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Effects of acetaldehyde on fruit quality and target pest mortality for harvested strawberries

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Abstract

Strawberry fruit and western flower thrips were exposed to 1, 2, 3, or 4% acetaldehyde (Aa) for 2 h in air or in 20 kPa CO_2. Following treatment, fruit were stored at 0 or 20 °C for 4 or 2 days, respectively. Aa treatment did not significantly impact fruit firmness, color, or soluble solids content; however, calyx damage increased with increasing concentration of Aa. Strawberry fruit tolerated exposure to 1 or 2% Aa with little or no damage to the fruit calyx. Fruit Aa, ethanol, and ethyl acetate concentrations increased initially, but decreased over time; the decrease being greater in fruit stored at 20 °C as compared with 0 °C. Methanol and acetone levels were lower in treated than untreated fruit. Western flower thrips were not completely controlled by any of the treatments, but >95% mortality was achieved by a 2 h exposure to 3 or 4% Aa. The presence of 20 kPa CO_2 enhanced mortality of western flower thrips at lower concentrations of Aa. Strawberry fruit, western flower thrips and two-spotted spider mites were also exposed to multiple applications of Aa over time. Strawberry fruit exposed to low concentrations of Aa in repeated doses showed higher tolerance than fruit exposed to the same dose as a single exposure. While repeated exposure to 1 or 2% Aa resulted in greater pest mortality than a single exposure to 1 or 2% Aa, mortality was significantly lower with repeated applications of low doses as compared with a single application of the accumulated dose (1, 1, 1 Aa vs. 3% Aa). None of the treatments resulted in complete control of either target pest.

Keywords: Arthropod; Carbon dioxide; Disinfestation; *Fragaria* X *ananassa* Duch; *Frankliniella occidentalis*; Postharvest; Quarantine; *Tetranychus urticae*; Two-spotted spider mite; Western flower thrips

1. Introduction

The strawberry industry needs alternative methods to break the reliance on methyl bromide for postharvest insect and mite disinfestation for some export shipments. Methyl bromide is scheduled to be phased out for soil fumigation in 2005, but currently has an exemption for postharvest quarantine uses. Methyl bromide is expected to become both more expensive and more restricted in use due to environmental and worker safety issues. Alternatives to methyl bromide for postharvest insect and mite control on strawberry fruit are limited because of the very perishable nature of the

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commodity. Treatment alternatives must be of short duration due to the limited postharvest life of the fruit. Cold treatments are ineffective against western flower thrips [*Frankliniella occidentalis* (Pergande)] and spider mites, the two major pests of concern (Mitcham et al., 1997). Heat treatments have been largely eliminated because of the potential for damage to the strawberry fruit. Irradiation shows promise as an alternative, but would be costly and may not be accepted by importing countries.

Acetaldehyde (Aa) is a naturally occurring metabolite that is present in small quantities (Fidler, 1968). Aa plays a role in both the flavor and odor of ripening fruit. During respiratory metabolism, the end result of glycolosis is pyruvate. Decarboxylation produces Aa which can be reduced to ethanol (Purvis, 1997). The effect of postharvest applications of Aa on fruit quality and storage have been investigated for a number of commodities. In some fruit, such as tomato, avocado (Pesis and Marinansky, 1993; Pesis et al., 1998), and mango (Burdon et al., 1996), postharvest application of Aa resulted in a delay in the ripening process. In contrast, postharvest Aa application was reported to stimulate ripening in pears, and kiwifruit (Mencarelli et al., 1991), and induced a respiratory upsurge in blueberries, strawberries, and oranges (Janes et al., 1978; Pesis and Avissar, 1989). Postharvest application of Aa has also been shown to have an effect on quality parameters such as flavor, aroma, acidity, and color. Odor and flavor were enhanced in 'Jonagored' and 'Granny Smith' apples exposed to low concentrations of Aa (40 mg Aa per 100 g apples for 24h). Higher concentrations of Aa (710mg Aa per 100 g apples) resulted in skin browning and inhibition of ethylene production (Vidrih et al., 1999). Flavor was also enhanced in strawberries treated with 500 μl/l Aa for 1 h, however, increased concentrations or longer exposure to Aa resulted in off flavor (Pesis and Avissar, 1990). When table grapes with low initial sugar concentrations and high acidity were exposed to Aa (0.2–0.9%) vapors for 24 h, they had an increase in total soluble solids and decreased acidity (Pesis and Frenkel, 1989). However, this response to Aa vapor was limited to fruit picked early in the season with low initial total soluble solids and high acidity. In addition, some off flavors were detected in treated grapes. Similarly, when 'Shamouti' oranges were exposed to Aa vapor, they exhibited a short term decrease in acidity. Exposure to Aa vapor also resulted in degreening of the fruit peel (Pesis and Avissar, 1989).

