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Comparison of Allyl Isothiocyanate and Metam Sodium with Methyl Bromide for Weed Control in Polyethylene-Mulched Bell Pepper

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Methyl bromide (MeBr), classified as a Class I ozone-depleting substance, has been banned for ordinary agricultural uses. Weed control in commercial bell pepper production is complicated by the ban on MeBr and the lack of other available and effective soil fumigants. A field study was conducted to evaluate the effectiveness of allyl isothiocyanate (ITC) and metam sodium (methyl ITC generator) as MeBr alternatives for control of Palmer amaranth, large crabgrass, and yellow nutsedge; and for increasing marketable yields in low-density polyethylene (LDPE) –mulched bell pepper. Allyl ITC was applied at 450, 600, and 750 kg ha^{-1}; metam sodium was applied at 180, 270, and 360 kg ha^{-1}; and MeBr plus chloropicrin (67% and 33%, respectively) was applied at 390 kg ha^{-1}. Allyl ITC and metam sodium did not injure bell pepper. Allyl ITC at 750 kg ha^{-1} or metam sodium at 360 kg ha^{-1} controlled Palmer amaranth ($\geq$ 83%), large crabgrass ($\geq$ 78%), and yellow nutsedge ($\geq$ 80%) comparably to MeBr. Yellow nutsedge tuber density was $\leq$ 84 tubers m^{-2} in plots treated with the highest rate of allyl ITC and metam sodium and was comparable to the tuber density in MeBr-treated plots. Although allyl ITC at 750 kg ha^{-1} controlled weeds comparable to MeBr, total marketable bell pepper yield with allyl ITC was lower than the yield with MeBr. Conversely, total marketable bell pepper yield with the highest rate of metam sodium (53.5 ton ha^{-1}) was equivalent to the yield (62.5 ton ha^{-1}) in plots treated with MeBr. In conclusion, metam sodium at 360 kg ha^{-1} is an effective MeBr alternative for weed control in LDPE–mulched bell pepper.

Nomenclature: Allyl isothiocyanate; metam sodium; methyl bromide (MeBr); large crabgrass, *Digitaria sanguinalis* (L.) Scop. DIGSA; Palmer amaranth, *Amaranthus palmeri* S. Wats. AMAPA; yellow nutsedge, *Cyperus esculentus* L. CYPES; bell pepper, *Capsicum annuum* L. 'Heritage'.

Key words: Isothiocyanate, low-density polyethylene mulch, methyl bromide alternatives, soil fumigation.

Methyl bromide (MeBr), clasificado como una sustancia Clase I degradante de ozono, ha sido prohibido para el uso ordinario en agricultura. Debido a la prohibición de MeBr y la falta de otros fumigantes de suelos disponibles que sean efectivos, el control de malezas en la producción comercial de pimiento morrón es complicado. Se realizó un estudio de campo para evaluar la eficacia de allyl isothiocyanate (ITC) y metam sodium (generador de methyl ITC) como alternativas a MeBr para el control de *Amaranthus palmeri*, *Digitaria sanguinalis*, y *Cyperus esculentus*; y para el incremento del rendimiento comercializable en producción de pimiento en cobertura plástica de polyethylene de baja densidad (LDPE). Se aplicó allyl ITC a 450, 600, y 750 kg ha^{-1}; metam sodium a 180, 270, y 360 kg ha^{-1}; y MeBr más chloropicrin (67% y 33%, respectivamente) a 390 kg ha^{-1}. Allyl ITC y metam sodium no dañaron al pimiento. Allyl ITC a 750 kg ha^{-1} o metam sodium a 360 kg ha^{-1} controlaron *A. palmeri* ($\geq$83%), *D. sanguinalis* ($\geq$78%), y *C. esculentus* ($\geq$80%), lo que fue comparable a MeBr. La densidad de tubérculos de *C. esculentus* fue $\leq$84 tubérculos m^{-2} en parcelas tratadas con la dosis más alta de allyl ITC y metam sodium, y fue comparable con la densidad de tubérculos en las parcelas tratadas con MeBr. Aunque el control de malezas con allyl ITC a 750 kg ha^{-1} fue comparable a MeBr, el rendimiento total de pimiento comercializable fue menor que el rendimiento con MeBr. Por el contrario, el rendimiento total de pimiento comercializable con la dosis más alta de metam sodium (53.5 ton ha^{-1}) fue equivalente al rendimiento (62,5 ton ha^{-1}) en parcelas tratadas con MeBr. En conclusión, metam sodium a 360 kg ha^{-1} es una alternativa efectiva al uso de MeBr para el control de malezas en la producción de pimiento con cobertura plástica LDPE.

