JOURNAL OF AGRICULTURAL AND FOOD CHEMISTRY

ARTICLE

pubs.acs.org/JAFC

Managing Root-Knot Nematodes and Weeds with 1,3-Dichloropropene As an Alternative to Methyl Bromide in Cucumber Crops in China

Kang Qiao,[†] Xugen Shi,[†] Hongyan Wang,[‡] Xiaoxue Ji,[§] and Kaiyun Wang*[,†]

[†]Department of Plant Protection, Shandong Agricultural University, Tai'an, Shandong 271018, People's Republic of China

[‡]Cotton Research Center, Shandong Academy of Agricultural Sciences, Jinan, Shandong 250100, People's Republic of China

[§]Plant Protection and Inspection Station of Feicheng, Feicheng, Shandong 271600, People's Republic of China

ABSTRACT: 1,3-Dichloropropene (1,3-D) was evaluated as a potential alternative for the widely used soil fumigant methyl bromide (MeBr) in cucumber (*Cucumis sativus* Linn.) crops in China. Six treatments were replicated five times in a randomized complete block design: fumigation with MeBr (400 $kg \cdot ha^{-1}$), three 1,3-D doses (90, 120, and 180 $L \cdot ha^{-1}$), an avermectin dose (7.5 $L \cdot ha^{-1}$), and a nontreated control. Results consistently indicated that MeBr was generally superior to the treatments involving all 1,3-D and avermectin, which in turn were superior to the control, for improving cucumber yield and to control nematode and weed. In two successive seasons, 1,3-D at a dose of 180 $L \cdot ha^{-1}$ was as effective as MeBr in increasing plant height, vigor, and yield, as well as showed excellent nematode control efficiency, but it had relatively poor potency to control weeds. The present data support the conclusion that 1,3-D is a promising MeBr alternative for managing nematodes and weeds in cucumber crops and can be used in integrated pest management programs.

KEYWORDS: 1,3-Dichloropropene, methyl bromide alternatives, nematode, weed control, cucumber

INTRODUCTION

Cucumber (*Cucumis sativus* Linn.) is one of the economically most important vegetables in China, which accounts for 5.4% of the total vegetable cultivation area.[1] In recent years, yield losses have been strongly associated with root-knot nematode (RKN) of *Meloidogyne* spp. and weeds, the invasion of which are high when crops are grown under intensive regimens.[2] At present, the standard treatment for management of nematodes and weeds in many high-value crop production systems is preplant soil fumigation with methyl bromide (MeBr). However, developing countries are committed to totally phasing out MeBr production and use by 2015 due to its detrimental effects on stratospheric ozone.[3] The absence of MeBr from the market will impact agricultural, silvicultural, and horticultural production unless safe and efficacious alternatives are found.

Several alternative fumigants have been suggested as MeBr replacements for high-value fruit, nut, and vegetable crops and tested in field experiments to evaluate their efficacy against nematodes and weeds.[4−6] Currently registered alternatives to MeBr are 1,3-dichloropropene (1,3-D),[7,8] chloropicrin (CP), methyl isothiocyanate (MITC) generators such as Metam sodium (MNa) and Dazomet, methyl iodide (iodomethane),[9] calcium cyanamide ($CaCN_2$),[10] and combinations of these products. Meanwhile, a variety of nonfumigant methods are also available for managing plant-parasitic nematodes and weeds, such as grafting,[11,12] soil solarization,[13,14] and biocontrol agents.[15,16]

As a well-known nematicide with fungicidal and insecticidal activity, 1,3-D has been registered in many countries.[17] Most reports about 1,3-D have been concerned with its excellent nematodes control efficacy on different crops with or without CP (1,3-D + CP),[18,19] its distribution and emission after application,[20−22] and its degradation characteristics.[23] For example, the half-life of 1,3-D ranges from a few days (minimum 0.3 days) to a few weeks (maximum 38.5 days), depending on soil microbial activity, type, moisture, and temperature.[24] Some reports suggested that phytotoxic effects of 1,3-D could inhibit the rhizome tissue and shoot development of weeds to control them.[25] For people, 1,3-D is a strong skin irritant and a potential inhalation hazard, requiring personal protective equipment when applied in liquid form.[22] However, little information on pest control and crop productivity in cucumber crop production systems has been reported.

