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# Herbicidal Performance of Phenyl Isothiocyanate in Polyethylene-Mulched Bell Pepper

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Methyl bromide is a common fumigant for effective weed control in polyethylene-mulched vegetable crops. However, the ban on methyl bromide in the United States has created a need to find a suitable alternative. This study investigated the herbicidal efficacy of phenyl isothiocyanate (ITC) as a methyl bromide alternative for weed control in polyethylene-mulched bell pepper during 2006 and 2007. Six rates of phenyl ITC (0, 15, 75, 150, 750, 1,500 kg ha$^{-1}$) under low-density polyethylene (LDPE) or virtually impermeable film (VIF) mulch were tested against yellow nutsedge, Palmer amaranth, and large crabgrass. Additionally, a standard treatment of methyl bromide/chloropicrin (67 : 33%) at 390 kg ha$^{-1}$ under LDPE mulch was included for comparison. VIF mulch provided no advantage over LDPE mulch in either improving weed control or marketable yield in bell pepper. Unacceptable pepper injury (≥ 60%) occurred at the highest phenyl ITC rate of 1,500 kg ha$^{-1}$ at 2 WATP in both years, regardless of mulch type. Higher bell pepper injury was observed in 2006 (≥ 36%) than in 2007 (≤ 11%) at 750 kg ha$^{-1}$ of phenyl ITC. The lower injury in 2007 could be attributed to aeration of beds 48 h prior to transplanting. Regardless of mulch type, phenyl ITC at 2,071 (± 197) and 1,655 (± 309) kg ha$^{-1}$ was required to control yellow nutsedge, Palmer amaranth, and large crabgrass equivalent to methyl bromide in 2006 and 2007, respectively. Bell pepper marketable yield at all rates of phenyl ITC was lower than methyl bromide in 2006. In contrast, marketable yield in phenyl ITC at 750–kg ha$^{-1}$ was equivalent to methyl bromide in 2007. It is concluded that phenyl ITC should be applied at least 4.2 times higher rate than methyl bromide for effective weed control, and bed aeration is required to minimize crop injury and yield loss. Additional research is needed to test phenyl ITC in combination with other weed control strategies to obtain effective weed control with acceptable crop safety.
**Nomenclature**: Large crabgrass, *Digitaria sanguinalis* (L.) Scop. DIGSA; Palmer amaranth, *Amaranthus palmeri* S. Wats. AMAPA; yellow nutsedge, *Cyperus esculentus* L. CYPES; bell pepper, *Capsicum annuum* 'Heritage'.
**Key words**: Fumigation, LDPE, low-density polyethylene mulch, methyl bromide alternative, plastic mulch, vegetable, virtually impermeable film, VIF, weed control.

Methyl bromide es un fumigante común para el control efectivo de malezas en la producción de vegetales con coberturas plásticas. Sin embargo, la prohibición de este fumigante en los Estados Unidos ha creado la necesidad de encontrar una alternativa apropiada. Este estudio investigó la eficacia como herbicida de phenyl isothiocyanate (ITC) como alternativa a methyl bromide para el control de malezas en chile (pimiento) producido con cobertura de polyethylene durante 2006 y 2007. Seis dosis de phenyl ITC (0, 15, 75, 150, 750 y 1500 kg ha$^{-1}$) bajo una cobertura de polyethylene de baja densidad (LDPE) o de película virtualmente impermeable (VIF) fueron evaluadas contra *Cyperus esculentus*, *Amaranthus palmeri* y *Digitaria sanguinalis*. Adicionalmente, un tratamiento estándar de methyl bromide-chloropicrin (67:33) a 390 kg ha$^{-1}$ bajo cobertura de LDPE fue incluido con fines de comparación. La cobertura VIF no brindó ninguna ventaja sobre la cobertura LDPE para mejorar el control de malezas o el rendimiento del chile comercializable. Daños inaceptables causados al chile (≥60%) ocurrieron a la dosis más alta de phenyl ITC 1,500 kg ha$^{-1}$ a 2 semanas después del tratamiento en ambos años, sin importar el tipo de cobertura. En 2006, se observaron mayores daños en el chile (≥36%) que en 2007 (≤11%) a 750 kg ha$^{-1}$ de phenyl ITC. El menor daño en 2007 podría ser atribuido a la aireación de las camas 48 h antes del trasplante. Independientemente del tipo de cobertura, se requirió phenyl ITC a 2071 (±197) y 1655 (±309) kg ha$^{-1}$ para controlar *C. esculentus*, *A. palmeri* y *D. sanguinalis* a niveles equivalentes a methyl bromide en 2006 y 2007, respectivamente. Los rendimientos de chile comercializable en todas las dosis de phenyl ITC fueron menores a los de methyl bromide en 2006. En contraste, el rendimiento comercializable del tratamiento phenyl ITC a 750 kg ha$^{-1}$ fue equivalente a methyl bromide en 2007. Se concluyó que phenyl ITC debería ser aplicado a dosis al menos 4.2 veces mayores que methyl bromide para un control efectivo de malezas, y que la aireación de la cama es necesaria para minimizar el daño al cultivo y las pérdidas en rendimiento. Se necesita más investigación para evaluar la combinación de phenyl ITC con otras estrategias de control de malezas para obtener un control de malezas efectivo con un nivel aceptable de seguridad para el cultivo.

