Methyl Iodide, an Ozone-Safe Alternative to Methyl Bromide as a Soil Fumigant

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ABSTRACT

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Methyl iodide was tested as a possible replacement for methyl bromide as a soil fumigant due to the scheduled removal of methyl bromide from the market. Methyl iodide is a better methylating agent than methyl bromide; it is rapidly destroyed by UV light and therefore unlikely to be involved in stratospheric ozone depletion. In laboratory and field trials, we tested methyl iodide alone or in comparison with methyl bromide for effectiveness in controlling the fungi *Phytophthora citricola, P. cinnamomi, P. parasitica,* and *Rhizoctonia solani;* the nematode *Heterodera schachtii;* and the plants *Abutilon theophrasti, Chenopodium album, C. murale, Convolvulus arvensis, Cyperus rotundus, Poa annua, Portulaca oleracea,* and *Sisymbrium irio.* In addition, we compared methyl iodide for biocidal effectiveness with seven other alkyl iodides. In both laboratory and field trials, when compared at equivalent molar rates, methyl iodide was equal to or better than methyl bromide in controlling the tested soilborne plant pathogens and weeds. When compared with other alkyl iodides, methyl iodide was the most effective fumigant.

Methyl bromide (CH_3Br) is extremely important to U.S. agriculture (2). It is the most widely used and effective universal fumigant in the world. It is used extensively for soil fumigation, fumigation of grain storage and milling facilities, as an export and import commodity quarantine treatment to control a variety of pests on numerous crops, and as a structural fumigant for wood-destroying pests.

The proceedings of the Montreal Protocol of 1991 and its 1992 amendment categorized methyl bromide as an ozone-depleting chemical with an estimated "Ozone Depletion Potential" (ODP) of 0.65 (1). Title 5, section 602 of the Clean Air Act dictates that the U.S. Environmental Protection Agency (EPA) must list as a Class 1 ozone depleter any substance with an ODP of 0.2 or greater. Once designated as such, all production, importation, and use of the substance in the United States must be phased out by the year 2001. For surface releases in agricultural operations, it is highly likely that the globally averaged ODP of methyl iodide is less than 0.016 (S. Solomon, personal communication), well below the level of Class 1 ozone depleters.

Recent data on the loss of methyl bromide to the atmosphere after soil fumigation indicate that of the total amount of methyl bromide applied to the soil for fumigation, approximately 87% is lost to the atmosphere within 7 days (20). Rolston and Glauz (14) found that as much as 70% escapes through the tarp and after the tarp is removed. On reaching the stratosphere, methyl bromide undergoes photo-oxidation, releasing bromine atoms that enter the ozone depletion cycle. Thirty to 40% of total ozone depletion is reported to be a result of bromine radicals, which are 30 to 60 times more efficient ozone depleters than chlorine radicals (12).

In 1990, 80% of the approximately 29 million kg of methyl bromide used in the United States was for agriculture-related purposes (2). Of this amount, 20 to 22.2 million kg were used for soil fumigation (control of insects, nematodes, weeds, and plant pathogens), and 2.3 million kg for post harvest, commodity, and quarantine treatments (2).

Currently available alternatives are less effective or more expensive than methyl bromide; thus, the removal of methyl bromide will be very costly (2). Projected annual losses to U.S. producers and consumers are estimated at $1.5 billion excluding quarantine and structural fumigation losses (2). California and Florida are the largest users of methyl bromide (approximately 11.4 million kg combined) in the United States and will be most heavily affected by its removal. Commodities most adversely affected include fresh market tomatoes, strawberries, peppers, melons, and ornamentals (2).

Methyl iodide (CH_3I) is analogous to methyl bromide in its ability to act as a biocide. The generally accepted mechanism for biological activity of the lower alkyl halide series is bimolecular nucleophilic displacement (S_N2) reactions with functional groups such as NH_2 and SH in various amino acids and peptides in target organisms (11). Methyl iodide reacts faster than methyl bromide under most S_N2 conditions that have been studied (15).

Methyl iodide absorbs the UV component of sunlight with an absorption maximum approximating 260 nm (7). It is these wavelengths that are believed to be responsible for the tropospheric degradation of methyl iodide. UV absorption causes the formation of methyl and iodine radicals that lead to the photo-degradation of methyl iodide (8).

