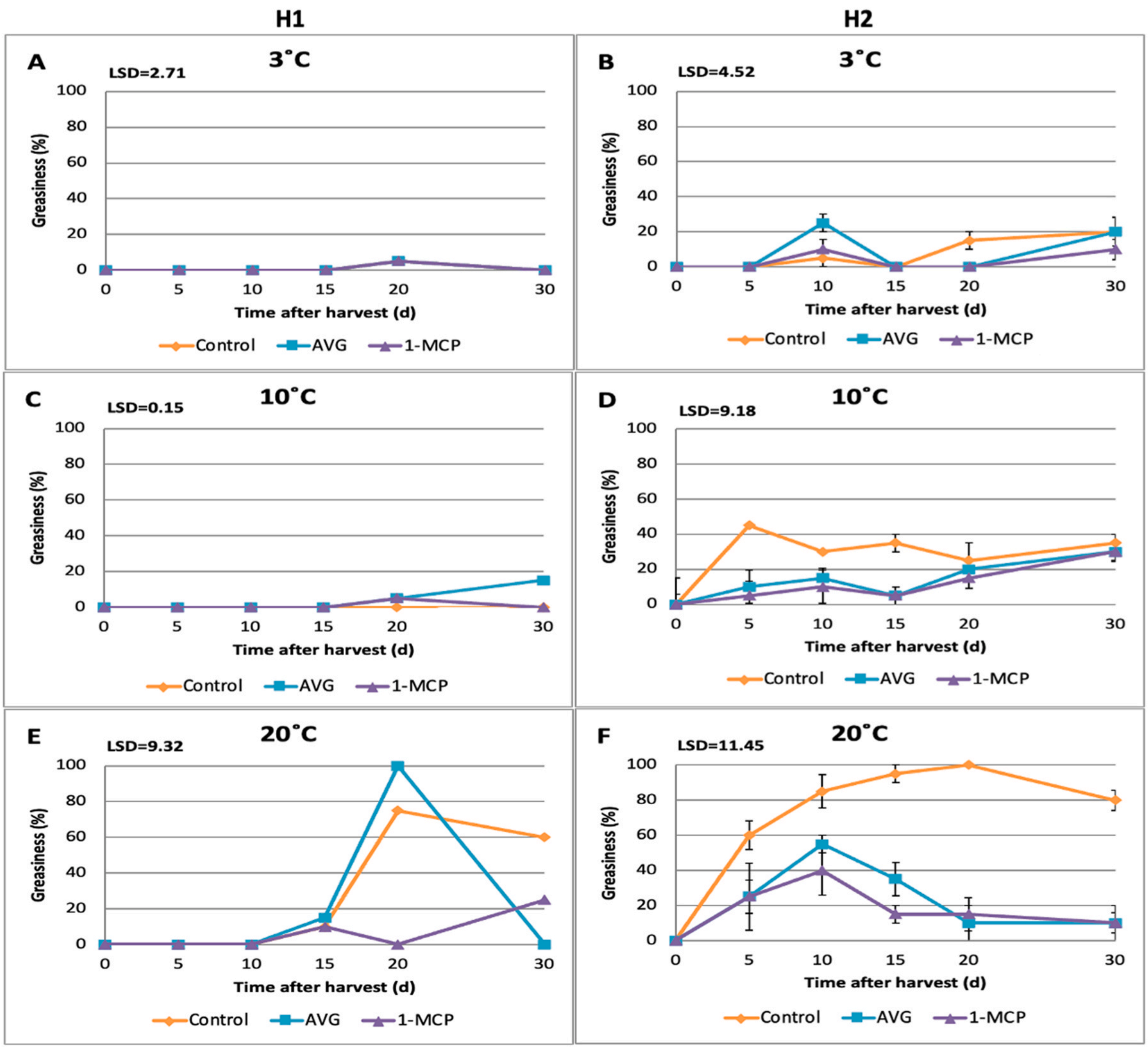

Fig. 6. Greasiness (%) of untreated, preharvest 1- methylcyclopropene (1-MCP) treated or 1-aminoethoxyvinylglycine (AVG) treated ’NY2’ fruit harvested on October 9 (H1) and October 20 (H2), 2020, and kept at 3 °C, 10 °C and 20 °C. Data are presented as means ± standard error (SE) where larger than the symbol. The least significant difference (LSD) is provided at P=0.05.

incidence was maintained higher in fruit stored at 3 °C than at 10 °C and 20 °C.