Bell pepper belongs to the Solanaceae family and is native to Central and South America (Swiader et al. 1992). In the United States, bell pepper is an important vegetable crop with an annual production value of more than $684 million (U.S. Department of Agriculture [USDA] 2012). Nearly 799,130 metric tons of both fresh-market and processing bell peppers were harvested from 21,970 ha in United States during 2011 (USDA 2012).

Bell pepper is a slow-growing plant grown in wide row spacing, making it less competitive with weeds. Most common weed problems in the southeastern United States

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in pepper production include purple nutsedge (*Cyperus rotundus* L.), yellow nutsedge, Palmer amaranth, and large crabgrass (Webster 2006). Interference from these species can cause yield loss up to 94% in bell pepper (Morales-Payan et al., 1998; Motis et al., 2003; Norsworthy et al., 2008).

Methyl bromide has been heavily used for effective control of weeds and other soil-borne pests in plasticulture vegetable production. Because of methyl bromide phaseout, pepper producers are facing weed management challenges that will ultimately lead to greater herbicide reliance (U.S. Environmental Protection Agency [USEPA] 2008). Unfortunately, few herbicides are registered for use in bell pepper, largely because of the lack of crop tolerance. As a result, there are limited weed management options within pepper rows, especially for nutsedge control (Bangarwa et al. 2009; Olson et al. 2012). Thus, an effective alternative is needed that can provide broad-spectrum weed control without injuring bell pepper.

Volatile biocidal compounds such as isothiocyanates (ITCs) beneath plastic are likely alternatives to methyl bromide for effective and broad-spectrum pest control. They are derived from Brassicaceae plants, which release ITCs upon enzymatic hydrolysis of secondary metabolites called glucosinolate (GSLs) (Brown and Morra 1995; Fenwick et al. 1983). These ITCs are toxic compounds and are used as a defense tool by Brassicaceae plants against pests. The biocidal activity of ITCs can be utilized to control weeds in vegetable crops. In previous research, naturally or synthetically produced ITCs have shown herbicidal properties against several monocot and dicot seeds (Al-Khatib et al. 1997; Krishnan et al. 1998; Norsworthy 2003; Peterson et al. 2001). In greenhouse experiments, Norsworthy et al. (2005a,b) tested herbicidal activity of five aliphatic and three aromatic ITCs on yellow nutsedge and other grassy and broadleaf weeds. They found that ITC effectiveness was dependent upon ITC structure and concentration and target weed species. Phenyl ITC was most effective at reducing yellow nutsedge emergence (Norsworthy et al. 2005b). These findings warrant further investigation of the effectiveness of ITCs to control yellow nutsedge and other problem weed species in peppers.

Plastic mulches are commonly used with fumigants to cover the treated soil and reduce atmospheric losses of gaseous fumigants. Low-density polyethylene (LDPE) mulch is most frequently used by growers in plasticulture vegetable production, which is attributed to its lower cost relative to other mulches. Although costlier, a newly designed virtually impermeable film (VIF) mulch is less permeable than LDPE mulch (Yates et al. 2002) and may reduce loss of volatile compounds. As a result, VIF mulch provides longer retention of lethal concentrations of fumigants in the soil and increases pest control efficacy. In previous research, 1,3-D and methyl bromide rate needed for effective disease suppression in strawberry was reduced by 50% under VIF compared with a standard mulch (Cal et al. 2004). Likewise, methyl bromide : chloropicrin (67 : 33%) at 98 kg ha$^{-1}$ under a VIF mulch provided purple and yellow nutsedge control equivalent to 392 kg ha$^{-1}$ of methyl bromide : chloropicrin under a LDPE mulch (Gilreath et al. 1999). Therefore, covering the treated soil with a VIF mulch may further improve weed control by minimizing loss of ITCs.

The present research was conducted to test herbicidal performance of multiple phenyl ITC rates under LDPE and VIF mulch in bell pepper. Three weed species tested in this research were yellow nutsedge, Palmer amaranth, and large crabgrass.

