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Evaluation of 1,3-Dichloropropene as a Methyl Bromide Alternative in Tomato Crops in China

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1,3-Dichloropropene (1,3-D, $C_3H_4Cl_2$) is a potential candidate as a soil disinfectant because of the restriction of methyl bromide (MeBr) in soil fumigation due to its ecological risk. Field trials were conducted to ascertain the efficiency of 1,3-D as a MeBr alternative in tomato (*Solanum lycopersicum* L.) and evaluate its application prospects in China. Five treatments were replicated five times in a randomized complete block design: fumigation with MeBr (400 kg ha^{-1}), three 1,3-D doses (180, 120, and 90 L ha^{-1}), an avermectin dose (7.5 L ha^{-1}), and a nontreated control. Results consistently indicated that MeBr was generally superior to the treatments involving all 1,3-D levels and avermectin, which in turn were superior to the control, for improving tomato yield and inhibiting nematode, weed, and mortality caused by plant disease. In both seasons, 1,3-D at the dose of 180 L ha^{-1} was as effective as MeBr in increasing plant height, vigor, and tomato yield and in reducing the incidence of soilborne disease, especially in maintaining excellent nematode control efficiency, but it provided relatively poor control over weeds. On the basis of these results, 1,3-D, in combination with other alternatives to MeBr, is recommended to achieve integrated pest management.

KEYWORDS: 1,3-Dichloropropene; soil fumigation; methyl bromide; nematode; soilborne pathogen; weed control

INTRODUCTION

Tomato (*Solanum lycopersicum* L.) is a leading vegetable crop throughout the world. In China, > 60000 ha were planted in 2006, and the production of tomato paste reached 1,000,000 t, ranking as the world's third largest in the production and first in the export (FAO, 2006). The vast majority of tomato production in China relies on soil sterilization for controlling nematodes, soilborne diseases, and weeds, the risks of which are high when crops are grown under such intensive regimens (*1−3*). At present, the standard treatment for the management of nematodes, soilborne pathogens, and weeds in many high-value crop production systems is preplant soil fumigation with methyl bromide (MeBr). However, the developing countries have been supposed to reduce the production and the use of MeBr by 20% in 2005 and totally phase out its use by 2015 due to its detrimental effects on stratospheric ozone (*4*). Furthermore, due to the nature of vegetable crops, only a few pesticides are registered to control nematodes, root diseases, and weeds in China, reducing the spectrum of products that growers could choose.

Many physical, chemical, and biological alternatives and their combinations have been suggested as MeBr replacements for high-value fruit, nut, and vegetable crops and have been tested in field experiments to evaluate their efficiencies to control nematodes, pathogens, and weeds (*5−7*). Among substitutive chemicals, currently registered alternatives to MeBr are 1,3-dichloropropene (1,3-D), chloropicrin (CP), methyl isothiocyanate (MITC) generators such as Metam sodium (MNa) and Dazomet, methyl iodide (iodomethane), calcium cyanamide ($CaCN_2$), and their combinations (*8−10*). Meanwhile, a variety of nonfumigant methods are also available for managing plant-parasitic nematodes, weeds, and other soilborne pest problems, such as grafting, soil solarization, organic amendments, and biocontrol agents (*11−14*).

As a well-known nematicide with fungicidal and insecticidal activity, 1,3-D has been registered in many countries. So far, most data for 1,3-D are concerned with its combination with CP (1,3-D+CP), which has shown to be effective against soilborne pathogens including fungi and nematodes, whereas it has limited herbicidal activity for some troublesome weeds, such as *Cyperus* species (*15*). López-Aranda et al. reported that 1,3-D+CP at the concentration of 300 kg ha^{-1} could provide effective control of several pests and high strawberry yield similar to that provided by MeBr+CP fumigation (*16*).

Due to the restriction by the current level of agriculture and economics, many advanced fumigant application methods and much of the equipment cannot be used in China. As one of the most promising short-term alternatives to MeBr, 1,3-D is going to be registered as preplant fumigant in China. Our research, conducted in field, was designed to ascertain the efficiency of 1,3-D as a MeBr alternative in tomato and evaluate its application prospects in China.