Due to the limitation by the current level of economic development, 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 a preplant fumigant in China. Our research, conducted in the field, was designed to ascertain the efficiency of 1,3-D as a MeBr alternative in cucumber crops and evaluate its applicability in China.

MATERIALS AND METHODS

Field trials were established in August 2008 and February 2009 in two successive cropping seasons in a commercial farm near Beiteng country, Tai'an city, Shandong province, China. The farm had been in conventional crop production for 10 years before the start of the experiment. The soil at the experimental site was a silt loam, composed of 15% sand, 80% silt, and 5% clay, with organic matter content 24.8 $g \cdot kg^{-1}$ soil, pH 7.2, and soil density 1.21 $g \cdot cm^{-3}$. The selected experimental site had a

Received: November 26, 2010
Accepted: February 11, 2011
Revised: February 10, 2011
Published: March 02, 2011

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history of heavy natural *Meloidogyne incognita* (Kofoid and White) Chitwood (southern root-knot nematode) and weeds 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 as follows: (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}, and nontreated control. Fumigant application rates were based on previous studies and label application directions for them used in the field.[7,33]

Each plot was irrigated with 1.3 cm of water the day before fumigation to allow for better bedding. On the day of fumigation (August 7, 2008), 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 0.70 m apart on center. Avermectin was root pouring applied to the soil and immediately incorporated 0.20 m through disking and then bedded as described above. Immediately after fumigant application, beds were pressed and covered with 0.025 mm high-density polyethylene mulch (HDPE) film.

Plastic films were removed from the site 2 weeks after application. Then 4-week-old Jinyou 3 cucumber transplants (Kerun Agricultural Science Co., Ltd., Tianjin, China) were transplanted into the top of the beds on August 21, 2008 and February 3, 2009. Raised beds were 1.50 m apart, and each plot contained 25 crop 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 weeks after transplanting (WAT) following current recommended practices.[26] Among the fallow between the two crops, the field received a broadcast application of 50 t·ha^{-1} of farmyard manure to make the soil fertile and a flood irrigation to dilute autotoxicity of cucumbers.

In cucumber 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. 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 cucumber plants per plot; then nematodes were separated by genera and counted from 100 cm^3 of soil using a standard sieving and centrifugation procedure.[27] *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.[28] Emerged weeds were identified and counted in one or two subsamples in each main plot unit at 6 WAT and standardized to a 1 m^2 area. Shortly after the weed counts were completed, plots were handweeded, and total handweeding time for each main plot was recorded.[29] In all the trials, the crop yields obtained from the different treatments were evaluated and graded according to current market standards (cucumber length) into the large (>30 cm), medium (25−30 cm), and small (<25 cm) 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).

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

fumigation program	dose per ha	plant height[a] (cm) 30 DAT	50 DAT	plant vigor[b]
		2008−2009 experiment		
MeBr	400 kg	106.7 a	136.2 a	93 a
1,3-D	180 L	103.9 a	135.7 a	91 a
1,3-D	120 L	95.8 b	124.8 b	85 ab
1,3-D	90 L	91.2 b	118.6 b	79 b
avermectin	7.5 L	84.5 c	107.4 c	71 c
control		80.2 c	102.5 c	69 c
		2009−2010 experiment		
MeBr	400 kg	118.3 a	152.4 a	94 a
1,3-D	180 L	115.4 a	152.7 a	92 a
1,3-D	120 L	106.7 b	142.8 ab	88 a
1,3-D	90 L	98.9 b	135.6 b	86 b
avermectin	7.5 L	88.9 bc	135.3 b	79 bc
control		80.4 c	123.2 c	71 c

[a] Cucumber plant height was determined 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. [b] Plant vigor was determined 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 ($P < 0.05$).