Methyl iodide appears to be uniformly distributed in the ocean and is produced principally by marine algae (8), which may be the source of most methyl iodide in the marine boundary layer. Methyl iodide has not been implicated in stratospheric or tropospheric ozone depletion (13). As with other halogens, the postulated chemistry of CH_3I indicates that it would be very effective in ozone destruction if it reached the stratosphere (14). However, methyl iodide undergoes atmospheric photolysis and its breakdown products are rapidly removed from the lower atmosphere (16). As a result, the chemical has an atmospheric residence time estimated at 4 to 8 days (8,13, 17), compared with 2 years for methyl bromide (1).

In this paper, we report the effectiveness of methyl iodide and methyl bromide for the control of selected fungi, weeds, and nematodes in laboratory and field trials.

MATERIALS AND METHODS

Soils used in fumigations were a 1:1 vol/vol potting mix of topsoil and fir sawdust (sand 85%; silt 11%; clay 4%; organic content 9.6%; pH 6.2) for the laboratory trials or field soil (sand 67%; silt 24%; clay 9%; organic content 0.6%; pH 6.7) passed through a 2-mm-opening screen for field trials. Soil moisture ranged from 8.4 to 32% depending on the trial. Soils were sterilized by autoclave before inoculum was added.

Soil containers were made from 45-ml clear plastic vials (No. 55-12, Thornton Plastic Co., Salt Lake City, UT) perforated by 16 1-cm-diameter holes made with an electric soldering iron. The holes were distributed in two rows of four and two of three (on opposite sides) with one hole in the bottom of the vial and one in the plastic snap-on cap.

After the vials were filled with soil, infested as described below, those used in laboratory trials were placed in a fumiga-

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tion container with either no soil around the vial or on a 1-cm layer of soil-sawdust mix and covered with the same mix to a depth of 1 to 1.5 cm. Fumigation containers were 1,893-ml wide-mouth canning jars. Methyl bromide was chilled in 454-g containers along with the necessary glassware and pipette tips in a portable ice chest with frozen CO_2 overnight. This treatment reduced the temperature of the methyl bromide to approximately –56°C with a vapor pressure below 28 kPa. The chemical was poured into a chilled beaker from which it was pipetted into the jars with chilled pipette tips. Methyl iodide was used at room temperature. The fumigants were pipetted onto the soil near the mouth of the jar or into a 0.5 × 2 cm glass evaporating dish near the jar mouth. The jars were sealed immediately with canning lids and rings and placed horizontally on the laboratory bench for 1, 2, or 3 days depending on the trial. Each trial contained four replications per treatment. All fumigation concentrations were based on a methyl bromide application rate of 0.454 kg/2.8 m^3 (1 lb/100 ft^3) equal to 4.78 mol/2.8 m^3 for field trials and 1.69 mM for laboratory trials.

After fumigation, the vials were removed from the soil and aerated under a fume hood for 1 h. The seeds were separated from the soil with a 2-mm screen. Ten or 25 seeds (depending on the trial) from each replicate were placed on agar in 15-cm-diameter petri plates. The selective medium PARPH was used for isolation of *Phytophthora* species (9). *Rhizoctonia* was isolated on a selective medium (10) or water agar. Seeds were incubated in the laboratory (23°C) and assessed microscopically for fungal growth after 2 days. Seeds showing fungal growth were counted and the plates were checked until no more seeds had fungal growth, usually 3 to 4 days. Means were separated with the Waller-Duncan *k*-ratio *t* test.

Laboratory trials with fungi. Tested fungi were grown on sterilized millet seeds amended 1:3 vol/vol with 1/4 strength V8 broth. Cultures were separated by hand into individual seeds and added to the appropriate autoclaved soil for each trial. The infected seeds were mixed thoroughly into the soil at a ratio of 300 ml to 3.5 liters of soil.

The fungi selected for laboratory trials were *Phytophthora cinnamomi* Rands, *P. citricola* Sawada, *P. parasitica* Dastur, and *Rhizoctonia solani* Kühn. Methyl iodide and methyl bromide concentrations used were 1.69, 1.27, 0.84, 0.42, 0.21, 0.105, or 0.0525 mM. Fumigation time periods were 1, 2, or 3 days. Each trial was conducted at least twice.