Bell pepper is an important vegetable commodity for fresh and processed product consumption, and it has huge economic importance in U.S. vegetable production. In 2011, bell pepper was planted on 22,753 ha in the United States, with a total production valued at $684.9 million (U.S. Department of Agriculture–National Agricultural Statistics Service [USDA-NASS] 2012). In commercial production, weeds are major pests, and effective weed management is critical for optimum bell pepper yield. Weeds cause allelopathic effects and physiological stress to the competing crop (Ferguson and Rathinasabapathi 2003). Moreover, weeds compete for available resources (sunlight, moisture, and nutrients) with the main crop, reduce fruit quality and yield, and contribute for the loss of millions of dollars annually in commercial production (Swaider et al. 1992). Weeds also interfere with intercultural activities such as scouting for insect pests, pesticide applications, and harvesting. In plasticulture bell pepper production, weed growth is often enhanced because of drip irrigation and fertigation. If weed management is poor, bell pepper foliage and fruit is severely reduced by weed infestation (Frank et al. 1988).

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Palmer amaranth grows rapidly, and within a few weeks shades the crop by rapid vertical and horizontal expansion (Norsworthy et al. 2008). With warm, moist soil and intense sunlight, an environment most likely to occur in plasticulture, Palmer amaranth can attain a 2-m height within 10 wk after emergence (Norsworthy et al. 2008). Another *Amaranthus* species similar to Palmer amaranth, redroot pigweed (*Amaranthus retroflexus* L.), is highly competitive and reduces yield significantly in bell pepper production (Fu and Ashley 2006).

Likewise, large crabgrass is one of the most important weeds in vegetable crops in the United States, and is common in most of the bell pepper production areas in the southern United States. In the early stages of growth, large crabgrass can be controlled effectively, but it is more difficult to manage after it starts forming tillers and adventitious roots (Hartzler and Foy 1983). Yield loss is prominent in vegetable crops from season-long interference with large crabgrass (Aguyoh and Masiunas 2003; Fu and Ashley 2006). Large crabgrass can attain the same height as bell pepper in plastic-mulched condition (Norsworthy et al. 2008), and season-long large crabgrass interference causes complete loss of marketable yield in bell pepper (Fu and Ashley 2006).

Yellow nutsedge is a major weed throughout the United States because of underground tubers that are highly tolerant to drought and freezing conditions (Benedixen and Nandihalli 1987). Yellow nutsedge interference for the entire growing season reduced bell pepper yield 74% (Motis et al. 2001). Similarly, season-long interference of yellow nutsedge at five or fewer shoots m^{-2} reduced bell pepper yield 10% (Motis et al. 2003). If yellow nutsedge is left uncontrolled, tuber production increases rapidly (Bangarwa 2010), leading to increased infestations and difficulty with control in subsequent growing seasons. Anderson (1999) reported that a single tuber can produce up to 36 plants and 332 tubers in 16 wk, and within a year it can form a patch of 6-m diameter with 1,900 plants and 7,000 tubers.

Methyl bromide (MeBr) was extensively used as a soil fumigant for decades for effective management of weed, nematode, and disease pests in vegetable production (Noling and Becker 1994). However, with the ban on ordinary use of MeBr (limited use under Critical Use Exemption), an effective fumigant alternative to MeBr is imperative for pest control in bell pepper production. In this regard, isothiocyanates (ITCs) have been evaluated widely in recent years. ITCs are effective in controlling different soil organisms such as nematodes (Lear 1956), insects (Borek et al. 1998), and soil pathogens (Smolinska et al. 1997). Moreover, ITCs are very effective in suppressing weed seed germination (Peterson et al. 2001). ITC application controlled various annual and perennial weeds, including nutsedge species in vegetable production (Bangarwa 2010; Norsworthy and Meehan 2005a, 2005b; Norsworthy et al. 2006).

Allyl ITC has been evaluated for weed control and is reported to have greater potential than propyl, butyl, benzyl, and 2-phenylethyl ITCs for suppressing the germination and growth of barnyardgrass [*Echinocloa crus-galli* (L.) Beauv.], redroot pigweed, and garden pea (*Pisum sativum* L.) (Al-Khatib et al. 1997). Inhibition of seed germination of dandelion (*Taraxacum officinale* Weber) from allyl ITC is also reported by Vaughn and Boydston (1997). Norsworthy and Meehan (2005b) estimated the lethal concentration 50% (LC_{50}) of allyl ITC to be 269, 807, and 4,260 nmol g^{-1} of soil for reducing the emergence of Palmer amaranth, pitted morningglory (*Ipomoea lacunosa* L.), and yellow nutsedge, respectively. In the same study, allyl ITC at 10,000 nmol g^{-1} of soil reduced yellow nutsedge emergence by 76%. Metam sodium, a widely used fumigant, degrades rapidly and forms methyl ITC as a primary active compound after soil fumigation (Ajwa et al. 2003). When incorporated properly into the soil, methyl ITC has activity against plant pathogens, weeds, insects, and nematodes (Duniway 2002). Gilreath et al. (2008) also reported metam sodium plus chloropicrin to be similar to MeBr for plant vigor, nematode control, and total marketable yield in strawberry (*Fragaria* spp.) production. In a MeBr-alternative study involving bell pepper and cucumber (*Cucumis sativus* L.) rotation, marketable bell pepper fruit increased by 38% with the metam sodium application compared to the nontreated check (Gilreath et al. 2004).