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MATERIALS AND METHODS

Field trials were established in September and March during the 2009−2010 and 2010−2011 cropping seasons, respectively, in a commercial field near Fang county, Tai'an city, Shandong province, China. The soil at the experimental site was a silt loam, composed of 15% sand, 80% silt, and 5% clay, with an organic matter content of 24.8 g kg^{-1} of soil, pH 7.2, and a soil density of 1.21 g cm^{-3}. The selected experimental site had a history of heavy natural *Meloidogyne incognita* (Kofoid & White) Chitwood (southern root-knot nematode), *Botrytis cinerea* Persoon, and weed infestation. On the basis of previous soil analysis and crop nutritional requirements, the field received a broadcast application of 245 kg ha^{-1} of 15N−0P−25K as starter fertilizer. Prior to treatment establishment, the plots were disked twice before planting bed formation.

Treatments were placed in a random block design with five replications. The fumigation programs were (a) MeBr as a reference treatment (98% GA, ai) (Lianyungang Dead Sea Bromine Compounds Co., Ltd., Jiangsu, China), furrow applied at a dose of 400 kg ha^{-1}; (b) 1,3-D (92% EC, ai) (Shengpeng Bio-Tech Co., Ltd., Shandong, China), furrow applied at a dose of 180 L ha^{-1}; (c) 1,3-D, furrow applied at a dose of 120 L ha^{-1}; (d) 1,3-D, furrow applied at a dose of 90 L ha^{-1}; (e) avermectin as a routine treatment (2.5% EC, ai) (Chinese Academy of Agricultural Sciences, Beijing, China), root pouring applied at a dose of 7.5 L ha^{-1}. A nontreated control was also included.

Each plot was irrigated with 1.3 cm of water the day before fumigation to allow for better bedding. On the day of fumigation (September 16, 2009), 1,3-D and MeBr were furrow applied to soil 0.25 m deep and 0.50 m apart just on the planting rows and then the planting rows bedded and pressed 0.80 m wide at the base, 0.70 m wide at the top, 0.20 m high, and spaced 0.75 m apart on center. Avermectin was root pouring applied to the soil and immediately incorporated 20 cm through disking and then bedded as described above. Immediately after fumigant application, beds were pressed and covered with 0.038 mm low-density polyethylene mulch film.

Six-week-old 'Chaoqun Fenguan F$_1$' tomato seedlings were transplanted into the top of the beds 2 weeks after treatment (WAT) on September 30, 2009, and March 1, 2010. Raised beds were 1.5 m apart, and each plot contained 20 tomato plants spaced 0.50 m apart in the row. Plants were staked and tied as needed during the season. Ordinary flood irrigation was provided according to the water requirements of the crops. No herbicides were applied in order to evaluate the effect of the different treatments in controlling weeds. Insecticides and fungicides were applied weekly beginning 3 WAT following current recommended practices (*17*).

In both tomato growth seasons, plant heights were measured from 10 plants per plot at 30 and 50 days after transplanting (DAT). Plant vigor was evaluated at 8 WAT and visually assessed using a percentage scale, where 100% represented optimum plant vigor and 0% indicated plant death. The number of plants per plot that had died due to soilborne diseases was counted on several occasions prior to harvest, and the total number of dead plants per plot was recorded. Nematode populations were determined at 20, 40, and 60 DAT by extracting soil samples with a soil probe (2.5 cm wide by 20 cm deep) from the rhizosphere of 10 tomato plants per plot, and the nematodes were separated by genera and counted from 100 cm^3 of soil using a standard sieving and centrifugation procedure (*18*). *M. incognita* root galling index was determined at 14 WAT by digging the roots of six plants per plot and evaluating root damage using a 0−10 scale, where 0 = no galls and 10 = 100% of roots galled (*19*). Emerged weed populations were counted over the whole area of each experimental unit at 4 WAT. Marketable tomato fruits were harvested twice (12 and 14 WAT), which is a typical practice in northern China greenhouses and graded according to current market standards into the extra large, large, and medium categories.

Prior to analysis, data expressed as percentages were arcsine transformed to homogenize variances. Sources of variation were treatments and blocks. The effects of different fumigation treatments were examined using analysis of variance (ANOVA), and when the *F* test was significant at $P < 0.05$, treatment means were compared using the Student−Newman−Keuls test (SPSS, version 13.0 for Windows).