Laboratory trials with nematodes. Cysts of *Heterodera schachtii* Schmidt were mixed with UC mix #2 (5), placed in vials, and fumigated as described for trials with fungi, with methyl iodide concentrations of 0.003, 0.006, 0.012, or 0.025 mM. After fumigation for 2 days, the vials were aerated for 1 h and the soil was placed on Baermann funnels (18) containing 3 mM zinc chloride to promote hatching. Egg viability was measured as the number of second stage juveniles (J2) that emerged after 4 days. The trial was conducted three times with four replications per treatment.

Laboratory trials with weeds. Seeds, 50 cm^3 of field bindweed, *Convolvulus arvensis* L.; 50 cm^3 of velvetleaf, *Abutilon theophrasti* Medik.; 2.5 cm^3 of purslane, *Portulaca oleracea* L.; and 2.5 cm^3 of annual bluegrass, *Poa annua* L., were each mixed with soil at 14% moisture, placed in containers, and fumigated with methyl bromide or methyl iodide for 2 days as described for trials with fungi. Containers were kept at 23°C overnight before fumigation. Fumigant concentrations were 0.21, 0.42, 0.84, and 1.69 mM in trial 1 and 0.025, 0.105, 0.21, and 0.42 mM in trial 2. After fumigation, each replicate was spread over 2 cm of sand in 12 cm^2 × 5.5 cm deep plastic planting trays. The soil was thoroughly moistened and the trays were placed in the greenhouse. The germinated seeds were counted after 10 days and results tabulated as a percentage of the nonfumigated control. Two trials were conducted with four replications of each treatment.

Laboratory trials with alkyl iodides. Closely related alkyl iodides were compared with methyl iodide for efficacy against *P. parasitica* in three trials. Alkyl iodides tested were methyl iodide, 1-iodoethane, 1-iodopropane, 2-iodopropane, 1-iodobutane, 1-iodopentane, di-iodomethane, and 1-iodo-2-methylpropane. Inoculum was prepared and trials were performed as described for the laboratory trials above. The chemicals were compared on a molar basis. In trial 1, rates of 1.27 and 0.42 mM were compared. In trial 2, methyl iodide at 1.27 and 0.42 mM was compared with 2.54 and 1.27 mM for all other compounds. In trial 3, the two most effective chemicals from the first two trials (di-iodomethane and 1-iodoethane) were compared with methyl iodide at 0.84, 1.69, and 2.11 mM. Beginning soil moistures were 24% for trial 1 and 32% for trials 2 and 3. Fumigation exposure time was 48 h with four replications of 25 infected millet seeds each per treatment. Containers and methods used were as described for trials with fungi.

Field container trials with weeds. Seeds of *P. annua* and *C. arvensis* were mixed with moist sandy soil (sand 89%; silt 8%; clay 3%; organic content 0.13%; pH 7.3; moisture 7%), placed in cotton bags, and buried 15 cm below the soil surface in 22.3-liter plastic containers filled to 2.5 cm from the top with the same soil. Containers had four 2.5-cm holes in the bottom. Open vials containing methyl bromide (held at –56°C) or methyl iodide were placed on the soil surface and the containers were covered with 0.1 mm thick (4 mil) black polyethylene tarp secured with a large rubber band. The containers were uncovered after 4 days and aerated 1 day. Chemicals were used at molar equivalents of 0.36, 0.18, 0.09, 0.045, and 0.022 mol/m^2. Treatments were arranged in a randomized block design with four replications per treatment. The trial was performed one time.

Field trials with fungi. *Phytophthora parasitica* inoculum was prepared as described for laboratory trials and placed at depths of 2.5, 15, and 30 cm halfway between the center and one arbitrarily chosen corner of each 3 × 3 m plot. Field trials were randomized blocks with four replications per treatment. Soil moisture averaged 9.5% between 15 and 30 cm soil depth. Trial 1 had seven treatments and trial 2 had eight treatments.