Aa has also been demonstrated to have fungicidal and insecticidal properties. It has been tested against decay microorganisms commonly found on strawberry fruit such as *Botrytis cinerea* and *Rhizopus stolonifer* (Avissar and Pesis, 1991). In addition, researchers have studied the effects of Aa on *Erwinia carotovora*, *Pseudomonas fluorescens*, *Monilinia fructicola* (Aharoni and Stadelbacher, 1973), *Penicilium* spp. (Stadelbacher and Prasad, 1974) and various species of yeast (Barkai-Golan and Aharoni, 1976) commonly found on fruits and vegetables.

Aa has been tested against a number of target arthropod pests. Harvested head lettuce infested with green peach aphid [*Myzus persicae* (Sulzer)] was fumigated with Aa in air (Aharoni et al., 1979a), Aa under reduced pressures (Stewart et al., 1980), and Aa in high CO_2 or low O_2 atmospheres (Hartsell et al., 1979). All treatments resulted in significant mortality of the target pest, but with mixed results for phytotoxicity. Complete mortality of California red scale [*Aonidiella aurantii* (Maskell)], on harvested grapefruit, was achieved with Aa fumigation without detectable off-flavor or phytotoxicity (Aharoni et al., 1987).

This study explores the possibility of using Aa for postharvest disinfestation of harvested strawberries. Aa fumigation in air or 20 kPa CO_2, applied in both single and repeated exposures, was tested against two of the main pests on harvested strawberry fruit, western flower thrips [*F. occidentalis* (Pergande)] and two-spotted spider mite (*Tetranychus urticae* Koch), and for effects on strawberry fruit quality.

2. Materials and methods

2.1. Fruit material

Strawberry fruit (*Fragaria* X *ananassa* Duch. cv. 'Seascape') obtained from a local distributor

were sorted for calyx and berry condition and for uniform color. Fruit had been harvested and shipped from Watsonville, California, the previous day. Strawberry fruit used in repeated exposure experiments (cv. 'Diamante') were shipped to Davis, Calif. from Baja Calif., and sorted as previously described.

2.2. Target pests

Western flower thrips were reared in the laboratory on fresh green beans at a constant temperature of 24 °C (12 h Light:12 h Dark). For exposure to Aa, a section of green bean as a food source was placed in a 59 ml plastic portion cup (Solo Cup Company, Urbana, IL) with a vented lid made of silkscreen and 100–200 second instar thrips were added. Two-spotted spider mites were reared in the laboratory on cotton seedlings under continuous light at 24 °C. For exposure to Aa, mite-infested cotton cotyledons with 50–200 mites of mixed stages were placed in portion cups with vented lids. Portion cups containing thrips or mites were placed inside the treatment jars (two cups per jar) along with strawberries, and treated as described below.

2.3. Acetaldehyde treatment of fruit and pests

2.3.1. Acetaldehyde treatment in air or in 20 kPa CO_2

Strawberry fruit (135 berries; 4.9 kg) and western flower thrips were exposed to 0, 1, 2, 3, or 4% Aa in air or Aa in 20 kPa CO_2 for 2 h at 24 °C in 19 l glass jars. A total of 30 jars (five treatments × two atmospheres × three replications), sealed with rubber stoppers, were used for the experiment. For treatments requiring 20 kPa CO_2, jars containing strawberry fruit and thrips were flushed with 20 kPa CO_2 in air, then sealed. Reagent grade, 2 °C liquid Aa (Fisher Scientific, Pittsburgh, Penn., purity 99.5%) was injected through a rubber septum covering an inlet port in the rubber stopper onto filter paper affixed to the underside of the stopper. A separate outlet port was used to sample the headspace in the treatment jars through a 3 mm diameter plastic tube protruding approximately half-way into the jar. Samples were obtained using a gas-tight, 1 ml syringe. Aa concentration was measured using a gas chromatograph (GC-9AM; Shimadzu Scientific Instruments, Columbia, Maryland) fitted with a 60/80 carbopack column with 5% carbowax (Supelco, Bellefonte, Penn.), and a flame ionization detector at 250 °C, injection port temperature of 250 °C and an oven temperature of 85 °C with nitrogen as the carrier gas. Airspace samples were quantified by comparison to a known Aa gas standard of 0.25% (Scott Specialty Gases, Plumstead, Penn.).

After treatment, the jar was vented and strawberry fruit and thrips were held in ambient air (24 °C) for 1 h. Western flower thrips were then held at 24 °C until evaluation for mortality 48 h post exposure. An initial sample of fruit was evaluated for quality 1 h after removal from treatment. Remaining fruit were transferred into unsealed 9.5 l jars. One half of the fruit were held at 20 °C (RH 60%) for 2 days, and the remaining were held at 0 °C (RH 95%) for 4 days, and proportionate subsamples of fruit were evaluated for quality every 24 h.