Because of the ban on MeBr, growers are left with only a few options in managing troublesome weeds in bell pepper production. The absence of an effective alternative to MeBr may contribute to the loss of millions of dollar annually in commercial bell pepper production because of yield and quality fruit losses from weed infestation. Therefore, research on effective weed control alternatives to MeBr is necessary. In previously conducted MeBr-alternative research, allyl ITC and metam sodium provided effective weed control (Bangarwa et al. 2011a; Gilreath et al. 2004). These fumigants were therefore reported as potential replacements to MeBr for weed control. However, there is a lack of knowledge of the allyl ITC and metam sodium rate that is comparable to a standard MeBr application for weed control and yield in bell pepper production. ITCs are highly volatile compounds, and greater than 90% of the applied ITC can escape from the soil within 1 d after application (Brown and Morra 1995). Therefore, for retention of the applied ITCs in the soil and the maximum weed control efficiency, use of polyethylene mulch is critical (Austerweil et al. 2006). There are various types of polyethylene mulches commercially available; however, low-density polyethylene (LDPE) mulch costs less and is as effective as virtually impermeable film (VIF) for allyl ITC retention (Bangarwa et al. 2011a). Therefore, a study was conducted with the primary objective of refining the allyl ITC and metam sodium rates and comparing their effectiveness with standard MeBr application in low-density polyethylene (LDPE) –mulched bell pepper.

Materials and Methods

A study was conducted at the Arkansas Agricultural Research and Extension Center at University of Arkansas, Fayetteville, AR, during summer 2010 and 2011. In the 2010 study field, the soil type was a Razort silt loam (fine–loamy, mixed, active, mesic Mollic Hapludalfs) with pH of 6.3 and organic matter content of 1.8% (USDA Web Soil Survey). In the 2011 study site, the soil type was a Captina silt loam (fine–silty, siliceous, active, mesic Typic Fragiudults) with pH of 6.1 and organic matter of 1.8%. For both years, study fields were tilled once in late March with disk harrow and twice in early April with a field cultivator to remove any plant residue present on the soil surface. Plant residue reduces the efficiency of soil-applied fumigants by preventing uniform spreading into the soil. At experimental plot setup, Palmer amaranth and large crabgrass seed and yellow nutsedge tubers (Azlin Seed Company, 112 Lilac Drive, Leland, MS 38756) were broadcasted and incorporated over the study field to achieve uniform weed populations throughout the plots.

The study was a randomized complete block design with four replications. Treatments consisted of three rates of allyl ITC (95% purity, Sigma-Aldrich Inc., 6000 North Teutonia, Milwaukee, WI 53209) and metam sodium (Vapam®HL, 42% purity, AMVAC Chemical Corporation, 4100 East Washington Boulevard, Los Angeles, CA 90023) applied under LDPE mulch (black, embossed, 1.0 mil thick, Polygro LLC, Tampa, FL 33655). Allyl ITC was applied at 450, 600, and 750 kg ha^{-1}, and metam sodium was applied at 180, 270, and 360 kg ha^{-1}. Rates for allyl ITC were chosen to define the effective rate based on a previous study conducted by Bangarwa et al. (2011a). For metam sodium, the highest rate was chosen based on previous MeBr-alternative studies, and lower rates were added to evaluate metam sodium effectiveness at lower rates (Gilreath et al. 2005; Johnson and Mullinix 2007). Additionally, a weedy check and a standard treatment of MeBr plus chloropicrin at 260 and 130 kg ha^{-1} (mixture of 67 and 33%, respectively, at 390 kg ha^{-1}) were used for comparison.

