CONDITIONS FOR LOW ETHYLENE CA STORAGE OF APPLES: A REVIEW

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Introduction

In 1977 Liu (9) reviewed the ethylene problem in apple storage but did not conclude whether or not ethylene removal would become a commercially feasible practice. He later reported more promising results of simulated low ethylene CA storage of 'McIntosh' apples (10, 11). Knee and Hatfield (4), Blanpied et al. (3) and Lidster et al. and Lange et al. (7, 6) also reported some benefits of ethylene removal for 'Bramley's Seedling', 'Empire' and 'McIntosh' apples, respectively.

In the last few years, the author and his co-workers have made extensive studies on the responses of 'McIntosh', 'Empire', 'Delicious' and 'Idared' apples to low ethylene CA storage. They also studied the effect of daminozide spray and other factors which influenced the effectiveness of low ethylene CA storage. This paper summarizes the major findings in the conditions for low ethylene CA storage of apples obtained from these studies. Detailed data have been submitted to professional journals for publication (14, 15, 16, 18, 19, 20). It is now much more conclusive than 8 years ago with regard to the feasibility of the commercial application of low ethylene CA storage for apples.

Low ethylene CA storage environment

The currently recommended CA storage environments are 2-3% O_2, 3→5% CO_2, 2.2-3.3°C and 90% relative humidity for 'McIntosh' and 2-3% O_2, 2-3% CO_2, 0°C and 90% relative humidity for 'Empire', 'Delicious' and 'Idared' apples (2). The normal CA storage is generally expected to have several hundred ppm ethylene. It was found in an earlier study (8) that apples stored in simulated CA with 10 and 500 ppm ethylene had little difference. Therefore, in the last few years, the benefit of low ethylene CA storage was studied by comparing apples stored in the above recommended CA environments with <1 and 500 ppm ethylene.

Many storage experiments discussed in this paper were conducted in a flow-through CA system. Apples were stored in 19-liter jars through each of which premixed gases simulating controlled atmospheres flowed at 200 ml min^{-1} (18). This type of simulated CA storage is also called CA storage in this paper. Unless indicated otherwise, the storage environments of "low ethylene CA" and "normal ethylene CA" discussed in this paper refer to the above recommended CA storage environments in accordance with cultivars with <1 and 500 ppm ethylene, respectively. The upper limit of 1 ppm ethylene for low ethylene CA was chosen rather

arbitrarily, because there has been little information available on the effect of very low concentrations (a fraction of 1 ppm to several ppm) of ethylene in CA storage for apples.

The effect of reducing O_2 concentrations in low ethylene CA storage of 'McIntosh' apples was studied for 2 years (16). The results revealed that reducing the O_2 concentration below 3% in low ethylene CA had little effect on the firmness of daminozide-sprayed 'McIntosh' apples. However, lowered O_2 concentration reduced the rate of ethylene production of the apples. The results suggested some benefits of using 2% O_2 + 3% CO_2 instead of 3% O_2 + 3→5% CO_2 in low ethylene CA storage of 'McIntosh' apples.

Benefits of low ethylene CA storage

The most significant benefit of low ethylene CA storage for apples was the effective control of fruit softening. Fruit firmness was evaluated at 2 stages, 1 and 7 days after the apples were transfered from the storage atmosphere to 20°C air at the conclusion of storage experiments. The first evaluation was a measure of firmness losses of the fruit in storage; the second evaluation was a measure of the shelf life of the fruit after storage.

