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Optimizing anaerobic soil disinfestation for fresh market tomato production: Nematode and weed control, yield, and fruit quality

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ABSTRACT

Anaerobic soil disinfestation (ASD) has potential as an alternative to chemical-fumigation for controlling soilborne pathogens and pests. Previously, control of nutsedge was sub-optimal and the quantity of inputs for commercial production was an impediment to adoption. Field studies were conducted in Citra and Immokalee, Florida to assess the effects of ASD with reduced amendments and inclusion of a pre-emergent herbicide on weed and nematode populations, tomato yield, and fruit quality. Pre-plant soil treatments included ASD with 6.9 m^3 ha^{-1} of molasses and 11 Mg ha^{-1} of composted poultry litter (CPL) (ASD0.5), ASD with 13.9 m^3 ha^{-1} of molasses and 22 Mg ha^{-1} of CPL (ASD1.0), and chemical soil fumigation using Pic-Clor 60 (CSF). Subplot treatments were halosulfuron-methyl (Sandea®) herbicide and no herbicide application. ASD0.5 reached high and equivalent accumulation of anaerobic conditions as ASD1.0 during the three-week soil treatment in both locations. Root galling and plant-parasitic nematode population at harvest in ASD treatments were similar in nematode suppression to CSF in both locations, while ASD1.0 resulted in higher non-parasitic nematode populations in soil compared to CSF in Citra. In Citra, ASD treatments did not differ from CSF in total marketable fruit yield; however, ASD0.5 resulted in higher total yield of extra-large fruit than CSF and ASD1.0. In Immokalee, no difference was observed in total marketable yield between ASD0.5 and CSF, whereas ASD1.0 produced 26.3% and 20.4% higher total marketable yield than that of CSF and ASD0.5, respectively. ASD treatments had no impact on fruit quality attributes including color, firmness, pH, total soluble solids, and dry matter content. Herbicide application improved nutsedge control and had no negative impact on the development of anaerobicity in ASD-treated plots, while total marketable yield and fruit quality were not impacted by herbicide treatment in either location. Despite some variations between the two locations, reduced application rates of CPL and molasses produced results similar to the full rates of amendment as well as the fumigation treatment. Overall, combining ASD with an herbicide had no negative impacts on crop production and resulted in improved weed control.

1. Introduction

Fresh-market tomato (*Solanum lycopersicum* L.) production is of great economic importance in Florida, the number one producer in the United States. In 2015, the 13,355 ha of tomatoes planted in Florida were valued at 453 million dollars and accounted for 35% of the U.S. tomato production (USDA-NASS, 2016). Soil fumigants such as chloropicrin, metam sodium/potassium, and dimethyl disulfide are used on a wide variety of vegetables as preplant soil treatment, particularly in Florida and California in the U.S. to control pests, pathogens, and weeds, while these soil fumigants are all strictly regulated by state and federal governments because of environmental quality and safety concerns (Qin et al., 2013; Butler et al., 2014). Considering the long-term sustainability of vegetable production, there is an urgent call for developing and adopting non-chemical alternatives to the use of synthetic soil fumigants.

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Anaerobic soil disinfestation (ASD), also known as biological soil disinfestation, is a potential alternative to chemical-dependent fumigation for controlling soilborne pathogens and plant-parasitic nematodes (Momma et al., 2013; Shennan et al., 2014; Rosskopf et al., 2015). Independently developed in Japan (Shinmura et al., 1999) and the Netherlands (Blok et al., 2000), this method involves the application of organic materials as a labile carbon source such as wheat/rice bran, composted broiler litter, cover crops, molasses, and ethanol (Muramoto et al., 2014; Strauss and Kluepfel, 2015), covering with polyethylene film or tarp after application, and irrigation to saturation of top soil to stimulate anaerobic decomposition of the organic carbon prior to transplanting (Blok et al., 2000; Butler et al., 2012a, 2014).

The promising effects of ASD have been demonstrated in commercial strawberry production in California of the U.S. (Muramoto et al., 2014), organic tomato production in Japan (Momma et al., 2013), double-cropping of bell pepper and eggplant, tomato, cucumber, and strawberry in Florida (Rosskopf et al., 2010; Butler et al., 2012a, 2012b, 2014; Shennan et al., 2014; Di Gioia et al., 2016), and production of strawberry runners and tree planting stocks at nurseries in Netherlands (Shennan et al., 2014). The possible mechanisms of ASD for soilborne pathogen suppression involve shifts of soil microbial diversity, production of volatile organic compounds, and generation of lethal anaerobic conditions resulting from release of organic acids and metal ions (Momma, 2015; Strauss and Kluepfel, 2015).

