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 m³ ha⁻¹ of molasses and 11 Mg ha⁻¹ of composted poultry litter (CPL) (ASD0.5), ASD with 13.9 m³ 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 (Sanda[®]) 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 hectares 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.

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](#); [Roskopf 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 ([Roskopf 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; Roskopf 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 (Roskopf 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 (Roskopf 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; Roskopf 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 m³ 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 - 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 - 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 $6.9 \text{ m}^3 \text{ ha}^{-1}$ 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 $13.9 \text{ m}^3 \text{ ha}^{-1}$ 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 $75.6 \text{ m} \times 0.9 \text{ m}$ 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 beds at both locations. In both locations, soil was rototilled and a pre-plant fertilizer mix was broadcast on a 60-cm wide band before forming the initial beds. The application rates for N, P_2O_5 , and K_2O were 56, 56, and 56 kg ha^{-1} in Citra, and

34, 112 and 45 kg ha⁻¹ in Immokalee. Molasses in a 1:1 (v:v) water dilution and CPL for the ASD0.5 and ASD1.0 soil treatments were applied on the initial bed top and tilled to a depth of 15 cm with a rotary cultivator before the final raised beds were formed. In both locations, the 24.4 m long whole bed/section was divided in half: one half was randomly assigned as Sandea treatment, and the other half with no Sandea control. Accordingly, each soil and herbicide treatment combination occupied a bed length of 12.2 m. In Citra, Sandea was applied using a regular back pack sprayer with a nozzle type of TeeJet 11008 brass, and the sprayer was calibrated following method of [Sellers et al. \(2016\)](#). In Immokalee, Sandea was applied at 207 kPa using three XR TeeJet 8003VS flat fan nozzles, and each nozzle had a delivery rate of 820 mL per minute. Prior to Sandea treatments, beds with CSF treatments were fumigated by shank injection with Pic-Clor 60. All beds were covered with a 0.03-mm black/white VaporSafe® TIF (Raven Industries Inc., Sioux Falls, SD, USA) polyethylene mulch containing an EVOH barrier layer. Two drip irrigation lines (Jain Irrigation Inc., Haines City, FL, USA; 20-cm emitter spacing, 0.98 L h⁻¹ emitter rate) were installed approximately 2.5 cm below the soil surface under the polyethylene mulch in each bed. At Citra, beds with ASD treatments were irrigated once using 69 kPa water pressure for four hours to saturate air-filled soil pore space in the top ten cm of the bed (5-cm irrigation) to enhance the development of anaerobic conditions ([Butler et al., 2012a](#)). In Immokalee, due to precipitation of approximately 71.9 mm (Fig. 1) immediately after application of soil treatments in the field, the initial 5-cm irrigation was not applied for ASD treatments. All beds in both locations were monitored for three weeks prior to transplanting of the tomato crop.

2.2. Soil redox potential and accumulated anaerobic conditions

To measure soil redox potential during the three-week soil treatment, two oxidation-reduction potential sensors (Pt combination electrodes with Ag/AgCl reference system; Sensorex, Garden Grove, CA, USA) were installed at a soil depth of 15 cm in each plot before initial

irrigation. Soil redox potential values were continually monitored and averaged hourly, and the raw soil redox potential values were corrected to correspond to the redox potential of a standard hydrogen electrode (Fiedler et al., 2007).

Anaerobic conditions were indicated by the soil redox potential below a critical redox potential (CEh), based on the average hourly values. Critical redox potential was calculated using the formula: $CEh = 595 \text{ mV} - (60 \text{ mV} \times \text{soil pH})$ with soil pH determined at the termination of ASD treatments. For values below CEh, the absolute value of the difference between each hourly redox value and CEh was summed to give a measure of accumulated mV under anaerobic soil conditions over the three-week treatment period (Butler et al., 2012b).

2.3. Tomato planting and management

After the three-week soil treatment, tomato transplants at the four-true-leaf stage were planted to the beds in a single row with an in-row spacing of 0.45 m, resulting in 26 plants in each subplot per replication. Determinate tomato cultivar ‘Tribute’ (Sakata, Morgan Hill, CA, USA) was planted on 3 September 2015 in Citra, and ‘Ridge Runner’ (Syngenta, Greensboro, NC, USA) was planted on 13 October 2015 in Immokalee. Tomato cultivars were selected based on standard grower selections in each region in the proceeding fall season. Plants were staked, tied, and pruned to eliminate the first side shoots in both locations. In both locations, plants were drip irrigated twice daily, and irrigation time was initially set as 30 min and then adjusted through the season based on plant development and weather conditions.

In Citra, in addition to pre-plant fertilization, weekly fertigation using a 6N-0P₂O₅-8K₂O plus micro blend (2% Ca, 0.4% Mg, 0.02% Zn, and 0.02% B) (Mayo Fertilizer Inc., Mayo, FL, USA) through the drip system was conducted starting seven days after transplanting (DAT). The total seasonal fertilizer application rates through fertigation for N, P₂O₅, and K₂O were 161, 0, and 215 kg ha⁻¹, respectively. In Immokalee, fertigation was performed twice a week starting 21 DAT, using ammonium nitrate (21N-0P₂O₅-0 K₂O) and potassium nitrate (13.7 N-0 P₂O₅ -46

K₂O). The total seasonal fertilizer application rates through fertigation for N, P₂O₅, and K₂O were 181, 0, and 355 kg ha⁻¹, respectively. Pests and diseases were managed following the UF/IFAS recommendations for Florida tomato production based on weekly scouting (Freeman et al., 2014). Weather data were obtained from the Florida Automated Weather Network (<http://fawn.ifas.ufl.edu/>) stations located in Citra and Immokalee, and 76 mm of rain in three days or 102 mm in seven days were defined as leaching rainfall event (Simonne and Hochmuth, 2011).