## Materials and Methods

**Location and Design.** A field experiment was conducted in 2006 at Clemson, SC, and was repeated in 2007 at Fayetteville, AR. The soil at the Clemson site was characterized as a Congaree silt loam (fine–loamy, mixed, active, nonacid, thermic Oxyaquic Udifluvents) with a pH of 6.1. The soil at Fayetteville was a Pembroke silt loam (fine–silty, mixed, active, nonacid, mesic Mollic Paleudalfs) with a pH of 6.0. In both years, treatments were arranged in 2 by 6 factorial structure with four blocks. The first factor was mulch type (LDPE [black, embossed, 1.0 mil thick] vs. VIF [black/white, 1.3 mil thick]; Polygro, LLC, Tampa, FL 33655) and second factor was phenyl ITC rate (0, 15, 75, 150, 750, and 1500 kg ha$^{-1}$) (Sigma-Aldrich Inc., Milwaukee, WI 53209). In addition, a benchmark treatment of methyl bromide : chloropicrin (67 : 33%) at 390 kg ha$^{-1}$ under LDPE mulch was also maintained.

**Experimental Procedure.** Experimental procedures were similar in both years unless specified. Both experimental sites were tilled (10 cm deep) in late March and late April with the use of a rototiller to remove winter vegetation. Prior to rototilling in late April, tubers of yellow nutsedge (22.4 kg ha$^{-1}$) and seeds of Palmer amaranth (1.1 kg ha$^{-1}$) and large crabgrass (11.2 kg ha$^{-1}$) (Azlin Seed Company, Leland, MS 38756) were manually broadcasted over the test sites to ensure a uniform weed population.

In late April, phenyl ITC was broadcast applied to the soil in 4.6-m-long and 1.5-m-wide plots with the use of a carbon-dioxide–pressurized backpack sprayer calibrated to deliver 280 L ha$^{-1}$. Acetone was used as a carrier instead of water because of greater solubility of allyl ITC in acetone than in water. In a previous study, acetone had no impact on germination of yellow nutsedge, Palmer amaranth, and large crabgrass when used at rates equivalent to that used as a carrier for phenyl ITC at 1,500 kg ha$^{-1}$ field application (Bangarwa et al. 2011). Following application, treated plots were immediately rototilled to incorporate phenyl ITC into the top 10-cm soil layer, and raised beds (0.70 m wide at top) were formed and covered with LDPE or VIF mulch. Simultaneously, a single row of drip tape was placed under the plastic mulch in the center of each bed for irrigation and fertigation purposes. In each block, a single treatment of methyl bromide : chloropicrin (67 : 33%) at 390 kg ha$^{-1}$ under LDPE mulch was also established as an industry standard. All plots were allowed to fumigate for 3 wk after treatment. Three weeks later, a double row of 10 pepper 'Heritage' transplants (4- to 6-leaf stage) was planted in each plot with a 30 by 30–cm spacing. Holes were punched in the plastic immediately before transplanting in 2006. In 2007, holes were punched 2 d



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before transplanting in order to aerate the beds and reduce the crop injury from residual phenyl ITC in the treated soil. Bell pepper management practices were according to standard recommendations for polyethylene-mulched bell pepper production in the southeastern United States (Holmes and Kemble 2010). All weeds except the test species were removed from the plots by hand weeding. Row middles were kept clean with as-needed applications of paraquat (Gramoxone Inteon 2EC, Syngenta Crop Protection, Inc., Greensboro, NC 27409).

**Sampling Procedure.** Visual estimates of percent crop injury and weed control (yellow nutsedge, Palmer amaranth, and large crabgrass) were taken in each plot from 2 to 8 wk after transplanting (WATP). Visual estimates were based on a scale of 0 to 100%, where 0 is no crop injury or weed control and 100 is complete crop or weed death. Palmer amaranth and large crabgrass ratings were based on occurrence in transplant holes at the base of pepper plants. Yellow nutsedge penetrated through both mulches and therefore entire plot was rated. Weed control was rated from 2 to 8 WATP; however, because the critical period of weed interference in bell pepper ranges from 3 to 6 WATP (Frank et al. 1992; Motis et al. 2004; Norsworthy et al. 2008), data from 6 WATP are presented. Besides visual estimates, yield data were recorded by manually harvesting pepper fruits from entire plot. Marketable fruits were harvested twice in 2006 and seven times in 2007. Harvested fruits were sorted by size into three grades (U.S. Fancy, U.S. No.1, and U.S. No. 2) according to USDA size standards for sweet peppers (USDA 2005). Fruit weight of each grade was combined to determine total marketable yield. Culls were discarded. After the final harvest, 10 soil cores (10 cm diam and 15 cm deep) were randomly taken throughout each plot to quantify the number of viable weed propagules in the soil. Germination of yellow nutsedge tubers and Palmer amaranth and large crabgrass seeds were tested for a 12-wk period under greenhouse conditions (32 to 35/24 to 25 C day/night temperature and 16-h photoperiod). Germinated seeds/tubers of each weed species were counted and hand-pulled weekly, and all counts were totaled to calculate viable weed propagule density of each species in each plot.

**Statistical Analysis.** All statistical analyses were performed at a 5% level of significance with the use of SAS statistical software (SAS Institute, Inc., Cary, NC 27513). Data from each parameter were analyzed separately by year because of variation in bed aeration time and harvest number between years. Percent weed control, viable propagule density, crop injury, and marketable yield data were subjected to two-way ANOVA to test for significance of main effect of phenyl ITC rate and mulch type and their interaction. Scatter plots were drawn to visualize the response curve of each parameter to increasing phenyl ITC rates under each mulch. Based on the shape of scatter plots, percentage weed control and viable propagule density of each species were regressed against natural log-transformed rates of phenyl ITC under each mulch.