Treatments were methyl bromide or methyl iodide at 4.8, 2.4, and 1.2 mol/9.29

Table 1. Percent recovery of *Phytophthora cinnamomi* and *P. parasitica* from infected millet seeds after fumigation in soil with different concentrations of methyl iodide[y]

		Trial[z]			
		P. cinnamomi		*P. parasitica*	
Treatment (mM)	Exposure (days)	1	2	1	2
0	1	100 a	100 a	100 a	100 a
	2	100 a	100 a	100 a	100 a
	3	100 a	100 a	100 a	100 a
0.21	1	100 a	62 c	100 a	98 a
	2	100 a	72 bc	100 a	19 b
	3	55 bc	62 c	100 a	0 b
0.42	1	65 b	62 c	100 a	0 b
	2	0 d	39 c	54 bc	0 b
	3	0 d	23 d	76 ab	0 b
0.84	1	0 d	0 d	0 d	0 b
	2	25 cd	0 d	0 d	0 b
	3	0 d	0 d	0 d	0 b

[y] Data are means of four replicates, and are expressed as a percentage of recovery from control plots.
[z] Numbers within each trial followed by the same letter are not different according to the Waller-Duncan *k*-ratio *t* test ($k = 100$).

m^2. Methyl bromide was chilled as described for laboratory trials. Chilled methyl bromide was poured into a chilled beaker and placed on the soil surface in the center of the plot. In trial 1, methyl iodide was applied the same way as methyl bromide but was not chilled. In trial 2, methyl bromide was applied as in trial 1 whereas methyl iodide was mixed with 95% ethanol in a 1:2 ratio and poured in an arbitrary pattern over the plot for better distribution. Untreated controls were included in both trials. Trial 2 had an additional control of ethanol at 160 ml/plot.

The beakers of fumigant were covered with inverted 15-cm-diameter black plastic pots to prevent spillage when the plots were covered with 0.1 mm clear polyethylene plastic sheeting and the edges buried 7 cm. After 4 days the plastic was removed and the plots were aerated for 2 days. The inoculum vials were removed and the seeds were evaluated as described for laboratory trials.

Field trials with weeds. A site with a fine sandy soil (sand 28%; silt 61%; clay 11%; organic content 1.2%; pH 7.3; moisture 15.2%) was selected in the Coachella Valley, CA. The soil, which had a history of abundant weed populations, was disked before fumigation. Seven treatments were established as follows: untreated control; black plastic; clear plastic; methyl iodide + black plastic; methyl iodide + clear plastic; methyl bromide + black plastic; and methyl bromide + clear plastic. Treatments were established in 9.29 m^2 plots in four randomized complete blocks. Methyl iodide and methyl bromide were used at 4.8 M/9.29 m^2. Methyl bromide was chilled as described for laboratory trials. The opened cans of methyl bromide were placed on the soil surface. Methyl iodide was premeasured and placed in open flasks on the soil surface. The plots were covered with 0.1 mm plastic and the edges were sealed with soil. The plastic covers were removed after 3 days. The trial was not repeated.

Forty-two days after fumigation, three arbitrarily chosen 0.33 m^2 areas in each plot were evaluated for populations of purple nutsedge, *Cyperus rotundus* L.; annual bluegrass, *P. annua;* lambs quarters, *Chenopodium album;* nettleleaf goosefoot, *C. murale* L.; and London rocket, *Sisymbrium irio* L. The three counts were summed to give a total count per m^2 per plot.

Fifty days after fumigation, 0.25 m^2 × 30 cm deep soil layers from the control, clear plastic + methyl bromide and clear plastic + methyl iodide treatments were carefully excavated keeping each 10-cm layer separate. The soil samples were placed in trays in a greenhouse and kept moist. After 3 weeks, nutsedge viability was evaluated by counting the total number of nutlets germinated in each treatment.

RESULTS

Laboratory trials with fungi. In one laboratory trial, *P. citricola* was 100% killed by 0.21 mM of methyl iodide after 3 days exposure and by 0.42 mM after 1 day. In the other two trials *P. citricola* was 0 to 39% killed by 0.21 mM methyl iodide after 3 days exposure and 2 to 46% killed at 0.42 mM after 1 day. In one trial, survival was 2% following exposure to 0.42 mM methyl iodide. All other concentrations achieved a 100% kill at all time periods except for a 4% survival of the test fungus after 2 days exposure at 1.69 mM methyl iodide.