Allyl ITC and metam sodium were applied as a broadcast spray using a CO_2-pressurized backpack sprayer and TeeJet XR 11003 nozzles (TeeJet Technologies, Spraying Systems Co., Wheaton, IL 60187) calibrated to deliver 280 L ha^{-1} at 207 kPa. In order to achieve the higher rates of allyl ITC and metam sodium, treatments were sprayed on a plot by multiple passes (one pass was equivalent to 150 and 90 kg ha^{-1} for allyl ITC and metam sodium, respectively). Allyl ITC or metam sodium was applied in 1.5-m swath to 4-m-long plots, and immediately incorporated into the top 0.1 m of soil with the use of a rototiller. Raised beds were formed with fumigant-incorporated soil and beds were covered with LDPE mulch in a single pass with the use of tractor-mounted raised-bed mulch layer. MeBr was injected into the soil with a double-rigged MeBr applicator attached to the raised-bed mulch layer, raised beds were formed, and beds were covered with LDPE mulch successively in a single pass. In weedy check, raised beds were formed and beds were covered with LDPE mulch. During raised-bed formation and LDPE mulching, drip tape was placed on top and at the center of the bed and underneath the LDPE mulch to facilitate irrigation and fertigation. For all the treatments, raised-bed formation, drip-tape placement, and LDPE mulching were performed by using a tractor-attached raised-bed mulch layer. Moreover, bedding height of the raised-bed mulch layer was set at 0.1 m in order to prepare raised beds of uniform height. In a single row of raised-bed plots, each plot was separated by cutting the LDPE mulch at the end of the plot and covering the cut ends of the mulch with soil. This prevented mixing of treatments across the plots within a single row. The final size of each plot was 3.6 m long and 0.75 m wide at the top of the raised bed with spacing of 1.8 m between plots. After setting the mulch and drip lines, plots were irrigated to activate the applied fumigants.

Three weeks after fumigant application, 20 openings (in a double row with 10 openings row^{-1} and spaced 0.3 by 0.3 m) of 5-cm diameter were punched in each bell pepper plot. Plots were left for aeration for 3 d before transplanting the seedlings. The aeration of plots allowed the escape of fumigant compound trapped between the soil surface and LDPE mulch, minimizing crop injury (Bangarwa et al. 2011a). After aeration, four- to six-leaf 'Heritage' bell pepper (Seedway LLC, 1734 Railroad Place, Hall, NY 11463) seedlings were transplanted. Plots were regularly fertigated, sprayed with insecticides and fungicides to prevent insect and disease damage, and managed with standard practices recommended for plasticulture bell pepper production (Holmes and Kemble 2010). Weeds between plastic-mulched beds were managed by hooded application of PRE *S*-metolachlor ((Dual Magnum 7.62 EC; Syngenta Crop Protection, Greensboro, NC) at 2 wk after transplanting (WATP) and POST paraquat (Gramoxone Inteon 2.76 EC; Syngenta Crop Protection, Greensboro, NC) at 4, 6, and 8 WATP.

Visual estimates of weed control and crop injury were recorded at 4, 6, and 8 WATP. Weed control and crop injury ratings were based on a 0 to 100% scale, where 0 = no weed control or no crop injury, and 100 = complete weed control or death of crop. Palmer amaranth and large crabgrass could not penetrate through the LDPE mulch. Therefore, Palmer amaranth and large crabgrass control ratings were based on plant emergence from the transplant openings of the LDPE mulch. However, yellow nutsedge penetrated through LDPE mulch. So, the yellow nutsedge control rating was based on the plants that emerged from the opening of the LDPE mulch as well as plants that penetrated through the LDPE mulch.

Mature marketable bell pepper fruits were harvested multiple times throughout the season and graded according to market standards for bell pepper (USDA 2005). Bell pepper fruits were graded for U.S. Fancy, U.S. No. 1, and U.S. No. 2 categories, and fruit weights were recorded by grades. First and second harvests from each season were added to determine the early-season bell pepper yield. Likewise, the total marketable bell pepper yield was calculated by summing fruit weights of all grades from all harvests. At the end of season (4 mo after transplanting), five soil-core samples (a sample sized 0.1 m in diameter and 0.15 m in depth) were collected from each plot. Core samples were sieved and washed to determine the number of yellow nutsedge tubers. Yellow nutsedge tubers that were firm were collected and recorded.

Data were analyzed with the use of PROC GLM procedure in Statistical Analysis Software (version 9.2, SAS Institute Inc, Campus Drive, Cary, NC 27513). Year and treatments were considered fixed effects, and replication was considered a random effect for the analysis. If the year-by-treatment interaction was not significant, data from the 2 yr were averaged. If the year-by-treatment interaction was significant, data were analyzed separately by year. Weed control data were

Table 1. Effect of allyl isothiocyanate (ITC), metam sodium, and methyl bromide plus chloropicrin on Palmer amaranth and large crabgrass control in low-density polyethylene-mulched bell pepper at 4, 6, and 8 wk after transplanting (WATP), averaged over 2010 and 2011.

