Low Temperature Phosphine Fumigation for Postharvest Control of Western Flower Thrips (Thysanoptera: Thripidae) on Lettuce, Broccoli, Asparagus, and Strawberry

YONG-BIAO LIU[1]

USDA–ARS, Crop Improvement and Protection Unit, Salinas, CA 93905

J. Econ. Entomol. 101(6): 1786–1791 (2008)

ABSTRACT U.S. exported lettuce, broccoli, asparagus, and strawberries often harbor western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae), a quarantined pest in Taiwan, and therefore require quarantine treatment. Fumigation with diluted pure phosphine at a low temperature of 2°C was studied to control western flower thrips and to determine effects on the quality of the treated products. Total thrips control was achieved in ≥18-h fumigation treatments with ≥250 ppm phosphine. One day fumigation treatment with 1,000 ppm phosphine was tested on lettuce and broccoli. One-day fumigation treatments with 500 ppm and 1,000 ppm phosphine were tested on asparagus and strawberry. Visual quality of lettuce, broccoli, and asparagus was evaluated after 2-wk posttreatment storage. Strawberry quality was evaluated immediately after fumigation and after 1-wk posttreatment storage. For all the products, there were no significant differences between the treatments and the controls in postharvest quality, and there were no injuries caused by the fumigation treatments. Therefore, phosphine fumigation at low temperature was promising for postharvest control of western flower thrips on lettuce, broccoli, asparagus, and strawberry.

KEY WORDS *Frankliniella occidentalis*, phosphine, quarantine control, lettuce, broccoli

Western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae), is a common pest on a variety of crops in the United States. But, it is a quarantined pest in Taiwan and therefore affects U.S. export of fresh commodities, including lettuce, broccoli, asparagus, and strawberries. Current practice of fumigation with methyl bromide cannot be sustained due to the global phase out of methyl bromide production mandated by the Montréal Protocol. Methyl bromide fumigation also has negative impacts on postharvest quality of lettuce. Exported broccoli is often shipped with ice and therefore is not compatible with methyl bromide fumigation at ambient temperature due to ice melting. Therefore, an alternative treatment is needed for control of western flower thrips on exported commodities to Taiwan.

Phosphine has been used as a fumigant for stored products over four decades, and it is a fumigant alternative to methyl bromide (Chaudhry 1997, Fields and White 2002). Phosphine is usually generated from metal phosphide and contains ammonia, which is generated from carbamate concurrently with phosphine to prevent generating phosphine too fast. But ammonia is phytotoxic. Recent advances in phosphine technology have resulted in the ability to place pure phosphine in compressed cylinders and the delivering technology, the Horn Dyluphos System, for safe fumigation (Horn et al. 2005). Pure phosphine has been tested and used on a variety of fresh fruits and vegetables for postharvest insect control at low temperatures in Chile (Horn et al. 2005), and it is being studied for pest quarantine treatments on a variety of fresh commodities in several countries.

Thrips have been studied for response to phosphine, and they were found to be very susceptible to phosphine fumigation compared with some other insects such as aphids and moth larvae at 24°C (Karunaratne et al. 1997). For fresh commodities such as fruits and vegetables, fumigation at low temperatures is a key factor to prevent injury to the products. There is a lack of published data on toxicity of low temperature phosphine fumigation to western flower thrips as well as its impact on the quality of perishable commodities. In the current study, we determined effective phosphine fumigation treatment at a low temperature for control of western flower thrips, and we evaluated the effects of the treatments on postharvest quality of lettuce, broccoli, asparagus, and strawberry.

Materials and Methods

Insects. Western flower thrips were reared on lettuce plants in a greenhouse at 18–30°C under natural lighting and collected in plastic vials for fumigation tests by using the same procedures as described by Liu (2005). Thrips were collected in vials (2.5 cm in di-

[1] Corresponding author, e-mail: yongbiao.liu@ars.usda.gov.

ameter by 7 cm in height) with lettuce leaf pieces by using a vacuum-powered aspirator. Each vial contained 10–20 thrips. Lettuce plants infested with thrips also were set up in plastic cups and sealed with screened lids and used in fumigation tests.