In contrast, treatment effects were pronounced for fruit from H2 (Fig. 7B, D, F). Watercore incidence of untreated and AVG treated fruit was high, and low in the 1-MCP treated fruit (Table 1). The dissipation of watercore, however, was accelerated by AVG, decreasing between day 5 and day 10 in fruit stored at 3 °C (Fig. 7B), and between day 0 and day 5 in fruit stored at 10 °C (Fig. 7D). The rate of watercore dissipation was rapid in both the untreated and AVG treated fruit that were stored at 20 °C (Fig. 7F). As found for H1 fruit, watercore incidence was higher in fruit stored at 3 °C than at 10 °C or 20 °C (Fig. 7B, D, F). Patterns of change for treatment and storage temperature effects on watercore severity were similar to those found for incidence (data not shown).

4. Discussion

The presence of watercore in harvested fruit has long been a concern of apple industries because of its association with development of watercore breakdown of fruit during storage. The main focus of research on watercore has been on cultivars such as ‘Delicious’ and ‘Fuji’, which develop glassiness in the core areas and vascular tissues in more mature fruit (Bowen and Watkins, 1997; Marlow and Loescher, 1984; Wang et al. 2023). However, a variant of watercore that occurs early as speckled watercore that occurs in the cortex and near the surface, and is associated with hot weather events is recognized (Carne, 1948; Wilkinson and Fidler, 1973; Yamada et al. 2001; Yamada et al. 1994). This variant, which we call stress watercore, has become more noticeable in recent years in several cultivars including ‘Jonagold’ and ‘NY2’ (Algul et al. 2021; Sazo and Cheng, 2017). We recently discovered that preharvest 1-MCP can enhance watercore dissipation from ‘Fuji’ and ‘Jonagold’ apples (Algul et al. 2021; Lee et al. 2019) and have extended this research to investigate the effects of preharvest AVG on the dissipation and at different storage temperatures.

Preharvest 1-MCP and AVG treatments generally slow fruit maturation but the extent of the effects can be influenced by cultivar and timing of application of the specific PGR (Amarante et al. 2002; McArtney et al. 2008; Scolaro et al. 2015; Stover et al. 2003; Yuan and Carbaugh, 2007; Doerflinger et al. 2024; Doerflinger et al. 2019; Al Shoffe et al., 2024). Although research on the effects of the PGRs on traditional watercore is limited, results to date show that disorder development is delayed in some (Amarante et al. 2010; Yuan and Li, 2008) but not all cases (Elfving et al. 2007; Lee et al. 2019; Park et al. 2024). Less is known about the effects of PGRs on stress or speckled watercore and its interaction with fruit maturity. Algul et al. (2021) found that incidence of watercore at harvest was not affected by preharvest 1-MCP treatment. In the current study, stress watercore was affected by harvest date being much higher

