Evaluation of Allyl Isothiocyanate as a Soil Fumigant for Tomato (*Lycopersicon esculentum* Mill.) Production

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Abstract

Fusarium wilt (*Fusarium oxysporum* f. sp. *lycopersici*), root-knot nematodes (*Meloidogyne* spp.), and purple nutsedge (*Cyperus rotundus* L.) are among the most damaging soilborne pests for tomato (*Lycopersicon esculentum* Mill.) production in the southeastern United States. Allyl isothiocyanate (allyl ITC) was evaluated as a potential fumigant alternative for control of soilborne pathogens, nematodes, and weeds. Shank- or drip-injected allyl ITC at rates ranging from 221 to 367 kg ha⁻¹ exhibited excellent performance, reducing the recovery of total *F. oxysporum* from treated soils. Shank- or drip-injected allyl ITC at 367 kg ha⁻¹ provided equivalent control of *C. rotundus* compared with 1,3-dichloropropene + chloropicrin and metam potassium, respectively. Totally impermeable

film (TIF) did not further reduce the recovery of *F. oxysporum* and various nematodes from soil treated with allyl ITC compared with virtually impermeable film (VIF). However, TIF mulch significantly improved *C. rotundus* control versus shank- or drip-injected allyl ITC treatments under VIF mulch. Overall, allyl ITC is an effective methyl bromide alternative against *F. oxysporum*, *C. rotundus*, and plant-parasitic nematodes *Criconebella* spp. and *Hoplolaimus* spp. in plasticulture tomato production.

Keywords: drip-application, Fusarium wilt, nematodes, plastic mulch, soil fumigant, vegetables

Tomato (*Lycopersicon esculentum* Mill.) is the most extensively cultivated and consumed vegetable crop in the southeastern United States (USDA 2010). Among the most detrimental soilborne pests, diseases, and weeds for tomato production in the southeastern United States are root-knot nematodes *Meloidogyne incognita* (Kofoid and White) Chitwood and *M. arenaria* (Neal) Chitwood; sting nematodes (*Belonolaimus* spp.); stubby-root nematodes (*Trichodorus* spp.), several *Fusarium*, *Pythium*, and *Rhizoctonia* spp.; as well as yellow (*Cyperus esculentus* L.) and purple (*C. rotundus* L.) nutsedges. Tomato production techniques include the application of broad-spectrum soil fumigants in raised beds under plastic polyethylene mulch. For many years, methyl bromide (MB) was extensively applied under plastic mulch in raised beds to provide effective control of bacteria, insects, fungi, plant-parasitic nematodes, soilborne viruses, and weeds (Schneider et al. 2003; Zasada et al. 2010). However, MB was classified as an ozone-depleting chemical in 1993 under the Montreal Protocol and was phased out in the United States in January 2005 (EPA 2018). Since that time, growers have adopted alternative fumigants for pest control.

Several fumigants have been identified as potential MB alternatives. At present, registered alternatives include 1,3-dichloropropene (1,3-D), chloropicrin (Pic), dimethyl disulfide (DMDS), and methyl isothiocyanate (methyl ITC) generators such as metam potassium (Boyd et al. 2017; Dayton et al. 2017; Hutchinson et al. 2004; Yu et al. 2019a; Zasada et al. 2010). These fumigants can be used alone but more frequently are applied in combination or as sequential applications to broaden the pest control spectrum (Boyd et al. 2017; Hutchinson et al. 2004; Mao et al. 2012; Yu et al. 2019a,b; Zasada et al. 2010). It is generally acknowledged, however, that none of the fumigants exhibit the broad-spectrum efficacy of MB. Therefore, the search for effective, safe, and cost-effective fumigants is ongoing.

Allyl isothiocyanate (allyl ITC) is a naturally occurring compound found in Brassicaceae plants such as broccoli (*Brassica oleracea* L.)

(Mithen et al. 2003), canola (*B. napus* L.) (Kirkegaard and Sarwar 1999), horseradish (*Armoracia rusticana* L.) (Wu et al. 2009), and white mustard (*Sinapis alba* L.) (Yu and Morishita 2014). It is the predominant ITC formed from hydrolysis of allyl glucosinolate (Brown and Morra 1996; Kirkegaard and Sarwar 1999). It rapidly degrades in soil and its half-life is reported from 20 h to 60 h (Borek et al. 1994). It also rapidly degrades when exposed to sunlight (<1 day) and does not deplete the ozone layer or contribute to greenhouse gas production in the atmosphere. The short persistence and low toxicity (acute oral toxicity [50% lethal dose] = 425.4 mg kg⁻¹) make allyl ITC a safe fumigant for plasticulture vegetable production (Vig et al. 2009). Currently, allyl ITC is registered in the United States under the trade name Dominus (Isagro USA, Inc., Morrisville, NC). Allyl ITC is documented to be detrimental to insects (Wu et al. 2009), nematodes (Ren et al. 2018; Yu et al. 2005), soilborne fungi (Baggio et al. 2018), and weeds (Brown and Morra 1996; Ren et al. 2018). Baggio et al. (2018) reported that allyl ITC was effective for managing *Macrophomina phaseolina* (Tassi) Goidanich, causal agent of charcoal rot in strawberry (*Fragaria x ananassa* D.).