Chemicals. Diluted pure phosphine (PH_3) at 1.4% balanced with 98.5% nitrogen in a compressed bottle from Cytec Canada, Inc. (Niagara Falls, ON, Canada) was used for fumigation treatments. The phosphine sample was released to fill up an aluminum foil bag (20 by 25 cm) fitted with a quick-connector. Gastight syringes of 100 and 500 ml were used to draw phosphine samples from the foil bag and injected into fumigation chambers to conduct fumigation treatments.

Response of Western Flower Thrips to Phosphine Fumigation Treatments. Western flower thrips in plastic vials were sealed in 1.9-liter glass jars. The lids of the jars were fitted with adaptors and quick-connectors for fumigant injection. In each fumigation test, four jars were used. Five vials were placed in each jar. The jars with thrips were first cooled in a refrigerator for up to 2 h and then injected with PH_3 in a fume hood. The treatment jars were then held at 2 ± 0.5°C in a walk-in cooler. ≈30–60 min after fumigant injection and 30–60 min before treatment termination, an aliquant of 50-ml air sample was taken from each jar and transferred into a foil bag (8 by 20 cm) with 150 ml of preloaded air to dilute the phosphine from the treatment jar. Phosphine concentration was measured using a Dräger PacIII gas detector equipped with a phosphine sensor (Dräger Safety Inc., Pittsburgh, PA).

Fumigation treatments with 250, 500, 1,000, and 2,000 ppm phosphine were conducted. Treatment durations were 6, 12, 18, 24, and 48 h, depending on phosphine concentrations. Phosphine concentrations in general declined over the course of fumigation treatment. The average concentration of initial and final measurements was used, and it fell within 15% range of each respective phosphine concentration. At the end of each fumigation treatment, treatment jars were vented for an hour in a fume hood. Thrips from the treatments and the controls were then held in an environmental chamber at 24°C and a photoperiod of 14:10 (L:D) h overnight before being scored for mortality. Thrips that did not move or did not respond to repeated probes with a soft brush were scored as dead. In total, 1,735 thrips were treated and 403 thrips were used as controls.

Fumigation Treatments of Lettuce. Vacuum-cooled commercial iceberg and romaine lettuce were obtained from Tanimura & Antle Co. (Salinas, CA) 1 d after harvest for the fumigation study. Lettuce was fumigated with 1,000 ppm phosphine for 24 h at 2°C in 76-liter metal drums in a walk-in cooler to determine effects of phosphine fumigation on product quality and mortality of thrips. Iceberg lettuce was wrapped individually in perforated plastic wrappers. Romaine lettuce was in two types of package: nonbagged in plastic lined boxes and bagged (five per bag).

For each fumigation treatment, lettuce and cups with thrips infested lettuce were packed and sealed in a metal drum chamber. Then, a moderate level (≈6 in Hg) of vacuum was drawn through a port on the lid, and phosphine was injected into the chamber by using a 500-ml gastight syringe. After fumigation injection, air was allowed to leak in through a liquid barrier device to equilibrate the pressure inside the treatment chamber to the outside atmosphere pressure. The chamber was held at 2°C in a walk-in cooler for 24 h. Phosphine concentrations ≈30–60 min after injection and before treatment termination were measured using the same procedures as described above. The average phosphine concentrations were 1,105 and 820 ppm at the start and end of treatments.

At the end of each fumigation treatment, the chamber was aerated for 1 h in a portable hood in the cooler. Lettuce was then packed in a lettuce carton and stored at 2°C for 2 wk in a walk-in cooler before being evaluated for postharvest quality. The cups with thrips infested lettuce were placed in an environmental chamber overnight at 24°C and a photoperiod of 14:10 (L:D) h before thrips mortality was scored. The fumigation treatments for iceberg lettuce and romaine lettuce were replicated two times. In total, 693 thrips were treated and 279 thrips were used as controls.