2.4. Weed evaluation and nematode analysis

Weed populations (categorized as nutsedge, grass, or broadleaf) emerging through the plastic or in planting holes were evaluated by counting the numbers of weeds present in the whole bed of each subplot at 28, 70, and 102 DAT in Citra, and at 36, 64 and 105 DAT in Immokalee. Weeds emerging through plastic and in planting holes were collected as per subplot and per planting hole, respectively. Soil samples were collected for nematode analysis from each subplot to a depth of 15 cm shortly after the soil treatment application (7 DAT in Citra, and 0 DAT in Immokalee), and during fruit harvest stage (76 DAT in Citra, and 84 DAT in Immokalee). At the fruit harvest stage, three randomly selected plants were also removed from each subplot and the roots were sampled to measure root fresh weight, stem diameter, root galling, root condition, and nematodes in roots. Nematode second stage juveniles (J2) were extracted from both soil and roots using the Baermann funnel technique, counted and identified as root-knot nematode (*Meloidogyne* spp.), stubby-root nematode (*Nanidorus minor*), stunt nematode (*Tylenchorhynchus* spp.), spiral nematode (*Helicotylenchus pseudorobustus*), *Tylenchus* spp., or non-parasitic free-living nematodes using inverted microscopes. Nematode populations in soil and roots were expressed as nematodes per 100 cm³ of soil and per gram of fresh root. Root galling was assessed on a scale of 0-10, with 0 representing no galling and 10 representing severe (100%) galling (Bridge and Page, 1980). A 0-5 rating scale was used to

assess root condition, with 0 representing healthy roots with no apparent signs of damage and 5 representing completely degraded roots (Butler et al., 2012a).

2.5. Assessment of tomato plant growth, yield, and fruit quality

Two plants from each subplot were randomly selected, and cut at the aboveground stem base level at the second harvest stage in Citra (76 DAT) and the 5-cm fruit diameter stage in Immokalee (58 DAT). The plants were separated into leaves, stems, and fruit, and fresh weight (FW) of each part was recorded. Leaves, stems, and fruit were dried at 65 °C until constant weight, and dry weight (DW) was recorded.

Tomato yields were measured from ten representative plants in each subplot. Mature green tomato fruit and fruit at more advanced ripening stages were harvested at 68, 75, 82, 89, and 96 DAT in Citra, and at 84, 91, and 105 DAT in Immokalee. Fruit were graded as extra-large (greater than 70.0 mm, XL), large (63.5 to 70.6 mm, L), medium (57.2 to 64.3 mm, M), and culls (small and defective fruit) according to USDA field tomato grade standards (USDA, 1991). Tomato fruit in each category were weighed. Total marketable yield (TMY) was calculated as the sum of extra-large, large, and medium fruit, and total yield (TY) was the yield sum of TMY and culls. At the second harvest in Citra, and at the first harvest in Immokalee, a sample of 20 representative mature-green tomato fruit was collected from each subplot for selecting tomatoes used for fruit quality assessment. In Citra, tomato fruit were placed in clean trays and stored at 20 °C and 85% relative humidity in a walk-in cooler on the UF campus until they reached table-ripe stage. In Immokalee, fruit were transported to the Gargiulo, Inc. packing house (Immokalee, FL) for ethylene treatment at 20 °C and 85-90% relative humidity until the breaker ripening stage (Sargent et al., 2005; USDA, 1997) and thereafter transported to the Vegetable Laboratory at UF/IFAS/SWFREC for ripening at ambient temperature (23-24 °C) until the table-ripe stage.

Fruit quality assessment was conducted at the table-ripe stage. In Citra, the external fruit color was measured on four tomatoes per treatment per replication using a CR-400 chroma meter

(Konica Minolta Sensing Americas, Inc., NJ, USA), and a^* values indicating redness-greenness were used to record fruit red color. Fruit firmness was measured on the blossom end of the same tomatoes using a TA HD Plus Texture Analyzer (Texture Technologies Corp., NY, USA) equipped with a 5 kg load cell. The maximum force (N) required to compress the fruit by 2 mm was recorded. In Immokalee, fruit firmness was measured on four tomatoes per treatment per replication as fruit deformation using an 11 mm probe and 1 kg force applied to the fruit equator area for 5 s using a portable digital firmness tester (Model C125EB; Mitutoyo, Corp., Aurora, IL, USA). Exterior fruit color was determined on the same four tomatoes using a 1 to 6 tomato ripening scale where 1 = green and 6 = red (USDA, 1991). For total soluble solids (TSS) and pH analyses in both locations, one-fourth of each of the four tomatoes were homogenized using a blender and centrifuged at 5 °C for 20 min, and the resulting supernatant was filtered through eight-layer cheesecloth for further analysis. TSS was assessed by an automatic temperature-compensated digital refractometer Digital Brix/RI-Chek (Reichert Inc., Depew, NY, USA) and expressed as °Brix (TSS %). Approximately 200 g sliced fresh tomato fruit sample for each treatment per replication were weighed and oven dried at 65 °C until constant weight to calculate fruit dry matter content.

2.6. Statistical analysis

Data from the two locations were analyzed separately. Data analysis was performed using the GLIMMIX procedure in SAS Version 9.3 software (SAS Institute, Cary, NC, USA) for split plot design and protected Fisher's least significant difference (LSD) test at $\alpha = 0.05$ was used for multiple comparisons of different measurements among treatments.