A four-parameter log-logistic curve was used to describe percentage control of yellow nutsedge, Palmer amaranth, and large crabgrass in response to phenyl ITC rates under each mulch with the use of PROC NLIN (Seefeldt et al. 1995):

$$Y = C + (D - C)/\{1 + \exp[b(\ln x - I)]\},$$

where $Y$ represents the percentage control of each species, $C$ is the upper asymptote, $D$ is the lower asymptote, $b$ is the slope of the response, $x$ is the 1 + phenyl ITC rate (kg ha$^{-1}$), and $I$ is the natural log-transformed phenyl ITC rate needed to provide 50% control.

The relationship of yellow nutsedge, Palmer amaranth, and large crabgrass viable propagule density to phenyl ITC rates under each mulch was described with the use of quadratic and linear models given below with the use of PROC GLM:

$$Y = Ax^2 + Bx + C,$$

where $Y$ represents square root of viable propagule density (number m$^{-2}$), $A$ is the quadratic coefficient, $B$ is the linear coefficient, $C$ is the intercept, and $x$ is the natural logarithm of 1 + phenyl ITC rate (kg ha$^{-1}$).

$$Y = Bx + C,$$

where $Y$ represents the square root of viable propagule density (number m$^{-2}$), $B$ is the slope of the linear model, $C$ is the intercept, and $x$ is the natural logarithm of 1 + phenyl ITC rate (kg ha$^{-1}$).

The criteria used to evaluate the quality of each fit included 1) meeting of convergence criteria by iteration process, 2) F-test for significance of regression, and 3) studentized residual plot, and 4) coefficient of determination. To compare percent control response of each weed species to increasing phenyl ITC rates under LDPE and VIF mulches, a sum-of-squares reduction test was performed with the use of PROC NLIN (Schabenberger and Pierce 2002). This test fits two models: full model (assuming different response under two mulches) and reduced model (assuming similar response under two mulches). If F statistics were significant, the reduced model was used to describe the response. Otherwise, the full model was used to describe the response. After selecting the final model, the equation was used to calculate the phenyl ITC rate required to produce a response equivalent to the observed mean response from the methyl bromide treatment ($LR_{mb}$). To compare viable propagule density response under LDPE and VIF mulches, analyses of covariance techniques were used to allow the intercept and slope to differ by mulch type with the use of PROC GLM. Standard errors for the phenyl ITC rates were obtained with the use of the delta method (Stuart and Ord 1994). For crop injury and marketable yield data, mean separation was performed by Fisher's Protected LSD.

## Results and Discussion

**Weed Species Response.** *Weed Control.* Weed control response to phenyl ITC rates under LDPE or VIF mulch at 6 WATP could be explained with a log-logistic model (Equation 1) each year. However, the sum–of-squares reduction test indicated that percentage control of yellow nutsedge, Palmer amaranth, and large crabgrass was not influenced by mulch type ($P \geq 0.07$). Therefore, a single model was used for both mulches to describe percentage



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Table 1. Parameter estimates for regression model of yellow nutsedge, Palmer amaranth, and large crabgrass control at 6 wk after transplanting bell pepper, averaged over mulch type (LDPE and VIF) in 2006 and 2007, and phenyl ITC rate needed to obtain weed control equivalent to methyl bromide.[a]

| Year and weed species | Parameter estimates[b] | | | | $R^{2c}$ | P value | $LR_{mb}$ (± SE)[d] |
|---|---|---|---|---|---|---|---|
| | *D* | *C* | *b* | *I* | | | |
| | | | | | | | kg/ha |
| 2006 | | | | | | | |
| Yellow nutsedge | 2.39 | 100.00 | 1.25 | 5.89 | 0.98 | < 0.0001 | 2,071 (197) |
| Palmer amaranth | 8.45 | 100.00 | 1.63 | 5.45 | 0.98 | < 0.0001 | 1,337 (228) |
| Large crabgrass | 4.59 | 97.78 | 1.82 | 5.87 | 0.97 | < 0.0001 | 1,571 (419) |
| 2007 | | | | | | | |
| Yellow nutsedge | 4.99 | 97.70 | 1.82 | 6.08 | 0.98 | < 0.0001 | 1,640 (281) |
| Palmer amaranth | 5.82 | 100.00 | 1.97 | 5.64 | 0.99 | < 0.0001 | 1,588 (195) |
| Large crabgrass | 3.14 | 92.07 | 2.66 | 5.58 | 0.98 | < 0.0001 | 1,273 (362) |

[a] Abbreviations: ITC, isothiocyanate; LDPE, low-density polyethylene mulch; VIF, virtually impermeable film.

