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Effects of fluensulfone combined with soil fumigation on root-knot nematodes and fruit yield of drip-irrigated fresh-market tomatoes

Gilma X. Castillo [a,*], Monica Ozores-Hampton [a], Pablo A. Navia Gine [b]

[a] Institute of Food and Agricultural Sciences, Southwest Florida Research and Education Center, University of Florida, Immokalee, FL 34142, USA
[b] ADAMA Agricultural Solutions Ltd., Raleigh, NC 27604, USA

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After the phase-out of methyl bromide (MeBr) and the constant challenges of root-knot nematodes (RKNs, *Meloidogyne* spp.), the need to evaluate the efficacy of additional alternatives in tomato (*Solanum lycopersicum* L.) production is vital. Fluensulfone (Nimitz, ADAMA Agricultural Solutions Ltd., Raleigh, NC) is a true, contact nematicide developed to target RKNs. Among available chemical soil fumigants, Pic-Clor 60 [1,3-dichloropropene plus chloropicrin (40:60, w/w)] has been identified as one of the main alternatives to MeBr; however, nematode management in sandy soils with drip irrigation has been unsatisfactory. During the fall of 2014 and the spring of 2016, two replicated field experiments were conducted in Myakka City, FL with the objective of evaluating the efficacy of pre-plant drip-injected fluensulfone at 1.96 and 2.80 kg a.i.$\cdot$ha^{-1} combined with pre-plant fumigated Pic-Clor 60 at 280 kg ha^{-1} on plant vigor, RKN soil population density, root galling index, and fruit yield of fresh-market tomatoes. All treatments showed uniform plant growth during both seasons. In 2014 and 2016, at final harvest, Pic-Clor 60 combined with fluensulfone at 1.96 and 2.80 kg a.i.$\cdot$ha^{-1} decreased RKN densities compared to Pic-Clor 60 alone by 96 and 85% and 81 and 94%, respectively. Similarly, during 2014 and 2016, at mid-season and final harvest, less root galling was observed with Pic-Clor 60 combined with both fluensulfone rates than with Pic-Clor 60 alone. However, the effect of the combination of fluensulfone and Pic-Clor 60 on tomato yield was significant only at the third harvest in 2014 when RKN infestation was high. Fluensulfone combined with Pic-Clor 60 could be a viable alternative for managing RKNs in fresh-market tomato production in sandy soils using drip irrigation and in fields with high RKN infestation.

1. Introduction

In 2015, with 13,030 ha harvested, Florida continued to be the leading fresh-market tomato (*Solanum lycopersicum* L.) state, generating a production value of US$453 million and an average yield of 37.2 t ha^{-1} [United States Department of Agriculture (USDA), 2016]. Nationally, Florida fresh-market tomato harvested area and production value accounted for 34% and 36%, respectively (USDA, 2016). Production of tomato mainly occurs in the central and southern regions of the state (Ozores-Hampton et al., 2015) extending from November to June (Ozores-Hampton et al., 2007). Tomatoes are typically grown on raised, polyethylene-mulched beds in sandy soils that have low water-holding capacity (Ozores-Hampton et al., 2015). Polyethylene mulch systems generally utilize drip irrigation to allow for controlled application of water, fertilizer, and pesticides (Simonne et al., 2015).

In spite of being the number one producer of fresh-market tomatoes, Florida faces many challenges. Plant-parasitic nematodes, for instance, including root-knot nematodes (RKNs, *Meloidogyne* spp.), are among the most devastating plant pathogens, affecting nearly all types of crops worldwide (USDA, 2013). In tomato production, RKNs can have adverse effects on fruit yield and quality (Duncan and Noling, 1998). Plant injury due to RKN infection involves the formation of galls that cause poor root uptake of water and nutrients (Duncan and Noling, 1998). Hence, plants may exhibit moisture and nutrient deficiency symptoms such as incipient wilting, stunting, yellowing of the leaves, and ultimately crop yield reduction or even plant death under conditions well tolerated by healthy plants (Duncan and Noling, 1998). Symptoms of RKNs occur in patches across the field due to the clustered distribution of RKN populations (Duncan and Noling, 1998). Sandy soils play a fundamental role in RKN movement, reproduction, and survival. Taylor

* Corresponding author.
E-mail address: gilma.castillo@ufl.edu (G.X. Castillo).