Traditionally, growers used low-density polyethylene (LDPE) plastic film in vegetable production. Totally impermeable film (TIF) and virtually impermeable film (VIF) are less permeable to fumigants compared with LDPE (McAvoy and Freeman 2013) and have been used increasingly in recent years. TIF and VIF are manufactured by coextrusion containing multilayers with barrier polymers such as polyamide or ethyl vinyl alcohol. The differences in fumigant retention and pest control efficacy among these plastic films have been documented. For example, Austerweil et al. (2006) reported that the losses of methyl ITC were reduced by 40% under VIF mulch compared with LDPE mulch. Motis et al. (2003) reported that 25% of the labeled rate of MB under VIF provided similar level of *C. esculentus* control compared with a full rate under LDPE mulch. To our knowledge, information regarding soilborne pest control and crop productivity with allyl ITC under different plastic films in tomato production systems has not been previously reported.

Allyl ITC can be applied by conventional shank injection. However, the volatilization and distribution in the soil profile may be limited by its higher boiling point and lower vapor pressure (boiling point = 150 to 151°C, flash point = 47°C, and vapor pressure = 1.33 kPa at 38.3°C) compared with MB. An alternative application method is applying allyl ITC with irrigation water through the drip

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irrigation systems. Applying soluble formulations through a drip irrigation system may be more economical and environmentally friendly, and reduce worker exposure (Ajwa et al. 2002). In addition, in the southern United States, growers often grow multiple crops in sequence using the same beds, drip tapes, and plastic mulches (Yu et al. 2018) and, therefore, value drip fumigation as an application technique between crops.

The objectives of the research were to determine soilborne pest control efficacy from shank- and drip-applied allyl ITC at different rates under TIF or VIF mulch on various nematodes, fungal pathogens, and weeds.

Materials and Methods

Experimental site. Six field research trials were conducted from January 2012 to December 2013 at the Gulf Coast Research and Education Center (GCREC) in Balm, FL (27.76°N, 82.22°W). The soil type at the experimental site was characterized as a Myakka fine sand (Sandy, Siliceous Hyperthermic Oxyaquic Alorthod) with a pH of 6.8, 98% sand, 1% silt, and 1% clay. Raised beds were formed using bed pressing equipment (Kennco Manufacturing, Ruskin, FL, U.S.A.) on 1.5-m centers, with a height of 20 cm, and were 81 cm wide at the base and 71 cm wide at the top. Two rows of drip tape with emitters every 30 cm and a flow rate of 0.95 liters min⁻¹ 30 m⁻¹ (Jain Irrigation Inc., Haines City, FL, U.S.A.) were installed 2.5 cm beneath the soil surface and centered 20 cm apart down the center of each bed.

Shank fumigation experiments. Three field research trials were conducted in spring and fall 2012 and spring 2013 at the GCREC in Balm, FL. Trials were established as a split-plot design with four blocks. The main plot consisted of three 45.6-m-long beds and the subplot was 22.8 m of a single raised bed. The main plot factor was plastic film treatments, including TIF (Berry Plastics Corp., Evansville, IN, U.S.A.) and VIF (Berry Plastics Corp.) plastic mulches. The subplot factor was the fumigant treatments, including allyl ITC at 183, 211, 275, or 367 kg ha⁻¹; 1,3-D at 112 kg ha⁻¹ + Pic (Pic-Clor 60; Soil Chem. Corp. DBA Cardinal Professional Products, Hollister, CA, U.S.A.) at 168 kg ha⁻¹; and a nonfumigated control in trial I; and allyl ITC at 183, 229, 275, or 367 kg ha⁻¹; 1,3-D at 134 kg ha⁻¹ + Pic at 202 kg ha⁻¹; and a nonfumigated control in trials II and III. The fumigants were applied with a three-shank fumigation rig (Kennco Manufacturing, Ruskin, FL, U.S.A.), with shanks set to evenly distribute fumigant at the base of the bed. Tomato plants were transplanted in the center of the bed with 61-cm spacing between the plants. Tomato plants were irrigated, fertilized, and managed for foliar pests as per industry standards in the region (Vallad et al. 2014). Fumigation dates and other details of the experiments are shown in Table 1.