3. Results

3.1. Weather conditions

In Citra, the mean daily air temperature was 27 °C during the three-week soil treatment period, and 22 °C during the production season (Fig. 1). During the soil treatment, the daily

minimum and maximum air temperatures ranged from 22 to 25 °C and 31 to 35 °C, respectively. During the tomato production season, the daily minimum and maximum air temperatures ranged from 6 to 24 °C and 17 to 33 °C, respectively (Fig. 1). Between transplanting and final harvest, the mean daily solar irradiance was 145 W m⁻², and the cumulative rainfall was 159 mm, with no leaching rainfall event recorded.

In Immokalee, during the three-week soil treatment period, the mean air temperature was 26 °C with the daily minimum and maximum air temperatures ranging from 19 to 24 °C and 27 to 33 °C, respectively. During the tomato production season, the mean air temperature was 22 °C with the daily minimum and maximum air temperatures ranging from 3 to 23 °C and 16 to 33 °C, respectively (Fig. 1). The mean daily solar irradiance was 133 W m⁻², and cumulative rainfall was 257 mm, with no leaching rainfall event recorded.

3.2. Accumulated anaerobic conditions during soil treatments

ASD treatments resulted in a significant increase of accumulated anaerobic conditions when compared with CSF in both locations (Table 1). Accumulation of anaerobic conditions did not differ significantly between the two ASD treatments in either location. Pre-emergent herbicide application (Sanda) did not impact accumulated anaerobic conditions.

3.3. Populations of nematodes

In Citra, no parasitic nematodes were observed in the soils of any treatment at 7 DAT, while ASD1.0 treatment increased the number of soil non-parasitic nematodes compared to CSF. At the second harvest stage (76 DAT), populations of root-knot, stubby-root, stunt, spiral, and *Tylenchus* nematodes increased across all the treatments in contrast to 7 DAT. Although CSF showed a numerically higher level of root-knot nematodes (average of 2,055 per 100 cm³ soil), the three soil treatments did not differ significantly in nematode numbers. Interestingly, ASD1.0 showed an increase in non-parasitic nematodes compared with CSF and ASD0.5 at 76 DAT. Sandea application did not result in any effect on soil nematode populations during the season

(Table 2). Neither soil treatment nor Sandea application affected stem diameter, root fresh weight, root condition and gall ratings, or number of parasitic and non-parasitic nematodes in plant roots at 76 DAT (Table 3).

In Immokalee, numbers of parasitic and non-parasitic nematodes in the soil were not influenced by soil treatment or herbicide application at 0 and 84 DAT (first harvest stage) (Table 4). At 84 DAT, ASD1.0 resulted in a significantly greater stem diameter and root fresh weight compared with CSF and ASD0.5, while ASD1.0 and ASD0.5 also showed a higher root weight than CSF. The number of root-knot nematodes in plant roots with Sandea application was 0.3 per 100 cm³ soil, although a very low level, it was significantly higher than without Sandea application. Other parasitic nematodes were not detected in plant roots at 84 DAT, while the non-parasitic nematode population was not affected by soil treatments or herbicide application (Table 3).

3.4. Populations of weeds

In Citra, nutsedge was the major weed penetrating the plastic mulch and remaining on the plastic beds throughout the season. The three soil treatments did not differ significantly in numbers of weeds including nutsedge, grass, and broadleaf weeds on plastic throughout the season, while Sandea application resulted in significantly lower numbers of nutsedge coming through the plastic compared with no Sandea application by 81, 82, and 80% at 28, 70 and 102 DAT, respectively (Table 5). No interaction was observed on numbers of weeds emerging through the plastic during the season. Despite the rather low weed pressure in planting holes during the season, Sandea application resulted in a statistically greater level of nutsedge control.

In Immokalee, the number of weeds emerging through the plastic was minimal throughout the season, and neither soil treatment nor Sandea application resulted in significant differences between treatments. Throughout the season, numbers of grass weeds in planting holes were significantly higher in ASD0.5 than CSF, and Sandea application led to a significant

decrease of broadleaf weed numbers in planting holes ([Table 6](#)). The soil treatment by herbicide application interaction effect was observed on numbers of grass weeds in planting holes during the season, with significantly lower numbers of grass weeds as a result of Sandea application under ASD0.5 but not under CSF and ASD1.0 (data not shown).

3.5. Biomass allocation

In Citra, destructive sampling of tomato plants was conducted at the second harvest (76 DAT). ASD treatments led to higher stem fresh weight than CSF. Total plant biomass did not differ between ASD and CSF treatments. With respect to fresh and dry weight biomass partitioning among leaf, stem, and fruit, ASD treatments resulted in a higher stem biomass and a lower fruit biomass in contrast to the CSF treatment. In addition, ASD1.0 showed an increase in fresh weight leaf biomass compared to CSF, and a decrease in fresh weight fruit biomass as opposed to ASD0.5 and CSF. Sandea application did not have any effect on plant biomass accumulation and partitioning ([Table 7](#)).

In Immokalee, plant destructive sampling was conducted at the 5-cm diameter fruit stage (58 DAT). ASD1.0 treatment resulted in significantly higher tomato leaf fresh and dry weight, stem dry weight, and total plant fresh and dry weight compared to ASD0.5 and CSF. The two ASD treatments also resulted in a significant increase in leaf fresh and dry weight, stem dry weight, fruit fresh and dry weight, and total plant fresh and dry weight in contrast to CSF. ASD0.5 significantly increased biomass partitioning to the fruit with a lower fresh biomass allocation to the leaf tissue as compared with CSF. Plant biomass accumulation and partitioning was not affected by Sandea application ([Table 7](#)).