		Weed control[a]					
		Palmer amaranth[b]			Large crabgrass		
Soil fumigants	Rate	4 WATP	6 WATP	8 WATP	4 WATP	6 WATP	8 WATP
	kg ai ha^{-1}	——————	——————	——————	—%—	——————	——————
Allyl ITC	450	88 d	64 c	49 cd	93 b	61 c	43 c
	600	90 cd	82 bc	69 bc	96 ab	69 bc	52 c
	750	93 cd	91 ab	83 ab	98 ab	89 a	78 ab
Metam sodium	180	94 bcd	65 c	46 d	95 ab	66 d	51 c
	270	95 bc	89 ab	78 b	96 ab	76 b	59 bc
	360	98 ab	96 ab	87 ab	98 ab	90 a	84 a
Methyl bromide + chloropicrin	260, 130	100 a	98 a	97 a	100 a	93 a	89 a
Weedy check	–	–	–	–	–	–	–

[a] Treatment means within a column followed by the same letter are not different based on Fisher's Protected LSD at $\alpha = 0.05$. Mean separation based on arcsine-transformed data.

[b] Palmer amaranth did not emerge until 4 WATP in 2010; therefore, only data for 2011 are shown for Palmer amaranth control at 4 WATP.

arcsine transformed and analyzed. However, yellow nutsedge tuber and bell pepper yield data did not require transformation. Data were subjected to ANOVA, and means were separated by Fisher's protected LSD ($\alpha = 0.05$). The weedy check was not included in the weed control analysis because of the lack of variability (rated 0 for weedy check) in data. However, for the analysis of yellow nutsedge tuber density and bell pepper yield, the weedy checks were included because of variability in the data.

Results and Discussion

Weed Control. The year-by-treatment interaction was nonsignificant for Palmer amaranth, large crabgrass, and yellow nutsedge control. Therefore, weed control was averaged over 2010 and 2011 and presented accordingly for result and discussion.

Palmer Amaranth Control. There were significant differences (α= 0.05) among allyl ITC and metam sodium rates for Palmer amaranth control in LDPE-mulched bell pepper (Table 1). In comparison to MeBr, the highest rates of allyl ITC and metam sodium were more effective than the lower rates for Palmer amaranth control. Palmer amaranth control was ineffective throughout the season from lower rates of allyl ITC and metam sodium, except at the medium rate of metam sodium at 6 WATP, compared to MeBr in bell pepper production. Allyl ITC at 750 kg ha^{-1} or metam sodium at 360 kg ha^{-1} was comparable to MeBr for Palmer amaranth control in bell pepper at 8 WATP (Table 1). At 8 WATP, Palmer amaranth control was 83 and 87% from allyl ITC at 750 kg ha^{-1} and metam sodium at 360 kg ha^{-1}, respectively. Although Palmer amaranth control from the highest rate of allyl ITC and metam sodium are statistically similar to control with MeBr, this level of control might be inadequate to prevent yield loss in bell pepper at greater weed pressure. Palmer amaranth control from allyl ITC at 750 kg ha^{-1} in this study corresponds with the results of Bangarwa et al. (2011a), who concluded that allyl ITC at 888 ($\pm$ 225) kg ha^{-1} was similar to the standard MeBr treatment for Palmer amaranth control in plasticulture bell pepper.

Large Crabgrass Control. Lower rates of allyl ITC and metam sodium were ineffective for large crabgrass control 4 WATP. Large crabgrass control was effective season long from allyl ITC at 750 kg ha^{-1} and metam sodium at 360 kg ha^{-1}. Large crabgrass control from the highest rates of allyl ITC and metam sodium was similar to control with MeBr (Table 1). At 8 WATP, allyl ITC at 750 kg ha^{-1} and metam sodium at 360 kg ha^{-1} controlled large crabgrass $\geq$78% in LDPE-mulched bell pepper production, and the control was comparable to the control with MeBr. In a previous study, Bangarwa et al. (2011a) reported that allyl ITC at 651 ($\pm$ 118) kg ha^{-1} controlled large crabgrass comparably to MeBr in plasticulture bell pepper. Weed control with metam sodium was comparable to MeBr treatment in tobacco and tomato transplant production (Csinos et al. 2002b).