Treated lettuce and controls were evaluated for injury by the fumigation treatment and visual quality for marketability. The procedures for quality evaluation of lettuce was the same as described by Liu (2005) by using the scoring method of Kader et al. (1973). The visual quality score ranged from 1 (extremely poor) to 9 (excellent) with 3, 5, and 7 in between representing poor, fair, and good, respectively. For both iceberg lettuce and romaine lettuce, lettuce was dissected to inspect for signs of injury such as discoloration. In total, 48 iceberg lettuce and 54 romaine lettuce from fumigation treatments was evaluated and 23 iceberg lettuce and 45 romaine lettuce from controls were evaluated.

Fumigation Treatments of Broccoli. Commercial broccoli was obtained from Tanimura & Antle Co. and fumigated with 1,000 ppm phosphine for 24 h at 2°C in 7.6-liter pressure cookers and in the metal drum chambers. For fumigation in the pressure cookers, broccoli crowns and thrips in plastic vials were packed in the pressure cookers. The pressure cookers were modified by adding ports to the lids for gas injection. Phosphine was injected using a 100-ml gastight syringe in a fume hood. After injection, the pressure cookers were kept for 24 h at 2°C in a walk-in cooler. For fumigation in the metal drums, broccoli crowns were loaded in plastic buckets with ice and sealed in the metal drum chambers, and fumigation treatments were conducted using the above-mentioned procedures. Cups with thrips infested lettuce were included in all fumigation treatments. Phosphine concentrations after injection and before treatment termination were measured using the same procedures as described above. For the treatments in the pressure cookers, the average phosphine concentrations at the start and end were 569 and 303 ppm for the 500 ppm treatment and 1,112 and 762 ppm for the 1,000 ppm treatment. For the 1,000 ppm treatment in the drum chambers, the average phosphine concentrations at the start and the end of the treatment were 950 and 690 ppm. In total, 501 thrips were treated and 214 thrips were used as controls. The fumigation treatments in the pressure cookers were replicated three times, and the fumigation treatment in the drum chamber was replicated two times.

At the end of each fumigation treatment, the fumigation chambers (pressure cookers and metal drums) were aerated for 30 min. The plastic vials and cups with thrips were held in an environmental chamber overnight before being scored for mortality by using the same procedures as described above. The treated broccoli was topped with ice and stored at 1 ± 0.5°C in a walk-in cooler for 2 wk together with the controls before being evaluated for postharvest quality by using the same procedures as described previously (Liu 2007). Color, tightness of beads, and presence of any dead beads were examined for postharvest quality. Color was measured using a spectrophotometer (ColorTec-PSM, Accuracy Microsensors, Inc., Pittsford, NJ). Each crown was measured three times and the average values of L^* (luminosity), a^* (green-red), b^* (blue-yellow), and $H°$ (hue angle, $H° = \tan^{-1}[b^*/a^*]$) parameters for each crown were collected for analyses. For fumigation treatments in the pressure cookers, four to five treated broccoli crowns and three untreated crowns were measured for color. For the treatment in the metal drum chambers, 15 treated and 15 untreated broccoli crowns were measured for color.

Fumigation Treatments of Asparagus. Commercial asparagus in bundles from supermarkets were tested in the pressure cookers with 500 and 1,000 ppm phosphine for 24 h at 2°C. Asparagus were screened for defects before testing and divided into three groups and bundled with rubber bands. One bundle of asparagus was used in each treatment in a test, and one bundle was set aside as controls. Fumigation treatments were conducted using the same procedures as described above. Each fumigation treatment was replicated three times. In total, nine bundles of asparagus were used. The average phosphine concentrations at the start and the end of treatments were 562 and 438 ppm for the 500 ppm treatment and 1,110 and 890 ppm for the 1,000 ppm treatment.