2.3.2. Multiple applications of acetaldehyde

In an effort to reduce phytotoxicity while maintaining pest control, strawberries and pests were exposed to multiple applications of lower concentrations of Aa. Strawberry fruit, western flower thrips and two-spotted spider mites were placed in 3.8 l glass jars (three replications per treatment; 20 fruit (550 g) per treatment and replication). Fruit and target pests were exposed to Aa as described previously. Berries, thrips and mites were fumigated for 1 h at 24 °C with 1% Aa three times (1–1–1%), or four times (1–1–1–1%), or two times with 2% Aa (2–2%) with 1 h in ambient air between the repeated exposures. In addition, fruit and pests were fumigated with 1, 2, 3, or 4% Aa for 1 h for comparison. Following the final Aa treatment, fruit and target pests were held in ambient air (24 °C) for 1 h, after which time strawberry fruit were placed at 0 °C (RH 57%) for 5 days. Target pests were held at 24 °C for 48 h, then evaluated for mortality.

2.4. Fruit quality

2.4.1. Measurement of firmness, color, calyx and berry damage and sensory quality

Three replicates of 15 fruit from each treatment were evaluated for firmness, soluble solid content, internal and external color, calyx damage, and berry damage 1 h after Aa exposure. Measurements of firmness and external color were made on opposite, paired sides of the fruit. Firmness was measured as penetration force (N) using a penetrometer (Ametek, Largo, Fla.) fitted with a round, 3 mm tip and mounted in a drill-press stand. Color was measured with the Minolta Chromameter (model CR-300; Ramsey, New Jersey) in CIE lab* mode under CIE Standard Illuminant C. Changes in hue angle (h°) were calculated as $h^\circ = \arctan\ b^*/a^*$ (°) (McGuire, 1992). Internal color was measured by slicing the berry longitudinally and taking two readings per side adjacent to the central cavity. Calyx and berry damage were evaluated subjectively and scored as 1 (no damage), 2 (slight damage, $<20\%$ affected), 3 (moderate damage, 20–60% affected), or 4 (severe damage, $>60\%$ affected). Calyx damage included vascular tissue darkening, discoloration, and drying. Berry damage included bruising, decay, and loss of fruit integrity (weakened and easily ruptured skin surface).

An informal duo–trio test was conducted with untrained taste test panelists. Untrained taste test panelists were asked to compare two coded strawberry samples with a marked control sample and indicate which coded sample tasted different than the marked control. Taste tests were conducted using strawberry fruit exposed to 1% Aa in air or in 20% CO_2 for 1 or 1.5 h and untreated fruit.

2.4.2. Measurement of soluble solids and volatile compounds

Five composite samples of three fruit each per replication were juiced together. Juice soluble solids content (%) was measured using a temperature-compensating digital refractometer (Abbe model 10450; American Optical, Buffalo, New York). Fermentative volatile content was determined as described by Ke et al. (1991). Five milliliters of juice were placed in a glass tube (16×125 mm), sealed with a rubber septum and stored at -22 °C. For subsequent analysis, samples were thawed in a 24 °C water bath for 5 min, then incubated for 1 h at 65 °C. A 1 ml headspace sample was analyzed for Aa, methanol, acetone, ethanol, and ethyl acetate by gas chromatography, as described previously for Aa, and peaks quantified by comparison with known standards.

Data were analyzed using Statistical Analysis System (SAS) software and means were separated by LSD (SAS Institute, 1989).

3. Results

3.1. Aa treatment in air or in 20 kPa CO_2

3.1.1. Firmness, color, soluble solids, calyx, berry damage, and sensory quality

Firmness, color, soluble solids and berry damage were not significantly different between treated and untreated fruit at any evaluation (Table 1). However, calyx damage was higher in fruit treated with 3 or 4% Aa (Table 1, Fig. 1). Fruit treated with Aa in 20 kPa CO_2, had slightly less calyx damage immediately after treatment than fruit treated with Aa in air (Table 1, Fig. 1). This effect was most pronounced for the 3 and 4% treatments, but did not persist beyond the initial evaluation. Taste panelists were unable to detect significant differences between treated and untreated fruit (data not shown).