RESULTS

Tomato Plant Height and Vigor. Fumigation programs significantly affected tomato plant vigor and height, where ratings were increased compared to untreated controls (**Table 1**). In the 2009−2010 experiment, the highest tomato plant heights were obtained in plots treated with MeBr (46.2 cm, 30 DAT) and 1,3-D at the dose of 90 L ha^{-1} (78.8 cm, 50 DAT), respectively. Other 1,3-D and MeBr treatments had intermediate height, better than the avermectin and the nontreated control. An unusually early freeze (−5.6 °C) occurred on November 8, 2009, doing visible damage to plants in the 1,3-D (doses of 120 and 180 L ha^{-1}) and MeBr treatment plots, and led to the result that higher 1,3-D dose and MeBr treatments had lower plant height. In the 2010−2011 experiment, the highest plant heights were both in plots treated with MeBr (45.3 and 118.4 cm); however, the heights of plants treated with 1,3-D at doses of 180 and 120 L ha^{-1} matched those from MeBr on both sampling dates in that test.

Tomato plant vigor had the same trend as plant height. The highest tomato plant vigor was obtained in plots treated with MeBr (90 and 92) in both growth seasons, and there was a significant positive relationship between plant vigor and 1,3-D dose except for the data obtained after the freeze in the 2009−2010 experiment. Also, all 1,3-D treatments had higher plant vigor than the avermectin treatment, which was better than the nontreated control (**Table 1**).

Table 1. Effect of Fumigation Programs on Tomato Plant Height and Vigor

fumigation program[a]	dose per ha	plant height[b] (cm)		plant vigor[c]
		30 DAT	50 DAT	
2009−2010 Experiment				
MeBr	400 kg	46.2 a	75.6 a	90 a
1,3-D	180 L	45. 6 a	75.3 a	86 a
1,3-D	120 L	45.5 a	76.1 a	82 b
1,3-D	90 L	42.5 b	78.8 a	88 a
avermectin	7.5 L	43.9 b	72.1 ab	80 b
control		35.1 c	65.1 b	71 c
2010−2011 Experiment				
MeBr	400 kg	45.3 a	118.4 a	92 a
1,3-D	180 L	43.4 a	116.7 a	90 a
1,3-D	120 L	39.6 ab	107.2 ab	87 a
1,3-D	90 L	31.0 bc	95.3 bc	77 b
avermectin	7.5 L	32.2 bc	92.6 c	75 b
control		29.6 c	92.2 c	72 c

[a] MeBr, methyl bromide; 1,3-D, 1,3-dichloropropene. [b] DAT, days after transplanting; WAT, weeks after transplanting. Tomato plant height was collected at 30 and 50 DAT in two growing seasons. Data are arithmetic means of five replications and means separated with Student−Newman−Keuls test ($P < 0.05$). Values followed by the same letter did not differ at the 5% significance level. [c] Plant vigor was collected at 8 WAT, using a 0−100% scale, where 0% = plant death and 100% = optimum growth. Data are arithmetic means of five replications and means separated with Student−Newman−Keuls test ($P < 0.05$).

Plant-Parasitic Nematode. Nematode infestations were evaluated at 20, 40, and 60 DAT and 14 WAT using a standard sieving and centrifugation procedure and calculating the root galling index, separately. *M. incognita* was isolated, but other kinds of nematodes were below detectable levels. The results confirmed the excellent nematicide activity of 1,3-D. In the 2009−2010 experiment, there were no significant fumigant effects on the number of nematodes in 100 cm^3 of soil and root galling index (data not shown) (**Table 2**). Treatments involving 1,3-D and MeBr were effective in lowering population levels of root-knot nematodes. Tomatoes grown in the untreated plots had the greatest number of nematodes and the highest root galling index (5.02). Nematode populations and galling from root-knot nematodes were light in 2009−2010, but had increased in all plots in 2010−2011, with fairly severe levels in control plots (8.49).