RESULTS

Plant Height and Vigor. In the 2008−2009 experiment, the highest plant heights were both obtained in plots treated with 400 kg·ha^{-1} of MeBr (106.7 cm, 30 DAT and 136.2 cm, 50 DAT). However, there was no statistical difference between plant height from treatment with MeBr and the highest dose of 1,3-D. Other treatments resulted in a plant height intermediate between that obtained from the MeBr treatments and the untreated control. It was observed that results of these treatments on cucumber plant vigor followed a similar trend to the plant height. The highest plant vigor was obtained in plots treated with MeBr (93%), while a dose-dependent relationship between plant vigor and 1,3-D was observed. Also, an intermediate dose of 1,3-D had higher plant vigor than the minimum dose of 1,3-D and avermectin. In the 2009−2010 experiment, the highest plant height was obtained in plots treated with MeBr (118.3 cm, 30 DAT) and 1,3-D at a dose of 180 L·ha^{-1} (152.7 cm, 50 DAT), respectively. Plant vigor exhibited a similar trend as last season: the highest plant vigor was obtained in plots treated with MeBr (94%), followed by 180 L·ha^{-1} of 1,3-D and then 120 L·ha^{-1} of 1,3-D with nonsignificant. Also, all 1,3-D treatments had higher plant vigor than the avermectin treatment, which was better than the nontreated control (Table 1).

Control of Plant-Parasitic Nematode. Fumigation programs significantly affected the nematode population and root galling index (Table 2). In both crop growing seasons, nematode infestations were evaluated at 20, 40, and 60 DAT and 14 WAT

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

fumigation program	dose per ha	nematodes 100 cm^{-3} soil[b] 20 DAT	40 DAT	60 DAT	root galling index[c]
		2008−2009 experiment			
MeBr	400 kg	4.4 c	5.8 c	4.7 c	1.48 c
1,3-D	180 L	3.8 c	4.6 c	3.7 c	1.16 c
1,3-D	120 L	6.5 c	11.3 c	10.6 b	1.84 c
1,3-D	90 L	12.1 b	20.6 b	18.7 b	2.36 b
avermectin	7.5 L	13.6 b	23.5 b	16.2 b	3.63 b
control		43.5 a	51.3 a	46.5 a	6.43 a
		2009−2010 experiment			
MeBr	400 kg	14.7 c	13.3 d	13.4 c	2.26 cd
1,3-D	180 L	7.8 d	8.3 e	5.5 d	1.48 d
1,3-D	120 L	16.3 c	15.2 d	12.4 c	2.52 cd
1,3-D	90 L	22.6 c	25.6 c	18.2 c	3.43 c
avermectin	7.5 L	32.8 b	43.6 b	38.1 b	7.12 b
control		64.3 a	71.7 a	76.9 a	8.35 a

[a] *M. incognita* = *Meloidogyne incognita* (Kofoid and White) Chitwood. [b] Nematodes (*M. incognita*) in 100 cm^3 soil were counted 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 determined 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 Handweeding Time and Weed Populations

fumigation program[a]	dose per ha	handweeding time per plot ($h \cdot ha^{-1}$)[b]	weed populations per plot[c] *E. indica*	*D. sanguinalis*	*P. oleracea*	total
MeBr	400 kg	45.1 d	5.7 e	5.4 d	6.4 d	17.5 e
1,3-D	180 L	52.3 cd	13.2 d	8.7 c	11.0 bc	32.9 d
1,3-D	120 L	60.4 c	16.2 c	15.3 b	13.2 b	44.7 c
1,3-D	90 L	81.5 c	19.4 bc	16.8 b	14.9 b	51.1 bc
avermectin	7.5 L	122.6 b	21.5 ab	16.0 b	18.7 ab	56.2 b
control		213.3 a	24.6 a	21.5 a	25.8 a	71.9 a

[a] WAT = weeks after transplanting, *E. indica* = *Eleusine indica* (L.) Gaertn., *D. sanguinalis* = *Digitaria sanguinalis* (Linn.) Scop., *P. oleracea* = *Portulaca oleracea* L.. [b] Handweeding time per plot was determined 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] Weed populations were determined at 6 WAT. Data are arithmetic means of five replications and means separated with Student−Newman−Keuls test ($P < 0.05$).