3.1.2. Volatile compounds

Immediately after treatment, treated strawberry fruit had increased concentrations of Aa and ethanol compared with that of the untreated control fruit (Table 2). However, after 2 days at 20 °C following treatment, treated fruit had similar concentrations of Aa and ethanol to the control fruit (Fig. 2). Aa and ethanol concentrations in fruit held at 0 °C after treatment decreased over time, but remained higher than in the control fruit (Fig. 3). Strawberry fruit treated with Aa in 20 kPa CO_2 exhibited higher ethanol and Aa concentrations than fruit exposed to Aa in air (Table 2). This

Table 1
Effects of Aa concentration, treatment atmosphere, storage temperature after treatment and storage time on strawberry fruit quality

	Calyx damage[z]	Berry damage[z]	Firmness (*N*)	Soluble solids (%)	Internal color (H)	External color (H)
Applied acetaldehyde concentration (%)						
Initial[y]						
0	1.8 a[x]	1.1 a	2.9 a	8.2 a	43.9 a	31.4 a
1	1.6 b	1.2 a	2.8 a	8.1 a	44.1 a	32.2 a
2	1.7 ab	1.2 a	2.8 a	8.0 a	43.8 a	32.2 a
3	2.7 c	1.2 a	2.8 a	7.9 a	44.0 a	32.5 a
4	3.3 d	1.2 a	2.7 a	8.0 a	43.5 a	31.3 a
0 °C						
0	1.6 a	1.4 a	3.0 a	8.3 a	44.7 a	31.9 a
1	1.6 a	1.4 a	3.0 a	8.4 a	44.7 a	31.9 a
2	1.9 a	1.5 a	3.0 a	8.3 a	44.6 a	32.0 a
3	2.7 b	1.5 a	2.9 a	8.4 a	44.6 a	31.5 a
4	3.5 c	1.4 a	3.0 a	8.3 a	44.5 a	31.5 a
20 °C						
0	1.8 a	2.1 a	3.1 a	8.4 a	43.5 a	30.7 a
1	1.7 a	2.0 a	3.1 a	8.3 a	43.7 a	30.8 a
2	2.0 a	1.9 a	3.3 a	8.3 a	43.5 a	30.7 a
3	2.9 b	2.0 a	3.2 a	8.3 a	43.4 a	30.7 a
4	3.6 b	2.0 a	3.3 a	8.2 a	43.5 a	30.6 a
Treatment atmosphere						
Initial						
Air	2.4 a	1.2 a	2.8 a	8.0 a	43.7 a	32.0 a
CO_2	2.1 b	1.1 a	2.8 a	8.1 a	44.0 a	31.8 a
0 °C						
Air	2.3 a	1.4 a	2.9 a	8.3 a	44.5 a	31.6 a
CO_2	2.2 a	1.5 a	3.1 a	8.4 a	44.7 a	32.0 a
20 °C						
Air	2.5 a	2.0 a	3.1 a	8.3 a	43.5 a	30.5 a
CO_2	2.4 a	2.0 a	3.3 a	8.3 a	43.5 a	30.8 a
Storage time (days)						
Initial	2.2	1.2	2.8	8.0	43.8	31.9
0 °C						
1	2.3 a	1.3 a	2.8 a	8.2 a	45.1 a	32.3 a
2	2.2 a	1.4 a	3.0 a	8.4 b	44.6 b	32.0 a
3	2.2 a	1.5 b	3.0 a	8.3 a	44.4 b	31.5 a
4	2.4 b	1.6 b	3.0 a	8.4 b	44.4 b	31.6 a
20 °C						
1	2.4 a	1.6 a	3.1 a	8.3 a	44.2 a	31.4 a
2	2.5 a	2.3 b	3.4 a	8.2 a	42.8 b	30.0 b

Results are pooled averages for all strawberry fruit over all storage days.
[x] Means followed by a different letter within a group are significantly different at the 5% level.
[y] Initial evaluation was 1 h after fruit were exposed.
[z] Damage score: 1 (none), 2 (slight), 3 (moderate), 4 (severe).

effect was most apparent for the initial observations, and remained significantly different for fruit stored at 0 °C after treatment.

Ethyl acetate was present at elevated levels in all treated fruit at all evaluation periods (Table 2). For treated fruit stored at 20 °C, ethyl acetate

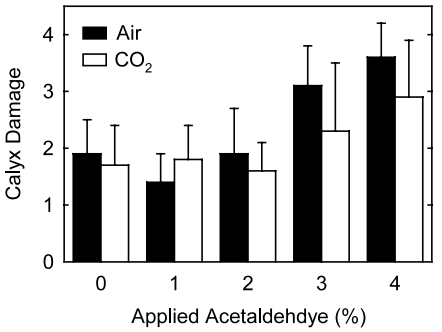

Fig. 1. Calyx damage for fruit treated with 0, 1, 2, 3, or 4% Aa for 2 h. Fruit were evaluated 1 h after exposure. Damage scale: 1, none; 2, slight; 3, moderate; and 4, severe.

levels were elevated on day 1, but declined sharply by day 2 (Fig. 2). Ethyl acetate increased during storage in all treated fruit held at 0 °C, and then declined after day 2 (Fig. 3). Treatment atmosphere had no effect on ethyl acetate concentration.