After fumigation, asparagus from the treatments and the controls were placed in plastic bag and stored at 2°C in a cooler for 2 wk before being evaluated for quality. Asparagus spears were examined for any discoloration or stains that might indicate injury by the fumigation treatments. Individual spears also were examined for tightness of spears and decay of tips. The general quality of all spears as a groups for each treatment was scored as 1 (poor), 2 (medium), 3 (good), and 4 (excellent).

Fumigation Treatments of Strawberry. The 'San Juan' strawberries were obtained from Driscoll's (Watsonville, CA) 1 d after harvest, and they were fumigated with 500 and 1,000 ppm phosphine for 24 h at 2°C in the pressure cookers. Strawberries were

Table 1. Responses of western flower thrips to phosphine fumigation treatments at 2°C

PH_3 (ppm)	Time (h)	CT (mg h/liter)	N	Mortality ± SE (%)
Fumigation in jars				
250	6	2.28	72	66.7 ± 6.1
	12	4.55	123	97.5 ± 2.5
	18	6.83	148	100
	24	9.11	153	100
500	6	4.55	133	82.3 ± 3.7
	12	9.11	268	89.2 ± 2.2
	18	13.65	138	100
	24	18.22	263	100
1,000	6	9.11	147	91.7 ± 2.2
	12	18.22	136	98.5 ± 1.0
2,000	6	18.22	154	98.8 ± 1.2
Fumigation treatments of lettuce				
1,000	24	36.43	693	100
Fumigation treatments of broccoli				
1,000	24	36.43	501	100

sorted for uniformity in color and maturity before fumigation. Sizes of strawberries ranged from medium to large. Strawberries were packed in plastic clam shell boxes. In each test, six boxes of strawberries were used (two boxes for each treatment and the control). Two boxes of strawberries were placed in each pressure cooker for fumigation treatment. Fumigation treatments were conducted using the same procedures as described above. Each fumigation treatment was replicated two times. The average phosphine concentrations at the start and the end of treatments were 590 and 452 ppm for the 500 ppm treatment and 1,140 and 921 ppm for the 1,000 ppm treatment.

After fumigation treatments, strawberries in the boxes were placed in a strawberry cardboard tray and stored in a walk-in cooler at 2°C. One half of strawberries (one box from each treatment and the control) were evaluated for quality 3 h after fumigation and the other half was evaluated after 1-wk posttreatment storage. Strawberries were evaluated for color, firmness, and damages to calyx and berry. For each berry, color was measured on opposite, paired sides of the fruit using the spectrophotometer. The average values of L^*, C, and $H°$ for each berry were collected for statistical analyses. Firmness of each berry was measured twice on opposite and paired sides of the berry using a handheld penetrometer fitted with a 3-mm round tip and measured as grams of force to penetrate the skin. The average value for each fruit was used for statistical analyses.

Berry damage was scored subjectively ranging from 1 to 4 by using the procedures described by Simpson et al. (2003). Berry damage included bruising, decay, and skin surface disintegration. Berry damage was scored as 1 (no damage), 2 (slight, <20% surface affected), 3 (moderate damage, 20–60% surface affected), or 4 (severe damage, >60% surface affected).

Data Analyses. For fumigation treatments with different phosphine concentrations, percentage of mortality rates of thrips were adjusted for control mortality by using Abbott's formula. Concentration and

Table 2. Postharvest quality of lettuce at 2 wk after 24-h phosphine fumigation treatment at 2°C

Lettuce type	PH_3 (ppm)	*N*	Visual quality (mean ± SE)
Iceberg	0	23	7.5 ± 0.2a
	1,000	48	7.3 ± 0.1a
Romaine, nonbagged	0	12	7.5 ± 0.2a
	1,000	18	7.6 ± 0.1a
Romaine, bagged	0	33	6.8 ± 0.3a
	1,000	36	6.3 ± 0.3a

The quality scores for each lettuce type were not significantly different ($P > 0.05$; Student's *t*-test; SAS Institute 2002).