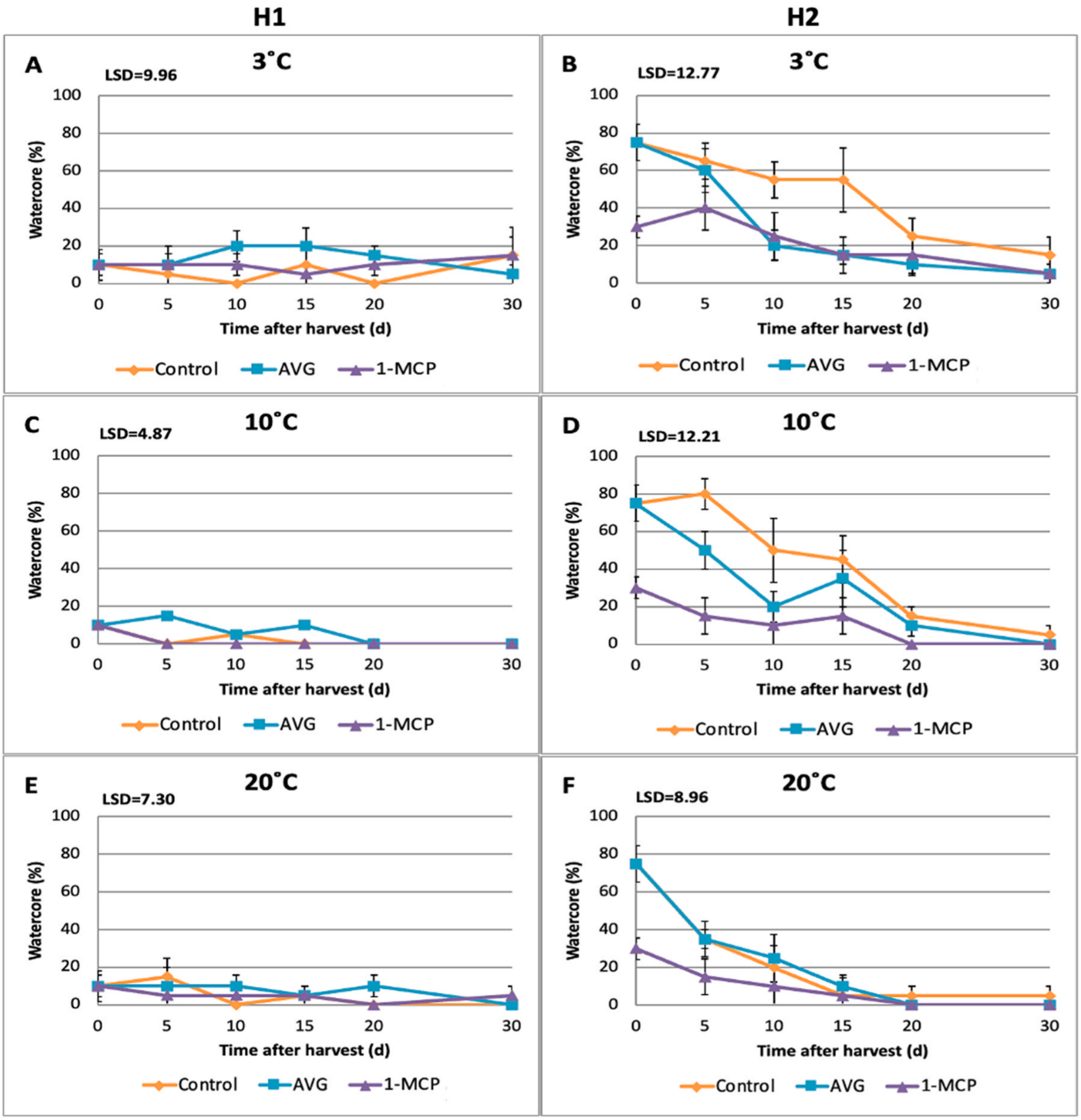

Fig. 7. Watercore incidence (%) of untreated, preharvest 1- methylcyclopropene (1-MCP) treated or 1-aminoethoxyvinylglycine (AVG) treated 'NY2' fruit harvested on October 9 (H1) and October 20 (H2), 2020, and kept at 3 °C, 10 °C and 20 °C Data are presented as means ± standard error (SE) where larger than the symbol. The least significant difference (LSD) is provided at P=0.05.

at H2 than at H1 (Table 1). However, development of watercore incidence was inhibited by 1-MCP but not by preharvest AVG. Surprisingly, few of the at harvest indices were affected by the PGRs; chlorophyll concentrations as indicated by I_{AD} values were higher in 1-MCP treated fruit than in the untreated controls or AVG treated fruit at both harvests, and fruit firmness was highest in AVG treated fruit at H2 (Table 1). The variant of watercore that is associated with extreme heatwaves (Wilkinson and Fidler, 1973), has been called early watercore as it is not associated with advancing fruit maturity in the same way that normal watercore is (Yamada et al. 2005; Yamada et al. 2001).

Despite the limited effect of the PGRs on harvest indices, the treatments had clear effect on ripening of the fruit after harvest as indicated by ethylene production and respiration rates of fruit kept at 20 °C (Fig. 1). In addition, IECs, I_{AD} values, TA, flesh firmness and greasiness indicated that fruit ripening was inhibited by both PGRs, albeit with effects varying by harvest date and by storage temperature (Figs. 2–6). In general, the most pronounced treatment effects were found for fruit kept at 20 °C, similar to that shown for 'Jonagold' treated with preharvest 1-MCP (Algul et al., 2021).

Storage temperatures are critical for watercore dissipation. It is known that keeping fruit with watercore at warm temperatures accelerates the watercore dissipation rates, so delayed establishment of CA/DCA or conditioning temperatures before storage can reduce flesh bowning and breakdown associated with watercore (Neuwald et al., 2010; Argenta et al., 2000). The overall watercore incidence was higher in fruit stored at 3 °C than at 10 °C and 20 °C. The dissipation of watercore occurred more rapidly in both untreated and AVG-treated fruit stored at 20°C compared to those stored at 3 °C and 10 °C. Lee et al. (2019) and Neuwald et al. (2010) reported that watercore dissipation was faster in preharvest 1-MCP treated and untreated 'Fuji' apple fruit at 20 °C and at 10 °C, respectively. In the current research, watercore dissipation was less pronounced for 1-MCP treated fruit because the watercore incidence was much lower at harvest than untreated and AVG treated fruit.