Yellow Nutsedge Control. Soil fumigation with allyl ITC and metam sodium affected yellow nutsedge population in bell pepper. At 4 WATP, yellow nutsedge control with allyl ITC at 750 kg ha^{-1} was lower than the control with MeBr (Table 2). However, yellow nutsedge control on allyl ITC at 750 kg ha^{-1}–treated plots was similar to MeBr plots in the later ratings (at 6 and 8 WATP). Similarly, metam sodium at 360 kg ha^{-1} was comparable to MeBr for yellow nutsedge control. At 8 WATP, yellow nutsedge control was 80 and 83% from the allyl ITC at 750 kg ha^{-1} and metam sodium at 360 kg ha^{-1}, respectively. Likewise, Bangarwa et al. (2011a) reported equivalent yellow nutsedge control from allyl ITC at 924 ($\pm$ 74) kg ha^{-1} and MeBr in plasticulture bell pepper. In the study conducted by Gilreath et al. (2005), drip-applied metam sodium at 710 L ha^{-1} (equivalent to 360 kg ha^{-1}) was comparable to MeBr plus chloropicrin at 400 kg ha^{-1} for *Cyperus* spp. control in two of three bell pepper growing seasons. Likewise, metam sodium plus chloropicrin was comparable to standard MeBr application for *Cyperus* spp. control in fresh market tomato (Santos et al. 2006). In the current study, metam sodium was broadcast applied and yellow nutsedge control did not vary between years. In a

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Table 2. Effect of allyl isothiocyanate (ITC), metam sodium, and methyl bromide plus chloropicrin on yellow nutsedge control at 4, 6, and 8 wk after transplanting (WATP), and yellow nutsedge tuber density in low-density polyethylene–mulched bell pepper averaged over 2010 and 2011.

Soil fumigants	Rate	Yellow nutsedge[a] 4 WATP	6 WATP	8 WATP	Tuber density[b]
	kg ai ha^{-1}	———	%	———	tubers m^{-2}
Allyl ITC	450	44 d	37 e	33 d	187 bc
	600	64 c	56 de	48 cd	149 c
	750	88 b	84 ab	80 ab	84 d
Metam sodium	180	71 c	64 cd	49 c	220 ab
	270	89 ab	78 bc	73 b	149 c
	360	92 ab	88 ab	83 ab	57 d
Methyl bromide + chloropicrin	260; 130	96 a	94 a	92 a	51 d
Weedy check	–	–	–	–	273 a

[a] Treatment means within a column followed by the same letter are not different based on Fisher's Protected LSD at $\alpha = 0.05$. Mean separation based on arcsine-transformed data.

[b] Tuber density (tubers m^{-2}) determined from five soil cores (0.1-m diam by 0.15-m depth) pulled for each tomato and bell pepper plot.

similar study, purple nutsedge (*Cyperus rotundus* L.) density in bell pepper plots at 10 WAT was 2.7 plants m^{-2} with broadcast-applied metam sodium at 485 kg ha^{-1} and was comparable to the density (7.3 plants m^{-2}) in MeBr-treated plots (Gilreath and Santos 2004).

Weed control was rate responsive for allyl ITC and metam sodium and weed control with the lower rates of allyl ITC and metam sodium was ineffective. On the other hand, weed control from the highest rate of allyl ITC and metam sodium was more effective than their respective lower rates compared with MeBr, and control lasted all season. Peterson et al. (2001) reported that the activity of ITCs increases rapidly after the ITC rate exceeds the effective dose for 50% control (ED_{50}). In addition, the higher rates of ITC have greater activity on seed enzymes, which causes loss of seed viability, and those seeds do not germinate (Brown and Morra 1995; Peterson et al. 2001). Therefore, the highest rates of ITCs were effective season-long for weed control and controlled weeds at a level comparable to MeBr.

Yellow Nutsedge Tuber Density. The lower rates of allyl ITC and metam sodium did not reduce yellow nutsedge tuber density compared to MeBr-treated plots. However, tuber density in plots treated with allyl ITC at 750 kg ha^{-1} or metam sodium at 360 kg ha^{-1} was similar to the MeBr treatment (Table 2). At the end of the season, yellow nutsedge tuber densities ($\leq$ 84 tuber m^{-2}) were comparable in bell pepper plots treated with allyl ITC at 750 kg ha^{-1} and metam sodium at 360 kg ha^{-1}. Although allyl ITC at 750 kg ha^{-1} and metam sodium at 360 kg ha^{-1} were comparable to MeBr for yellow nutsedge tuber density, no fumigant controlled tubers at a level to prevent yellow nutsedge interference in the next growing season. Previous research has shown that bell pepper dry weight and marketable yield reduction were $\geq$ 42 and $\geq$ 47%, respectively, with an initial yellow nutsedge tuber density of 50 tuber m^{-2} (Bangarwa et al. 2011b).