Table 2. Effect of Fumigation Programs on Number of Nematodes (*M. incognita*) in Soil and Root Galling

fumigation program[a]	dose per ha	nematodes[b] (100 cm^{-3} of soil) 20 DAT	40 DAT	60 DAT	root galling index[c]
		2009−2010 Experiment			
MeBr	400 kg	0.9 b	1.8 b	2.1 b	0.68 b
1,3-D	180 L	1.0 b	1.8 b	2.0 b	0.66 b
1,3-D	120 L	1.8 b	0.7 b	7.3 b	1.34 ab
1,3-D	90 L	2.0 b	1.0 b	8.8 b	2.66 ab
avermectin	7.5 L	3.0 b	3.5 ab	9.8 b	4.00 ab
control		11.3 a	5.8 a	25.5 a	5.02 a
		2010−2011 Experiment			
MeBr	400 kg	0.8 c	0.3 c	12.4 c	1.24 d
1,3-D	180 L	1.0 c	0.3 c	12.3 c	1.02 d
1,3-D	120 L	4.0 b	0.7 c	19.7 b	1.92 cd
1,3-D	90 L	8.0 ab	1.3 c	24.0 b	3.28 c
avermectin	7.5 L	5.5 b	4.5 b	21.8 b	7.35 b
control		12.5 a	12.5 a	46.0 a	8.49 a

[a] MeBr, methyl bromide; 1,3-D, 1,3-dichloropropene. [b] DAT, days after transplanting; WAT, weeks after transplanting. Nematodes (*Meloidogyne incognita* (Kofoid & White) Chitwood) in 100 cm^3 soil were collected at 20, 40, and 60 DAT using a standard sieving and centrifugation procedure in two growing seasons. Data are arithmetic means of five replications and transformed with arc sine square root and means separated with Student−Newman−Keuls test ($P < 0.05$). Values followed by the same letter did not differ at the 5% significance level. [c] Nematode root galling index collected at 14 WAT obtained using a 0−10 scale, where 0 = no galls and 10 = 100% of roots galled. Data transformed with arc sine square root and means separated with Student−Newman−Keuls test ($P < 0.05$).

Table 3. Effect of Fumigation Programs on Number of Dead Plants and Weed Populations

fumigation program[a]	dose per ha	total dead plants per plot[b]	weed populations per plot[c] *A. serpyllifolia*	*D. sanguinalis*	*C. bursa-pastoris*	total
MeBr	400 kg	7.4 d	8.5 e	4.5 c	4.8 d	17.8 d
1,3-D	180 L	8.1 cd	11.5 d	8.8 b	6.0 c	26.3 c
1,3-D	120 L	10.4 c	14.5 c	13.3 ab	11.5 b	39.3 b
1,3-D	90 L	11.5 bc	17.0 bc	16.0 a	14.5 ab	47.5 a
avermectin	7.5 L	12.3 ab	19.5 ab	14.0 a	12.8 ab	46.3 a
control		13.7 a	21.3 a	16.5 a	15.8 a	53.5 a

[a] MeBr, methyl bromide; 1,3-D, 1,3-dichloropropene. [b] Total dead plants per plot was counted on several occasions prior to harvest. Data are arithmetic means of five replications and means separated with Student−Newman−Keuls test ($P < 0.05$). Values followed by the same letter did not differ at the 5% significance level. [c] WAT, weeks after transplanting; *A. serpyllifolia*, *Arenaria serpyllifolia* L.; *D. sanguinalis*, *Digitaria sanguinalis* (Linn.) Scop.; *C. bursa-pastoris*, *Capsella bursa-pastoris* (L.) Medic. Weed populations were collected at 4 WAT. Data are arithmetic means of five replications and means separated with Student−Newman−Keuls test ($P < 0.05$).

In contrast, 1,3-D at the dose of 180 L ha^{-1} was the most effective treatment for reducing galling from root-knot nematodes in both seasons (0.66 and 1.02) (**Table 2**). Avermectin treatment made some headway in efforts to reduce nematode population and root galling, but could not match those of 1,3-D or MeBr.

Number of Dead Plant and Weed Population. There were no significant treatment by planting season interactions; thus, data from two seasons were combined for analysis and interpretation.

Many plants showed symptoms and died from soilborne disease. The major factor causing death was withering due to *Botrytis cinerea*. Mortality was initially greatest in the nontreated control plots and progressed quickly into plots treated with avermectin. By the end of the experiments, only the MeBr and the maximum dose of 1,3-D treatment protected the plants and significantly reduced plant mortality (**Table 3**).