[b] Regression model used to predict percent control of each weed species is represented by Equation 1, $Y = C + (D - C)/[1 + \exp\{b(\ln x - I)\}]$.

[c] Coefficient of determination to test quality of fit for regression models. For nonlinear models, coefficient of determination is approximate and is calculated as pseudo $-R^2 = 1$ (sum of squares of the residual/total sum of squares).

[d] $LR_{mb}$ = phenyl ITC rate required to provide percent control of a particular weed species equivalent to methyl bromide : chloropicrin (67 : 33%) at 390 kg ha$^{-1}$. SE = standard error of the mean.

control of each weed species to increasing phenyl ITC rate (Table 1). VIF mulch was not effective in improving control of all three weed species over LDPE mulch. In a previous field experiment, Haar et al. (2003) tested methyl ITC efficacy against little mallow (*Malwa parviflora* L.) seeds under VIF and standard mulch and found that viable seed density of little mallow was not statistically different under standard and VIF mulch. In another study, Bangarwa et al. (2011) reported that herbicidal efficacy of allyl ITC was not improved by replacing LDPE mulch with VIF mulch. According to Noling et al. (2011), the permeability of VIF mulches can change, depending upon changes in the physical and environmental conditions to which they are exposed. For example, in a closed system, VIF mulch proved to be 40% less permeable to methyl ITC compared to LDPE mulch (Austerweil et al. 2006). However, when tested under field conditions, VIF mulch failed to improve methyl ITC retention in treated soil compared to LDPE mulch (Hadiri et al. 2003). It is suspected that VIF mulch permeability in field conditions can increase two to three times compared to that under laboratory conditions, which could be attributed to breakdown of the polyamide layer due to stretching and tearing during laying (Noling et al. 2011).

Based on the value of parameter *I* of the model (equivalent to $LC_{50}$ on a normal scale), yellow nutsedge was the most tolerant among the weed species tested, whereas Palmer amaranth and large crabgrass were comparatively less tolerant to phenyl ITC (Table 1). Similarly, Norsworthy and Meehan (2005a,b) reported less activity of phenyl ITC on yellow nutsedge than on Palmer amaranth and large crabgrass in a greenhouse trial. One possible reason of greater tolerance of yellow nutsedge to phenyl ITC could be associated with the larger tuber size compared to relatively small-seeded Palmer amaranth or large crabgrass. In other studies, naturally produced ITCs have been proved to be more active on small-seeded weeds than on large-seeded weeds (Al-Khatib et al. 1997; Norsworthy 2003; Peterson et al. 2001).

In 2006, percentage control of yellow nutsedge, Palmer amaranth, and large crabgrass in the methyl bromide treatment at 6 WATP was 90, 95, and 92%, respectively (data not shown). Based on the predicted model for each weed species, the phenyl ITC rate required to obtain yellow nutsedge, Palmer amaranth, and large crabgrass control equivalent to methyl bromide was 2,071 (± 197), 1,337 (± 228), and 1,571 (± 419) kg ha$^{-1}$, respectively, averaged over mulch type in 2006 (Table 1). Likewise, phenyl ITC rates of 1640 (± 281), 1,588 (± 195), and 1,273 (± 362) kg ha$^{-1}$ is required to obtain 90% yellow nutsedge, 97% Palmer amaranth, and 92% large crabgrass control, respectively (Table 1), equivalent to methyl bromide in 2007. Therefore, phenyl ITC should be applied at rates at least four times higher than methyl bromide to ensure effective and broad-spectrum weed control in polyethylene-mulched bell pepper.

**Viable Weed Propagules.** Viable propagule density of all three weed species decreased as phenyl ITC rate increased, with no significant effect ($P \geq 0.26$) of mulch type (Table 2). Negative linear or quadratic equations were used to describe the relationship between viable propagule density and phenyl ITC rates, depending upon weed species. Averaged over mulch type, check plots had 40.3, 44.6, and 54.6 viable propagules m$^{-2}$ of yellow nutsedge, Palmer amaranth, and large crabgrass, respectively, in 2006. Preplant fumigation with methyl bromide reduced the viable propagule density of yellow nutsedge by 97% (1.1 tubers m$^{-2}$), Palmer amaranth 99% (0.5 seeds m$^{-2}$), and large crabgrass 96% (2.1 seeds m$^{-2}$) in 2006 (data not shown). Based on predicted models, phenyl ITC should be applied at 1,074 (± 137), 961 (± 259), and 1,131 (± 483) kg ha$^{-1}$ to reduce the viable propagule density of yellow nutsedge, Palmer amaranth, and large crabgrass equivalent to methyl bromide (Table 2). In 2007, viable propagule density of yellow nutsedge, Palmer amaranth, and large crabgrass was 22.3, 31.2, and 52.2 tubers or seeds m$^{-2}$, respectively. Methyl bromide reduced the viable propagule densities of weeds from 92 to 95% in 2007 (data not shown). Based on conditions in 2007, a phenyl ITC rate of 1,145(± 226), 1,655 (± 309), and 1,470 (±376) kg ha$^{-1}$ was required to reduce the viable propagule density of yellow