3.6. Fruit yield and quality

Five harvests of tomato fruit were conducted in Citra. ASD0.5 led to a significant increase in the total extra-large fruit yield from the second to final harvests as compared with ASD1.0 and CSF. The total seasonal extra-large fruit yield of ASD0.5 was 95.1% and 112.5%

higher than CSF and ASD1.0, respectively. In addition, ASD0.5 resulted in significantly higher total yields of large fruit from the third to final harvests in comparison with ASD1.0. ASD1.0 resulted in significantly higher total cull fruit yields than CSF and ASD0.5 by 25.3% and 30.6%, respectively. Interestingly, Sandea application significantly reduced the cumulative total marketable yield from the second to fourth harvests. Interaction effects were observed on extra-large fruit yield of the first two harvests and total cull fruit yield (Table 8). Extra-large fruit yield from the first two harvests was significantly higher with no Sandea application than with Sandea application in the ASD0.5 but not with CSF and ASD1.0 treatments, while total cull fruit yield was significantly increased by Sandea application in ASD0.5 but not with CSF and ASD1.0 (data not shown). Yields of medium-size fruit and total marketable fruit as well as total fruit yields throughout the production season were not significantly influenced by soil treatment nor herbicide.

There were three tomato fruit harvests in Immokalee. Both ASD treatments led to significant increases in extra-large fruit and total marketable fruit yield for the first two harvests compared to CSF. Moreover, ASD1.0 significantly increased the total yields of extra-large fruit and marketable fruit as well as the total yield in comparison with CSF and ASD0.5. Total extra-large fruit yields of ASD1.0 treatment were 54.8% and 19.3% higher than CSF and ASD0.5, respectively, while total marketable yield of ASD1.0 were 26.3% and 20.4% higher than CSF and ASD0.5, respectively. Compared with CSF, both ASD treatments lowered the total yields of large fruit and medium size fruit, and showed higher total cull fruit yields. Total and marketable fruit yields were not significantly affected by herbicide application; however, Sandea treatment significantly increased the total cull fruit (Table 9).

Overall, soil treatments and Sandea application did not show significant effects on fruit color, firmness, pH, total soluble solids, and dry matter content, except for a significant soil treatment by herbicide application interaction effect on fruit color in Citra (Table 10). Sandea

application resulted in a significant increase of a^* values in ASD0.5 but not with CSF and ASD1.0 (data not shown).

4. Discussion

Accumulated anaerobic condition during the ASD treatment is one of the key indicators for efficacy of disease and pest control in a production system. It is affected by soil temperature (Katase et al., 2009; Momma et al., 2013; Roskopf et al., 2015), soil texture, initial water volume applied (Butler et al., 2012a), and organic amendment used including source and application rate (Butler et al., 2012b, 2014; McCarty et al., 2014; Shennan et al., 2014). Shennan et al. (2011) reported that an accumulated anaerobic condition of 50,000 mVhr at 25 °C soil temperature was necessary for control of *V. dahliae*, and could be used to gauge the effectiveness of ASD treatments. In this study, the anaerobic soil conditions that accumulated during the ASD treatments in both locations were above 50,000 mVhr, and average air temperatures during ASD treatments were 27 °C in Citra and 26 °C in Immokalee, which provided an essential prerequisite for the success of ASD. Besides the quality and quantity of organic amendment (Husson, 2013), soil redox potential and its buffering capacity were also related to three important parameters in determining organic matter decomposition rate: types of microbial metabolism, bacterial efficiency, and the capacity of the soil system to supply electron acceptors (Reddy et al., 1986). The amounts of CPL and molasses used in ASD1.0 were two-fold higher than that of ASD0.5; however, ASD1.0 did not differ significantly from ASD0.5 in accumulated anaerobic condition in either location, suggesting that the two ASD treatments might have resulted in a similar level of metabolic capacity of microbial communities in the soil (Strauss and Kluepfel, 2015).

The two ASD treatments were as effective in controlling populations of plant-parasitic nematodes and resulting root galling as CSF in both locations, which is consistent with other findings regarding ASD (20 Mg molasses ha⁻¹, wet basis) and CPL (16 Mg dry matter ha⁻¹) effects on root-knot nematodes and root galling in raised-bed bell pepper-eggplant double crop

production systems (Butler et al., 2012a) and other regions (Momma et al., 2013; Shennan et al., 2014). The total numbers of plant-parasitic nematodes at harvest averaged 952 per 100 cm³ soil in Citra and 16 per 100 cm³ soil in Immokalee, indicating higher nematode pressure, particularly for root-knot nematodes in Citra. In Citra, ASD1.0 maintained a significantly higher level of soil non-parasitic nematode populations compared with CSF. These results corroborate the findings of Di Gioia et al. (2016) in which, three weeks after treatment application, there was a substantial increase of non-parasitic nematodes in ASD treated soil as compared to CSF soil. Similarly, Rosskopf et al. (2014) showed a significantly higher level of non-parasitic nematodes in the soil under ASD vs. fumigation treatments in a strawberry cropping system. Due to the broad biocidal activity of soil fumigants (Ibekwe et al., 2001), many studies showed that chemical soil disinfection significantly reduced non-target nematodes when achieving effective control of soil parasitic nematodes in contrast to organic disinfection (Langat et al., 2008; Kapagianni et al., 2010). In addition, compared with CSF, the large amount of organic amendment incorporated into the top soil for ASD could promote soil microbial populations such as bacteria, which in turn may largely increase non-parasitic nematodes such as microbial-feeding nematodes in amended soils (Zelenev et al., 2004).

