Crop Protection 67 (2015) 223–227

Contents lists available at ScienceDirect

Crop Protection

journal homepage: www.elsevier.com/locate/cropro

Evaluation of chemical alternatives to methyl bromide in tomato crops in China

Kang Qiao [a,*], Zhongtang Wang [b,d], Min Wei [b,**], Hongyan Wang [c], Yang Wang [a], Kaiyun Wang [a]

[a] College of Plant Protection, Shandong Agricultural University, Tai'an, Shandong 271018, People's Republic of China
[b] College of Horticulture Science and Engineering, Shandong Agricultural University, Tai'an, Shandong 271018, People's Republic of China
[c] Cotton Research Center, Shandong Academy of Agricultural Sciences, Jinan, Shandong 250100, People's Republic of China
[d] Shandong Institute of Pomology, Tai'an Shandong 271000, People's Republic of China

A R T I C L E I N F O

Article history:
Received 17 June 2014
Received in revised form
18 October 2014
Accepted 20 October 2014
Available online 11 November 2014

Keywords:
Soil fumigation
Methyl bromide alternatives
Nematode
Weed control
Tomato

A B S T R A C T

Tomato is a high-value cash crop in China that requires vigorous transplants free of pathogens. However, local tomato growers commonly face heavy root-knot nematode and weed infestations, especially while phasing out methyl bromide (MB). The soil fumigants chloropicrin (CP), 1,3-dichloropropene (1,3-D) and dazomet (DZ) were evaluated at several rates alone and in combination as alternatives to MB soil fumigation in tomato production. Field trials revealed that used alone, CP, 1,3-D and DZ were not comparable to MB in the reduction of *Meloidogyne incognita*, weeds or increase of tomato marketable yield. Only the combination of reduced rates of 1,3-D and CP which had excellent nematicide efficacy and good to moderate weed control, matched the efficacy of MB. The present data indicate that the combination of 1,3-D plus CP is an efficient MB alternative for managing nematodes and weeds in tomato crops and can be used in integrated pest management programs. To get a better weeds control efficacy, it is recommended to add herbicides to the two fumigants combination.

1. Introduction

Tomato (*Solanum lycopersicum* L.) is a major vegetable crop worldwide. In China, area under tomato production was more than 1,500,000 ha in 2009 and the production reached 34,000,000 t, placing China as the world's leader both in cultivated area and production (Gao et al., 2011). In recent years, tomato yield losses have been strongly associated with soil exhaustion, weeds and, especially, root nematodes which are a consequence of monoculture (Collange et al., 2011).

At present, the standard soil pests management practice in tomato crop production systems is pre-plant soil fumigation with methyl bromide (MB). MB has been used in China for over 20 years and is effective in controlling fungi, bacteria, soil-borne viruses, insects, mites, nematodes and rodents (MBTOC, 2002). MB has provided a reliable return on investment for soil pest control; growers thus have obtained good profits when using it and have therefore become dependent on it. Although MB is one of the most useful chemicals for pest management, the 1992 Montreal Protocol, included MB on the list of ozone-depleting substances (UNEP, 2000). The withdrawal of MB from use as an agricultural fumigant has raised concerns the agricultural production will be negatively impacted if effective and economical alternatives are not identified.

Many chemical alternatives and their combinations have been suggested as MB replacements and have been tested in field experiments to evaluate their efficacies in controlling various soil pests (Devkota et al., 2013; Cao et al., 2014; Mao et al., 2014a). Among substitutive chemicals, currently registered alternatives to MB are chloropicrin (CP); 1,3-dichloropropene (1,3-D); methyl isothiocyanate (MITC) generators such as Metam sodium (MNa) and Dazomet (DZ), abamectin (AB) and their combinations (Qiao et al., 2012; Mao et al., 2012; Yan et al., 2012). Other alternatives to MB fumigation may be the use of non-chemical methods, such as soil solarization, organic amendments and biocontrol agents (Klein et al., 2011; Caboni et al., 2013; Hu et al., 2013). However, non-chemical control methods alone are often unsuitable because they do not provide the broad-spectrum activity or the degree of consistency achieved with MB fumigation (Chellemi, 2002).

* Corresponding author. College of Plant Protection, Shandong Agricultural University, 61 Daizong Street, Tai'an, Shandong 271018, People's Republic of China. Tel.: +86 0538 8248596.
** Corresponding author.
E-mail address: qiaokang11-11@163.com (K. Qiao).

http://dx.doi.org/10.1016/j.cropro.2014.10.017
0261-2194/

The present work was initiated to evaluate the most widely used logical alternatives for substituting MB under typical greenhouse conditions in north China. The experimental activities were carried out in tomato greenhouses which were infested with root-knot nematodes and weeds.