time products (CT) were calculated for all treatments as milligrams hour/liter. Phosphine concentrations in ppm were first converted into values in cubic centimeters/liter and further converted into values in milligrams per /liter by using the formula cm^3/liter × 34/22.4 (Bond 1984). Analyses of variance was used to analyze lettuce head weight, visual quality of iceberg lettuce and romaine lettuce, and color measurements of broccoli using Oneway platform of JMP Statistical Discovery software. Tukey–Kramer multiple range test was used to compared three or more means and Student *t*-test was used to compared two means (SAS Institute 2002). For broccoli, L^*, a^*, b^*, and $H°$ measurements were compared between treatment and control. For strawberries, the L^*, C, and $H°$ were compared among the treatments and control using Oneway platform of JMP Statistical Discovery software (SAS Institute 2002).

Results

Response of Western Flower Thrips to Phosphine Fumigation Treatments. All phosphine fumigation treatments of 18 h or longer at a concentration of 250 ppm or higher at 2°C achieved complete control of western flower thrips (Table 1). Comparing shorter and higher concentration fumigation treatments with longer and lower concentration fumigation treatments, the 1,000 ppm phosphine treatment for 12 h and the 2,000 ppm phosphine treatment for 6 h did not kill all thrips, but it had higher CT products than the 500 ppm phosphine treatment for 18 h, which killed all thrips. The 500 ppm phosphine treatment for 12 h also did not kill all thrips, but it had higher CT product than the 250 ppm phosphine treatment for 18 h, which killed all thrips (Table 1). Therefore, longer treatments with lower levels of phosphine were more effective against western flower thrips than shorter treatments with higher levels of phosphine. Complete control of western flower thrips also was achieved in the 24-h fumigation treatments of lettuce and broccoli at 2°C (Table 1).

Fumigation Treatments of Lettuce. The 24-h fumigation with 1,000 ppm phosphine at 2°C did not have significant negative effects on postharvest quality of iceberg lettuce or romaine lettuce (Table 2). There were no significant differences in visual quality between the treatment and the control for both iceberg and romaine lettuce. Both iceberg and romaine lettuce from the treatment and the control had good quality. Bagged romaine lettuce from both the treatment and the control had quality score below 7.0 (Table 2). This was due to decay of the lettuce in the sealed bags. There was no any sign of injury to either iceberg lettuce or romaine lettuce by phosphine fumigation.

Fumigation Treatments of Broccoli. The 24-h fumigation treatments with 500 ppm and 1,000 ppm phosphine at 2°C did not have any noticeable effects on visual appearance of broccoli. All broccoli crowns from the treatments and the control had good quality and had dark green color and tight beads. There was no any sign of injury to treated broccoli by phosphine fumigation. There were also no significant differences between the treatments and the control in color parameters except for L^* value for the fumigation treatments in pressure cookers (Table 3).

Fumigation Treatments of Asparagus. The 24-h fumigation treatments did not cause any reduction in the quality of asparagus. There was no injury by phosphine fumigation. The overall quality of asparagus from the treatments was the same as that from the control. There were also no significant differences among the treatments and the control in the percentages of tight spears and the rate of spears with tip decay (Table 4). Therefore, the 24-h fumigation treatments with 500 and 1,000 ppm phosphine at 2°C were safe to asparagus quality. Most spears (87–90%) had tight tips after 2 wk of posttreatment storage. Approximately 2–5% of spears from both treatments and controls had tip decay.