Methanol concentrations were similar between treated and untreated fruit for the initial evaluation, and remained relatively constant during storage for fruit held at 0 °C (Table 2). Only fruit treated with 4% Aa had higher concentrations after 0 °C storage. Untreated fruit held at 20 °C showed a sharp rise in methanol levels on day 2, but treatment with Aa inhibited the increase in methanol. (Table 2, Fig. 2).

Acetone concentrations in treated fruit were lower than in the control fruit, particularly for higher concentrations of Aa (Table 2). Acetone levels in fruit held at 0 °C decreased during storage, while those of fruit held at 20 °C increased (Table 2, Figs. 2 and 3). However, the relative differences between treated and untreated fruit were maintained during storage. Immediately after treatment, fruit exposed to Aa in CO_2 exhibited slightly higher levels of acetone as compared with fruit exposed to Aa in air; but this difference did not persist

3.1.3. Fumigant concentration

The concentration of Aa in the treatment jars during fumigation decreased rapidly in the presence of strawberry fruit (Fig. 4). The rate of decline in Aa concentration was influenced by the weight of the fruit in the jar (load factor). A load factor of 12% (volume by weight) resulted in approximately a 70, 84, and 95% decrease in Aa concentration after a 0.5, 1, and 2 h exposure, respectively, when 3% Aa was applied.

3.1.4. Target pest mortality

Thrips mortality increased with increasing concentration of Aa fumigant; however, there was no significant difference in mortality between western flower thrips exposed to Aa in air or Aa in 20 kPa CO_2 ($P < 0.05$), with the exception of fumigation with 1% Aa in the presence of strawberries (Table 3). Complete mortality was not achieved, even with 4% Aa.

3.2. Multiple applications of acetaldehyde

3.2.1. Fruit tolerance

Calyx damage increased with increasing concentration and with repeated application of the same concentration of Aa (Table 4). Although fruit treated four times with 1% Aa (1–1–1–1%) or two times with 2% Aa (2–2%) each had a cumulative exposure of 4% Aa, calyx damage ratings for these fruit were significantly lower than for fruit treated once with 4% Aa, and 2–2% Aa was intermediate. Berries treated with 4% Aa, either as a single application or two applications of 2% Aa (2–2%) were softer and had more berry damage than berries from other treatments (Table 4).

3.2.2. Target pest mortality

Western flower thrips were more susceptible to Aa than two-spotted spider mites (Table 5). However, complete control was not achieved by any of the treatments for either target pest. Exposure to a cumulative concentration $\geq 1\%$ Aa resulted in $> 89\%$ mortality for western flower thrips and $\geq 40\%$ mortality for two-spotted spider mites. Multiple exposures to Aa resulted in western flower thrips mortality comparable to that of single exposures of the same cumulative concentration. Exposure to 4% Aa was necessary to elicit $> 90\%$ mortality for two-spotted spider mites (Table 5). However, multiple exposures to

Table 2
Effects of Aa concentration, treatment atmosphere, storage temperature and storage time on volatile content (μmol/mol) of strawberry fruit

	Acetaldehyde	Ethanol	Ethyl acetate	Methanol	Acetone
Applied acetaldehyde concentration (%)					
Initial[z]					
0	1.5 a[y]	23.3 a	5.4 a	5.0 a	6.7 a
1	3.7 a	122.8 b	31.0 b	7.3 a	5.3 b
2	7.7 a	224.3 c	41.2 c	6.6 a	4.3 c
3	9.4 a	322.8 d	52.3 d	5.8 a	4.2 c
4	30.6 b	434.9 e	49.7 d	7.0 a	3.8 c
0 °C					
0	0.9 a	8.8 a	5.9 a	5.6 a	4.3 a
1	3.3 b	32.1 b	49.6 b	7.0 a	3.5 b
2	4.8 c	71.7 c	80.7 c	7.1 a	3.2 bc
3	6.5 d	120.7 d	115.1 d	6.0 a	2.8 c
4	9.4 e	191.8 e	137.1 e	10.4 b	2.8 c
20 °C					
0	1.6 a	22.1 a	3.3 a	35.4 a	9.5 a
1	1.5 a	24.7 a	14.5 b	20.5 b	7.6 b
2	2.1 a	31.3 a	31.8 c	14.1 c	6.2 c
3	3.1 b	45.5 b	49.3 d	13.0 c	5.5 c
4	4.0 c	63.5 c	71.1 e	14.1 c	4.2 d
Treatment atmosphere					
Initial					
Air	4.9 a	178.6 a	37.8 a	7.0 a	4.5 a
CO_2	14.8 b	253.1 b	33.1 a	5.8 a	5.2 b
0 °C					
Air	4.2 a	73.3 a	74.6 a	7.5 a	3.6 a
CO_2	5.6 b	103.1 b	83.7 a	7.0 a	2.9 a
20 °C					
Air	2.0 a	32.1 a	28.8 a	21.7 a	6.6 a
CO_2	2.8 a	43.4 a	38.5 a	17.3 b	6.5 a
Storage time (days)					
Initial	10.3	219.4	35.2	6.3	4.9
0 °C					
1	5.3 a	153.1 a	93.7 a	10.7 a	4.3 a
2	4.9 ab	89.1 b	84.2 b	6.2 b	3.6 b
3	4.5 b	62.1 c	80.3 b	3.4 b	3.1 b
4	4.6 b	46.7 d	58.1 c	5.6 b	2.2 c
20 °C					
1	3.5 a	50.8 a	55.2 a	10.8 a	4.8 a
2	1.6 b	24.3 b	17.3 b	26.0 b	8.0 b