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and Sasser (1978) have indicated that RKN infestation is more severe in sandy soils than in clay soils since RKN larval movement depends on pore space; the larger the pore spaces, the easier RKNs move through the soil. Drip irrigation can be used to deliver nematicides directly to the plant root zone either before planting to control RKNs or after planting to rescue infested crops (Noling, 2005).

Since 1961, Florida tomato growers relied on methyl bromide (MeBr) as a broad spectrum soil fumigant against soil-borne diseases, weeds, and nematodes (Gilreath et al., 1994). However, after the complete phase-out of MeBr in 2005 under the Montreal protocol [U.S. Environmental Protection Agency (EPA), 2000], tomato growers were left with limited options against RKNs (Noling, 2016). Pic-Clor 60 [1,3-dichloropropene plus chloropicrin (40:60, w/w)] (Agrian, Inc., Fresno, CA) was identified as one of the main alternative fumigants to MeBr in a survey conducted among Florida tomato growers in 2011 (Snodgrass et al., 2013). Growers indicated that pest-pathogen problems were increasing, and that production losses were experienced due to the unsatisfactory efficacy of available alternatives (Snodgrass et al., 2013). Preliminary research has shown that currently available pre-plant chemical soil fumigants alone may not offer optimal RKN management (Di Gioia et al., 2016). In addition, recent studies have shown that current fumigant alternatives to MeBr with low vapor pressures and high boiling points do not distribute vertically in the soil profile and thus allow nematode survival in deeper layers (Noling, 2016). Oxamyl (Vydate, DuPont Crop Protection, Hayward, CA) a non-fumigant nematistat that paralyzes nematodes, is commonly used as a post-plant treatment (Wright, 1981; Rich et al., 2004). Post-plant applications of oxamyl have not shown optimal plant growth and yield recovery since once RKN infection takes place and plant damage occurs, crop rescue becomes dependent on frequency of product application and time of RKN detection (Noling, 2016). Oxamyl is one of two non-fumigant nematicides that have been used for RKN management in tomato in Florida (Noling, 2016). Currently, production of oxamyl has been halted due to a factory incident involving a toxic chemical release [U.S. Chemical Safety Board (CSB), 2016].

Fluensulfone [5-chloro-2 (3,4,4-trifluoro-but-3-ene-1-sulfonyl)-thiazole], (Nimitz, ADAMA Agricultural Solutions Ltd., Raleigh, NC), is a novel chemistry of the fluoroalkenyl thioester group developed to target RKNs on lowbush berries and cucurbit, leafy, and fruiting vegetables (Navia, 2014a). The dosage and method of application of fluensulfone is 1.96–3.92 kg a.i.$\cdot$ha^{-1} applied via drip irrigation, banded incorporated, or broadcast incorporated (Navia, 2014a). Fluensulfone is the first new chemical, non-fumigant nematicide to be introduced into the market in more than 20 years having the signal word of 'Caution' found on the product label (Navia, 2014b). In contrast to carbamates and organophosphates, fluensulfone does not act by nematode paralysis via inhibition of acetylcholinesterase activity (Kearn et al., 2014; Oka et al., 2009, 2013). Previous studies have shown that fluensulfone has true nematicidal activity as well as systemic activity in the plant (Kearn et al., 2014; Oka et al., 2009, 2011).

Since 2008 preliminary studies on carrot (*Daucus carota* subsp. *sativus*), cucumber (*Cucumis sativus* L.), eggplant (*Solanum melongena*), squash (*Cucurbita* spp.), potato (*Solanum tuberosum* L.), sweet potato (*Ipomoea batatas*), lettuce (*Lactuca sativa*), and tomato have shown that applications of fluensulfone reduced RKN galling on plant roots and soil population densities of larvae compared with an untreated control (Dickson and Mendes, 2013; Rubin et al., 2011). In a tomato-cucumber double cropping system, fluensulfone reduced the root galling index by 73% in the tomato crop with RKN suppression persisting into the second crop (Morris et al., 2015). Combining fluensulfone and Pic-Clor 60 can be viewed as a combination of tactics to obtain a more effective RKN management since previous studies have shown that chemical fumigants alone do not provide optimal RKN management (Di Gioia et al., 2016). Therefore, the objective of this study was to evaluate the effect of drip-applied fluensulfone combined with shank-applied Pic-Clor 60 on fresh-market tomato plant vigor, RKN soil population density, root galling index, and fruit yield.