Fumigation Treatments of Strawberry. The 24-h fumigation treatments did not reduce the quality of the strawberries. There were no significant differ-

Table 3. Effects of 24-h phosphine fumigation treatments at 2°C on color parameters of broccoli after 2-wk posttreatment storage

PH_3 (ppm)	*N*	L^*	a^*	b^*	$H°$
Fumigation in pressure cookers					
Control	9	36.08 ± 0.31a	−3.87 ± 0.22a	7.69 ± 0.46a	117.08 ± 0.83a
500	15	34.76 ± 0.45ab	−4.17 ± 0.17a	8.38 ± 0.29a	116.49 ± 0.54a
1,000	14	34.37 ± 0.38b	−3.95 ± 0.24a	7.45 ± 0.34a	117.60 ± 0.70a
Fumigation in metal drums					
Control	30	39.74 ± 0.26a	−4.73 ± 0.11a	8.18 ± 0.27a	120.47 ± 0.59a
1,000	30	39.53 ± 0.24a	−4.47 ± 0.15a	7.80 ± 0.22a	119.92 ± 0.61a

The values (mean ± SE) in each column for each type of treatment followed by the same letter were not significantly different ($P > 0.05$; Tukey–Kramer multiple range test for fumigation in pressure cookers and Student's *t*-test for paired means of fumigations in metal drums; SAS Institute 2002).

Table 4. Effects of 24-h phosphine fumigation treatments at 2°C on asparagus quality after 2-wk posttreatment storage

Phosphine (ppm)	N	Quality	Tight spear (%)	Tip decay (%)
Control	82	3.0 ± 0.0a	90.2 ± 5.4a	5.1 ± 3.0a
500	81	3.0 ± 0.0a	86.8 ± 13.2a	1.6 ± 1.6a
1,000	81	3.0 ± 0.0a	88.4 ± 3.4a	5.5 ± 3.1a

The values (mean ± SE) in each column followed by the same letter were not significantly different ($P > 0.05$; Tukey–Kramer multiple range test; SAS Institute 2002).

ences in the level of berry surface damage, firmness, or L^* value among the treatments and the controls (Table 5). There were increased berry damage and reduced firmness after 1-wk posttreatment storage compared with the strawberries immediately after fumigation. The level of berry damage in all treatments including the control was slight (<2) even after 1-wk posttreatment storage, indicating good quality of the strawberries from all treatments. The firmness decreased from ≈150 g (force to penetrate skin with a 3-mm round tip) immediately after fumigation to ≈120 g after 1-wk posttreatment storage. The L^* remained constant and the C and $H°$ values showed a trend of slight increase with the 1-wk posttreatment storage. The C and $H°$ values, however, did not show a consistent variation pattern associated with fumigation treatments (Table 5).

Discussion

The western flower thrips were very susceptible to phosphine fumigation at low temperature. In comparison, other insects such as aphid *Nasonovia ribisnigri* Mosley were much more tolerant (Y.-B.L., unpublished data). These results were consistent with other published studies showing high susceptibility of thrips to phosphine relative to other insects. In direct comparisons, thrips *Heliothrips hemorrhoidalis* Bouché is far more susceptible to phosphine than green peach aphid, *Myzus persicae* (Sulzer), or light brown apple moth, *Epiphyas postvittana* (Walker), larvae at 24°C (Karunaratne et al. 1997). The high susceptibility of western flower thrips to phosphine made it possible to control the pest with low phosphine concentration and shorter treatment time compared with many other pests. The shorter fumigation with lower phosphine levels also would help to prevent injuries to fresh fruits and vegetables. The results of no negative impact on product quality by the low temperature phosphine fumigation treatments indicated that phosphine could be used effectively as an alternative quarantine treatment to methyl bromide fumigation for control of western flower thrips on exported fresh commodities to Taiwan.

Comparing CT values for different concentration and time combinations, treatments with high phosphine concentrations and shorter treatment times resulted in incomplete control of thrips even though they had higher CT product values compared with treatments with low phosphine concentrations and longer treatment times. This indicated that longer treatment time at lower phosphine concentrations were more effective in controlling western flower thrips. Similarly, low dose phosphine fumigation with longer treatment time was suggested for controlling aphids on cut flower because of its higher efficacy compared with shorter fumigation with higher phosphine concentrations at a higher temperature of 24°C (Karunaratne et al. 1997). Phosphine enters insect bodies through spiracles and inhibits aerobic respiration. It also requires the presence of oxygen to be toxic to insects (Bond 1984, Chaudhry 1997). Long treatment duration may be more effective in overcoming temporary closure of spiracles or respiration cessation in responding to phosphine fumigation. Such events would result in much large reduction of uptake of phosphine in shorter fumigation treatments. The toxicity of phosphine to insects also declines with reduced temperature (Bond 1984). Therefore, longer treatment time is needed for insect control at low temperatures.