In two trials, *P. cinnamomi* was eliminated after 1 to 3 days exposure to 0.84 mM methyl iodide but not after 3 days to 0.42 mM (Table 1). In the same two trials, *P. parasitica* was eliminated in one trial after 1 day of exposure to 0.42 mM and in both trials after 1 day to 0.84 mM. In the second trial, the fungus was eliminated after 3 days exposure to 0.21 mM and after 1 day to all higher concentrations (Table 1).

In two trials with *R. solani,* all controls were recovered at 100%. Concentrations of methyl iodide at 0.21 mM or higher eliminated *Rhizoctonia* whereas methyl bromide achieved a complete kill only at 0.42 mM or higher (Table 2).

Laboratory trials with nematodes. Nematodes were affected by very low concentrations of methyl iodide (Table 3). In two of three trials, *H. schachtii* numbers were reduced 47 to 57% at 0.003 mM but reductions were significant ($P = 0.05$) in only one trial. All three trials showed reductions ($P = 0.05$) in *H. schachtii* J2 at 0.006 mM and complete elimination at 0.025 mM. A concentration of 0.025 mM is equivalent to 8.7 g/2.3 m^3 (0.25 oz/100 ft^3 or 38 kg/ha).

Laboratory trials with weeds. In trial 1, there was no survival of *P. annua* or *A. theophrasti* with either chemical at any concentration (data not shown). *P. oleracea* was killed at all concentrations by methyl iodide but had 11% survival at 0.0525 mM methyl bromide. Neither chemical achieved a complete kill of *C. arvensis.* The survival rate was 3% at 0.42 mM methyl iodide and 5% at the high concentration of methyl bromide. In trial 2, at lower concentrations, methyl iodide was more effective than methyl bromide in killing seeds of all 4 species of weeds (Table 4).

Table 2. Percent recovery of *Rhizoctonia solani* from infected millet seeds after fumigation in soil with different concentrations of methyl iodide (MI) or methyl bromide (MB) for 2 days[x]

	Trial[y]			
	1		2	
Treatment (mM)	MI	MB	MI	MB
0	100 a	100 a	100 a	100 a
0.0525	NT[z]	NT	93 a	93 a
0.105	NT	NT	10 c	78 b
0.21	0 c	68 b	0 c	13 c
0.42	0 c	0 c	0 c	0 c

[x] Data are means of four replicates, and are expressed as a percentage of recovery from control plots.
[y] Numbers within each trial followed by the same letter are not different according to the Waller-Duncan *k*-ratio *t* test ($k = 100$).
[z] Not tested.

Table 3. Egg viability as determined by numbers of *Heterodera schachtii* second-stage juveniles recovered from soil fumigated with different concentrations of methyl iodide for 2 days[y]

	Trial[z]		
Treatment (mM)	1	2	3
Control	127 a	56 a	1,638 a
0.003	68 ab	61 a	700 b
0.006	5 b	10 b	71 b
0.012	0.3 b	0 c	6 c
0.025	0 b	0 c	0 c

[y] Data are means of four replicates.
[z] Numbers within each trial followed by the same letter are not different according to the Waller-Duncan *k*-ratio *t* test ($k = 100$).

Table 4. Percent germination of *Poa annua, Convolvulus arvensis, Portulaca oleracea,* and *Abutilon theophrasti* seeds after fumigation in soil with different concentrations of methyl bromide (MB) or methyl iodide (MI) for 2 days[y]

	Poa annua[z]		*Convolvulus arvensis*[z]		*Portulaca oleracea*[z]		*Abutilon theophrasti*[z]	
Treatment (mM)	MB	MI	MB	MI	MB	MI	MB	M
0.0	100 a	100 a	100 a	100 a	100 a	100 a	100 a	100 a
0.0525	82 a	93 a	85 a	80 a	71 b	50 d	5 b	0 c
0.105	35 b	0 c	22 b	4 b	63 c	0 e	0 c	0 c
0.21	0 c	0 c	4 b	3 b	0 e	0 e	0 c	0 c
0.42	0 c	0 c	3 b	0 b	0 e	0 e	0 c	0 c

[y] Data are means of four replicates, and are expressed as a percentage of germination of seed from control treatments.
[z] Numbers within each species followed by the same letter are not different according to the Waller-Duncan *k*-ratio *t* test ($k = 100$).