Recoverable levels of total *Fusarium oxysporum* from soils were determined by collecting soil cores from each subplot using a standard soil core sampler (2.5 cm in diameter by 30.5 cm in depth) prior to transplanting (3 and 4 weeks following fumigation for drip and shank fumigant trials, respectively). Three separate cores were collected to a 20.3-cm depth from bed centers within the center 3 m of each treated plot, discarding the top 5 cm of soil (approximately 20 g of soil per sample). Each soil sample was placed in individually labeled 16.5-by-14.9-cm plastic bags, mixed, and allowed to air dry at 24°C with the bag tops open for 1 week. After drying, three 2.5-g subsamples were added to 10 ml of sterile distilled water in individual test tubes, vortexed for 10 s, and serially diluted 10-fold in sterile distilled water. A 200-μl aliquot of each dilution was spread onto a plate of either Komada's or Malachite Green Agar at 2.5 ppm (MGA 2.5) (Castellá et al. 1997; Komada 1975) using an autoclavable plastic cell spreader (Fisher Scientific, Waltham, MA, U.S.A.). All plates were allowed to air dry and stored at room temperature in the dark. Total soil populations of *F. oxysporum* were enumerated after 7 days and converted to CFU per gram of soil based on average recovery across all three soil samples.

Various parasitic nematodes, including *Belonolaimus*, *Cricone-mella*, *Hoplolaimus*, *Meloidogyne*, *Tylenchorhynchus*, and *Trichodorus* spp., were counted at harvest from a composite of 15

random soil cores randomly collected near the base of plants using a standard soil core sampler (2.5 cm in diameter by 30.5 cm in depth) to a 25-cm depth from the soil surface. Soils were pooled and mixed by plot and nematodes were extracted from a 100-g subsample, based on a standard sieving and centrifugation procedure (Jenkins 1964) performed at the University of Florida Entomology and Nematology, Nematode Assay Lab (University of Florida, Gainesville, FL, U.S.A.).

The number of *C. rotundus* shoots emerging through the plastic mulch and in the planting hole was counted over the entire bed at 4 and 8 weeks after transplanting (WATP). Twenty tomato plants per plot were harvested on 21 May and 31 May in spring 2012, 31 October in fall 2012, and 23 May in spring 2013. All tomato fruit were graded prior to weighing as small (<5.5 cm in diameter), medium (5.5 cm < diameter < 6.5 cm), large (6.5 cm < diameter < 7 cm), or extra large (>7 cm in diameter).

Drip fumigation experiments. Three field research trials were conducted in spring and fall 2012 and spring 2013 at the GCREC in Balm, FL. Trials were established as a split-plot design with four blocks. The main plot consisted of three 45.6-m-long beds and the subplot was 22.8 m of a single raised bed. The main plot factor was the plastic film treatments, including TIF and VIF plastic mulches, while the subplot factor was the fumigation treatments, including allyl ITC at 138, 211, 275, or 367 kg ha⁻¹; metam potassium at 390 kg ha⁻¹; and the nonfumigated control in trial I; and allyl ITC at 183, 229, 275, or 367 kg ha⁻¹; metam potassium at 390 kg ha⁻¹; and the nonfumigated control in trials II and III. Fumigant treatments were applied into soil beds covered with TIF or VIF plastic mulch through the drip tapes. Two high-flow drip tapes (0.9 liters/h/emitter on 30-cm emitter spacing) were installed, offset by 10 cm on each side of the bed center at a soil depth of 2.5 cm beneath the soil surface. The fumigant treatments were injected through drip tapes using an electric water pump with a maximum flow rate of 13.25 liters min⁻¹ fitted to a manifold and adjusted to deliver fumigant treatments from a 151-liter recirculating tank in 25.7 m³ of water followed by 19 liters of water to flush the irrigation lines; each plot injection took approximately 60 to 75 min to complete.

Tomato plants were transplanted in the center of the bed with 61-cm spacing between plants (Table 1). Dates of fumigation, tomato transplanting, and harvesting are shown in Table 1. The data of *F. oxysporum*, nematodes, *C. rotundus* density, and tomato yield were collected by using the method described previously. The number of *C. rotundus* growing through the plastic mulch was counted at 4 and 8 WATP. Twenty tomato plants per plot were harvested and fruit were graded by using the method described earlier.