The predominant grasses present were *Capsella bursa-pastoris* (L.) Medic., *Digitaria sanguinalis* (Linn.) Scop, and *Arenaria serpyllifolia* L. Effects of fumigation programs on different weed populations exhibited a similar trend. Weeds in plots treated with MeBr were greatly suppressed and had the least population; however, other treatments, including all three 1,3-D doses, could not match the efficiency of MeBr (**Table 3**).

Tomato Marketable Yield. Tomato fruit weight per category and total changed with fumigation programs are shown in **Table 4**. In the 2009−2010 experiment, the highest yield of extra large fruit (5.2 t ha^{-1}) was obtained in the MeBr treatment and 1,3-D treatment at the dose of 180 L ha^{-1}, whereas the lowest was achieved in the nontreated control (1.3 t ha^{-1}). Other treatments produced yields ranging between 2.8 and 4.4 t ha^{-1} within the same fruit category. There were no significant differences among the fumigants in the large and medium fruit categories of the MeBr and the maximum dose of 1,3-D treatment. A similar trend was observed for total marketable fruit yield, where the highest yield (49.0 t ha^{-1}) was produced in the MeBr treatment plots; however, the higher 1,3-D doses matched the yield from MeBr.

Yields were higher in 2010−2011 than in 2009−2010, but trends were similar, with maximum weight of extra large, large, and medium categories produced in plots treated with MeBr (**Table 4**). However, in this growth season, performances of the 1,3-D treatment at the dose of 180 L ha^{-1} and the MeBr treatments were similar in all terms. On the other hand, a lower dose of 1,3-D showed moderate performance on all three categories and total yields, better than the avermectin treatment and the nontreated control (**Table 4**).

DISCUSSION

Use of fumigant is an essential practice to protect many crops from nematodes, weeds, and soilborne pathogens, which are important considerations for any MeBr replacement. Our experiment revealed that 1,3-D was effective in the suppression

Table 4. Effect of Fumigation Programs on Tomato Marketable Yields

fumigation program[a]	dose per ha	extra large (t ha^{-1})	large (t ha^{-1})	medium (t ha^{-1})	marketable (t ha^{-1})
		2009−2010 Experiment			
MeBr	400 kg	5.2 a[b]	14.3 a	29.5 a	49.0 a
1,3-D	180 L	5.2 a	14.6 a	28.3 ab	48.1 a
1,3-D	120 L	2.8 c	14.1 ab	26.1 b	46.3 ab
1,3-D	90 L	4.0 b	12.9 c	29.4 a	43.0 b
avermectin	7.5 L	4.4 b	12.3 c	26.6 b	43.3 b
control		1.3 d	12.8 c	22.3 c	36.4 c
		2010−2011 Experiment			
MeBr	400 kg	15.3 a	42.3 a	85.8 a	143.4 a
1,3-D	180 L	14.8 a	41.7 a	82.3 a	138.8 ab
1,3-D	120 L	12.5 b	34.9 b	71.1 b	118.5 b
1,3-D	90 L	11.7 bc	34.6 b	69.7 b	116.0 b
avermectin	7.5 L	8.9 c	32.3 b	64.1 b	105.3 c
control		6.2 d	18.2 c	37.6 c	62.0 d

[a] MeBr, methyl bromide; 1,3-D, 1,3-dichloropropene. [b] Numbers in the same column followed by the same letter are not significantly different according to Student−Newman−Keuls test ($P < 0.05$).

of nematodes, soilborne pathogens, and weed while maintaining high tomato marketable yields.

On the basis of our field results, MeBr and 1,3-D treatments were very effective in enhancing plant height and vigor, in contrast with the traditional avermectin treatment and the non-treated control. Affected by the early freeze (−5.6 °C) occurring on November 8, 2009, the data of the 2009−2010 experiment did not show the typical tendency but resulted in a higher 1,3-D dose with a lower plant height. However, in the next growth season, data exhibited a normal trend that a positive relationship existed between 1,3-D dose and plant height and vigor.

Our study also found that increasing rates of 1,3-D resulted in reduced numbers of nematodes in soil and lower root galling index, which confirmed the excellent nematicide activity of 1,3-D. Some studies have emphasized the efficiencies of 1,3-D in controlling nematodes on different crops (*20*, *21*). Gilreath et al. found 1,3-D could provide good nematode control in tomato crop, and it was also proved to be effective against root galling by Wang et al. in *Bellis perennis* L. (*22*, *23*).

