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Allyl Isothiocyanate and Metham Sodium as Methyl Bromide Alternatives for Weed Control in Plasticulture Tomato

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Isothiocyanates (ITCs) were evaluated as an alternative to methyl bromide (MeBr) for control of Palmer amaranth, large crabgrass, and yellow nutsedge; reduction of tuber density; and increase in marketable tomato yield in low density polyethylene (LDPE)-mulched tomato production. Allyl ITC was applied at 450, 600, and 750 kg ai ha^{-1}; metham sodium (methyl ITC generator) was applied at 180, 270, and 360 kg ai ha^{-1}; and MeBr plus chloropicrin (mixture of MeBr and chloropicrin at 67 : 33%, respectively) was applied at 390 kg ai ha^{-1}. A nontreated weedy check was included for comparison. There was no injury to tomato plants following allyl ITC, metham sodium, or MeBr application. Allyl ITC at 750 kg ha^{-1} or metham sodium at 360 kg ha^{-1} controlled Palmer amaranth $\geq$ 79%, large crabgrass $\geq$ 76%, and yellow nutsedge $\geq$ 80% and was comparable to the weed control with MeBr. Highest rates of allyl ITC and metham sodium reduced yellow nutsedge tuber density ($\leq$ 76 tubers m^{-2}) comparable to the MeBr application. Total marketable tomato yield was $\geq$ 31.6 t ha^{-1} in plots treated with allyl ITC at 750 kg ha^{-1} or metham sodium at 360 kg ha^{-1}. Marketable tomato yield from the highest rate of allyl ITC or metham sodium were similar to the yield (38.2 t ha^{-1}) with MeBr treatment. Therefore, allyl ITC at 750 kg ha^{-1} and metham sodium at 360 kg ha^{-1} are effective alternatives to MeBr for Palmer amaranth, large crabgrass, and yellow nutsedge control in LDPE-mulched tomato.

Nomenclature: Allyl isothiocyanate; metham sodium; methyl bromide; large crabgrass, *Digitaria sanguinalis* (L.) Scop. DIGSA; Palmer amaranth, *Amaranthus palmeri* S. Wats. AMAPA; yellow nutsedge, *Cyperus esculentus* L. CYPES; tomato, *Solanum lycopersicum* L. 'Amelia'.

Key words: Isothiocyanates, low-density polyethylene mulch, methyl bromide alternatives, plasticulture tomato, weed control.

Se evaluaron isothiocyanates (ITCs) como alternativa a methyl bromide (MeBr) para el control de *Amaranthus palmeri*, *Digitaria sanguinalis*, *Cyperus esculentus*, para la reducción de la densidad de tubérculos, y para el incremento en el rendimiento comercializable del tomate en producción de este cultivo en coberturas de polyethylene de baja densidad (LPDE). Se aplicó allyl ITC a 450, 600, y 750 kg ai ha^{-1}; metham sodium (generador de methyl ITC) se aplicó a 180, 270, y 360 kg ai ha^{-1}, y MeBr más chloropicrin (mezcla de MeBr y chloropicrin a 67:33%, respectivamente) se aplicó a 390 kg ai ha^{-1}. Un testigo no-tratado con malezas se incluyó para fines de comparación. No hubo daño en las plantas de tomate después de las aplicaciones de allyl ITC, metham sodium, o MeBr. Allyl ITC a 750 kg ha^{-1} o metham sodium a 360 kg ha^{-1} controlaron *A. palmeri* $\geq$79%, *D. sanguinalis* 76%, y *C. esculentus* $\geq$80%, y este control fue comparable al control observado con MeBr. Las dosis más altas de allyl ITC y metham sodium redujeron la densidad de los tubérculos de *C. esculentus* ($\leq$76 tubérculos m^{-2}), lo que fue comparable a la aplicación de MeBr. El rendimiento comercializable total del tomate fue $\geq$31.6 ton ha^{-1} en las parcelas tratadas con allyl ITC a 750 kg ha^{-1} o con metham sodium a 360 kg ha^{-1}. El rendimiento comercializable del tomate con la dosis más alta de allyl ITC o metham sodium fue similar al rendimiento del tratamiento con MeBr (38.2 ton ha^{-1}). De esta manera, allyl ITC a 750 kg ha^{-1} y metham sodium a 360 kg ha^{-1} son alternativas efectivas al MeBr para el control de *A. palmeri*, *D. sanguinalis*, y *C. esculentus* en tomate con cobertura LDPE.