Statistical analysis. Two-way analysis of variance was performed by the PROC GLIMMIX procedure in SAS (version 9.4; SAS Institute Inc., Cary, NC, U.S.A.) to test for the significance of plastic films, fumigant treatments, and their interactions for data collected in the shank and drip fumigation experiments. Seasons were analyzed separately because they were conducted as separate experiments; weather conditions, nematodes, disease incidences, and weed populations varied between seasons. Treatments were compared

Table 1. Dates of fumigation, tomato transplanting, and harvesting

Experiment, run	Fumigation application	Transplanting date	Harvesting date
Shank fumigation			
Trial I	12 January	15 February	21 May and 31 May 2012
Trial II	21 August	24 September	3 January 2013
Trial III	9 January	13 February	23 May 2013
Drip fumigation			
Trial I	10 February	6 March	13 June 2012
Trial II	28 August	25 September	8 January 2013
Trial III	14 January	13 February	23 May 2013

using the least squares means statement with the Tukey adjustment at $P = 0.05$. Data were checked for normality and constant variance prior to analysis. Data such as *C. rotundus* control that were collected over time were analyzed using the repeated statement in SAS.

Results

Shank fumigation experiment. Allyl ITC at rates of 211, 271, and 367 kg ha⁻¹ was effective in controlling *F. oxysporum* (Table 2). In trial I, all rates of allyl ITC and 1,3-D + Pic significantly reduced *F. oxysporum* compared with the nonfumigated control. In trial III, a low rate of allyl ITC at 183 kg ha⁻¹ as well as 1,3-D + Pic were not effective. In trial III, application of allyl ITC at a rate of 367 kg ha⁻¹ provided better *F. oxysporum* control than 183 kg ha⁻¹ or 1,3-D + Pic. There were no significant differences in *F. oxysporum* control between TIF and VIF.

All rates of allyl ITC effectively reduced *Criconebella* spp. compared with the nonfumigated control and there was no significant difference in *Criconebella* spp. control among the fumigant treatments (Table 2). However, none of the fumigant treatments reduced *Meloidogyne* and *Belonolaimus* spp. compared with the nonfumigated control. There were no differences in nematode control between VIF and TIF.

The densities of *C. rotundus* were averaged over dates because the time by treatment interaction was not significant in the repeated-measures analysis. Application of allyl ITC at rates of 211 and 367 kg ha⁻¹ significantly reduced *C. rotundus* in trial I (Table 2). None of the allyl ITC rates significantly reduced *C. rotundus* density compared with the nonfumigated control in trials II and III, though densities tended to decline with increasing rate. 1,3-D + Pic significantly reduced *C. rotundus* density in all trials. In addition, *C. rotundus* populations were 35 to 71% lower in TIF than VIF in all three trials.

In all trials, there were no consistent yield trends in the various grading categories and, therefore, only the total marketable yields are presented in Table 3. All fumigant treatments produced significantly higher total marketable yield (65 to 125%) compared with

the nonfumigated control in trial I. A similar trend was observed in trial II (7 to 25% yield increase) but not in trial III. There were no differences in yield between VIF and TIF in any trial.

Drip fumigation experiment. All fumigant treatments significantly reduced *F. oxysporum* compared with the nonfumigated control in all three trials (Table 4). All allyl ITC rates except for 183 kg ha⁻¹ in trial II provided equal or greater control of *F. oxysporum* compared with metam potassium. The type of plastic film had no effect on the recovery of total *F. oxysporum* from soil.

Table 3. Effect of shank injection of allyl isothiocyanate (allyl ITC) and type of plastic film on tomato yield in field experiments conducted in Balm, FL^w

Treatment ^x	Rate (kg ha ⁻¹)	Tomato yield (kg ha ⁻¹)		
		Trial I	Trial II	Trial III
Fumigant				
Allyl ITC	183	8,680 a	65,925	29,864
Allyl ITC	229 ^y	10,426 a	65,729	25,202
Allyl ITC	275	7,654 a	61,135	22,714
Allyl ITC	367	9,812 a	59,079	29,375
1,3-D + Pic	134 + 202 ^z	9,723 a	56,448	30,971
Nonfumigated control	0	4,629 b	52,790	25,391
Film				
VIF	...	8,191	61,212	25,670
TIF	...	8,786	59,155	28,836
Fumigant	...	0.0075	0.0523	0.2529
Film	...	0.1075	0.4465	0.1711
Fumigant × film	...	0.9754	0.9591	0.2639

^w Treatment means separated with Tukey adjustment means comparison at the 0.05 significance level. Trials I, II, and III were conducted in spring and fall 2012 and spring 2013, respectively.

^x Abbreviations: 1,3-D + Pic, 1,3-dichloropropene + chloropicrin, VIF = virtually impermeable film, and TIF = totally impermeable film.

^y Allyl ITC rate was 211 kg ha⁻¹ in trial I.

^z 1,3-D + Pic rate was 134 + 202 kg ha⁻¹ in trial I.