2. Materials and methods

2.1. Field preparation and treatment application

During the fall 2014 and spring 2016 seasons, two experiments were conducted in fields with a history of high RKN soil infestation on a commercial farm located at Myakka City, FL that specializes in fresh-market tomato production. The soil type was a Myakka fine sand (sandy, siliceous, hyperthermic Aeric Haplaquods) (Natural Resources Conservation Service, 2016). On 5 Aug. 2014 and 21 Dec. 2015, prior to bedding, a starter fertilizer mix of nitrogen (N) and potassium (K) was broadcasted and incorporated at rates of 22 and 212 kg ha^{-1} [sources: ammonium nitrate (NH_4NO_3) and potassium sulfate (K_2SO_4)]. Then, 12-m-long and 20-cm-tall, raised beds were formed on 1.83-m centers using a 91-cm-wide bed shaper. Subsequently, beds were fumigated with Pic-Clor 60 at 280 kg ha^{-1}, shank-applied with three chisels per bed, spaced 15 cm apart, and placed 20 cm deep. Immediately after fumigation, a single 8-mm drip tape (Model Jain Turbo Cascade 11653050; Jain Irrigation, Inc., Jalgaon, India) with 32-cm emitters spacing and a flow rate of 0.98 L h^{-1} was placed off center at 20 cm from the bed shoulder and 5 cm deep from the bed top. Beds were then covered with virtually impermeable film (Berry Plastics, Evansville, IN), white-on-black and black-on-black in 2014 and 2016, respectively. Three weeks after fumigation, on 2 Sept. 2014 and 11 Jan. 2016, fluensulfone treatments were injected into plots according to a randomized complete block design with four replications. Treatments were injected into the drip tape at two different rates: 1.96 and 2.80 kg a.i$\cdot$ha^{-1} using a spot sprayer[1] with an open flow of 498 L h^{-1} (Model GRN-7822-201; Countyline Tractor Supply Co., LaBelle, FL). Pic-Clor 60 alone represented the control grower standard treatment. In each plot, the drip tape was cut at the end and closed using end caps (DripWorks, Inc., Willits, CA) to prevent cross-contamination among treatments. For treatment injection, 10 m^3 ha^{-1} of water were first applied, followed with 47 m^3 ha^{-1} of water for fluensulfone application, and 6 m^3 ha^{-1} of water to flush residues and clear the drip tape. After treatment application, drip tape was re-connected using couplers (DripWorks, Inc., Willits, CA) to allow for continuous irrigation across experimental plots. On 6 Sept. 2014 and 16 Jan. 2016 [4 and 5 days after application (DAA)], the crop was irrigated with 7 m^3 ha^{-1}. On 12 Sept. 2014 (10 DAA) and 20 Jan. 2016 (9 DAA), six-week-old seedlings of large, round, determinate, fresh-market tomato cv. 'HM 1823' (HM.CLAUSE, Inc., Davis, CA) grown in 128-cell styrofoam trays (Mobley Plant World, LaBelle, FL), were transplanted 61 cm apart in a single row for each bed establishing 20 plants per plot and a population of 8970 plants$\cdot$ha^{-1}. 'HM 1823' is an early season tomato with 70–74 days to maturity, which required tying and staking and is susceptible to RKNs. Fertigation was used to supplement the pre-plant fertilizer

[1] A spot sprayer consists of a 15-gallon storage tank and one ON/OFF switch in which a 12-V battery is connected. The pump is also equipped with an electronic pressure switch pre-set to stop at 60 PSI. Once the sprayer is on, the solution is drawn from the tank by the pumping system. The solution then passes through the strainers and to the pump, which forces the solution to the boom and subsequently into the drip tape.