Low ethylene CA storage was very effective in controlling the firmness losses in storage for daminozide-sprayed 'McIntosh' and daminozide-sprayed and unsprayed 'Empire' apples. These apples lost <10% of their original firmness in 7.5 months of low ethylene CA storage (18, 20). These apples immediately after storage had or exceeded the most desirable firmness for 'McIntosh' found by Liu and King (17). Similar apples lost 20-33% of their original firmness in normal ethylene CA. However, low ethylene CA storage only had a marginal benefit in reducing firmness losses in storage of 'McIntosh' apples which were not sprayed with daminozide (8) and had no benefit in this regard for 'Delicious' and 'Idared' apples with or without daminozide spray (15). 'McIntosh', 'Delicious' and 'Idared' apples which were not sprayed with daminozide softened significantly in both low and normal ethylene CA. Daminozide-sprayed 'Delicious' and 'Idared' apples remained very firm for at least 7 months in both low and normal ethylene CA (15). Low ethylene CA kept daminozide-sprayed 'McIntosh', 'Empire', 'Delicious' and 'Idared' apples and unsprayed 'Empire' apples very firm (<10% losses of their original firmness) for at least 7 months. Normal ethylene CA kept daminzoide-sprayed 'Delicious' and 'Idared' apples very firm, but did not keep daminzoide-sprayed 'McIntosh' and 'Empire' or unsprayed 'Empire' apples equally firm (15, 18, 20).

Low ethylene CA storage significantly reduced the firmness losses of daminozide-sprayed 'Idared' apples during the 7-day holding period at 20°C after storage (15). This is equivalent to extending the shelf life of the apples. Low ethylene CA storage had no such benefit on other cultivars of apples, however. In fact, low ethylene CA 'McIntosh' apples softened faster than normal CA apples during the 7-day holding period at 20°C (18). There was a tendency for 'McIntosh' apples that the firmer the apples immediately after storage, the faster the firmness losses during the post-storage holding period (18). However, low ethylene CA

'McIntosh' apples were so much firmer than normal CA apples immediately after storage that the former was still firmer than the latter even after 7 days of holding at 20°C (18).

Low ethylene CA storage effectively controlled senescent breakdown of daminozide-sprayed 'McIntosh' apples (11) and significantly reduced the incidence of storage scald of 'Delicious' apples which were not sprayed with daminozide (15). Since these two storage disorders were not severe in other cultivars of apples in the experiments, no such benefits of low ethylene CA storage was found for other cultivars.

Low ethylene CA storage slightly reduced the acidity losses of 'McIntosh', 'Empire' and 'Delicious' apples (18, 20, 15). However, the differences were often statistically insignificant due to large variations among fruit samples and among trees. Low ethylene CA had no effect on the soluble solids content of 'McIntosh', 'Empire', 'Delicious' and 'Idared' apples.

The benefits of low ethylene CA storage for the four cultivars of apples with or without daminozide spray are summarized in Table 1.

Table 1. Benefits of low ethylene CA storage of apples.

Cultivar	Daminozide spray	Benefit				
		Firmness[1]	Shelf life	Acidity	Senescent breakdown	Storage scald
'McIntosh'	No	*[2]	--	*	*	--
	Yes	***	--	*	***	--
'Empire'	No	***	--	*	--	--
	Yes	***	--	*	--	--
'Delicious'	No	--	--	*	--	**
	Yes	--	--	*	--	--
'Idared'	No	--	--	--	--	--
	Yes	--	**	--	--	--

[1] Firmness measured 1 day after storage.
[2] -- no benefit, * marginal benefit, ** significant benefit, *** very significant benefit.

Factors influencing the effectiveness of low ethylene CA storage

Liu (13) has reported 3 factors which influenced the effectiveness of low ethylene CA storage of apples. The 3 factors were cultivar, daminozide spray and harvest date.

Cultivar differences in response to low ethylene CA have been discussed above. 'McIntosh' and 'Empire' had very dramatic responses, but 'Delicious' and 'Idared' only had minor responses.

The influence of daminozide spray (1000 ppm daminozide tree spray in mid-July) on the effectiveness of low ethylene CA storage differed from one cultivar to another. Daminozide spray was indispensable for a successful low ethylene CA storage of 'McIntosh' apples. Without a daminozide spray, low ethylene CA storage only had a marginal benefit for 'McIntosh'; with daminzoide spray, low ethylene CA storage had a great benefit (11). Daminozide spray was not a necessary condition for a successful low ethylene CA storage for 'Empire' apples (20). However, daminozide spray extended the optimum harvest date of 'Empire' apples for low ethylene CA storage for at least one week (20). Daminozide spray improved the keeping quality of 'Delicious' apples in normal and low ethylene CA so much that it "musked" the effect (if any) of low ethylene CA storage (15). Daminozide spray also greatly improved the keeping quality of 'Idared' apples (15). Daminozide-sprayed 'Idared' apples were equally firm after low and normal ethylene CA storage, but those stored in low ethylene CA had better shelf life (15). Daminozide spray dramatically suppressed the rates of ethylene production for all 4 cultivars of apples (15, 18, 20).