using a standard sieving and centrifugation procedure and calculating the root galling index separately. *M. incognita* was isolated, but the counts of other kinds of nematodes were at low levels. The results confirmed the excellent nematicide activity of 1,3-D. Treatments involving 1,3-D and MeBr were effective in lowering population levels of root-knot nematodes. Cucumbers grown in the untreated plots had the greatest number of nematodes and the highest root galling index in two growing seasons (6.43 and 8.35). Nematode populations and galling from root-knot nematodes were light in 2008−2009, compared to that in the 2009−2010 season. It was found that 1,3-D at a dose of 180 $L \cdot ha^{-1}$ was the most effective treatment for reducing galling from root-knot nematodes in both seasons (1.16 and 1.48) (Table 2). On the other hand, avermectin treatment made some headway in efforts to reduce nematode population and root galling but could not match those of a higher dose of 1,3-D or MeBr, especially in the 2009−2010 season.

Weed Population. Because there were no significant between the two seasons, data from two seasons were combined for analysis and interpretation. Handweeding time was substantially reduced by all treatments compared with the untreated control (Tables 3). The predominant grasses present were *Eleusine indica* (L.) Gaertn., *Digitaria sanguinalis* (Linn.) Scop, and *Portulaca oleracea* L. Handweeding time in both crop seasons followed the weed count trends; all fumigation treatments resulted in a 43−79% reduction in man hours required for the initial weeding. Effects of fumigation programs on different weed populations exhibited a similar tendency. 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).

Cucumber Marketable Yield. Cucumber fruit weight per category and total changed with fumigation programs are shown in Table 4. In the 2008−2009 experiment, the highest yield of

Table 4. Effect of Fumigation Programs on Cucumber Marketable Yields

fumigation program	dose per ha	large (g·plant^{-1})	medium (g·plant^{-1})	small (g·plant^{-1})	marketable (g·plant^{-1})
			2008−2009 experiment		
MeBr	400 kg	452.6 a[a]	947.1 a	329.5 a	1729.2 a
1,3-D	180 L	485.2 a	984.6 a	228.7 b	1698.5 a
1,3-D	120 L	392.8 b	914.1 ab	239.4 b	1546.3 ab
1,3-D	90 L	324.0 bc	842.9 b	306.4 a	1473.3 b
avermectin	7.5 L	334.4 bc	812.3 b	197.1 b	1343.8 b
control		251.3 d	702.8 c	82.3c	1036.4 c
			2009−2010 experiment		
MeBr	400 kg	572.4 a	1025.1 a	271.9 b	1869.4 a
1,3-D	180 L	525.1 a	934.2 a	362.3 a	1821.6 a
1,3-D	120 L	462.4 ab	864.4 ab	422.9 a	1749.7 ab
1,3-D	90 L	383.7 bc	812.5 b	327.5 ab	1523.7 b
avermectin	7.5 L	314.8 c	742.7 b	377.4 a	1434.9 b
control		271.7 d	652.3 c	192.6 c	1116.6 c

[a] Numbers in the same column followed by the same letter are not significantly different according to Student−Newman−Keuls test ($P < 0.05$).

large fruit was obtained in the 1,3-D treatment at a dose of 180 L·ha^{-1} (485.2 g·plant^{-1}) while the lowest was achieved in the nontreated control (251.3 g·plant^{-1}). Other treatments produced yields ranging between 324.0 and 452.6 g·plant^{-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 a maximum dose of 1,3-D treatment. A similar trend was observed for total marketable fruit yield, where the highest yield (1729.2 g·plant^{-1}) was produced in the MeBr treatment plots; however, the higher 1,3-D doses matched those from MeBr.