Nutrient availability can directly influence the balance between vegetative growth and fruit development in tomato plants and fruit yield (Besford and Maw, 1975; Atherton and Rudich, 1986). Plant growth analysis at the harvest stage in Citra showed that both ASD treatments led to a significantly higher biomass allocation to stem, and a significantly lower biomass allocation to fruit compared with CSF. In Immokalee, the dry weight biomass allocation among aboveground plant tissues did not differ significantly between ASD and CSF treatments. However, ASD treatments significantly increased leaf, stem, and fruit dry weights in comparison to CSF. ASD1.0 also resulted in significantly higher leaf and stem dry weights as well as total aboveground dry weight when compared to ASD0.5. The different responses of tomato biomass

accumulation resulting from ASD treatments [in the two locations](#) may be attributed to the differences in tomato genotypes ([Rengel and Damon, 2008](#)), soil properties, weather conditions ([Adams et al., 2001](#)), irrigation, and fertilization ([Djidonou et al., 2013](#)).

The determinate tomato cultivar ‘Tribute’ planted in Citra has high yield potential with good heat set ability, and fruit size is medium to large. Tomato ‘[Ridge Runner](#)’ planted in Immokalee is a determinate cultivar with medium tall plants, and fruit size is large to extra-large ([Freeman et al., 2014](#)). In Citra, the relative yield contributions of extra-large, large, medium, and cull fruit to total seasonal yield averaged at [11, 23, 43 and 23%](#), respectively. In Immokalee, the averages were [65, 15, 6 and 14%](#) of the total seasonal yield, respectively. Tomato yield performance under ASD treatments varied with locations in this study. In Citra, ASD and CSF did not differ significantly in total seasonal marketable fruit yield, while ASD0.5 led to a significant increase of extra-large fruit yield compared with CSF and ASD1.0. Significantly higher numbers of cull fruit were observed under ASD1.0 in contrast to CSF and ASD0.5, primarily owing to small fruit size. Balancing vegetative growth and fruit reproduction is a key factor in determining tomato yield performance ([Huett, 1996](#)), and excessive vegetative growth caused by high soil fertility conditions may delay flowering and fruiting. The delayed fruit maturity of ASD1.0 at the Citra site may have been associated with high soil fertility, suggesting the need for modifying fertilization programs in ASD treatments to optimize fruit yield. By contrast, in Immokalee, ASD1.0 resulted in significantly higher total marketable yields than ASD0.5 and CSF, which might be attributed to an overall improvement of soil nutrient availability and water holding capacity as a result of high amounts of CPL and molasses applied ([Ozores-Hampton et al., 2011](#); [Butler et al., 2014](#)), in addition to the site-specific soil and weather conditions and the tomato genotype ([Rengel and Damon, 2008](#)). In general, ASD treatments had no negative impact on fruit quality including color, firmness, pH, total soluble solids, and dry matter content when compared to soil fumigation.

Sandea application significantly suppressed the growth of nutsedge in the raised beds including the planting holes in Citra, as well as the growth of broadleaf weeds in the planting holes in Immokalee during the production season. However, Sandea application did not improve fruit yields in either location, which might be explained by the relatively low weed pressure in both locations. In Citra, Sandea application significantly reduced marketable yield for the first four harvests, which may indicate plant injury or other influences of halosulfuron, the active ingredient in Sandea (Culpepper et al., 2009), but the interaction with soil treatment was not significant, therefore unlikely to have been caused by the application of water associated with ASD.

5. Conclusions

As an alternative to chemical soil fumigation, anaerobic soil disinfestation using a mixture of CPL and molasses as C source in tomato production showed promising results in controlling plant parasitic nematodes, maintaining and improving marketable fruit yield, without impacting fruit quality, in two locations of Florida. ASD0.5 reached high and equivalent accumulation of anaerobic condition as ASD1.0 in both locations. Application of the pre-emergent herbicide Sandea improved weed control during the tomato production season and did not affect total marketable fruit yield. Given the economic and environmental considerations of ASD treatments with organic amendments derived from animal waste, the application rates of CPL and molasses and alternative sources for optimizing ASD treatments deserve further studies.

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Fig. 1. Daily mean air temperature (MeanT), maximum air temperature (MaxT), minimum air temperature (MinT), rainfall (Rain), and solar radiation during the tomato season in Citra and Immokalee, Florida. Data source: Florida Automated Weather Network (<http://fawn.ifas.ufl.edu/>).

Table 1

The effects of soil treatment and Sandea application on accumulated anaerobic conditions (mVhr) recorded during the three-week soil treatment in Citra and Immokalee.

Treatment	Citra ^x	Immokalee ^x
Soil treatment		
CSF	1,412 b	1,128 b
ASD0.5	73,315 a	87,894 a
ASD1.0	81,989 a	118,515 a
<i>p value</i>	*	**
Sandea		
Without	61,123	77,613
With	43,354	60,745
<i>p value</i>	NS	NS
Interaction		
<i>p value</i>	NS	NS

CSF: Chemical soil fumigation control with Pic-Clor 60; ASD0.5: Anaerobic soil disinfestation with 6.9 m³ ha⁻¹ of molasses and 11 Mg ha⁻¹ of composted poultry litter; ASD1.0: Anaerobic soil disinfestation with 13.9 m³ ha⁻¹ of molasses and 22 Mg ha⁻¹ of composted poultry litter.

** indicates significant difference at $p \leq 0.01$, * indicates significant difference at $p \leq 0.05$, NS indicates not significantly different at $p \leq 0.05$.

^x Means within the same column for soil treatment or Sandea application followed by the same letter were not significantly different by Fisher's LSD test at $p \leq 0.05$.

Table 2

Effects of soil treatment and Sandea application on populations of soil nematodes during the tomato production season (August – December 2015) in Citra.