The current ASD practice in Florida typically includes using composted poultry litter (CPL) and feed-grade blackstrap molasses as organic sources, although some cover crops used as green manure may also be effective (Butler et al., 2012b, 2014; Rosskopf et al., 2015; Di Gioia et al., 2016), followed by application of 5 cm of water via double drip tapes under totally impermeable (TIF) polyethylene mulch (Rosskopf et al., 2014; Di Gioia et al., 2016). CPL in ASD can improve microbial diversity in soils with a history of soil fumigation as well as water holding capacity, which is important for Florida sandy soils (Ozores-Hampton et al., 2011; Butler et al., 2014). Nitrogenous organic inputs have also shown potential for control of plant-parasitic nematodes through release of toxic materials (McSorley, 2011). Butler et al. (2012a) found that molasses amendment played a key role in controlling introduced inoculum of *Fusarium oxysporum* f. sp. *lycopersici*, while the combined use of molasses and CPL demonstrated great potential for controlling soilborne pests including fungi and nematodes (Rosskopf et al., 2014). Application rates of CPL ranged from 16 to 26 Mg dry matter ha^{-1}, with molasses ranging from 8.2 to 14.5 Mg dry matter ha^{-1} (Butler et al., 2012a, 2012b; Rosskopf et al., 2014). In our previous field study (Di Gioia et al., 2016), it was observed that ASD application using a mixture of CPL (22 Mg ha^{-1}) and molasses (13.9 and 27.7 m^3 ha^{-1}) showed similar performance in terms of root-knot nematode and weed control, yield, and fruit quality as the chemical soil fumigation in fresh market tomato production. The adoption of the ASD technique is largely limited by its cost and uncertainty about its effectiveness at controlling different pathogens across a range of environments (Shennan et al., 2014). Accordingly, more work is needed to test ASD effect with lower quantities of organic amendments in order to facilitate widespread adoption of ASD in vegetable production.

Previous studies showed variable results regarding the potential of ASD for weed control which were attributed to differences in carbon source, molasses type, incorporation method, soil type, and weed species (Muramoto et al., 2008; Butler et al., 2012b; Strauss and Kluepfel, 2015). Two economically important weeds in Florida tomato production are purple and yellow nutsedge. Many Florida vegetable growers use a combination of soil fumigants and herbicides for weed management because currently available fumigants lack the robust broad-spectrum activity that the discontinued methyl bromide possessed, even when used in mixed formulations (Santos et al., 2013). In the previous tomato study (Di Gioia et al., 2016), ASD did not provide complete control of weeds, particularly nutsedge. For site-specific use of ASD in fields with high weed pressure, the integrated application of herbicide with ASD may provide more desirable weed control than ASD alone.

To develop the most cost-effective and commercially viable approach of ASD for tomato production in Florida, more studies are needed to optimize the technique concerning amount of CPL and molasses used and herbicide application. In this study, field experiments were conducted in two locations in Florida to determine the responses of tomato growth, nematode populations, weeds, and fruit yield and quality to ASD treatments with differing levels of CPL and molasses, and in combination with a pre-emergent herbicide application.

2. Materials and methods

2.1. Experimental design and treatment establishment

Two field experiments were conducted, one at the University of Florida (UF) Plant Science Research and Education Unit in Citra, Florida (Citra) from August to December 2015 and repeated at the UF/Institute of Food and Agricultural Sciences (IFAS)/South West Florida Research and Education Center (SWFREC) in Immokalee, FL (Immokalee) from September 2015 to January 2016. The Citra experimental field soil was characterized as Gainesville loamy sand (hyperthermic, coated Typic Quartzipsamments). The field was known for its relatively dense weed population (predominantly mixed yellow and purple nutsedge) and root-knot nematodes (*Meloidogyne* spp.). The soil type at the Immokalee experimental field was classified as Spodosol (Immokalee fine sand; sandy, siliceous, hyperthermic Arenic Haplaquod), and the field was previously characterized as having moderate weed, and root-knot nematode pressure.

Both experiments were arranged in a split plot design with the pre-plant soil treatment as the whole plot factor and pre-emergent herbicide treatment as the subplot factor, while the whole plot soil treatments were arranged in a randomized complete block design with four replications (blocks). The soil treatments included 1) ASD with 6.9 m^3 ha^{-1} of molasses (Agricultural Carbon Source, TerraFeed, LLC, Plant City, FL, USA) and 11 Mg ha^{-1} of CPL (Boyd Brothers, Live Oak, FL) (ASD0.5); 2) ASD with 13.9 m^3 ha^{-1} of molasses and 22 Mg ha^{-1} of CPL (ASD1.0); and 3) chemical soil fumigation control with Pic-Clor 60 (Soil Chemical Corporation, Hollister, CA, USA) containing a mixture of 1,3-dichloropropene (39.0%) and chloropicrin (59.6%) at a rate of 224 kg ha^{-1} (CSF). The pre-emergent herbicide treatment included application of Sandea® (Gowan Company, Yuma, AZ, USA) containing 75% halosulfuron-methyl at a rate of 70 g ha^{-1} (with Sandea), and a control without Sandea application (without Sandea). The basic concept of choosing Sandea for evaluation was based on the label, which states that the compound has potential to cause crop injury when applied with more than 2.54 cm of water. If the application of water associated with ASD does not result in crop injury with an herbicide partner, this would be a likely candidate compound for weed control in the ASD treatment.

In Citra, three raised beds were formed to accommodate the three soil treatments in each of the four blocks. Each bed was 24.4 m long and 0.9 m wide and spaced 1.8 m between centers of two adjacent beds (bed spacing). In Immokalee, each of the four blocks consisted of one 75.6 m × 0.9 m raised bed divided into three 24.4 m long sections with 1.2 m between sections and a bed spacing of 1.8 m. Soil was rototilled and a pre-plant fertilizer mix was surface broadcast on a 60 cm wide band before making the initial