Tomato is the most important vegetable crop in the United States (U.S.) and ranks first in terms of economic value as a fresh-market vegetable as well as for processed product production. In 2012, fresh market tomato and processed tomato were valued at $864 million and $1.01 billion, respectively, in the U.S. (USDA 2013a). In commercial production, plasticulture is widely adopted by U.S. growers. The

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plasticulture, irrigated system aids management and delivery of plant nutrients, suppresses weeds, achieves earlier harvest, obtains superior quality fruit, and maximizes yield (Sanders et al. 1996). However, weeds are often a major constraint for optimum tomato yield in plasticulture production. In plasticulture system, weeds emerge from the openings punched for transplanting and subsequently interfere with the crop. In addition, nutsedge species penetrate through the polyethylene mulch and compete with the vegetable crop.

Palmer amaranth is widely distributed throughout the vegetable-growing states in the southern United States. Palmer amaranth grows rapidly, is highly competitive with vegetable crops, and significantly reduces yields (Norsworthy et al. 2008). Under favorable environmental conditions, Palmer amaranth grows 0.18 to 0.21 cm per growing degree day (GDD) at a base temperature of 10 C (Horak and Loughin 2000) and attains a 2-m height within 10 wk after emergence (Norsworthy et al. 2008). Meyers et al. (2010) reported 36 to 81% loss of marketable sweet potato (*Ipomoea batatas* L.) from Palmer amaranth at 0.5 to 6.5 plants m^{-1}.

Among the weeds of U.S. vegetable crops, large crabgrass is one of the most common and important (Bridges and Baumann 1992). The establishment and season-long interference of large crabgrass caused significant loss of bell pepper fruit yield (Fu and Ashley 2006). In seeded tomato, season-long presence of large crabgrass at 55 plants m^{-2} reduced tomato yield by 76% compared to weed-free tomato plots (Monaco et al. 1981).

Yellow nutsedge is a perennial weed that reproduces via underground tubers. Morales-Payan et al. (2003a) reported 34% reduction in aboveground tomato dry weight production with season-long interference of yellow nutsedge. The presence of yellow nutsedge throughout the growing season reduced tomato fruit yield by 50% (Stall and Morales-Payan 2003). Futhermore, yellow nutsedge penetrates through and ruptures the polyethylene mulch, and lowers the durability of the mulch. If yellow nutsedge is not controlled effectively, infestation can be more severe later in the growing season because of its rapid spread from tubers. Anderson (1999) reported that a single tuber can produce up to 36 plants and about 332 tubers in 16 wk, and within a year it can form a patch of 6-m diam with 1,900 plants and 7,000 tubers.

In tomato production, MeBr was the most extensively used soil fumigant for weed control until it was phased out in 2005 for ordinary agricultural uses by the U.S. Environmental Protection Agency (USEPA 2005). The ban on use of MeBr accounts for millions of dollars of annual losses in commercial tomato production, and weeds cause a significant portion of these losses (Carpenter et al. 2000). With the elimination of MeBr, tomato growers need viable alternatives to manage problematic weed species. ITCs are soil fumigants reported to have potential broad-spectrum activity, including herbicidal properties (Borek et al. 1998; Smolinska et al. 1997). Peterson et al. (2001) reported that ITCs are effective in suppressing weed seed germination. Furthermore, allyl ITC has been reported to have activity on many of the most common and troublesome weeds of vegetables (Al-Khatib et al. 1997; Bangarwa 2010; Norsworthy and Meehan 2005ab). In previous studies, allyl ITC and metham sodium (methyl ITC generator) have shown a high degree of weed control (Ajwa et al. 2002; Bangarwa et al. 2012). ITCs are highly volatile compounds; in addition to proper incorporation into the soil after application, the use of polyethylene-mulch is critical for preventing volatilization losses and for higher use efficiency of ITCs (Austerweil et al. 2006).

In previously conducted MeBr-alternative research, allyl ITC was evaluated over a wide range of rates (0 to 1,500 kg ha^{-1}) in plasticulture tomato and was reported as a potential MeBr alternative (Bangarwa et al. 2012). There is a need to identify the specific allyl ITC rate needed for weed control comparable to MeBr in plasticulture tomato. In another study, metham sodium was reported as an effective alternative to MeBr (Gilreath and Santos 2004; Gilreath et al. 2008); however, there is no published report of allyl ITC and metham sodium evaluated in a single study and in comparison with a standard MeBr application. Therefore, a study was conducted with the primary objective of better defining the allyl ITC rate and comparing the effectiveness of allyl ITC with metham sodium and MeBr for weed control in LDPE-mulched tomato.