On the issue of soilborne pathogens and weeds, our previous field trials found 1,3-D played a role in promoting plant growth, which we attributed to the result that 1,3-D provided some effects on pathogen and weed control. The literature on the effects of 1,3-D on soilborne pathogens is mixed, and many earlier papers presented 1,3-D as being effective against soilborne pathogens such as *Fusarium oxysporum* and *Verticillium dahliae* (*24*, *25*). A recent study reported that the 1,3-D gelatin capsule showed efficacy to soil pathogens such as *Phytophthora* spp. and *Fusarium* spp., although it was lower than the nematode control effect (*23*). However, more studies showed that 1,3-D did not control many soilborne fungal pathogens or troublesome weeds such as *C. rotundus* and *C. esculentus* (*26*−*28*). Our field trial results also indicated that 1,3-D could offer only moderate control performance to pathogens and weeds, which is consistent with the former research.

After all, the ultimate judgment on the success of the alternative to the MeBr system depends on crop yield. Although the unusually early freeze affected the yield data of the 2009−2010 experiment, resulting in a relatively low yield in this growth season, overall, our results indicated that all treatments had a positive effect on tomato yield, and a higher 1,3-D dose could reach the same marketable yield level as MeBr. The result in this research with 1,3-D agreed with previous studies (*16*, *29*), and this also proved that 1,3-D was a promising alternative to MeBr.

However, currently no single chemical or nonchemical method can exhibit the efficiency of MeBr (*30*). 1,3-D is known to be effective against nematodes and soilborne insects but relatively weak for the control of soilborne fungal pathogens and weeds (*31*). Therefore, it is necessary to combine 1,3-D with other nonchemical alternatives and chemical replacements for MeBr to reach an integrated control and match MeBr's efficiency and cost. Gilreath and Santos reported that the herbicides napropamide plus trifluralin in pre-emergence and postdirected trifloxysulfuron in combination with either CP and fosthiazate or 1,3-D+CP and MNa proved to be effective means to suppress root galling and *Cyperus* interference while maintaining high tomato yield (*6*). The use of totally impermeable film (TIF) and virtually impermeable film (VIF) would allow greater retention of 1,3-D than the conventional polyethylene (PE) mulch, trapping the fumigant for a longer period near the soil surface and thereby increasing the dose and prolonging the exposure of nematodes, weed seeds, and pathogens to the fumigant (*32*, *33*). Recent field studies showed that Telone C-35 provided equivalent pest control and crop yield as MeBr under metalized polyethylene film mulch (*34*).

In conclusion, the results of this study suggested that 1,3-D was an excellent nematicide with good to moderate soilborne pathogen control efficiency but relatively weak in weeds. On the basis of our results, 1,3-D, in combination with other alternatives to MeBr, is recommended to achieve integrated pest management. However, more detailed studies on its application rate, duration between applications, and planting under field conditions are necessary before it could be recommended as a routine practice for agricultural production in China.

LITERATURE CITED

(1) Bailey, D. J.; Kleczkowski, A.; Gilligan, C. A. Epidemiological dynamics and the efficiency of biological control of soil-borne disease during consecutive epidemics in a controlled environment. *New Phytol.* **2004**, *161*, 569−575.
(2) Gilligan, C. A.; Simons, S. A.; Hide, G. A. Inoculum density and spatial pattern of *Rhizoctonia solani* in field plots of *Solanum tuberosum*: effects of cropping frequency. *Plant Pathol.* **1996**, *45*, 232−244.
(3) Hide, G. A.; Read, J. Effects of rotation length, fungicide treatment of tubers and nematocide on diseases and the quality of potato tubers. *Ann. Appl. Biol.* **1991**, *119*, 77−87.
(4) Ajwa, H. A.; Trout, T.; Mueller, J.; Wilhelm, S.; Nelson, S. D.; Soppe, R.; Shatley, D. Application of alternative fumigants through drip irrigation systems. *Phytopathology* **2002**, *92*, 1349−1355.