Bell Pepper Injury. Allyl ITC and metam sodium did not injure bell pepper at any rate evaluated in this study. This study shows that bell pepper seedlings at the four- to six-leaf stage can be transplanted into LDPE-mulched raised beds at 3 wk after applying these fumigants. However, direct exposure of the seedling to the fumigant vapor trapped between the soil surface and LDPE mulch should be prevented by aerating the raised beds for 3 d prior to transplanting seedlings. In a similar study, Bangarwa (2010) observed 11% injury at 2 WATP in bell pepper from allyl ITC at 1500 kg ha^{-1} applied under virtually impermeable film (VIF). However, injury was $\leq$ 3% from allyl ITC applied at 1,500 kg ha^{-1} under LDPE mulch.

Table 3. Effect of allyl isothiocyanate (ITC), metam sodium, and methyl bromide plus chloropicrin on early-season bell pepper yield, averaged over 2010 and 2011.

Soil fumigants	Rate	Early-season yield according to grade and total yield[ab] U.S. Fancy	U.S. No. 1	U.S. No. 2	Total yield[c]
	kg ai ha^{-1}	———	ton ha^{-1}	———	
Allyl ITC	450	3.5 ab	3.4 abc	2.7 b	9.6 bcd
	600	2.6 bc	3.0 bc	3.4 ab	9.0 cd
	750	4.2 ab	4.7 a	4.4 a	13.3 ab
Metam sodium	180	1.5 c	2.3 c	2.9 b	6.8 d
	270	4.5 ab	3.6 abc	4.2 a	12.3 abc
	360	4.7 ab	3.8 ab	4.4 a	12.9 ab
Methyl bromide + chloropicrin	260; 130	5.4 a	4.7 a	4.3 a	14.4 a
Weedy check	–	2.9 bc	3.1 bc	2.8 b	8.9 cd

[a] Treatment means within a column followed by the same letter are not different based on Fisher's Protected LSD at $\alpha = 0.05$.

[b] Early-season bell pepper yield according to the U.S. Department of Agriculture grade and the early total yield.

[c] Early-season yield determined by summing first and second harvest from 2010 and 2011.

Bell Pepper Yield. Early-season bell pepper yield from plots treated with allyl ITC at 750 kg ha^{-1} and metam sodium at 270 and 360 kg ha^{-1} was $\geq$ 12.3 ton ha^{-1}, and these yields were equivalent to the early-season bell pepper yield from MeBr (Table 3). Likewise, early-season bell pepper yield according to USDA grade is similar for allyl ITC at 750 kg ha^{-1}, metam sodium at 270 and 360 kg ha^{-1}, and MeBr treatment. Furthermore, early-season yield contributed > 23% of total marketable bell pepper yield. In a similar study, Bangarwa et al. (2011a) reported similar early-season yield from plots treated with allyl ITC and MeBr. Total marketable bell pepper yield in plots treated with allyl ITC at 750 kg ha^{-1} was lower than in MeBr-treated plots because of a lower yield of U.S. Fancy category fruit (Table 4). The total marketable bell pepper yield with allyl ITC at 750 kg ha^{-1} was about 12 ton ha^{-1} less compared to yield with MeBr.

Bell pepper treated with metam sodium at 270 and 360 kg ha^{-1} yielded 13.2 and 12.4 ton U.S. Fancy pepper ha^{-1}, respectively, and was similar to plots treated with MeBr (Table 4). However, yields of U.S. No. 1 and No. 2 fruit from bell pepper treated with metam sodium at 270 kg ha^{-1} were lower than yields of those categories from MeBr-treated bell pepper. Bell pepper treated with metam sodium at 360 kg ha^{-1} yielded 53.5 ton ha^{-1} total marketable bell pepper,

Table 4. Effect of allyl isothiocyanate (ITC), metam sodium, and methyl bromide plus chloropicrin on marketable bell pepper yield, averaged over 2010 and 2011.

Soil fumigants	Rate	Yield according to grade and total yield[ab]			
		U.S. Fancy	U.S. No. 1	U.S. No. 2	Total yield[c]
	kg ai ha^{-1}	ton ha^{-1}			
Allyl ITC	450	9.5 bc	9.9 cd	12.0 e	31.4 d
	600	9.6 bc	11.4 bcd	17.1 dc	38.0 cd
	750	11.6 b	14.9 ab	24.2 ab	50.6 b
Metam sodium	180	6.0 c	7.9 d	13.8 de	27.8 d
	270	13.2 ab	13.3 bc	20.9 bc	47.3 bc
	360	12.4 ab	14.7 ab	26.4 a	53.5 ab
Methyl bromide + chloropicrin	260; 130	17.1 a	18.4 a	27.0 a	62.5 a
Weedy check	–	6.1 c	8.1 d	13.8 de	27.8 d

[a] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at $\alpha = 0.05$.

[b] Marketable bell pepper yield according to the U.S. Department of Agriculture grade and the total yield.