Materials and Methods

A field study was conducted at the Arkansas Agricultural Research and Extension Center at the

University of Arkansas, Fayetteville, AR, during summer 2010 and 2011. In the 2010 study site, 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 2013b). 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% (USDA 2013b). For both years, the field was tilled once in late March and twice in early April to remove any plant residue present on the soil surface. At field preparation, Palmer amaranth and large crabgrass seed, and yellow nutsedge tubers (Azlin Seed Company, 112 Lilac Drive, Leland, MS 38756) were broadcasted to establish 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 N. Teutonia, Milwaukee, WI 53209) and metham sodium (Vapam®HL, 42% purity, AMVAC Chemical Corporation, 4100 E. Washington Blvd., Los Angeles, CA 90023) applied in LDPE-mulched (black, embossed, 0.1 cm thick, Polygro LLC, Tampa, FL 33655) system. Allyl ITC was applied at 450, 600, and 750 kg ha^{-1}, and metham sodium was applied at 180, 270, and 360 kg ha^{-1}. Rates for allyl ITC were chosen to narrow and refine the effective rate based on a previous study conducted by Bangarwa et al. (2012). For metham sodium, the highest rate was chosen based on previous MeBr-alternative studies (Gilreath et al. 2005; Johnson and Mullinix 2007). Within 1 d after application, greater than 90% of the applied ITC can escape from the soil because of volatilization (Brown and Morra 1995). Therefore, use of polyethylene mulch is critical for retention of the applied ITCs in the soil and for maximum weed control. There are various types of polyethylene mulch commercially available; LDPE mulch costs less and it is as effective as virtually impermeable film for retention of allyl ITC in the soil (Bangarwa et al. 2010). These are the reasons for using LDPE mulch in this experiment. Additionally, a non-treated check and a standard treatment of MeBr plus chloropicrin at 261 and 129 kg ha^{-1} (mixture of 67 and 33%, respectively at 390 kg ha^{-1}) were used for comparison.

Allyl ITC and metham sodium were applied as a broadcast spray using a CO_2-pressurized backpack sprayer, and spray was delivered at 280 L ha^{-1}. In order to achieve the higher rates of allyl ITC and metham sodium, treatments were sprayed by multiple passes (one pass was equivalent to 150 and 90 kg ha^{-1} for allyl ITC and metham sodium, respectively). Immediately after application, ITCs were incorporated into the top 0.1 m of soil using a rototiller. Immediately after incorporation of treatments into the soil, beds were formed and covered with LDPE mulch successively in a single pass. MeBr was injected into the rototilled plot with two knives attached to a tractor-mounted MeBr applicator, the raised bed was formed, and bed was covered with LDPE mulch. During mulch application, a single row of drip tape was placed underneath the LDPE mulch and at the center of the bed for irrigation and fertigation. In a raised bed, 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. The final size of each plot was 4.5 m long and 0.75 m wide at the top of the bed.

Three weeks after ITC application, seven openings (in a single row, at 0.6 m apart) were punched through the LDPE mulch in each plot for transplanting tomato. Plots were aerated for 3 d before transplanting to allow for release of the fumigant trapped between the LDPE mulch and raised bed and to minimize crop injury. After aeration, four- to six-leaf 'Amelia' tomato (Seedway LLC, 1734 Railroad Place, Hall, NY 11463) seedlings were transplanted. Plots were fertigated three times weekly, sprayed weekly with insecticides and fungicides to prevent insect and disease damage, and managed with standard practices recommended for plasticulture tomato production (Holmes and Kemble 2010). Weeds between plastic-mulched beds were managed by hooded application of *S*-metolachlor at 2 wk after transplanting (WATP) and paraquat at 4, 6, and 8 WATP.

Visual estimates of crop injury and weed control 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 emergence of these weeds from the

LDPE mulch openings. However, yellow nutsedge penetrated through LDPE mulch and yellow nutsedge control ratings were based on emergence from the LDPE mulch openings as well as plants penetrating the LDPE mulch.