For color measurements, the results of no significant differences among the treatments for all broccoli color measurements except L^* (luminosity) for the fumigation in the pressure cookers indicated that fumigation treatments had no effects on broccoli color. For strawberries, L^* value was related to brightness and consistent L^* values among the treatments indicated no change in brightness. The $H°$ (hue angle) varied inconsistently among the treatments and storage times. Similar inconsistency for hue value also was reported on strawberries during postharvest storage and was thought to be a consequence of a complex color changes. Changes in C (chrome) value were attributed to water loss (Nunes et al. 2005). For fumigated strawberries, aeration would likely result in

Table 5. Effects of 24-h phosphine fumigation treatments at 2°C on postharvest quality of strawberries

Posttreatment storage (d)	PH_3 (ppm)	N	Berry damage	Firmness (g)	L^*	C	$H°$
0	Control	41	1.17 ± 0.06a	154 ± 6a	32.8 ± 0.4a	44.0 ± 1.0b	47.4 ± 1.0b
	500	43	1.21 ± 0.06a	149 ± 6a	33.1 ± 0.4a	42.0 ± 0.6b	44.8 ± 0.7c
	1000	42	1.24 ± 0.07a	148 ± 7a	33.5 ± 0.3a	48.0 ± 0.6a	53.6 ± 0.4a
7	Control	43	1.98 ± 0.10a	122 ± 3a	33.1 ± 0.4a	52.1 ± 0.8a	58.9 ± 0.5a
	500	41	1.85 ± 0.10a	122 ± 3a	32.9 ± 0.4a	48.8 ± 1.2b	53.1 ± 1.2b
	1000	41	1.76 ± 0.10a	127 ± 3a	33.2 ± 0.4a	52.9 ± 0.8a	58.0 ± 0.8a

The values (mean ± SE) in each column for each posttreatment storage time followed by the same letter were not significantly different ($P > 0.05$; Tukey–Kramer multiple range test; SAS Institute 2002).

greater water loss compared with the controls. It is not known such difference would be a major factor for the observed variation in C value.

Studies on phosphine residue in perishable products are very limited. Phosphine is a small molecule. It penetrates deeply into products and also dissipates quickly from treated products after fumigation. Its solubility in water is 26 cc/100 ml at 17°C (Bond 1984). Phosphine fumigated fruits were reported to have mild off-taste and the off-taste disappeared after 5–6 d of storage (Horn and Horn 2004). For phosphine-fumigated table grapes, no phosphine can be detected after they were processed to release phosphine residue 9 d after fumigation by chromatography with detection limit of 0.003 ppm (Klementz et al. 2005). In the United States, the maximum residue limit (MRL) for phosphine is 0.1 ppm for stored products and 0.01 ppm for fresh and processed food stuff. The MRLs of PH_3 for several fresh products are 0.1 mg/kg in Taiwan, and no MRL data are available for lettuce, broccoli, or strawberries (New Zeland Food Safety Authority 2007). Given that phosphine is highly toxic to humans (Chaudhry 1997, Brautbar and Howard 2002), more studies are needed to provide data on phosphine residue in perishable products to ensure that phosphine fumigated fresh commodities do not impose risk to human health. There may be less concern on phosphine residue on exported lettuce and broccoli as it takes >10 d for treated products to reach any overseas markets in Asia by sea transport. For air-shipped strawberries, however, the treated products would reach markets much sooner after fumigation and phosphine residue data seem to be necessary to ensure that phosphine residue level is below the permitted level.