Treatment	Root-knot	Stubby-root	Stunt	Spiral	<i>Tylenchus</i>	NP ^{x,y}
(nematode count per 100 cm ³ soil)						
Post-treatment (7 DAT)						
Soil treatment						
CSF	0	0	0	0	0	26.9 b
ASD0.5	0	0	0	0	0	788.1 ab
ASD1.0	0	0	0	0	0	3287.2 a
<i>p value</i>						*
Sandea						
Without	0	0	0	0	0	1175.6
With	0	0	0	0	0	1559.3
<i>p value</i>						NS
Interaction						
<i>p value</i>						NS
Harvest stage (76 DAT)						
Soil treatment						
CSF	2055.4	11.3	1.4	21.3	11.3	440.8 b
ASD0.5	663.4	0	0	8.5	12.8	691.7 b
ASD1.0	21.3	15.6	0	21.3	11.3	1075.9 a
<i>p value</i>	NS	NS	NS	NS	NS	**
Sandea						
Without	562.3	3.8	0.9	11.3	18	791
With	1264.4	14.2	0	22.7	5.7	681.4
<i>p value</i>	NS	NS	NS	NS	NS	NS
Interaction						
<i>p value</i>	NS	NS	NS	NS	NS	NS

DAT: Days after transplanting; CSF: Chemical soil fumigation control with Pic-Clor 60; ASD0.5:

Anaerobic soil disinfestation with 6.9 m³ ha⁻¹ of molasses and 11 Mg ha⁻¹ of composted poultry litter;

ASD1.0: Anaerobic soil disinfestation with 13.9 m³ ha⁻¹ of molasses and 22 Mg ha⁻¹ of composted poultry litter.

** indicates significant difference at $p \leq 0.01$, * indicates significant difference at $p \leq 0.05$, NS indicates not significantly different at $p \leq 0.05$.

^x NP: non-parasitic nematodes.

^y Means within the same column for soil treatment or Sandea application at each sampling followed by the same letter were not significantly different by Fisher's LSD test at $p \leq 0.05$.

Table 3

Effects of soil treatment and Sandea application on plant stem diameter, root weight, root condition, root gall rating, and root nematodes populations at the second harvest stage (76 DAT) in Citra, and at the first harvest stage (84 DAT) in Immokalee.

Treatment	Stem diameter (mm) ^w	Root weight (g) ^w	Root condition (0-5 scale) ^x	Galling rating (0-10 scale) ^y	Root-knot ^w	Stubby-root	Stunt	Spiral	<i>Tylenchus</i>	NP ^z
(nematode count per g root)										
Citra (76 DAT)										
Soil treatment										
CSF	17.1	41.4	1.4	1.6	62.2	1.1	0	0.6	0.2	27.1
ASD0.5	18.5	49.6	1.3	1.6	16.6	0.5	0	0.2	0.1	27.3
ASD1.0	18.2	46.8	1.4	0.9	4.9	0.1	0	0.4	0.1	38.3
<i>p value</i>	NS	NS	NS	NS	NS	NS		NS	NS	NS
Sandea										
Without	18.1	46.2	1.3	1.4	33.5	0.6	0	0.5	0.2	32.4
With	17.8	45.8	1.4	1.3	22.3	0.5	0	0.3	0.1	29.3
<i>p value</i>	NS	NS	NS	NS	NS	NS		NS	NS	NS
Interaction										
<i>p value</i>	NS	NS	NS	NS	NS	NS		NS	NS	NS
Immokalee (84 DAT)										
Soil treatment										
CSF	14.4 b	24.3 c	0	0	0	0	0	0	0	5.5
ASD0.5	15.1 b	29.0 b	0.1	0	0.2	0	0	0	0	11.9
ASD1.0	16.6 a	34.2 a	0.1	0	0.2	0	0	0	0	17.6
<i>p value</i>	**	**	NS		NS					NS
Sandea										
Without	15.5	30.5	0.1	0	0.0 b	0	0	0	0	10.8
With	15.3	27.9	0.1	0	0.3 a	0	0	0	0	12.6
<i>p value</i>	NS	NS	NS		**					NS
Interaction										
<i>p value</i>	NS	NS	NS		NS					NS

DAT: Days after transplanting; CSF: Chemical soil fumigation control with Pic-Clor 60; ASD0.5:

Anaerobic soil disinfestation with 6.9 m³ ha⁻¹ of molasses and 11 Mg ha⁻¹ of composted poultry litter;

ASD1.0: Anaerobic soil disinfestation with 13.9 m³ ha⁻¹ of molasses and 22 Mg ha⁻¹ of composted poultry litter.

** indicates significant difference at $p \leq 0.01$, NS indicates not significantly different at $p \leq 0.05$.

^w Means within the same column for soil treatment or Sandea application at each sampling followed by the same letter were not significantly different by Fisher's LSD test at $p \leq 0.05$.

^x Root condition: 0 = clean, white roots, 5 = completely rotted and discolored roots.

^y Nematode gall index: 0 = no galling, 10 = complete galling.

^z NP: non-parasitic nematodes.

Table 4

Effects of soil treatment and Sandea application on populations of soil nematodes during the tomato production season (September 2015 – January 2016) in Immokalee.