Mature marketable tomato fruits were harvested multiple times throughout the season and graded according to market standards for tomato (USDA 1997). Tomato fruits were graded for jumbo, extra large, large, medium, and small categories. Fruit weights were recorded according to the grades. First and second harvests from each season were combined to assess early-season tomato yield. Likewise, the total marketable yield of tomato was calculated by summing fruit weights of different grades from all the harvests. At the end of the season (at 4 mo after transplanting), five soil core samples (a sample sized 10 cm diam and 15 cm deep) were collected from each tomato plot. Soil cores were sieved and washed, and yellow nutsedge tubers were obtained. Tubers that were firm and creamy white were deemed viable.

Data were analyzed with PROC GLM using SAS (version 9.2, SAS Institute Inc, Campus Drive, Cary, NC 27513). If the year by treatment interaction was nonsignificant, data from the 2 yr were averaged. If the year by treatment interaction was significant, data were analyzed separately by year. In addition, nonnormal data were transformed with arcsine and log transformations for weed control and yield data, respectively. Data were subjected to one-way ANOVA, and means were separated by Fisher's Protected LSD ($\alpha = 0.05$).

Results and Discussion

Tomato Injury. Allyl ITC and metham sodium did not injure tomato (data not shown); hence, tomato seedlings at the four- to six-leaf stage can be transplanted into LDPE-mulched raised beds 3 wk after applying allyl ITC and metham sodium at a rates of up to 750 and 360 kg ha^{-1}, respectively. Additionally, seedbeds must be aerated for 3 d after punching transplant holes to allow the fumigant vapor trapped between the soil surface and LDPE mulch to dissipate. In other research, Devkota et al. (2013) also found that that allyl ITC and metham sodium were safe on polyethylene-mulched bell pepper.

Weed Control. The year by treatment interaction was nonsignificant for Palmer amaranth, large crabgrass, and yellow nutsedge control in tomato; therefore weed control was averaged over 2010 and 2011. Weed control was rate-responsive for allyl ITC and metham sodium. The lowest rates of allyl ITC and metham sodium were less effective than MeBr for weed control. Likewise, allyl ITC at 600 kg ha^{-1} was less effective than MeBr for Palmer amaranth, large crabgrass, and yellow nutsedge control.

Palmer Amaranth Control. Allyl ITC and metham sodium rates differed ($\alpha = 0.05$) for Palmer amaranth control. The two lower rates of allyl ITC and the lowest rate of metham sodium were ineffective on Palmer amaranth compared to MeBr. However, the highest rate of allyl ITC and two higher rates of metham sodium were comparable to MeBr for Palmer amaranth control in tomato (Table 1). Allyl ITC at 750 kg ha^{-1} and metham sodium at 270 and 360 kg ha^{-1} provided $\geq$ 79% Palmer amaranth control throughout the season in LDPE-mulched tomato. In a previous study, Bangarwa et al. (2012) reported that allyl ITC at 913 $\pm$ 191 kg ha^{-1} controlled Palmer amaranth equivalent to MeBr in polyethylene-mulched tomato.

In the current study, metham sodium at 270 kg ha^{-1} controlled Palmer amaranth comparable to the control with MeBr. The effectiveness of metham sodium on Palmer amaranth is most likely because of the small seed size. The smaller the seed size, the less tolerant is the seed to physical and chemical stresses (Westoby et al. 1996). Peterson et al. (2001) reported that weed control effectiveness of methyl ITC, the product of metham sodium, is directly related to seed size. Moreover, the activity of ITCs on seed increases rapidly after the rate exceeds the effective dose for 50% control, resulting in loss of seed viability (Peterson et al. 2001).

Large Crabgrass Control. The lower rates of allyl ITC and metham sodium were not as effective as MeBr for large crabgrass control. Metham sodium at 270 kg ha^{-1} controlled large crabgrass similar to MeBr at 4 WATP. However, large crabgrass control from metham sodium at 270 kg ha^{-1} was lower compared to MeBr at 6 and 8 WATP. Large crabgrass control from allyl ITC at 750 kg ha^{-1} and metham sodium at 360 kg ha^{-1} was similar to

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

		Weed control[a]					
		Palmer amaranth			Large crabgrass		
Soil fumigants	Rate	4 WATP[b]	6 WATP	8 WATP	4 WATP[c]	6 WATP	8 WATP[c]
	kg ai ha^{-1}	%					
Allyl ITC	450	76 e	41 c	23 c	87 cd	49 d	31 c
	600	88 cd	67 b	41 bc	93 bcd	59 c	38 c
	750	90 bcd	88 a	79 a	95 abc	86 a	76 ab
Metham sodium	180	84 de	66 b	49 b	86 d	61 c	36 c
	270	93 abc	87 a	83 a	96 ab	78 b	63 b
	360	98 ab	94 a	85 a	98 a	89 a	85 a
Methyl bromide + chloropicrin	261	100 a	98 a	94 a	99 a	93 a	91 a
	129						

[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] Palmer amaranth did not emerge until 4 WATP in 2010; therefore, only data for 2011 are shown at 4 WATP.
[c] Mean separation based on arcsine transformed data.

control with MeBr (Table 1). At 8 WATP, large crabgrass control was $\geq$ 76 and $\geq$ 85% from allyl ITC at 750 kg ha^{-1} and metham sodium at 360 kg ha^{-1}, respectively.