[c] Total yield determined by summing four and five harvests from 2010 and 2011, respectively.

which was 92% greater than the yield (27.8 ton ha^{-1}) from weedy check plots. Total marketable yield was higher from the highest rate of metam sodium because of the effective weed control. However, at lower rates, metam sodium–treated plots provided less yield compared to MeBr-treated plots because of lower weed control. Gilreath et al. (2004) observed higher bell pepper yield in the first year and equivalent bell pepper yield in the second year in plots treated with metam sodium at 483 kg ha^{-1} compared to yields in plots treated with MeBr at 400 kg ha^{-1}.

Total marketable bell pepper yield in plots treated with allyl ITC at 750 kg ha^{-1} was lower than in MeBr-treated plots (Table 4). Lower bell pepper fruit yield of U.S. Fancy and U.S. No. 1 categories following allyl ITC at 750 kg ha^{-1} contributed to the lower total yield compared to MeBr. Bell pepper yields with allyl ITC were less than those with MeBr, likely because of lower weed control with allyl ITC relative to MeBr. Bell pepper has a short stature, an open canopy, and a slow growth habit, so yield loss because of weed interference is more pronounced in bell pepper than in other robust vegetable crops (Norsworthy et al. 2008). Morales-Payen et al. (1998) observed more yield loss (73%) in bell pepper than yield loss (42%) in tomato because of purple nutsedge interference. In the present study, U.S. Fancy grade yield and total marketable yield in the plots treated with the highest rate of allyl ITC was lower than in MeBr-treated plots. This result illustrates that weed interference reduces U.S. Fancy grade fruit, the highest quality of bell pepper fruit, and eventually lowers the total marketable yield. In a previous study, Bangarwa et al. (2011a) reported equivalent bell pepper yield with allyl ITC applied at 932 ($\pm$ 127) kg ha^{-1} and MeBr at 390 kg ha^{-1} in polyethylene-mulched system. However, in this study we applied allyl ITC at 750 kg ha^{-1}, a lower rate than the predicted rate by Bangarwa et al. (2011a), and at this rate, total marketable bell pepper yield from allyl ITC–treated plots was not comparable to MeBr-treated plots.

Factors such as soil type, fumigation incorporation method, and bed width and height influence the effectiveness of the soil-applied fumigant (Ajwa et al. 2002). In the current study, the fumigant application and MeBr application methods were different. Therefore, it is possible that some allyl ITC and metam sodium (methyl ITC) could have been lost during the few minutes between application and laying of polyethylene mulch. However, it is unlikely that an appreciable amount of fumigant was lost during application. Csinos et al. (2002b) reported that metam sodium efficacy did not differ when it was injected with chisels or sprayed onto soil surfaces and incorporated into soil. Allyl ITC and metam sodium were applied as a liquid. For metam sodium, the liquid form changes into active fumigant after reacting with water/moisture in the soil. For optimal effectiveness of soil-applied fumigants, uniform irrigation and complete wetting of the raised bed after fumigant application is very critical (Csinos et al. 2002a). If the beds are partially wet, dissipation of methyl ITC from wet regions to dry regions is slow because of the higher affinity of methyl ITC to the moisture (Noling and Becker 1994). As the irrigation period and amount of water needed to irrigate the field vary according to soil type and soil gradient, the irrigation system should be managed accordingly.

In conclusion, preplant soil fumigation with allyl ITC ($\leq$ 750 kg ha^{-1}) and metam sodium ($\leq$ 360 kg ha^{-1}) is safe for LDPE-mulched bell pepper. Allyl ITC at 750 kg ha^{-1} and metam sodium at 360 kg ha^{-1} was similar for weed control, yellow nutsedge tubers, and bell pepper yield. Weed control and yellow nutsedge tuber density from allyl ITC at 750 kg ha^{-1} was comparable to MeBr. U.S. No. 1 and U.S. No. 2 bell pepper yield from allyl ITC at 750 kg ha^{-1} were comparable to MeBr. However, U.S. Fancy grade yield was lower from allyl ITC at 750 kg ha^{-1} compared to MeBr. LDPE-mulched bell pepper plots treated with metam sodium at 360 kg ha^{-1} provided equivalent weed control, yellow nutsedge tuber density, and total marketable yield compared to plots treated with MeBr. Therefore, this study illustrates that metam sodium at 360 kg ha^{-1} is a potential alternative to MeBr for weed control and maintaining yields in LDPE-mulched bell pepper production. Allyl ITC has potential to replace MeBr; however, allyl ITC would need to be applied at a rate slightly higher than 750 kg ha^{-1}. Moreover, further studies evaluating allyl ITC at $>$ 750 kg ha^{-1} and comparing with MeBr will be helpful in determining the most effective allyl ITC rate.

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