(5) Díaz-Pérez, M.; Camacho-Ferre, F.; Diánez-Martínez, F.; De Cara-García, M.; Tello-Marquina, J. C. Evaluation of alternatives to methyl bromide in melon crops in Guatemala. *Microb. Ecol.* **2009**, *57*, 379–383.

(6) Gilreath, J. P.; Santos, B. M. Managing weeds and nematodes with combinations of methyl bromide alternatives in tomato. *Crop Prot.* **2008**, *27*, 648–652.

(7) Johnson, W. C.; Mullinix, B. G. Cultural control of yellow nutsedge (*Cyperus esculentus*) in transplanted cantaloupe (*Cucumis melo*) by varying application timing and type of thin-film mulches. *Crop Prot.* **2008**, *27*, 735–739.

(8) Ajwa, H. A.; Klose, S.; Nelson, S. D.; Minuto, A.; Gullino, M. L.; Lamberti, F.; López-Aranda, J. M. Alternatives to methyl bromide in strawberry production in the United States of America and the Mediterranean region. *Phytopathol. Mediterr.* **2003**, *42*, 220–244.

(9) Santos, B. M.; Gilreath, J. P. Tomato nutrient absorption and nutsedge and sting nematode management with propylene oxide. *Proc. Fla. State Hortic. Soc.* **2005**, *118*, 166–168.

(10) Shi, K.; Wang, L.; Zhou, Y. H.; Yu, Y. L.; Yu, J. Q. Effects of calcium cyanamide on soil microbial communities and *Fusarium oxysporum* f. sp. *cucumberinum*. *Chemosphere* **2009**, *75*, 872–877.

(11) McSorley, R.; Wang, K.-H.; Rosskopf, E. N.; Kokalis-Burelle, N.; Hans Petersen, H. N.; Gill, H. K.; Krueger, R. Nonfumigant alternatives to methyl bromide for management of nematodes, soil-borne disease, and weeds in production of snapdragon (*Antirrhinum majus*). *Int. J. Pest Manage.* **2009**, *55*, 265–273.

(12) Ślusarski, C.; Pietr, S. J. Combined application of dazomet and *Trichoderma sperellum* as an efficient alternative to methyl bromide in controlling the soil-borne disease complex of bell pepper. *Crop Prot.* **2009**, *28*, 668–674.

(13) Smith, R. F.; Bendixen, W. E.; Fennimore, S. A. *University of California Integrated Pest Management Pest Mangement Guidelines: Strawberry*; Publication 3339; Division of Agriculture and Natural Resources, University of California: Los Angeles, CA, 2001.

(14) Talavera, M.; Verdejo-Lucas, S.; Ornat, C.; Torres, J.; Vela, M. D.; Macias, F. J.; Cortada, L.; Arias, D. J.; Valero, J.; Sorribas, F. J. Crop rotations with *Mi* gene resistant and susceptible tomato cultivars for management of root-knot nematodes in plastic houses. *Crop Prot.* **2009**, *28*, 662–667.

(15) Santos, B. M.; Gilreath, J. P.; Motis, T. N.; Noling, J. W.; Jones, J. P.; Norton, J. A. Comparing methyl bromide alternatives for soilborne disease nematode and weed management in fresh market tomato. *Crop Prot.* **2006**, *25*, 690–695.

(16) López-Aranda, J. M.; Miranda, L.; Medina, J. J.; Soria, C.; de los Santos, B.; Romero, F.; Perez-Jimenez, R. M.; Talavera, M.; Fennimore, S. A.; Santos, B. M. Methyl bromide alternatives for high tunnel strawberry production in southern spain. *HortTechnology* **2009**, *19*, 187–192.

(17) Maynard, D. N.; Hochmuth, G. J.; Olson, S. M.; Vavrina, C. S.; Stall, W. M.; Kucharek, T. A.; Webb, S. E.; Taylor, T. G.; Smith, S. A. Tomato production in Florida. In *Vegetable Production Guide for Florida, 2002–2003*; Olson, S. M., Maynard, D. N., Eds.; IFAS, University of Florida: Gainesville, FL, 2003; pp 259–270.

(18) Jenkins, W. R. A rapid centrifugal-flotation technique for separating nematodes from soil. *Plant Dis. Rep.* **1964**, *48*, 692.