Yellow Nutsedge Control and Tuber Reduction. Soil fumigation with different rates of allyl ITC and metham sodium affected yellow nutsedge. The highest rates of allyl ITC and metham sodium were more effective than the respective lower rates for yellow nutsedge control in tomato (Table 2). At 8 WATP, yellow nutsedge control with allyl ITC at 750 kg ha^{-1} or metham sodium at 360 kg ha^{-1} was similar to that of MeBr (80 to 92%). Likewise, comparable yellow nutsedge control with allyl ITC at 827 $\pm$ 118 kg ha^{-1} and MeBr has been reported in polyethylene-mulched tomato (Bangarwa et al. 2012). Johnson and Mullinix (2007) reported 85% yellow nutsedge control with the soil fumigation of metham sodium at 380 kg ha^{-1} under black polyethylene mulch in cantaloupe (*Cucumis melo* var. *cantalupensis* L.) production. Metham sodium applied at 485 kg ha^{-1} was comparable to MeBr for controlling purple nutsedge (*Cyperus rotundus* L.)

Table 2. Effect of allyl isothiocyanate (ITC), metham sodium, and methyl bromide plus chloropicrin on yellow nutsedge control at 4, 6, and 8 wk after transplanting (WATP) and tuber density in LDPE-mulched tomato, averaged over 2010 and 2011.[a]

		Control			
Soil fumigants	Rate	4 WATP[b]	6 WATP	8 WATP	Tuber density[c]
	kg ai ha^{-1}	%			tubers m^{-2}
Allyl ITC	450	54 c	45 d	38 c	116 b
	600	57 c	48 cd	41 c	140 ab
	750	89 ab	84 ab	80 ab	76 bcd
Metham sodium	180	68 c	59 c	49 c	123 b
	270	88 b	79 b	71 b	97 bc
	360	93 ab	89 ab	86 a	30 cd
Methyl bromide + chloropicrin	261	97 a	94 a	90 a	22 d
	129				
Nontreated control	—	—	—	—	193 a

[a] Treatment means within a column followed by the same letter are not different based on Fisher's protected LSD at $\alpha = 0.05$.
[b] Mean separation based on arcsine transformed data.
[c] Tuber density (tubers m^{-2}) determined from five soil cores (0.1 m diam by 0.15 m deep) pulled for each tomato plot.

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Table 3. Effect of allyl isothiocyanate (ITC), metham sodium, and methyl bromide plus chloropicrin on early-season tomato yield, averaged over 2010 and 2011.[a]

Soil fumigants	Rate	Tomato yield[b]					
		Jumbo	Extra large	Large	Medium	Small	Total yield[c]
	kg ai ha^{-1}	t ha^{-1}					
Allyl ITC	450	1.8 bcd	0.8 bcd	0.6 bc	0.3 b	0.2 ab	3.7 bcd
	600	1.6 bcd	0.6 cd	0.2 c	0.1 b	0.1 b	2.6 cd
	750	1.9 abc	0.9 abc	0.9 b	0.6 ab	0.3 a	4.7 ab
Metham sodium	180	1.1 cd	0.5 cd	0.5 bc	0.2 b	0.1 b	2.4 d
	270	2.5 ab	1.0 abc	0.6 bc	0.4 ab	0.1 b	4.6 abc
	360	3.6 ab	1.4 ab	0.8 b	0.4 ab	0.2 ab	6.4 ab
Methyl bromide + Chloropicrin	261 129	4.7 a	2.2 a	1.8 a	0.7 a	0.1 b	9.5 a
Nontreated control	—	1.0 d	0.5 d	0.4 bc	0.4 ab	0.1 b	2.5 cd

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

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

[c] Total yield determined by summing first and second harvest from 2010 and 2011, respectively.

throughout the growing season (Gilreath and Santos 2004). In another study, Locascio et al. (1997) evaluated metham sodium at 155 kg ha^{-1} and concluded the rate was not sufficient for reducing yellow nutsedge density comparable to MeBr. Similarly, in the present experiment, metham sodium at 180 kg ha^{-1} did not control yellow nutsedge equivalent to MeBr; however, yellow nutsedge control with metham sodium at 360 kg ha^{-1} was comparable to the control with MeBr.