2. Materials and methods

Field trials were established in August 2011, in two commercial farms near Beiteng country, Tai'an city, Shandong province, China. Both farms were in conventional crop production for more than 10 years before the start of the experiments. The selected experimental sites had a history of heavy natural *Meloidogyne incognita* (Kofoid & White) Chitwood (southern root-knot nematode) and weed infestations. The soils at the experimental sites were sieved through a 2-mm mesh, and then mixed together, respectively. Particle size analyses were performed using the pipette method (Schinner et al., 1995). Total organic matter was determined by dry heating at 550 °C for 8 h and calculating the weight loss following the heating process. The pH was measured in a 1:2.5 soil to H_2O extract. Soil moisture content was determined by heating soil in a drying oven at 105 ± 5 °C for 8 h until mass constancy was achieved, then subtracting dry weight from fresh weight (Margesin and Schinner, 2005). Soil characteristics of trials I and II are provided in Table 1.

The following products were used in the study: (a) MB as a reference treatment (98% gas, ai, Lianyungang Dead Sea Bromine Compounds Co., Ltd., Jiangsu, China); (b) CP (99.5% liquid, ai, Dalian Dyestuffs & Chemicals Co., China); (c) 1,3-D (92% emulsifiable concentrate, ai, Shengpeng Bio-Tech Co., Ltd., China); (d) DZ (98% microgranule, ai, Nantong Shizhuang Chemical Co., Ltd., China); (e) abamectin as a routine treatment (0.5% granule, ai, Jinan Shibang Chemical Co., Ltd., China). The soil mulches were 0.06 mm low density polyethylene film (LDPE) (Baoding Baoshuo Plastic Co., Ltd., Hebei province, China).

Treatments were arranged in a randomized complete block design with five replications. Plot size was 40 m^2, and there were about 120 tomato plants per plot. The tested treatments were MB, CP, 1,3-D, 1,3-D plus CP, DZ, AB, and untreated control. Application rates of fumigants were based on previous studies and label application directions. Chemical formulations and application rates are provided in Table 2.

Prior to treatment establishment, the plots were disked twice before planting beds were made. 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 1, 2011), MB, CP, 1,3-D, 1,3-D plus CP, and DZ were chisel injected into soil 0.25 m deep and 0.50 m apart just on the planting rows and then the planting rows were 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. Abamectin was applied to the soil by pouring and immediately incorporated to 0.20 m depth through disking and then bedded as described above. Immediately after application of fumigants, beds were pressed and covered with LDPE mulch film.

Plastic films were removed from the site 10 days after application. Then six-week-old tomato seedlings were transplanted into the top of the beds 3 weeks after treatment (WAT). Raised beds were 1.5 m apart and each 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 tomatoes. Insecticides and fungicides were applied weekly beginning 3 WAT following current recommended practices. No herbicides were applied in order to evaluate the effect of these treatments in controlling weeds.

Table 2
Experimental program for Trial I & II.

Chemicals and formulation[a]	Rate (kg ha^{-1})	Application method	Abbreviation
MB (98% gas)	400	Chisel injection	MB 400
CP (99.5% liquid)	500	Chisel injection	CP 500
1,3-D (92% emulsifiable concentrate)	300	Chisel injection	1,3-D 300
1,3-D plus CP	150 plus 250	Chisel injection	1,3-D + CP
DZ (98% microgranule)	300	Chisel injection	DZ 300
AB (0.5% granule)	50	Root pouring	AB 50
Untreated control	–	–	–

[a] Abbreviations: MB = methyl bromide; CP = chloropicrin; 1,3-D = 1,3-dichloropropene; DZ = Dazomet; AB = abamectin.

During the tomato growing season, plant heights were measured on 10 plants per plot at 7 and 10 WAT. 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 6, 9, and 12 WAT by extracting soil samples with a soil probe (2.5 cm wide and 20 cm deep) from the rhizosphere of 10 plants per plot, then nematodes were counted from 100 cm^3 of soil using a standard sieving and centrifugation procedure (Jenkins, 1964). The classification of this isolate was performed by perineal configuration, esterase electrophoretic pattern, and host range analyses. 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 (Barker et al., 1986). 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 (Hanson et al., 2010). In all the trials, the marketable tomato fruits were harvested twice (12 and 14 WAT), which was a typical practice in north China greenhouse and graded according to current market standards into the large, medium and small categories. Trial dates for treatment, planting, and evaluation are provided in Table 3.

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 at $P = 0.05$ (SPSS, version 15.0 for Windows).

3. Results

Chemical treatments significantly affected plant height and vigor at 7, 10, 8 WAT, respectively (Table 4). Just as expected, the untreated controls in trial I and trial II had the lowest plant height (66 and 69 cm, 7 WAT; 114 and 105 cm, 10 WAT). The highest plant heights were both obtained in plots treated with 400 kg ha^{-1} of MB

Table 1
Soil characteristics in the experimental sites.

Sites	pH (1:2.5)	Organic matter (g kg^{-1})	Soil density (g cm^{-3})	Available P (mg kg^{-1})	Available K (mg kg^{-1})	Silt (%)	Clay (%)	Sand (%)	Soil moisture (%)
Trial I	7.2	16.8	1.2	248.5	653.9	67.3	8.3	24.4	14.2
Trial II	6.7	21.3	1.3	363.2	542.8	78.2	6.7	15.1	16.1