Laboratory trials with alkyl iodides. Methyl iodide gave complete control of *P. parasitica* at all concentrations. None of the chemicals tested were as effective as methyl iodide in eliminating *P. parasitica.*

Table 5. Percentage seed germination of *Poa annua* or *Convolvulus arvensis* after fumigation in soil with different concentrations of methyl bromide (MB) or methyl iodide (MI) for 4 days[y]

Treatment	*Poa annua*[z]		*Convolvulus arvensis*[z]	
(mM/m²)	MB	MI	MB	MI
0	100 a	100 a	100 a	100 a
22.2	57 b	55 b	60 bc	58 bc
44.5	54 b	34 c	65 b	15 de
88.9	29 cd	19 de	35 cd	19 de
177.8	9 ef	0 f	2 e	1 e
355.7	0 f	0 f	1 e	1 e

[y] Data are means of four replicates, and are expressed as a percentage of germination of seed from control plots.
[z] Numbers followed by the same letter within each species are not different according to the Waller-Duncan *k*-ratio *t* test ($k = 100$).

The percent recovery of *P. parasitica* from infected millet seeds fumigated with different concentrations of seven different alkyl iodides ranged from 62 to 100% and was not different ($P = 0.05$) from the control in most cases. Other than methyl iodide, the most effective chemical was 1-iodoethane at 2.54 mM. This concentration of 1-iodoethane was six times greater than the lowest concentration of methyl iodide that was equally efficacious.

Field container trials with weeds. Methyl bromide and methyl iodide were effective but not different ($P = 0.05$) in their ability to kill seeds of *P. annua* and *C. arvensis* (Table 5). With concentrations ranging from 22.2 to 355.7 mM/m², methyl iodide completely controlled *P. annua* at 177.8 and 355.7 mM/m² and methyl bromide did so at 355.7 mM/m². Neither chemical achieved complete kill of *C. arvensis.*

Field trials with fungi. In two field trials, methyl iodide and methyl bromide performed similarly (Table 6). There were low percentages of recovery of *P. parasitica* in seven of the fumigated plots with the highest at 30 cm soil depth with 1.2 M/9.29 m² methyl iodide. *Phytophthora parasitica* was recovered at 99 to 100% in all untreated plots. In the second trial, all *P. parasitica* inoculum buried at the 2.5 cm depth was killed. In the controls, based on unpublished data, the kill was most probably due to high temperatures created under the plastic by solarization.

Field trials with weeds. Methyl bromide or methyl iodide treatments covered with 0.1 mm clear or black polyethylene tarp were effective but not different ($P = 0.05$) in controlling populations of *C. rotundus, P. annua, C. album, S. irio,* and *C. murale* (Table 7). When compared for effectiveness against germination of *C. rotundus* nutlets, methyl iodide was as effective or more effective than methyl bromide at all soil depths (Table 8).

DISCUSSION

In a series of 15 laboratory and field trials, methyl iodide was an effective fumigant for control of four species of plant-pathogenic fungi, one species of nematode, and seven species of weeds. In seven trials in which the chemicals were directly compared on a molar basis, the performance of methyl iodide was equal to or better than methyl bromide. In comparison with seven related alkyl-iodides, methyl iodide was the most effective fumigant in killing *P. parasitica.* Based on these results, we conclude that methyl iodide is as effective or more effective than methyl bromide as a fumigant for control of the soilborne fungi, nematode, and weeds used in these trials.

Methyl bromide is scheduled to be phased out of production, importation, and use as an agricultural chemical in the United States by the year 2001. Researchers around the world are searching for alternate chemicals for soil, quarantine, commodity, and structural fumigation. The general conclusions of a 1993 workshop on methyl bromide alternatives and a 1994 research conference on methyl bromide alternatives were that no one chemical could replace methyl bromide, and that replacements would have to be a combination of chemicals and/or other methods and would likely not be as effective or have the wide-spectrum activity of methyl bromide

Table 6. Percentage recovery of *Phytophthora parasitica* from infected millet seed buried in field soil fumigated with methyl iodide (MI) or methyl bromide (MB)[v]