The lower rates of allyl ITC and metham sodium failed to reduce nutsedge tuber density to a level comparable to that of MeBr-treated plots in LDPE-mulched tomato production (Table 2). However, yellow nutsedge tuber density in plots treated with allyl ITC at 750 kg ha^{-1} or metham sodium at 360 kg ha^{-1} was similar to that of the MeBr-treated plots. At the end of season, yellow nutsedge tuber counts were ≤ 76 tubers m^{-2} in tomato plots treated with allyl ITC at 750 kg ha^{-1}, metham sodium at 360 kg ha^{-1}, or MeBr plus chloropicrin at 390 kg ha^{-1}. Allyl ITC at 750 kg ha^{-1} or metham sodium at 360 kg ha^{-1} reduced yellow nutsedge tubers comparably to MeBr treatment; however, ITCs did not reduce the tuber density at the level to prevent yellow nutsedge interference for the next growing season. Morales-Payan et al. (2003b) have reported that the presence of yellow nutsedge tubers at a density more than 25 tubers m^{-2} reduces 25% of total marketable yield in tomato production. Furthermore, Bangarwa (2010) have reported > 25% reduction of tomato dry weight and > 24% reduction in marketable yield from initial yellow nutsedge tuber density at 50 tubers m^{-2} in LDPE-mulched tomato.

Tomato Yield. Tomato yield was dependent on the weed control efficacy. Plots with low weed density or high levels of weed control resulted in greater tomato yield than plots with high weed density or lower weed control. Early-season tomato yield from plots treated with the highest rate of allyl ITC and metham sodium were similar to early-season yield from MeBr-treated plots (Table 3). Likewise, tomato plots treated with allyl ITC at 750 kg ha^{-1} and metham sodium at 360 kg ha^{-1} provided early-season yield of jumbo, extra large, medium, and small category tomato fruit similar to these categories in MeBr-treated plots.

Among tomato fruit grades, the jumbo category contributed the highest percentage toward total marketable yield. The jumbo category yield was 13.1 t ha^{-1} (41% of the total yield) for allyl ITC at 750 kg ha^{-1}, 14.8 t ha^{-1} (43% of the total yield) for metham sodium at 360 kg ha^{-1}, and 16.9 t ha^{-1} (44% of the total yield) for MeBr (Table 4). Likewise, extra large fruit contributed > 19% toward total yield for these treatments. The total marketable tomato yield, the sum of yield from all the grades of tomato, was comparable for the highest rate of allyl ITC or metham sodium and

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Table 4. Effect of allyl isothiocyanate (ITC), metham sodium, and methyl bromide plus chloropicrin on marketable tomato yield, averaged over 2010 and 2011.[a]

Soil fumigants	Rate	Tomato yield[b] Jumbo	Extra large	Large	Medium	Small	Total yield[c]
	kg ai ha^{-1}	t ha^{-1}					
Allyl ITC	450	7.2 de	3.6 de	3.4 cd	2.9 bc	1.8 bc	18.9 d
	600	8.6 cd	3.9 cd	3.2 d	2.5 c	1.4 c	19.6 cd
	750	13.1 abc	6.1 abc	5.3 ab	3.9 ab	3.2 a	31.6 ab
Metham sodium	180	5.2 ef	2.8 ef	3.0 d	3.2 bc	2.8 a	17.0 de
	270	11.9 bc	5.4 bcd	4.4 bc	3.4 ab	2.3 abc	27.4 bc
	360	14.8 ab	6.9 ab	6.0 a	4.4 a	2.6 ab	34.8 ab
Methyl bromide + chloropicrin	261 129	16.9 a	7.6 a	5.9 a	4.9 a	2.9 a	38.2 a
Nontreated control	—	3.9 f	2.2 f	2.8 d	2.7 bc	1.7 bc	13.3 e

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

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

MeBr-treated plots (Table 4). Marketable tomato yield in this study corresponds with the yield reported in previous studies. Bangarwa et al. (2012) reported that marketable tomato yield was similar in plots treated with allyl ITC at 887 ± 84 kg ha^{-1} and those treated with MeBr plus chloripicrin at 390 kg ha^{-1}. Likewise, marketable tomato yield in plots treated with metham sodium at 360 kg ha^{-1} was equivalent to the yield in plots treated with MeBr (Gilreath and Santos 2004). In the current study, total marketable tomato yields in plots treated with allyl ITC at 750 kg ha^{-1} or metham sodium at 360 kg ha^{-1} were 2.38 and 2.62 times, respectively, greater than the total marketable tomato yield in nontreated plots.