Yields were higher in the 2009−2010 than in the 2008−2009 season, but trends were similar, with maximum weight of large and medium categories produced in plots treated with MeBr (Table 4). However, in this growing season, there was no statistical difference between large and medium categories and total yields from treatment with MeBr and 1,3-D at a dose of 120 and 180 L·ha^{-1}. On the other hand, the lowest dose of 1,3-D showed moderate performance on all three categories and total yields, and there was no significant difference with avermectin treatment.

■ DISCUSSION

Use of fumigant is an essential practice to protect many crops from nematodes and weeds, which are important considerations for any MeBr replacement. This study demonstrated that 1,3-D was a promising MeBr alternative for managing nematodes and weeds in cucumber crops.

On the basis of our field results, MeBr and 1,3-D treatments were effective in enhancing plant height and vigor in contrast with the traditional avermectin treatment and the nontreated control. In both of the tested seasons, there was a positive relationship between 1,3-D dose and plant height and vigor. The greater effect of 1,3-D may be due to its effectiveness in preventing nematode attack of the roots, which slows plant development, and/or to its effect of increasing nitrogen mineralization which increases plant growth.[30] Further study on the promotion mechanism of 1,3-D to different crops is in progress.

Our study also found that increasing rates of 1,3-D resulted in a reduced number of nematodes in soil and lower root galling index, which confirmed the excellent nematicidal activity of 1,3-D. Although some reports showed that the nematocide control effect of 1,3-D was unstable and mutable,[30,31] many investigators ensured the efficiency of 1,3-D in controlling nematodes on different crops in the worldwide scale.[4,32] 1,3-D was used for control of potato cyst nematodes, *Globodera pallida* and *Globodera rostochiensisin* on potato crop in the United Kingdom,[32] and it was also proved to be effective against root galling by Wang et al. in *Bellis perennis* L. in China.[33]

On the issue of weeds, the soil fumigant 1,3-D, as a broad spectrum soil sterilant, affects many organisms in the soil other than nematodes.[19] However, the results were mixed. In an earlier study done by Altman and Fitzgerald,[34] reductions in weed germination and growth by the soil fumigant D-D (1,3-dichloropropene and 1,2-dichloropropane) were attributed in part to a direct effect on the weed seed and in part to shading from the more vigorous growth of beet foliage in treated plots relative to the untreated. A recent study conducted in the United Kingdom implied that 1,3-D fumigation had a suppressive effect on the weed seed bank population.[19] However, some studies revealed that 1,3-D did not control many of the troublesome weeds such as *Cyperus rotundus* and *C. esculentus*.[35,36] Our previous studies also indicated that 1,3-D could only offer moderate control performance to pathogens and weeds.[7,8] Variations in these studies may be caused by the fact that the efficacy of 1,3-D is dependent upon achieving an appropriate soil structure and moisture content at application followed by effective sealing of the soil surface to reduce loss of 1,3-D directly to the atmosphere. Differences in field conditions make the results distinct.

After all, the ultimate judgment on the success of the alternative to the MeBr system depends on crop yield. Our results indicated that all treatments had a positive effect on cucumber 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 is in agreement with previous studies, which proved that 1,3-D was a promising alternative to MeBr.[7,8,19,33,37]

However, currently no single chemical or nonchemical method can exhibit the efficiency of MeBr.[38] 1,3-D is known to be effective against nematodes and soil-borne insects but relatively weak for control of soil-borne fungal pathogens and weeds.[39]

In conclusion, the results of this study suggested that 1,3-D was an excellent nematicide with good to moderate weed control efficiency. On the basis of our results, 1,3-D, in combination with other nonchemical alternatives and chemical replacements, is recommended to reach an integrated pest management and match MeBr's efficiency and cost. However, further studies need to be carried out by considering different dosages of 1,3-D under different field conditions, duration between application, and transplanting time after application before presenting the final recommendations to use it in China.

AUTHOR INFORMATION

Corresponding Author

*Phone: 86-0538-8242345. E-mail: kywang@sdau.edu.cn.

Funding Sources

This work was supported by the National Key Technology R&D Program of China (2008BADA6B02).

ACKNOWLEDGMENT

The authors wish to thank the chemical manufacturers for providing technical assistance for the execution of the soil fumigation treatments.

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