Treatments	Root-knot	Stubby-root	Stunt	Spiral	<i>Tylenchus</i>	NP ^x
(nematode count per 100 cm ³ soil)						
Post-treatment (0 DAT)						
Soil treatment						
CSF	1.4	5.7	0	8.5	0	143.2
ASD0.5	0.0	1.4	0	2.8	0	126.2
ASD1.0	2.8	2.8	0	2.8	0	102.1
<i>p value</i>	NS	NS		NS		NS
Sandea						
Without	0.9	4.7	0	0.9	0	127.6
With	1.9	1.9	0	8.5	0	120.0
<i>p value</i>	NS	NS		NS		NS
Interaction						
<i>p value</i>	NS	NS		NS		NS
Harvest stage (84 DAT)						
Soil treatment						
CSF	1.4	2.8	0	0	0	453.6
ASD0.5	18.4	9.9	0	0	0	988.0
ASD1.0	2.8	12.8	0	0	0	1342.4
<i>p value</i>	NS	NS				NS
Sandea						
Without	2.8	10.4	0	0	0	823.1
With	12.3	6.6	0	0	0	1032.9
<i>p value</i>	NS	NS				NS
Interaction						
<i>p value</i>	NS	NS				NS

DAT: Days after transplanting; CSF: Chemical soil fumigation control with Pic-Clor 60; ASD0.5:

Anaerobic soil disinfestation with 6.9 m³ ha⁻¹ of molasses and 11 Mg ha⁻¹ of composted poultry litter;

ASD1.0: Anaerobic soil disinfestation with 13.9 m³ ha⁻¹ of molasses and 22 Mg ha⁻¹ of composted poultry litter.

NS indicates not significantly different at $p \leq 0.05$.

^x NP: non-parasitic nematodes.

Table 5

Effects of soil treatment and Sandea application on weed populations on plastic^x and in planting holes^y of raised beds during the tomato production season (August – December 2015) in Citra.

Treatment	28 DAT			70 DAT			102 DAT		
	Nutsedge ^z	Grass	Broadleaf ^z	Nutsedge ^z	Grass	Broadleaf ^z	Nutsedge ^z	Grass ^z	Broadleaf
On plastic (weed count per subplot bed)									
Soil treatment									
CSF	9.0	0	0	20.3	0	0	27.0	0	0
ASD0.5	38.4	0.3	0	76.9	0.1	0	93.5	0.1	0
ASD1.0	23.5	0	0	47.8	0.1	0	53.6	0	0
<i>p value</i>	NS	NS		NS	NS		NS	NS	
Sandea									
Without	39.8 a	0.2	0	81.8 a	0.1	0	96.9 a	0.1	0
With	7.5 b	0	0	14.8 b	0.1	0	19.2 b	0	0
<i>p value</i>	*	NS		*	NS		*	NS	
Interaction									
<i>p value</i>	NS	NS		NS	NS		NS	NS	
Planting hole (weed count per hole)									
Soil treatment									
CSF	0	0.0	0	0	0	0	0	0 b	0
ASD0.5	0.1	0.1	0	0.1	0.1	0	0.1	0.1 a	0
ASD1.0	0	0.0	0	0.1	0	0	0	0 ab	0
<i>p value</i>	NS	NS		NS	NS		NS	*	
Sandea									
Without	0.1 a	0	0	0.1 a	0	0	0.1 a	0	0
With	0 b	0	0	0 b	0	0	0 b	0	0
<i>p value</i>	*	NS		*	NS		*	NS	
Interaction									
<i>p value</i>	NS	NS		NS	NS		NS	NS	

DAT: Days after transplanting; CSF: Chemical soil fumigation control with Pic-Clor 60; ASD0.5:

Anaerobic soil disinfestation with 6.9 m³ ha⁻¹ of molasses and 11 Mg ha⁻¹ of composted poultry litter;

ASD1.0: Anaerobic soil disinfestation with 13.9 m³ ha⁻¹ of molasses and 22 Mg ha⁻¹ of composted poultry litter.

* indicates significant difference at $p \leq 0.05$, NS indicates not significantly different at $p \leq 0.05$.

^x Weeds emerging through plastic were recorded for the entire bed of each subplot.

^y Weed count per planting hole was reported.

^z Means within the same column for soil treatment or Sandea application followed by the same letter were not significantly different by Fisher's LSD test at $p \leq 0.05$.

Table 6

Effects of soil treatment and Sandea application on weed populations on plastic^x and in planting holes^y of raised beds during the tomato production season (September 2015 – January 2016) in Immokalee.

Treatment	36 DAT			64 DAT			105 DAT		
	Nutsedge	Grass ^z	Broadleaf ^z	Nutsedge	Grass ^z	Broadleaf ^z	Nutsedge	Grass ^z	Broadleaf ^z
On plastic (weed count per subplot bed)									
Soil treatment									
CSF	0	0	0	0	0	0	0	0	0
ASD0.5	0.1	0	0	0.3	0	0	0.3	0	0
ASD1.0	0	0	0	0.1	0	0	0.8	0	0
<i>p value</i>	NS			NS			NS		
Sandea									
Without	0.1	0	0	0.3	0	0	0.7	0	0
With	0	0	0	0	0	0	0.0	0	0
<i>p value</i>	NS			NS			NS		
Interaction									
<i>p value</i>	NS			NS			NS		
Planting hole (weed count per hole)									
Soil treatment									
CSF	0	0 b	0.9	0.1	0 b	0.9	0	0.1 b	1.5
ASD0.5	0	0.4 a	2.0	0	0.3 a	2.7	0	0.4 a	2.7
ASD1.0	0	0.3 ab	1.4	0	0.2 a	1.4	0	0.2 ab	1.7
<i>p value</i>		*	NS	NS	*	NS		*	NS
Sandea									
Without	0	0.3	2.3 a	0	0.3	2.3 a	0	0.3	2.6 a
With	0	0.2	0.5 b	0	0.1	1.1 b	0	0.2	1.3 b
<i>p value</i>		NS	*	NS	NS	**		NS	*
Interaction									
<i>p value</i>		*	NS	NS	*	NS		*	NS

DAT: Days after transplanting; CSF: Chemical soil fumigation control with Pic-Clor 60; ASD0.5:

Anaerobic soil disinfestation with 6.9 m³ ha⁻¹ of molasses and 11 Mg ha⁻¹ of composted poultry litter;

ASD1.0: Anaerobic soil disinfestation with 13.9 m³ ha⁻¹ of molasses and 22 Mg ha⁻¹ of composted poultry litter.