In conclusion, preplant soil fumigation with allyl ITC at 750 kg ha^{-1} or metham sodium at 360 kg ha^{-1} was safe for LDPE-mulched tomato. At these rates, allyl ITC and metham sodium controlled Palmer amaranth, large crabgrass, and yellow nutsedge, and reduced yellow nutsedge tuber density to a level comparable to that provided by a standard MeBr application. Furthermore, total marketable tomato yield from allyl ITC at 750 kg ha^{-1} and metham sodium at 360 kg ha^{-1} was comparable to the tomato yield from MeBr-treated plots. Allyl ITC at 750 kg ha^{-1} or metham sodium at 360 kg ha^{-1} is an effective alternative to MeBr in LDPE-mulched tomato; however, only metham sodium is currently labeled (Anonymous 2013).

Literature Cited

Ajwa HA, Trout T, Mueller J, Wilhelm S, Nelson SD, Soppe R, and Shatley D (2002) Application of alternative fumigants through drip irrigation systems. Phytopathology 92:1349–1355

Al-Khatib K, Libbey C, Boydston RA (1997) Weed suppression with *Brassica* green manure crops in green pea. Weed Sci 45:439–445

Anderson, WP (1999) Perennial Weeds: Characteristics and Identification of Selected Herbaceous Species. 1st edn. Ames, IA: Iowa State University Press. Pp 228.

Anonymous (2013) Vapam HL Soil Fumigant. http://www.cdms.net. Accessed September 9, 2013

Austerweil M, Steiner B, Gamliel A (2006) Permeation of soil fumigants through agricultural plastic films. Phytoparasitica 34:491–501

Bangarwa SK (2010) Integrated strategies for purple (*Cyperus rotundus*) and yellow nutsedge (*Cyperus esculentus*) management in tomato and bell pepper. Ph.D dissertation. Fayetteville, AR: University of Arkansas. 208 p

Bangarwa SK, Norsworthy JK, Gbur EE (2012) Allyl isothiocyanate as a methyl bromide alternative for weed management in polyethylene-mulched tomato. Weed Technol 26:449–454

Bangarwa SK, Norsworthy JK, Gbur EE, Mattice JD (2010) Phenyl isothiocyanate performance on purple nutsedge under virtually impermeable film mulch. HortTechnology 20:402–408

Borek V, Elberson LR, McCaffrey JP, Morra MJ (1998) Toxicity of isothiocyanates produced by glucosinolates in Brassicaceae species to black vine weevil eggs. J Agric Food Chem 46:5318–5323

Bridges DC, Baumann PA (1992) Weeds causing losses in the United States. Pages 75–147 *in* Bridges DC, ed. Crop Losses Due to Weeds in Canada and the United States. Champaign, IL: Weed Science Society of America

https://doi.org/10.1614/WT-D-13-00147.1 Published online by Cambridge University Press

Brown PD, Morra MJ (1995) Glucosinolate-containing plant tissues as bioherbicides. Agric Food Chem 43:3070–3074.

Carpenter J, Gianessi L, Lynch L (2000) The economic impact of the scheduled U.S. phaseout of methyl bromide. National Center for Food and Agricultural Policy. Pp 70–137

Devkota P, Norwsorthy JK, Rainey R (2013) Comparison of allyl isothiocyanate and metham sodium with methyl bromide for weed control in polyethylene-mulched bell pepper. Weed Technol 27:468–474

Fu R, Ashley RA (2006) Interference of large crabgrass (*Digitaria sanguinalis*), redroot pigweed (*Amaranthus retroflexus*), and hairy galinsoga (*Galinsoga ciliata*) with bell pepper. Weed Sci 54:364–372

Gilreath JP, Santos BM (2004) Efficacy of methyl bromide alternatives on purple nutsedge (*Cyperus rotundus*) control in tomato and pepper. Weed Technol 18:341–345

Gilreath JP, Santos BM, and Motis TN (2008) Performance of methyl bromide alternatives in strawberry. HortTechnology 18:80–83

Gilreath JP, Santos BM, Motis TN, Noling JW, Mirusso JM (2005) Methyl bromide alternatives for nematode and *Cyperus* control in bell pepper (*Capsicum annuum*). Crop Prot 24:903–908.