Treatment (M/9.29 m³)	Depth (cm)	Trial 1[w]		Trial 2[w]	
		MI	MB	MI	MB
0	2.5	100 a	100 a	0 c[x]	0 c[x]
	15.0	100 a	100 a	100 a	100 a
	30.0	100 a	100 a	99 a	99 a
Ethanol[y]	2.5	NT[z]	NT	0 c	0 c
Control	15.0	NT	NT	99 a	99 a
	30.0	NT	NT	99 a	99 a
1.2	2.5	0 c	0 c	0 c	0 c
	15.0	0 c	0 c	24 bc	25 bc
	30.0	1 bc	0 c	45 b	25 bc
2.4	2.5	2 bc	0 c	0 c	0 c
	15.0	4 b	1 bc	0 c	0 c
	30.0	0 c	3 bc	0 c	25 bc
4.8	2.5	0 c	0 c	0 c	0 c
	15.0	1 bc	0 c	0 c	0 c
	30.0	0 c	0 c	0 c	0 c

[v] Data are means of four replicates, and are expressed as a percentage of recovery from control plates.
[w] Numbers within each trial followed by the same letter are not different according to the Waller-Duncan *k*-ratio *t* test ($k = 100$).
[x] All propagules at 2.5 cm in trial 2 controls were most likely killed by solarization.
[y] Ethyl alcohol used had no apparent effect on survival of *P. parasitica.*
[z] Not tested.

Table 7. The effect of fumigating soil with methyl bromide (MB) and methyl iodide (MI) at 4.8 M per 9.29 m² under clear (CP) or black (BP) 0.1 mm polyethylene on the survival of weed species

Treatment	Weed species[y]				
	Cyperus rotundus	*Poa annua*	*Chenopodium album*	*Sisymbrium irio*	*Chenopodium murale*
Control	102 a[z]	89 a	31 a	38 a	27 a
CP	71 a	49 ab	10 b	42 a	18 a
BP	64 a	78 a	9 b	17 a	19 a
MB+CP	7 b	10 b	2 c	2 b	3 b
MI+BP	2 b	4 b	0 c	0 b	0 b
MB+BP	1 b	2 b	0 c	1 b	1 b
MI+CP	0 b	13 b	1 c	0 b	1 b

[y] Data are means of plants per m² in four replicates.
[z] Numbers in columns followed by the same letter are not different according to the Waller-Duncan *k*-ratio *t* test ($k = 100$).

Table 8. Germination of *Cyperus rotundus* nutlets from different depths in a field fumigated with methyl bromide (MB) or methyl iodide (MI) at 4.8 M/9.29 m²[y]

Depth (cm)	Control	MB	MI
0 to 10	38 a[z]	3 b	1 c
10 to 20	20 a	1 b	0 b
20 to 30	13 a	2 b	0 c

[y] Data are means of four replications. Numbers are plants emerging from soil within 71 days after fumigation.
[z] Numbers in rows followed by the same letter are not different according to the Waller-Duncan *k*-ratio *t* test ($k = 100$).

(3,4). Based on our results and the properties of methyl iodide, it appears that these conclusions may have been premature. Methyl iodide appears to be a logical, single chemical replacement for methyl bromide in most, if not all of its uses. Methyl iodide is a liquid with a boiling point of 42.5°C and as such is much easier to handle than methyl bromide, which boils at 3.56°C and is pressurized under normal use (6). Because it is a liquid, methyl iodide would probably be much safer than methyl bromide for workers to apply. Methyl iodide can be applied using the same equipment as methyl bromide with few or no modifications.

Methyl iodide is destroyed rapidly by UV light, which gives it a very short residence time in the atmosphere compared with methyl bromide (8,13,17). Because of this UV lability, devices could be designed to make methyl iodide safe to use and dispose of following use in greenhouse and commodity fumigations. Both chemicals have short half-lives in water; methyl bromide is hydrolyzed in 20 to 40 days and methyl iodide in 50 to 110 days (15). The fate of iodide in the soil is not well known (19), but unlike bromide, iodide is a recognized plant and human nutrient.

Methyl iodide, as a liquid with a high boiling point, a vapor pressure 25% that of methyl bromide, and lability in the presence of UV, would be the safer product to use due to a substantially reduced probability of worker exposure compared with methyl bromide. Based on the characteristics of methyl iodide and the efficacy data we presented, methyl iodide would be a logical candidate to consider as an alternative for methyl bromide.

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