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Table 2. Parameter estimates for regression model of square root of viable propagule density of yellow nutsedge, Palmer amaranth, and large crabgrass in bell pepper averaged over mulch type (LDPE and VIF) in 2006 and 2007, and phenyl ITC rate needed to reduce viable propagules density equivalent to methyl bromide.[a]

| Year and weed species | Parameter estimates[b] A | B | C | $R^2$ [c] | P value | $LR_{mb}$ (± SE)[d] |
|---|---|---|---|---|---|---|
| | | | | | | kg/ha |
| 2006 | | | | | | |
| Yellow nutsedge | −0.21 (0.03) | 0.75 | 5.99 | 0.85 | < 0.0001 | 1,074 (137) |
| Palmer amaranth | – | −0.91 | 6.95 | 0.83 | < 0.0001 | 961 (259) |
| Large crabgrass | – | −0.74 | 6.69 | 0.68 | < 0.0001 | 1,131 (483) |
| 2007 | | | | | | |
| Yellow nutsedge | −0.16 | 0.68 | 4.58 | 0.86 | < 0.0001 | 1,145 (226) |
| Palmer amaranth | −0.11 | 0.26 | 5.56 | 0.81 | < 0.0001 | 1,655 (309) |
| Large crabgrass | – | −0.72 | 7.32 | 0.89 | < 0.0001 | 1,470 (376) |

[a] Abbreviations: ITC, isothiocyanate; LDPE, low-density polyethylene mulch; VIF, virtually impermeable film.

[b] Regression model used to predict square root of viable propagule density of yellow nutsedge in 2006 and yellow nutsedge and Palmer amaranth in 2007 is represented by Equation 2, $Y = Ax^2 + Bx + C$; and viable propagule density of Palmer amaranth and large crabgrass in 2006 and large crabgrass in 2007 is represented by Equation 3, $Y = Bx + C$.

[c] Coefficient of determination to test quality of fit for regression models. For nonlinear models, coefficient of determination is approximate and is calculated as pseudo $-R^2 = 1$ (sum of square of the residual/total sum of squares).

[d] $LR_{mb}$ = phenyl ITC rate required to reduce viable propagules of a particular weed species equivalent to methyl bromide : chloropicrin (67 : 33%) at 390 kg ha$^{-1}$. SE = standard error of the mean.

nutsedge, Palmer amaranth, and large crabgrass equivalent to methyl bromide, respectively (Table 2). These results indicate that phenyl ITC can effectively reduce a diverse weed seedbank in treated soil when applied at a rate up to 4.2 times higher than methyl bromide rate.

**Bell Pepper Response.** *Bell pepper injury.* Injury symptoms in bell pepper were interveinal chlorosis and necrosis of lower leaves, stunting, or plant death, depending on the phenyl ITC rates. Crop injury at 2 WATP was not affected by mulch type or the mulch by phenyl ITC interaction ($P \geq 0.3274$) either year. However, injury was affected by phenyl ITC rates ($P < 0.0001$) in both years. The highest rate of phenyl ITC (1,500 kg ha$^{-1}$) was highly injurious to pepper plants, with ≥ 60% injury both years (data not shown). In 2006, bell pepper injury with the second highest phenyl ITC rate, 750 kg ha$^{-1}$, was 36% regardless of mulch type. However, at phenyl ITC rates of 150 kg ha$^{-1}$ or lower, injury was 16% or less. In contrast, a maximum of 11% injury was observed in 2007 at phenyl ITC rate of 750 kg ha$^{-1}$ or lower, averaged over mulch type. In a previous laboratory trial, Bangarwa et al. (2010) reported that phenyl ITC can persist longer than 3 wk in soil covered with plastic mulch compared with no cover. The possible reason for injury could be a lethal amount of residual phenyl ITC present in treated soil covered with LDPE or VIF mulch, especially at higher rates. Overall, injury level was higher in 2006 than in 2007, when beds were aerated for 48 h before transplanting. Aeration probably resulted in dissipation of residual phenyl ITC from the beds, thereby reducing injury in 2007 compared to 2006. These results indicate that bed aeration for 48 h before transplanting would be helpful in reducing crop injury from phenyl ITC.