(19) Barker, K. R.; Townshend, J. L.; Bird, G. W.; Thomason, I. J.; Dickson, D. W. Determining nematode population responses to control agents. In *Methods for Evaluating Pesticides for Control of Plant Pathogens*; Hickey, K. D., Ed.; APS Press: St. Paul, MN, 1986; pp 283–296.

(20) Himelrick, D. G.; Dozier, W. A. Soil fumigation and soil solarization in strawberry production. *Adv. Strawberry Prod.* **1991**, *10*, 12–28.

(21) Kinloch, R. A.; Rich, J. R. Management of root-knot and reniform nematode in ultra-narrow row cotton with 1,3-dichloropropene. *Suppl. J. Nematol.* **2001**, *33*, 311–313.

(22) Gilreath, J. P.; Noling, J. W.; Santos, B. M. Methyl bromide alternatives for pepper (*Capsicum annuum*) and cucumber (*Cucumis sativus*) rotations. *Crop Prot.* **2004**, *23*, 347–351.

(23) Wang, Q.; Song, Z.; Tang, J.; Yan, D.; Wang, F.; Zhang, H.; Guo, M.; Cao, A. Efficacy of 1,3-dichloropropene gelatin capsule formulation for the control of soilborne pests. *J. Agric. Food Chem.* **2009**, *57*, 8414–8420.

(24) Zhou, K.; Wang, Q.; Zhang, L.; Xia, J. Observation on the growth and decline of the causal organism of cotton *Fusarium* and *Verticillium* wilt in the treated soil with eradicants. *J. Shandong Agric. Univ.* **1984**, *15*, 41.

(25) Wang, Q.; Zhang, L.; Zhou, K.; Wu, X.; Xia, J. Study on cotton spots of *Fusarium* and *Verticillium* wilt in the treated soil with the D-D emulsion. *Shandong Agric. Sci.* **1985**, *3*, 18.

(26) Csinos, A. S.; Johnson, W. C.; Johnson, A. W.; Sumner, D. R.; McPherson, R. M.; Gitaitis, R. D. Alternative fumigants for methyl bromide in tobacco and pepper transplant production. *Crop Prot.* **1997**, *16*, 585–594.

(27) Gilreath, J. P.; Santos, B. M.; Noling, J. W.; Locascio, S. J.; Dickson, D. W.; Rosskopf, E. N.; Olson, S. M. Performance of containerized and bare-root transplants with soil fumigants for Florida strawberry production. *HortTechnology* **2006**, *16*, 461–465.

(28) Haar, M. J.; Fennimore, S. A.; Ajwa, H. A.; Winterbottom, C. Q. Chloropicrin effect on weed seed viability. *Crop Prot.* **2003**, *22*, 109–115.

(29) Gilreath, J. P.; Santos, B. M. Methyl bromide alternatives for weed and soilborne disease management in tomato (*Lycopersicon esculentum*). *Crop Prot.* **2004**, *23*, 1193–1198.

(30) Yates, S. R.; Gan, J.; Papiernik, S. K.; Dungan, R.; Wang, D. Reducing fumigant emissions after soil application. *Phytopathology* **2002**, *92*, 1344–1348.

(31) Noling, J. W.; Becker, J. O. The challenge of research and extension to define and implement alternatives to methyl bromide. *J. Nematol.* **1994**, *26*, 573–586.

(32) Fennimore, S. A.; Kabir, Z.; Ajwa, H. A.; Daugovish, O.; Roth, K. Chloropicrin and InLine lethal dose on nutsedge and knotweed under impermeable film. *Proceedings Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions*, Oct 31–Nov 3 2005, San Diego, CA, **2005**; Abstract 54, pp 1–4.

(33) Ou, L.-T.; Thomas, J. E.; Allen, L. H., Jr.; Vu, J. C.; Dickson, D. W. Comparison of surface emissions and subsurface distribution of *cis*- and *trans*-1,3-dichloropropene and chloropicrin in sandy field beds covered with four different plastic films. *J. Environ. Sci. Health B* **2008**, *43*, 376–381.

(34) Thomas, J. E.; Ou, L.; Allen, L. H., Jr.; Vu, J. C.; Dickson, D. W. Nematode, fungi, and weed control using Telone C35 and colored plastic mulches. *Crop Prot.* **2009**, *28*, 338–342.

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