Table 2. Effect of shank injection of allyl isothiocyanate (allyl ITC) and type of plastic film on *Fusarium oxysporum*, nematodes, and *Cyperus rotundus* in field experiments conducted in Balm, FL[†]

Treatment ^w	Rate ^x	Nematodes per 100 cm ³ of soil ^a							
		<i>F. oxysporum</i> ^v					<i>C. rotundus</i> shoots m ⁻²		
		<i>Bel</i>	<i>Cri</i>	<i>Mel</i>					
		Trial I	Trial III	Trial I	Trial I	Trial I	Trial I	Trial II	Trial III
Fumigant									
Allyl ITC	183	1.80 b	2.79 ab	11.2	2.1 b	23.5	17.0 ab	9.1 ab	11.1 a
Allyl ITC	229 ^y	1.49 b	2.64 bc	8.3	1.8 b	45.0	9.4 bc	8.5 ab	9.7 ab
Allyl ITC	275	1.57 b	2.66 bc	7.9	3.6 b	22.9	15.4 ab	8.2 ab	9.8 ab
Allyl ITC	367	1.57 b	2.37 c	6.6	1.5 b	25.3	8.2 bc	6.7 ab	7.3 ab
1,3-D + Pic	134 + 202 ^z	1.97 b	2.91 ab	7.3	2.1 b	11.3	4.7 c	4.1 b	5.2 b
Ctrl	0	2.83 a	3.07 a	10.5	26.2 a	32.0	28.3 a	10.6 a	12.7 a
Film									
VIF	...	2.13	2.76	7.8	4.6	25.0	21.8 a	9.7 a	11.3 a
TIF	...	1.61	2.72	9.3	2.3	24.2	6.4 b	6.1 b	7.3 b
Fumigant	...	0.0007	0.0152	0.9095	0.0002	0.4449	0.0062	0.0461	0.0047
Film	...	0.1124	0.8079	0.6787	0.0529	0.9471	0.0324	0.0030	0.0005
Fum × film	...	0.3790	0.1276	0.9388	0.2831	0.3315	0.3325	0.3152	0.0570

[†] Treatment means separated with Tukey adjustment means comparison at the 0.05 significance level. Within each treatment, values followed by the same letter did not differ at the 0.05 significance level. Trials I, II, and III were conducted in spring and fall 2012 and spring 2013, respectively. *F. oxysporum* was not detected in trial II. Nematode species, including *Meloidogyne*, *Belonolaimus*, and *Criconebella* spp., were detected in trial I but were not detected in trials II and III. Recoverable levels of *F. oxysporum* were determined prior to transplanting, parasitic nematodes were counted at harvesting, and *C. rotundus* shoots were counted at 4 and 8 weeks after transplanting.

^a Species of *Belonolaimus* (*Bel*), *Criconebella* (*Cri*), and *Meloidogyne* (*Mel*).

^v *F. oxysporum* (log₁₀ CFU g⁻¹ of soil).

^w Abbreviations: 1,3-D + Pic, 1,3-dichloropropene + chloropicrin, Ctrl = nonfumigated control, VIF = virtually impermeable film, TIF = totally impermeable film, and Fum = fumigant.

^x Rate in kilograms per hectare.

^y Allyl ITC rate was 211 kg ha⁻¹ in trial I.

^z 1,3-D + Pic rate was 112 + 168 kg ha⁻¹ in trial I.

The experimental site was infested by *Belonolaimus*, *Cricone-mella*, and *Trichodorus* spp. in trial I and *Hoplolaimus*, *Meloidogyne*, and *Tylenchorhynchus* spp. in trial III (Table 4). Only allyl ITC at 211 kg ha⁻¹ and the metam potassium fumigation treatment significantly reduced *Cricone-mella* spp. in trial I; none of the fumigant treatments affected *Belonolaimus* or *Trichodorus* spp. in this trial. All fumigant treatments significantly reduced *Hoplolaimus* spp. but did not affect other nematodes in trial III. The effect of plastic film on nematodes did not differ between TIF and VIF in either trial.

At the rates tested, allyl ITC and metam potassium significantly reduced *C. rotundus* density compared with the nonfumigated control in trials I and II (Table 4). In trial II, low rates of allyl ITC at 183 and 229 kg ha⁻¹ were less effective than metam potassium for controlling *C. rotundus*, while high rates of allyl ITC at 275 and 367 kg ha⁻¹ provided control similar to metam potassium. In trial III, *C. rotundus* densities were low and the nonfumigated control had 2.2 shoots m⁻². TIF mulch resulted in lower *C. rotundus* density than VIF mulch in trials I and II. There were no differences in *C. rotundus* density among fumigant treatments and nonfumigated control in trial III. In general, results showed that the TIF plastic mulch reduced *C. rotundus* density better than VIF. *C. rotundus* populations were 32 to 68% lower in TIF than VIF in all three trials.