**Bell Pepper Yield.** Total marketable yield of bell pepper was influenced by main effect of phenyl ITC rate ($P < 0.0001$), but effects of mulch type and mulch by rate interaction ($P \geq 0.0771$) were not significant either year. Therefore, marketable yield was averaged over mulch type in each year. Plots treated with methyl bromide produced 16 and 49.2 t ha$^{-1}$ of total marketable pepper fruit in 2006 and 2007, respectively (Table 3). The lower fruit yield in 2006 is mainly due to fewer harvests compared to 2007. In 2006, none of the treatments provided marketable yield equivalent to methyl bromide. The lower fruit yield in 2006 from untreated plants and those treated with low phenyl ITC rates (≤ 150 kg ha$^{-1}$) were due to weed competition. In contrast, lower fruit yield in treatments with high phenyl ITC rates (750 and 1,500 kg ha$^{-1}$) is likely due to high crop injury and plant death. In 2007, high crop injury at phenyl ITC 1,500 kg ha$^{-1}$ resulted in significant bell pepper yield reduction, regardless of mulch type (Table 3). However, phenyl ITC at 750 kg ha$^{-1}$ provided marketable yield (48.2 t ha$^{-1}$) statistically similar to methyl bromide treatment in 2007. This could be attributed to two factors: (1) higher level of weed control because of high phenyl ITC rate, and (2) minimal crop injury due to bed

Table 3. Effect of phenyl ITC rates, averaged over mulches (LDPE and VIF) and methyl bromide under LDPE mulch on total marketable yield of bell pepper in 2006 and 2007.[ab]

| Phenyl ITC/methyl bromide | Rate | 2006 | | 2007 | |
|---|---|---|---|---|---|
| | kg ha$^{-1}$ | t ha$^{-1}$ | | t ha$^{-1}$ | |
| Phenyl ITC | 0 | 6.8 | c | 21.7 | c |
| Phenyl ITC | 15 | 8.2 | b | 24.3 | c |
| Phenyl ITC | 75 | 9.3 | b | 29.7 | b |
| Phenyl ITC | 150 | 9.2 | b | 32.0 | b |
| Phenyl ITC | 750 | 7.2 | bc | 47.8 | a |
| Phenyl ITC | 1,500 | 5.1 | c | 20.0 | c |
| Methyl bromide[c] | 390 | 16.0 | a | 49.2 | a |

[a] Abbreviations: ITC, isothiocyanate; LDPE, low-density polyethylene mulch; VIF, virtually impermeable film.

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

[c] Methyl bromide : chloropicrin (67 : 33%) at 390 kg ha$^{-1}$.



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aeration 48 h before transplanting. Phenyl ITC at 150 kg ha$^{-1}$ or lower rates failed to control weeds and thereby caused significant yield reduction compared to the methyl bromide treatment.

This research showed that the quality of plastic mulch (VIF vs. LDPE) did not influence weed control or marketable yield in polyethylene-mulched bell pepper. Moreover, because VIF mulch is 1.5 to 2 times more costly than LDPE mulch (Noling 2005), it would be economical to use LDPE mulches with phenyl ITC. Second, this research predicted excellent herbicidal activity of phenyl ITC when applied at 2,071 (± 197) and 1,655 (± 309) kg ha$^{-1}$, rates that are at least 4.2 times higher than methyl bromide rate (390 kg ha$^{-1}$). Unfortunately, these rates of phenyl ITC can cause severe crop injury and yield reduction in bell pepper, and therefore require either a longer transplanting interval or bed aeration time. In contrast, phenyl ITC at 750 kg ha$^{-1}$ provided marketable pepper yield equivalent to methyl bromide in 2007 when beds were allowed to aerate for 48 h prior to transplanting. Therefore, it would be worthwhile to test phenyl ITC at rate ranges around 750 kg ha$^{-1}$ in combination with different aeration times in future research. In addition, there is a need to test phenyl ITC in combination with herbicides or other weed management practices to obtain effective weed control with acceptable crop safety.

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## Literature Cited

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

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

Bangarwa, S. K., J. K. Norsworthy, and E. E. Gbur. 2009. Cover crop and herbicide combinations for weed control in polyethylene-mulched bell pepper. HortTechnology 19:405–410.

Bangarwa, S. K., J. K. Norsworthy, and E. E. Gbur. 2011. Allyl isothiocyanate: A methyl bromide replacement in polyethylene-mulched bell pepper. Weed Technol. 25:90–96.

Bangarwa, S. K., J. K. Norsworthy, E. E. Gbur, and J. D. Mattice. 2010. Phenyl isothiocyanate performance on purple nutsedge under virtually impermeable film mulch. HortTechnology 20:402–408.

Brown, P. D. and M. J. Morra. 1995. Glucosinolate-containing plant tissues as bioherbicides. J. Agric. Food Chem. 43:3070–3074.

Cal, D., A. Martinez-Treceno, J. M. Lopez-Aranda, and P. Melgarejo. 2004. Chemical alternatives to methyl bromide in Spanish strawberry nurseries. Plant Dis. 88:210–214.

Fenwick, G. R., R. K. Heaney, and W. J. Mullin. 1983. Glucosinolates and their breakdown products in food and food plants. Crit. Rev. Food Sci. Nutr. 18:123–201.

Frank, J. R., P. H. Schwartz, Jr., and W. E. Potts. 1992. Modeling the effect of weed interference periods and insects on bell peppers (*Capsicum annuum*).- Weed Sci. 40:308–312.