Acknowledgments

I thank K. Duun and J. Wasson for technical assistance, Tanimura & Antle Co. for providing lettuce and broccoli, and Driscoll's for providing strawberries used in the study. I also thank Drs. T.-X. Liu, Peter Follett, and James McCreight for helpful suggestions and comments to an earlier version of the manuscript. This study was supported in part by funding from U.S. Department of Agriculture, Foreign Agricultural Service.

References Cited

Bond, E. J. 1984. Manual of fumigation for insect control. FAO Plant Production and Protection Paper 54. Food and Agriculture Organization of the United Nations, Rome, Italy.

Brautbar, N., and J. Howard. 2002. Phosphine toxicity: report of two cases and review of the literature. Toxicol. Ind. Health 18: 71–75.

Chaudhry, M. Q. 1997. A review of the mechanisms involved in the action of phosphine as an insecticide and phosphine resistance in stored-product insects. Pestic. Sci. 49: 213–228.

Fields, P. G., and D. G. White. 2002. Alternatives to methyl bromide treatments for stored-product and quarantine insects. Annu. Rev. Entomol. 47: 331–359.

Horn, F., and P. Horn. 2004. Fresh fruit fumigation with phosphine as alternative for methyl bromide. *In* Proceedings of 2004 Annual Research Conference on Methyl Bromide Alternatives and Emissions Reductions, 31 October–3 November 2004, Orlando, FL. Methyl Bromide Alternatives Outreach, Fresno, CA.

Horn, F., P. Horn, and J. Sullivan. 2005. Current practice in fresh fruit fumigation with phosphine in Chile. *In* Proceedings of 2005 Annual Research Conference on Methyl Bromide Alternatives and Emissions Reductions, 31 October–3 November 2005, San Diego, CA.

Kader, A. A., W. J. Lipton, and L. L. Morris. 1973. Systems for scoring quality of harvested lettuce. HortScience 8: 408–409.

Karunaratne, C., G. A. Moore, R. Jones, and R. Ryan. 1997. Phosphine and its effect on some common insects in cut flowers. Postharv. Biol. Technol. 10: 255–262.

Klementz, D., H. Heckemüller, Ch. Reichmuth, S. Huyskens-Keil, C. Büttner, F. Horn, and P. Horn. 2005. Disinfestation of table grapes with pure phosphine – Residue and quality aspects. *In* Proceedings of 2005 Annual Research Conference on Methyl Bromide Alternatives and Emissions Reductions, 31 October–3 November, San Diego, CA. Methyl Bromide Alternatives Outreach, Fresno, CA.

Liu, Y.-B. 2005. Ultralow oxygen treatment for postharvest control of *Nasonovia ribisnigri* (Homoptera: Aphididae) on iceberg lettuce. J. Econ. Entomol. 98: 1899–1904.

Liu, Y.-B. 2007. Ultralow oxygen treatment for postharvest control of western flower thrips on broccoli. J. Econ. Entomol. 100: 717–722.

New Zealand Food Safety Authority. 2007. Pesticide MRL database: Taiwan. (http://www.nzfsa.govt.nz/plant/subject/horticulture/residues/taiweb.pdf).

Nunes, M.C.N., J. K. Brecht, A.M.M.B. Morais, and S. A. Sargent. 2005. Possible influences of water loss and polyphenol oxidase activity on anthocyanin content and discoloration in fresh ripe strawberry (cv. Oso Grande) during storage at 1°C. J. Food Sci. 70: S79–S83.

SAS Institute. 2002. JMP statistics and graphics guide, version 5. SAS Institute, Cary, NC.

Simpson, T., V. Bikoba, and E. J. Mitcham. 2003. Effects of acetaldehyde on fruit quality and target pest mortality for harvested strawberries. Postharv. Biol. Technol. 28: 405–416.

Received 14 February 2008; accepted 6 June 2008.