There were no significant differences among treatments for various grading categories and, as a result, only the total marketable yields are presented (Table 5). Plastic film–fumigant interactions had no significant effect on tomato yield in trial I ($P = 0.2323$) and trial II ($P = 0.8813$) but had a significant effect in trial III ($P = 0.0198$). In trials I and II, the total marketable yields were not statistically different among the fumigant treatments. In trial III, none of the fumigant treatments produced tomato yields that were significantly higher than the nonfumigated control, with the exception of allyl ITC at 229 kg ha⁻¹ under TIF.

Discussion

In the southern United States, tomato yield losses have frequently been associated with various nematodes and fungal pathogens, in which phytopathogenic forms of *F. oxysporum* and various nematodes such as *Meloidogyne* spp. have become particularly problematical for

tomato production. Our results showed that *F. oxysporum* populations were effectively reduced by shank- or drip-applied allyl ITC, confirming the sensitivity of *Fusarium* spp. to this fumigant. Our findings suggest that allyl ITC would also be effective for managing tomato diseases caused by phytopathogenic forms of *F. oxysporum* such as formae speciales *lycopersici* and *radicis-lycopersici*. In previous investigations, Gilreath et al. (2003) reported that drip-injected allyl ITC + furfural was effective in reducing Fusarium wilt in tomato. Recently, Ren et al. (2018) reported that chisel-applied allyl ITC was effective against *Fusarium*, *Phytophthora*, and *Pythium* spp.

In this research, allyl ITC was observed to be effective against *Cricone-mella* spp. and *Hoplolaimus* spp. when it was drip- and shank-applied, respectively, but was ineffective against *Belonolaimus*, *Meloidogyne*, *Trichodorus*, and *Tylenchorhynchus* spp. In previous research, Gilreath et al. (2008) reported that drip-injected allyl ITC with furfural was ineffective in controlling *Belonolaimus* spp. in strawberry crops (*Fragaria* × *ananassa* (Weston) Duchesne). Previous researchers have also revealed the relatively poor activity of metam sodium, a methyl ITC generator, against *Meloidogyne* spp. (Desaeger et al. 2008; Locascio et al. 2000; Noling and Becker 1994).

TIF did not further reduce soil levels of *F. oxysporum* and various nematodes from allyl ITC over VIF mulch. Allyl ITC has relatively low volatility and the type of plastic film may have limited effect on allyl ITC retention. TIF improved *C. rotundus* control from shank- or drip-injected fumigant treatments compared with VIF. The improved nutsedge control under TIF is probably due to a stronger physical barrier to *C. rotundus* emergence, which kept the rigid shoots from penetrating the TIF plastic mulch. This finding agrees with those of McAvoy and Freeman (2013), who previously reported that the nonfumigated plots under TIF provided significantly greater *C. esculentus* L. control than nonfumigated plots under VIF in plasticulture tomato. The authors also reported that DMDS/Pic (79:21 [wt/wt]) rates could be reduced from a standard 468 liters ha⁻¹ under VIF to 187 liters ha⁻¹ under TIF while maintaining nutsedge control.

In the present research, *C. rotundus* populations varied among trials. The differences in *C. rotundus* densities among trials are likely due to specific site location of the experiment. At the rates tested,

Table 4. Effect of drip injection of allyl isothiocyanate (allyl ITC) and type of plastic film on *Fusarium oxysporum*, nematodes, and *Cyperus rotundus* in field experiments conducted in Balm, FL¹