Harvest date is a crucial factor influencing the keeping quality of apples in probably any kind of storage environment. For 'McIntosh' apples which were not sprayed with daminozide, only those which were harvested at the preclimacteric stage had a response to low ethylene CA storage (8). For daminozide-sprayed 'McIntosh' apples, those which were harvested within 10 days after the onset of the climacteric rise in ethylene production of comparable apples which were not sprayed with daminozide had the best keeping quality in low ethylene CA (18). The last day of each year's optimum harvest dates evaluated by this method was 0 to 6 days earlier than Blanpied's (1) optimum harvest date in 4 consecutive years (1981-84) of observations. For 'Empire' apples which were not sprayed with daminozide, those which were harvested before the onset of the climacteric rise in ethylene production had very good keeping quality in low ethylene CA in 2 years of observations (20). Daminozide-sprayed 'Empire' apples which were harvested one week later than unsprayed apples also had similarly good keeping quality in low ethylene CA (20). The internal ethylene concentration was used as an index in evaluating optimum harvest dates for these two cultivars of apples in these experiments (18, 20). 'Delicious' and 'Idared' apples for low ethylene CA storage experiments (15) were harvested at the optimum harvest dates suggested by Blanpied (1) or slightly earlier. Whether or not the optimum harvest dates for these two cultivars of apples for low ethylene CA storage coincide with Blanpied's (1) suggestions have not been thoroughly studied.

The fourth factor which also influenced the effectiveness of low ethylene CA storage of apples was the rapidity of cooling and establishment of CA environment. For daminozide-sprayed 'McIntosh' apples, delayed cooling or delayed CA for 1 to 4 days had little adverse effect on the keeping quality of the apples in low ethylene CA (14). Delayed cooling for 5 days or delayed CA for 5 to 7 days caused slight decreases in fruit firmness and acidity and caused slight increases in ethylene production of the apples. Delayed cooling for 7 to 11 days or delayed CA for 9 to 11 days caused significant decreases in firmness and acidity and significant increases in ethylene production (14). Therefore, "rapid

CA" as described by Lau (5) is probably the minimum requirement for the speed of establishing CA environment for a successful low ethylene CA storage for 'McIntosh' apples. The requirements in this regard for other cultivars have not been studied.

Rates of ethylene production of apples

The rates of ethylene production of apples in low ethylene CA storage were affected by cultivars (15, 18, 20), daminozide spray (15, 18), harvest dates (18, 20), rapidity in the establishment of CA environments (14), the atmosphere composition in CA (16) and duration of storage (15, 18, 20).

'McIntosh' apples had the highest and 'Empire' apples had the lowest rate of ethylene production among the 4 cultivars studied. The rates of ethylene production of 'Delicious' and 'Idared' apples were roughly equal (15) and were in between the rates of 'McIntosh' and 'Empire'.