Both types of watercore in apple and pear, traditional or stress-induced, are characterized by higher sorbitol levels resulting from its accumulation in the intercellular space in the fruit core or cortex tissues (Marlow and Loescher, 1984; Gao et al., 2005; Yamada et al., 2006a; Liu et al., 2022). The sorbitol level in the intercellular space is determined by sorbitol import to the fruit from leaves and the ability of the fruit parenchyma cells to take up (remove) the sorbitol from the intercellular space after it is unloaded from the phloem. Sorbitol transporters (SOTs) transport sorbitol along with protons across the plasma membrane into parenchyma cells against a concentration gradient by using a proton gradient in a thermodynamically active process (Gao et al., 2005). The expression level of the gene encoding sorbitol transporter (SOT) 2 decreases throughout fruit development in both 'Greensleeevs' and 'Fuji' (Li et al., 2012; Zhu et al., 2022), and its expression was not detected by RNA blotting in the watercore tissues of 'Winesap' apple (Gao et al., 2005). In 'Akibae' pear, SOT3 expression was lower in the water-soaked outer cortex tissue of watercore fruit close to the peel than in the healthy fruit, and transient overexpression of *SOT3* decreases sorbitol accumulation (Liu et al., 2022). While we did not look at the *SOT2* expression level in this work, higher watercore incidence found at the second harvest date (H2) is in general agreement with its expression pattern during fruit development. As sorbitol continues to be imported into the fruit from leaves, a decrease in the ability of parenchyma cells to take up sorbitol from the intercellular space would be expected to result in sorbitol accumulation in the intercellular space, and high temperarture stress is likely to further decrease this ability. Reduction of watercore incidence by pre-harvest application of 1-MCP, not AVG, suggests that inhibition of ethylene action rather than synthesis maintains the ability of cells to take up sorbitol from the intercellular space. Once fruit are harvested, the import of sorbitol from leaves is stopped so the dissipation of watercore is entirely dependent on the ability of the parenchyma cells to take up (remove) sorbitol from the intercellular space. The faster dissipation of watercore at 20 °C and 10 °C than at 3 °C is consistent with the transport of sorbitol across the plasma membrane being a thermodynamically active process (Gao et al., 2005), i.e. the sorbitol transporter activity is higher at high temperatures. As 1-MCP application reduced watercore at H2, the only relevant comparision for watercore dissipation is between the AVG treatment and the untreated control. The faster dissipation of watercore in the AVG-treated fruit at 3 °C and 10 °C suggests that inhibition of ethylene production somehow enhanced the ability of sorbitol transport and/or membrane integrity and stability that makes the transport more efficient, but this effect is overridden at 20 °C. Regardless of the mechanism, the results presented here together with those on 'Fuji' and 'Jonagold' obtained earlier (Algul et al. 2021; Lee et al. 2019) suggest that the 1-MCP and AVG treatments either reduce watercore at harvest and/or increase the rates of dissipation of both early and late watercore types. These treatments may decrease the risk of development of flesh browning disorders associated with watercore. Futher research is needed to understand how use of the PGRs interacts with delay treatments of fruit such as 'Fuji' that is currently practiced to ensure watercore associated disorders are avoided.

5. Conclusion

Preharvest 1-MCP and AVG treatments had few measurable effects on maturity of 'NY2' apples, being limited to 1-MCP effects on I_{AD} values and AVG effects on firmness of fruit from one of two harvests. However, fruit quality during storage, as judged by factors such as flesh firmness, I_{AD} values and greasiness incidence, was maintained by PGR treatments, especially at 20 °C. Stress watercore incidence at harvest was inhibited by 1-MCP treated fruit but not by preharvest AVG. Watercore dissipation was faster at 10 °C and 20 °C compared to cold storage at 3°C, and was faster in AVG treated fruit than in untreated fruit. The mechanism by which PGRs can affect watercore incidence at harvest and affect the rate of watercore dissipation is not known. Nevertheless, the results suggest that AVG and 1-MCP may offer benefits to growers and storage operators by enhancing dissipation of watercore before long term storage and thereby decrease the potential flesh breakdown development.

CRediT authorship contribution statement

Chris Watkins: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Lailiang Cheng:** Writing – review & editing, Writing – original draft, Investigation. **DoSu Park:** Writing – review & editing, Methodology, Investigation. **Yosef Al Shoffe:** Writing – review & editing, Supervision, Methodology, Investigation. **Burak Algul:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that there are no competing interests.

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Authorship statement

- The work described has not been published previously except in the form of a preprint, an abstract, a published lecture, academic thesis or registered report.
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- If accepted, the article will not be published elsewhere in the same form, in English or in any other language, including electronically, without the written consent of the copyright-holder.

Data Availability

Data will be made available on request.

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