Results are pooled averages for all strawberry fruit over all storage days.
[y] overall means are shown, those with different letter within a group are significantly different at the 5% level.
[z] Initial evaluation was 1 h after fruit were exposed.

Aa did not achieve the same mortalities for two-spotted spider mites as a single exposure to the same cumulative concentrations (Table 5). Mortality of western flower thrips was close to 100% in all treatments, too close to distinguish differences between the treatments.

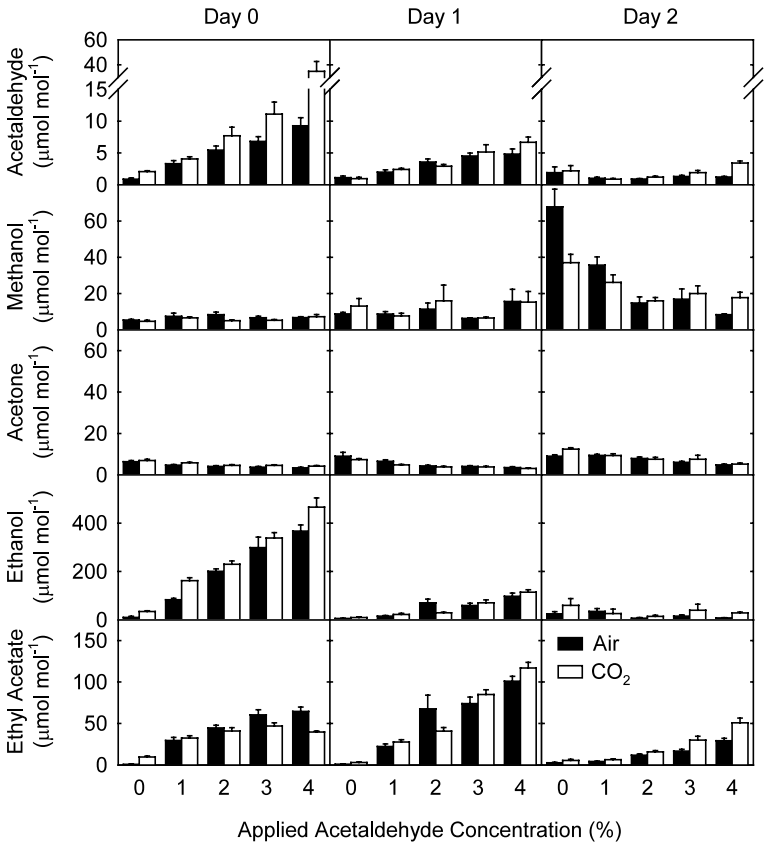

Fig. 2. Volatiles detected in strawberry fruit after Aa exposure for 2 h at 24 °C and storage at 20 °C for 0 (1 h), 1 or 2 days.

4. Discussion

Our results have demonstrated the pesticidal properties of Aa; however, effective Aa treatments negatively affected the quality of strawberry fruit, as indicated by calyx damage, and loss of firmness. Calyx damage occurred when berries were exposed to $\geq 3\%$ Aa for 2 h. Similar results have been reported by other researchers (Aharoni et al., 1979a,b, 1980; Morris et al., 1979; Prasad and Stadelbacher, 1974).

Although Aharoni et al. (1979b) indicated that elevated CO_2 concentrations during Aa fumigation resulted in less phytotoxicity to strawberry fruit, our results do not concur. Initially (1 h after treatment), fruit exposed to 2, 3, or 4% Aa in the presence of 20 kPa CO_2 exhibited slightly less calyx damage than fruit exposed to Aa in air. However, these minor differences did not persist beyond the initial observations of the fruit.