Treatment ^w	Rate ^x	Nematodes per 100 cm ³ of soil ^a											<i>C. rotundus</i> shoots m ⁻²		
		<i>F. oxysporum</i> ^y													
		Trial I	Trial II	Trial III	Trial I			Trial III						Trial I	Trial II
					<i>Bel</i>	<i>Cri</i>	<i>Tri</i>	<i>Hop</i>	<i>Tyl</i>	<i>Mel</i>					
Fumigant															
Allyl ITC	183 ^y	1.41 b	2.39 b	42.6 b	4.5	1.8 ab	0.3	1.9 bc	1.8	3.4	2.1 b	6.1 b	2.5		
Allyl ITC	229 ^z	0.00 d	1.66 c	82.9 b	4.5	0.9 b	2.1	2.3 b	2.2	4.8	2.1 b	7.2 b	1.5		
Allyl ITC	275	0.58 cd	0.77 c	28.9 b	6.1	2.5 ab	1.3	2.4 b	1.5	4.1	1.2 b	4.1 bc	2.5		
Allyl ITC	367	0.32 d	0.96 c	48.7 b	3.8	1.9 ab	0.9	3.1 b	2.9	3.8	1.3 b	4.1 bc	2.9		
MetPot	390	0.95 bc	1.46 c	21.4 b	9.7	1.1 b	1.2	0.4 c	4.3	1.3	2.3 b	1.7 c	0.6		
Ctrl	0	2.58 a	3.35 a	1,002.1 a	4.9	5.7 a	1.5	12.5 a	2.2	13.0	18.0 a	15.4 a	2.2		
Film															
VIF	...	1.08	2.01	67.2	5.0	1.9	0.8	2.4	1.7	7.0	4.8 a	8.8 a	2.5		
TIF	...	0.86	2.25	71.8	5.7	2.7	1.6	3.0	3.3	3.2	1.5 b	4.0 b	1.7		
Fumigant	...	<0.0001	<0.0001	0.0192	0.8849	0.0265	0.3653	0.0003	0.8753	0.0912	<0.0001	<0.0001	0.2347		
Film	...	0.2208	0.1988	0.9175	0.8154	0.3343	0.1013	0.4734	0.1946	0.0943	0.0006	<0.0001	0.1816		
Fum × film	...	0.8353	0.3051	0.7122	0.9457	0.3627	0.0213	0.2383	0.1582	0.0686	0.3501	0.0538	0.8815		

¹ Treatment means separated with Tukey adjustment means comparison at the 0.05 significance level. Within each treatment, values followed by the same letter did not differ at the 0.05 significance level. Trials I, II, and III were conducted in spring and fall of 2012 and spring 2013, respectively. Recoverable levels of *F. oxysporum* were determined prior to transplanting, parasitic nematodes were counted at harvesting, and *C. rotundus* shoots were counted at 4 and 8 weeks after transplanting.

^a Species of *Belonolaimus* (*Bel*), *Cricone-mella* (*Cri*), *Trichodorus* (*Tri*), *Hoplolaimus* (*Hop*), *Tylenchorhynchus* (*Tyl*), and *Meloidogyne* (*Mel*).

^y *F. oxysporum* (log₁₀ CFU g⁻¹ of soil).

^w Abbreviations: MetPot = metam potassium, Ctrl = nonfumigated control, VIF = virtually impermeable film, TIF = totally impermeable film, and Fum = fumigant.

^x Rate in kilograms per hectare.

^y Allyl ITC rate was 138 kg ha⁻¹ in trial I.

^z Allyl ITC rate was 211 kg ha⁻¹ in trial I.

shank-injected allyl ITC is generally less effective against *C. rotundus* compared with 1,3-D + Pic. However, the highest rate of allyl ITC at 367 kg ha⁻¹ provided statistically equivalent control of *C. rotundus* compared with 1,3-D + Pic. Moreover, our results showed that shank-injected allyl ITC exhibited similar efficacy compared

with 1,3-D + Pic in terms of the control of *F. oxysporum* and nematodes.

In the drip fumigation experiment, at the rates evaluated, allyl ITC significantly reduced the *C. rotundus* densities in two of three trials. During all three tomato seasons, drip-injected allyl ITC at

Table 5. Effect of drip injection of allyl isothiocyanate (allyl ITC) and type of plastic film on tomato yield in field experiments conducted in Balm, FL^w

Film ^x	Fumigant	Rate (kg ha ⁻¹)	Tomato yield (kg ha ⁻¹)		
			Trial I	Trial II	Trial III
VIF	Allyl ITC	183 ^y	39,229	39,273	32,538 ab
	Allyl ITC	229 ^z	35,933	46,862	26,757 b
	Allyl ITC	275	41,702	45,261	26,131 b
	Allyl ITC	367	28,104	48,914	33,052 ab
	Metam potassium	390	38,323	46,176	34,567 ab
	Nonfumigated control	...	28,351	39,154	25,872 b
TIF	Allyl ITC	183	26,703	48,495	34,425 ab
	Allyl ITC	229	33,735	46,527	43,156 a
	Allyl ITC	275	33,735	49,288	34,130 ab
	Allyl ITC	367	37,416	50,981	34,476 ab
	Metam potassium	390	39,065	49,593	35,181 ab
	Nonfumigated control	...	33,048	42,591	25,399 b
Fumigant	...	...	0.5890	0.4400	0.0042
Film	...	...	0.8265	0.1759	0.0068
Fumigant × film	...	...	0.2323	0.8813	0.0198

^w Treatment means separated with Tukey adjustment means comparison at the 0.05 significance level. Values within the same column followed by the same letter did not differ at the 0.05 significance level. Trials I, II, and III were conducted in spring and fall 2012 and spring 2013, respectively.