The rates of ethylene production of 'McIntosh' apples which were not sprayed with daminozide exceeded 2 $\mu l\ kg^{-1}\ hr^{-1}$ within 2 months after storage had begun (13). These apples continued to produce ethylene at very high rates ($>2\ \mu l\ kg^{-1}\ hr^{-1}$) for the rest of the storage periods. Daminozide-sprayed 'McIntosh' apples which were harvested at the optimum harvest dates, cooled within 2 days and exposed to low ethylene CA within 7 days after harvest had very low rates ($<0.1\ \mu l\ kg^{-1}\ hr^{-1}$) of ethylene production in the first 4 months of storage (14, 18). The rates gradually increased thereafter, but remained at $<0.5\ \mu l\ kg^{-1}\ hr^{-1}$ from the fifth month to the seventh month and $<3\ \mu l\ kg^{-1}\ hr^{-1}$ from the eighth month to the ninth month in low ethylene CA (14, 18). The ethylene production peaks of daminozide-sprayed 'Delicious' and 'Idared' apples were $<0.4\ \mu l\ kg^{-1}\ hr^{-1}$ and the peaks of unsprayed 'Delicious' and 'Idared' apples were slightly below $2\ \mu l\ kg^{-1}\ hr^{-1}$ in 7 months of low ethylene CA storage in 2 years of observations (15). Daminozide-sprayed as well as unsprayed 'Empire' apples which were harvested before the onset of the climacteric rise in ethylene production had extremely low rates ($<0.01\ \mu l\ kg^{-1}\ hr^{-1}$) of ethylene production throughout the 7.5 months of low ethylene CA storage period (20). Although non-daminozide 'Empire' apples which were harvested several days after the onset of the climacteric rise in ethylene production had significantly higher rates of ethylene production than the apples harvested one week earlier, the rates of the former were still $<0.05\ \mu l\ kg^{-1}\ hr^{-1}$ during 7.5 months of low ethylene CA storage (20).

For 'McIntosh', those apples which had very low rates of ethylene production in storage did not soften much in storage and those which had high rates of ethylene production softened significantly in storage (13). A similar relationship was not found for 'Empire' apples, however. Some 'Empire' apples which had very low rates of ethylene production softened significantly in storage (20). Because 'Delicious' and 'Idared' apples stored in low and normal ethylene CA were equally firm immediately after storage (15), a relationship between the rate of ethylene production and fruit firmness could not be established.

Feasibility of the commercial application of low ethylene CA storage for apples

The commercial application of low ethylene CA storage for 'Empire' apples is feasible. Low ethylene CA storage has very significant benefits for 'Empire' apples (3, 20). 'Empire' apples produce very little ethylene (20) which needs to be removed from low ethylene CA storage. Daminozide spray has little benefit for 'Empire' apples except that the spray enables growers to delay harvest for at least one week.

The commercial application of low ethylene CA storage for daminozide-sprayed 'McIntosh' apples is feasible. Significant benefits of low ethylene CA storage have been demonstrated in simulated low ethylene CA as well as in semi-commercial low ethylene CA storage (12, 18, 19). If the apples are harvested at the optimum maturity and stored in low ethylene CA rapidly, the rate of ethylene production can be kept fairly low and therefore, the cost of ethylene scrubbing will not be prohibitive. However, commercial application of low ethylene CA storage for 'McIntosh' apples which are not sprayed with daminozide is not feasible at this stage. The benefits are marginal at most and the rates of ethylene production of the apples are so high that ethylene scrubbing in storage will be very costly.

The commercial application of low ethylene CA storage for daminozide-sprayed 'Idared' apples is feasible. Although daminozide-sprayed 'Idared' apples may be equally firm after low and normal ethylene CA storage, the low ethylene CA apples have longer shelf life (15). The rates of ethylene production of these apples are low (15). However, commercial application of low ethylene CA storage for 'Idared' apples which are not sprayed with daminozide is not feasible at this stage. No significant benefit has been found in using low ethylene CA stroage for this type of apples.

The commercial application of low ethylene CA storage for 'Delicious' apples is not feasible at this stage. The only benefit of low ethylene CA storage for 'Delicious' apples which are not sprayed with daminozide is reducing the incidence of storage scald (15). However, chemical control such as diphenylamine or ethoxyquin will be much less costly than low ethylene CA storage. Daminozide-sprayed 'Delicious' apples can be kept so well in normal ethylene CA that low ethylene CA storage for this type of apples is unnecessary.

It is now possible to keep 'McIntosh', 'Empire', 'Delicious' and 'Idared' apples very firm (<10% losses of their pre-storage firmness) for at least 7 months, yet these apples will still have reasonably good shelf life. Low ethylene CA storage can keep 'Empire' apples firm and "fresh". Daminozide spray plus normal ethylene CA storage can keep 'Delicious' apples firm and "fresh". Daminozide spray plus low ethylene CA storage can keep 'McIntosh', 'Empire', 'Idared' and 'Delicious' apples firm and "fresh".

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