Gilreath, J. P., C. A. Chase, and D. O. Chellemi. 1999. Nutsedge control with reduced rates of methyl bromide and virtually impermeable film mulch. http://mbao.org/altmet00/39gilreath.pdf. Accessed: March 2, 2012.

Haar, M. J., S. A. Fennimore, H. A. Ajwa, and C. Q. Winterbottom. 2003. Chloropicrin effect on weed seed viability. Crop Prot. 22:109–115.

Hadiri, N. El., M. Ammati, M. Chgoura, and K. Mounir. 2003. Behavior of methyl isothiocyanate in soils under field conditions in Morocco. Chemosphere 52:927–932.

Holmes, G. J. and J. M. Kemble, eds. 2010. Vegetable crop handbook for the southeastern United States. 11th ed. Lincolnshire, IL: Vance.

Krishnan, G., D. L. Holshouser, and S. J. Nissen. 1998. Weed control in soybean (*Glycine max*) with green manure crops. Weed Technol. 12:97–102.

Morales-Payan, J. P., B. M. Santos, W. M. Stall, and T. A. Bewick. 1998. Interference of purple nutsedge (*Cyperus rotundus*) population densities on bell pepper (*Capsicum annum*) yield as influenced by nitrogen. Weed Technol. 12:230–234.

Motis, T. N., S. J. Locascio, and J. P. Gilreath. 2004. Critical yellow nutsedge-free period for polyethylene-mulched bell pepper. HortScience 39:1045–1049.

Motis, T. N., S. J. Locascio, J. P. Gilreath, and W. M. Stall. 2003. Season-long interference of yellow nutsedge (*Cyperus esculentus*) with polyethylene-mulched bell pepper (*Capsicum annuum*). Weed Technol. 17:543–549.

Noling, J. W. 2005. Reducing methyl bromide field application rates with plastic mulch technology. http://edis.ifas.ufl.edu/pdffiles/IN/IN40300.pdf. Accessed: January 11, 2010.

Noling, J. W., D. A. Botts, and A. W. McRae. 2011. Alternatives to methyl bromide soil fumigation for Florida vegetable production. http://edis.ifas.ufl.edu/pdffiles/CV/CV29000.pdf. Accessed: March 8, 2012.

Norsworthy, J. K. 2003. Allelopathic potential of wild radish (*Raphanus raphanistrum*). Weed Technol. 17:307–313.

Norsworthy, J. K. and J. T. Meehan 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, J. K. and J. T. Meehan 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, J. K., M. J. Oliveira, P. Jha, M. Malik, J. K. Buckelew, K. M. Jennings, and D. W. Monks. 2008. Palmer amaranth and large crabgrass growth with plasticulture-grown bell pepper. Weed Technol. 22:296–302.

Olson, S. M., P. J. Dittmar, G. E. Vallad, S. E. Webb, E. J. McAvoy, S. A. Smith, M. Ozores-Hampton, M., and B. M. Santos. 2012. Pepper production in Florida. Pages 223–242 *in* S. M. Olson and B. M. Santos, eds. Vegetable Production Handbook for Florida 2012–2013. Gainesville, FL: University of Florida.

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

Schabenberger, O. and F. J. Pierce. 2002. Contemporary statistical models for the plant and soil sciences. Boca Raton, FL: CRC Press. Pp. 213–222.

Seefeldt, S. S., J. E. Jensen, and E. P. Fuerst. 1995. Log-logistic analysis of herbicide dose–response relationships. Weed Technol. 9:218–227.

Stuart, A. and J. K. Ord. 1994. Kendall's advanced theory of statistics. London, UK: Edward Arnold. Pp. 350–354.

Swiader, J. M., J. P. McCollum, and G. Ware. 1992. Producing Vegetable Crops. 4th ed. Danville, IL: Interstate.

[USDA] U.S. Department of Agriculture. 2005. United States standards for grades of sweet peppers. http://www.ams.usda.gov/AMSv1.0/getfile?dDocName =STELPRDC5050318. Accessed: March 2, 2012.

[USDA] U.S. Department of Agriculture, National Agricultural Statistics Service. 2012. Vegetable 2011 summary. http://usda01.library.cornell.edu/usda/current/VegeSumm/VegeSumm-01-26-2012.pdf. Accessed: March 2, 2012.

[USEPA] U.S. Environmental Protection Agency. 2008. Ozone Layer Depletion–Regulatory Programs: The Phaseout of Methyl Bromide Montreal Protocol. Available at: http://www.epa.gov/ozone/mbr/index.html. Accessed: September 15, 2008.

Webster, T. M. 2006. Weed survey—southern states: vegetable, fruit and nut crops subsection. . South. Weed Sci. Soc. 59:260–277.

Yates, S. R., J. Gan, S. K. Papiernik, R. Dungan, and D. Wang. 2002. Reducing the fumigant emission after soil application. Phytopathology 92:1344–1348.

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