Holmes GJ, Kemble JM (2010) Vegetable Crop Handbook for the Southeastern United States. 11th edn. Lincolnshire, IL: Vance. Pp. 93–94, 269.

Horak MJ, Loughin TM (2000) Growth analysis of four *Amaranthus* species. Weed Sci 48:347–355

Johnson WC III, Mullinix BG Jr (2007) Yellow nutsedge (*Cyperus esculentus*) control with metham-sodium in transplanted cantaloupe (*Cucumis melo*). Crop Prot 26:867–871

Locascio SJ, Gilreath JP, Dickson DW, Kucharek TA, Jones JP, Noling JW (1997) Fumigant alternatives to methyl bromide for polyethylene-mulched. HortScience 32:1208–1211

Meyers SL, Jennings KM, Schultheis JR, Monks DW (2010) Interference of Palmer amaranth (*Amaranthus palmeri*) in sweet potato. Weed Sci 58:199–203

Monaco TJ, Grayson AS, Sanders DC (1981) Influence of four weed species on the growth, yield, and quality of direct-seeded tomatoes (*Lycopersicon esculentum*). Weed Sci 29:394–397

Morales-Payan JP, Stall WM, Shilling DG, Charudattan R, Dusky JA, Bewick TA (2003a) Above- and below-ground interference of purple and yellow nutsedge (*Cyperus* spp.) with tomato. Weed Sci 51:181–185

Morales-Payan JP, Stall WM, Shilling DG, Dusky JA, Bewick TA, Charudattan R (2003b) Initial weed-free period and subsequent yellow nutsedge population's density affect tomato yield. Proc Fla State Hort Soc 116:73–75

Norsworthy JK, Meehan JT IV (2005a) Herbicidal activity of eight isothiocyanates on Texas panicum (*Panicum texanum*), large crabgrass (*Digitaria sanguinalis*), and sicklepod (*Senna obtusifolia*). Weed Sci 53:515–520

Norsworthy JK, Meehan JT IV (2005b) Use of isothiocyanates for suppression of Palmer amaranth (*Amaranthus palmeri*), pitted morningglory (*Ipomoea lacunosa*), and yellow nutsedge (*Cyperus esculentus*). Weed Sci 53:884–890

Norsworthy JK, Oliveira MJ, Jha P, Malik M, Buckelew JK, Jennings KM, Monks DW (2008) Palmer amaranth and large crabgrass growth with plasticulture-grown bell pepper. Weed Technol 22:296–302

Peterson J, Belz R, Walker F, Hurle K (2001) Weed suppression by release of isothiocyanates from turnip–rape mulch. Agron J 93:37–43

Sanders DC, Cook WP, Cranberry D (1996) Plasticulture of Commercial Vegetables. North Carolina Cooperative Extension Services, North Carolina State University. Pub. AG–489.

Smolinska U, Knudsen GR, Morra MJ, Borek V (1997) Inhibition of *Aphanomyces euteiches* f. sp. *pisi* by volatile allelochemicals form *Brassica napus* seed meal. Plant Dis 81:288–292

Stall WM, Morales-Payan JP (2003) The Critical Period of Nutsedge Interference in Tomato. http://www.imok.ufl.edu/liv/groups/IPM/weed_con/nutsedge.htm. Accessed September 10, 2010

[USDA] U.S. Department of Agriculture (1997) United States Standards for Grades of Fresh Tomato. http://www.ams.usda.gov/AMSv1.0/getfile?dDocName=STELPRDC5050331. Accessed August 16, 2010

[USDA] U.S. Deparment of Agriculture (2013a) Crop Values. 2012 Summary. http://usda01.library.cornell.edu/usda/current/CropValuSu/CropValuSu-02-15-2013.pdf. Acessed September 20, 2013

[USDA] U.S. Department of Agriculture (2013b) Web Soil Survey. http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx. Accessed September 24, 2013

[USEPA] U.S. Environmental Protection Agency (2005) The Phaseout of Methyl Bromide. http://www.epa.gov/ozone/mbr/ Acessed September 24, 2013

Westoby M, Leishman M, Lord J (1996) Comparative ecology of seed size and dispersal. Philos Trans R Soc Lond B Biol Sci 351:1309–1318

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