Fruit fumigated with Aa had higher concentrations of Aa, ethanol and ethyl acetate, in agreement with the results of Pesis and Avissar (1990). Increased volatile production was reported in oranges, cherries, and grapes exposed to postharvest applications of Aa (Pesis and Avissar, 1989; Pesis and Frenkel, 1989; Vidrih et al., 1998). In our study, although these volatiles were detected at higher concentrations at the initial evaluation and subsequent evaluations of fruit stored at 0 °C, levels of Aa and ethanol were comparable to the untreated fruit by day 2 at 20 °C. Ethyl acetate levels remained slightly elevated, but decreased significantly in fruit stored at 20 °C. Methanol and acetone concentrations were generally lower in treated fruit, perhaps indicating a shift in volatile

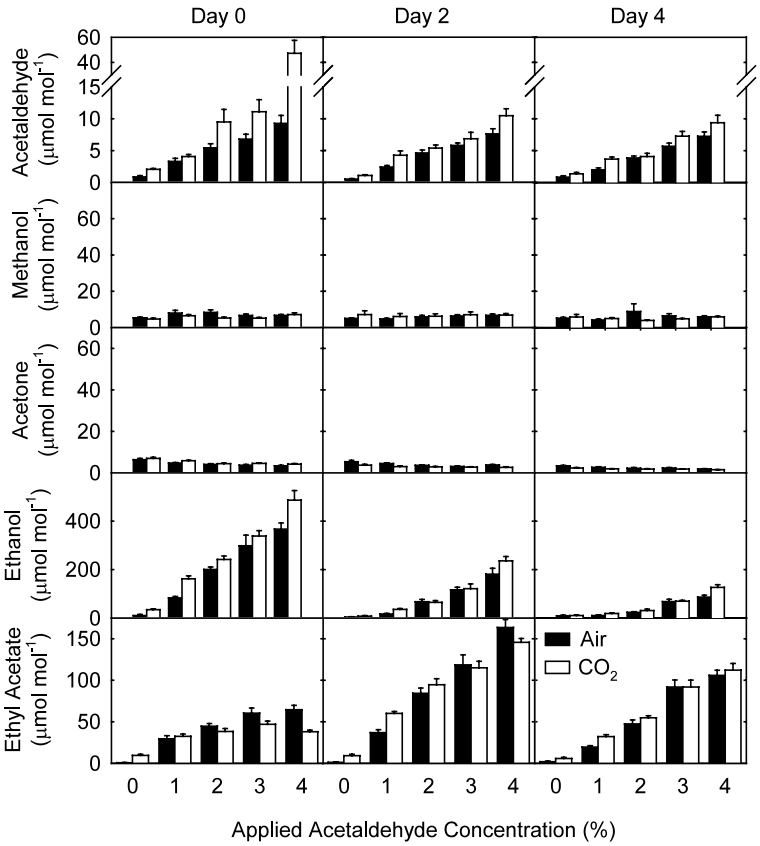

Fig. 3. Volatiles detected in strawberry fruit after Aa exposure for 2 h at 24 °C and storage at 0 °C for 0 (1 h), 2 or 4 days.

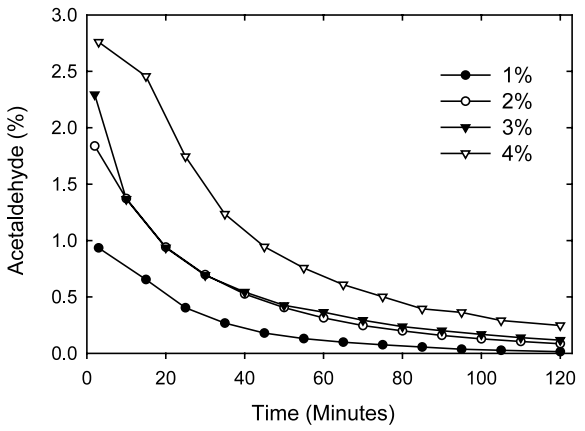

Fig. 4. Aa concentration (%) in the jar headspace over time during exposure of strawberry fruit to 1, 2, 3, or 4% Aa for 2 h at 24 °C (load factor 12% by weight).

production. The reduction in methanol could be a result of less pectin methyl esterase (PME) activity as a result of exposure to Aa. Although there are no significant differences in firmness for fruit treated with increasing concentrations of Aa (Table 1), there is a gradual trend towards increased firmness with increased Aa exposure which is correlated with the significant decrease in methanol at 20 °C (Table 2). In addition, decreases in polygalacturonase (PG) activity in Aa treated fruit have been correlated with the inhibition of ripening in tomatoes (Pesis and Marinansky, 1993). Higher levels of Aa and ethanol were detected in fruit treated with Aa in 20 kPa CO_2 compared with Aa in air. Elevated Aa and ethanol concentrations have been reported in fruit held for extended periods of time in elevated CO_2 (Wszelaki and Mitcham, 2000), and we also