^x Abbreviations: VIF = virtually impermeable film and TIF = totally impermeable film.

^y Allyl ITC rate was 138 kg ha⁻¹ in trial I.

^z Allyl ITC rate was 211 kg ha⁻¹ in trial I.

Fig. 1. Control of *Cyperus rotundus* in totally impermeable film plastic-mulched beds from shank- and drip-injected allyl isothiocyanate (allyl ITC) on the day of tomato transplanting in field experiments in Balm, FL.

rates of 275 and 367 kg ha⁻¹ provided *C. rotundus* control comparable with metam potassium. Although differences in *C. rotundus* control between shank- and drip-application experiments were observed (Fig. 1), it is unknown which application method can provide better pest control because they have not been examined in the same experiment in the present research. Uniform distribution of allyl ITC in the soil profile is critical to improve pest control (Baggio et al. 2018). For controlling *M. phaseolina*, Baggio et al. (2018) recommended applying allyl ITC via shank with a dual-port rig during the formation of new plastic-mulched beds, and applying allyl ITC through two drip tapes if the plastic beds need to be reused from the previous seasons.

The mode of action of allyl ITC for weed control is currently not known but it is suggested that allyl ITC interacts with glycolysis-related enzymes during the weed seed germination or tuber sprouting and, thereby, prevents or delays seed germination or tuber sprouting (Drobnica et al. 1977). Previous research evaluated the efficacy of allyl ITC at concentrations ranging from 0 to 10,000 nmol g⁻¹ soil for controlling large crabgrass (*Digitaria sanguinalis* (L.) Scop.), Palmer amaranth (*Amaranthus palmeri* (S.) Watson), and *Cyperus esculentus* in greenhouse conditions (Norsworthy and Meehan 2005). The authors reported that allyl ITC concentrations required to control 50% *D. sanguinalis*, *A. palmeri*, and *C. esculentus* were 982, 269, and 4,206 nmol g⁻¹ soil, respectively. In other research, allyl ITC at 932 kg ha⁻¹ provided effective control of *D. sanguinalis*, *A. palmeri*, and *C. esculentus* in field conditions (Bangarwa et al. 2011, 2012). Further research is needed to determine the control efficacy of allyl ITC on other weed species.

Previous studies have shown that fumigants such as 1,3-D, Pic, methyl iodide, and metam sodium, when applied singly, do not normally provide the same broad-spectrum pest control as MB (Boyd et al. 2017; Desaeger et al. 2008; Haar et al. 2003; Hutchinson et al. 2004). However, fumigant combinations such as 1,3-D + Pic (Desaeger et al. 2008; Hutchinson et al. 2004), methyl iodide + Pic (Hutchinson et al. 2004), and metam sodium + Pic (Haar et al. 2003; Hutchinson et al. 2004) proved to be as effective as MB in many situations. Perhaps combining allyl ITC with Pic could provide broad-spectrum control of nematodes, soilborne pathogens, and weeds and warrants further investigation.

The results suggested that shank- and drip-applied allyl ITC have the potential to improve the marketable tomato yield compared with the nonfumigated control. There were significant incidences of *Fusarium* crown and root rot (*F. oxysporum* f. sp. *radicis-lycopersici*) in trial I in the shank fumigation experiment and trial III in the drip fumigation experiment, which had affected fruit yield in nonfumigated beds. However, plots treated with allyl ITC generally exhibited less disease incidence due to its efficacy on soilborne diseases and, as a result, produced greater marketable tomato yield compared with the nonfumigated control.

In summary, allyl ITC was highly effective at reducing soil levels of *F. oxysporum*. Allyl ITC controlled plant-parasitic nematodes *Criconebella* spp. and *Hoplotaimus* spp. but failed to effectively control *Belonolaimus*, *Meloidogyne*, *Trichodorus*, and *Tylenchorhynchus* spp. At the rates tested, shank-injected allyl ITC had similar efficacy compared with 1,3-D + Pic in reducing initial soil levels of *F. oxysporum* and the level of plant-parasitic nematodes *Belonolaimus*, *Criconebella*, and *Meloidogyne* spp. at the end of the season but was generally less effective compared with 1,3-D + Pic in controlling *C. rotundus*. Drip-injected allyl ITC at 275 and 367 kg ha⁻¹ provided *C. rotundus* control similar to metam potassium. TIF mulch improved the *C. rotundus* control from shank- or drip-applied allyl ITC compared with VIF mulch. However, the type of plastic film had little or no effect on soil levels of *F. oxysporum* and nematodes. Furthermore, allyl ITC seemed to increase the marketable yield of tomato. Additional research is needed to refine rates and application techniques to ensure effective pest control.

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