Table 3
Percent mortality of second instar western flower thrips exposed to Aa for 2 h at 24 °C in air or 20 kPa CO_2 in the presence of strawberry fruit

Acetaldehyde (%)	Air	20 kPa CO_2
0	8.2 a[z]	9.9 a
1	57.6 b	75.8 b
2	89.1 c	89.5 bc
3	95.1 c	98.1 c
4	98.1 c	96.2 bc

[z] Means within a column followed by the same letter are not significantly different at the 5% level. Load factor by weight 13%.

found small increases in these volatiles following only 2 h of exposure to 20 kPa CO_2 at 24 °C.

This study did not include a formal organoleptic evaluation of treated strawberry fruit, although some informal evaluations were made on strawberry fruit treated with low concentrations of Aa. It was generally agreed that fruit exposed to Aa had a more appealing strawberry odor than untreated fruit. Paz et al. (1981) found similar results with pears, tomatoes and blueberries. In most cases, the tasters in our study could not detect differences in flavor between treated and untreated fruit (data not shown). This concurs with results of taste tests reported by Prasad and Stadelbacher (1974) and Pesis and Avissar (1990). Anecdotal evidence of off-flavors in fruit treated with higher concentrations of Aa (3 and 4%) were reported by some tasters.

Our treatments did not result in complete control of either target pest. While western flower thrips were susceptible to Aa, and several treatments resulted in nearly 100% mortality, the level of control necessary to satisfy quarantine standards were not achieved. These results are similar to those reported by Aharoni et al. (1980), who found that Aa in combination with 70 kPa CO_2 under vacuum was necessary to achieve complete control. Under these conditions, strawberry quality was compromised. Our report is the first to show the effects of Aa on two-spotted spider mites. Although exposure to Aa was toxic to the two-spotted spider mite, it only approached complete control at concentrations well above the range of strawberry fruit tolerance. We developed the multiple application method in an attempt to mitigate phytotoxicity, while maintaining high target pest mortality. Multiple applications of Aa resulted in improved fruit tolerance to the treatments, but did not maintain the same level of target pest mortality as a single, high dose of Aa.

The rapid absorption of Aa by plant materials agrees with the results of Hartsell et al. (1979) with

Table 4
Strawberry fruit quality following single (1 h exposure) and multiple injections of Aa

Acetaldehyde (%)	Calyx damage[z]	Berry damage[z]	Firmness (*N*)
0	1.5 a[y]	2.4 bc	2.5 ab
1–1–1[x]	1.8 a	2.0 d	2.4 ab
1–1–1–1	2.1 b	2.3 cd	2.6 a
2–2	2.4 c	2.7 ab	1.9 d
3	3.2 d	2.5 abc	2.2 bc
4	3.9 e	2.7 a	1.9 cd

Fruit were evaluated after 5 days at 0 °C (57% RH). Load factor by weight 12%.

[x] Series of numbers refers to multiple injections; 2-2 refers to exposure to 2% Aa for 1 h, jar opened for 1 h, then repeated exposure to 2% Aa for a second hour.

[y] Means in a column followed by the same letter are not significantly different at the 5% level.

[z] Damage score: 1 (none), 2 (slight), 3 (moderate), 4 (severe).

Table 5
Percent mortality of second instar western flower thrips and two-spotted spider mites (mixed stages) exposed to single (1 h exposure) and multiple injections of Aa

Acetaldehyde (%)	Western flower thrips	Two-spotted spider mites
0	5.1 e[z]	10.6 e
1	12.3 d	14.6 e
2	89.0 c	39.9 d
3	93.8 abc	73.6 b
4	95.1 abc	93.3 a
1–1–1[y]	92.2 bc	51.5 cd
2–2[y]	99.1 a	59.7 bc
1–1–1–1[y]	96.4 ab	61.7 bc

Load factor by weight 12%.

[z] Means within columns followed by different letters are significantly different at the 5% level.

[y] Series of numbers refers to multiple injections; 2–2 refers to exposure to 2% Aa for 1 h, jar opened for 1 h, then repeated exposure to 2% Aa for second hour.

head lettuce and Aharoni et al. (1979a) with strawberries. Hartsell et al. (1979) reported that in the presence of head lettuce, Aa concentrations were reduced to 20–24% of the initial concentration within 30 min. Aa is readily absorbed and metabolized by strawberry fruit. This rapid and near complete absorption of the chemical makes it necessary to consider commodity and load factor when designing fumigation treatments with Aa. Although Aa uptake may be variable among commodities, in the presence of strawberry fruit the fumigant was rapidly reduced to concentrations ineffective for control of target pests under the conditions of our experiments.

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