** indicates significant difference at $p \leq 0.01$, * indicates significant difference at $p \leq 0.05$, NS indicates not significantly different at $p \leq 0.05$.

^x Weeds emerging through plastic were recorded for the entire bed of each subplot.

^y Weeds count per planting hole was reported.

^z Means within the same column for soil treatment or Sandea application followed by the same letter were not significantly different by Fisher's LSD test at $p \leq 0.05$.

Table 7

Effects of soil treatment and Sandea application on tomato biomass accumulation and partition at the second harvest stage (76 DAT) in Citra and at fruit 5-cm diameter stage (58 DAT) in Immokalee.

Treatments	Fresh weight ^x				Dry weight ^x				Fresh weight biomass allocation ^x			Dry weight biomass allocation ^x		
	Leaf	Stem	Fruit	Total	Leaf	Stem	Fruit	Total	Leaf	Stem	Fruit	Leaf	Stem	Fruit
	(g plant ⁻¹)								(% of total plant biomass)					
Citra (76 DAT)														
Soil treatment														
CSF	873.7	583.7 b	5681.3	7138.8	121.1	71.7	215.9	408.7	11.9 b	8.2 c	79.9 a	29.4	17.5 b	53.1 a
ASD0.5	1011.3	760.0 a	5160.0	6931.3	137.4	85.8	211.4	434.6	14.7 ab	11.1 b	74.2 b	31.6	19.9 a	48.5 b
ASD1.0	1071.3	839.4 a	4691.2	6601.9	140.8	84.6	198.2	423.5	16.8 a	13.1 a	70.1 c	33.2	20.0 a	46.8 b
<i>p value</i>	NS	*	NS	NS	NS	NS	NS	NS	*	**	**	NS	*	*
Sandea														
Without	984.6	734.2	5342.9	7061.7	133.4	81.1	215.1	429.6	14.1	10.5	75.4	30.9	18.9	50.2
With	986.3	721.3	5012.1	6719.6	132.9	80.3	201.9	415.0	14.9	11.0	74.1	31.9	19.4	48.7
<i>p value</i>	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Interaction														
<i>p value</i>	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Immokalee (58 DAT)														
Soil treatment														
CSF	324.2 c	186.5 b	803.7 b	1314.4 c	36.3 c	23.0 c	22.4 b	81.6 c	26.2 a	15.5	58.3 b	45.0	28.6	26.4
ASD0.5	409.9 b	235.9 b	1498.3 a	2144.1 b	46.7 b	29.5 b	39.0 a	115.2 b	19.4 b	11.2	69.3 a	40.6	25.8	33.6
ASD1.0	590.8 a	367.4 a	1584.3 a	2542.5 a	63.2 a	41.8 a	43.9 a	148.8 a	23.5 ab	14.6	61.9 ab	42.5	28.1	29.4
<i>p value</i>	**	**	**	**	**	**	**	**	*	NS	*	NS	NS	NS
Sandea														
Without	444.8	268.2	1284.8	1997.8	49.3	32.4	34.0	115.7	23.0	13.8	63.2	42.8	28.2	29.0
With	438.5	258.3	1306.1	2002.9	48.1	30.4	36.1	114.7	23.1	13.7	63.2	42.6	26.8	30.6
<i>p value</i>	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Interaction														
<i>p value</i>	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

DAT: Days after transplanting; CSF: Chemical soil fumigation control with Pic-Clor 60; ASD0.5: Anaerobic soil disinfestation with 6.9 m³ ha⁻¹ of

molasses and 11 Mg ha⁻¹ of composted poultry litter; ASD1.0: Anaerobic soil disinfestation with 13.9 m³ ha⁻¹ of molasses and 22 Mg ha⁻¹ of composted poultry litter.

** indicates significant difference at $p \leq 0.01$, * indicates significant difference at $p \leq 0.05$, NS indicates not significantly different at $p \leq 0.05$.

^x Means within the same column for soil treatment or Sandea application followed by the same letter were not significantly different by Fisher's LSD test at $p \leq 0.05$.

Table 8

Effects of soil treatment and Sandea application on tomato yield components^x of accumulative and total fruit harvests in Citra.

Treatment	1 st harvest (Mg ha ⁻¹) ^x				1 st + 2 nd harvest (Mg ha ⁻¹) ^x				1 st + 2 nd + 3 rd harvest (Mg ha ⁻¹) ^x				1 st + 2 nd + 3 rd + 4 th harvest (Mg ha ⁻¹) ^x				Total season harvest (Mg ha ⁻¹) ^x					
	XL	L	M	TMY	XL	L	M	TMY	XL	L	M	TMY	XL	L	M	TMY	XL	L	M	TMY	Culls	TY
Soil treatment																						
CSF	1.9	2.0	1.0	4.9	5.1 b	10.2	7.2	22.5	6.0 b	14.2 ab	15.7	35.9	6.1 b	16.4 ab	26.0	48.5	6.1 b	16.6 ab	31.5	54.2	15.0 b	69.2
ASD0.5	3.8	2.9	1.0	7.7	10.4 a	12.2	6.4	29.0	11.5 a	16.9 a	13.7	42.1	11.8 a	19.3 a	24.1	55.2	11.9 a	19.6 a	29.9	61.4	14.4 b	75.8
ASD1.0	2.0	2.6	1.0	5.6	4.8 b	8.3	5.5	18.6	5.6 b	10.7 b	11.8	28.1	5.6 b	12.5 b	24.9	43.0	5.6 b	12.7 b	30.6	48.9	18.8 a	67.7
<i>p</i> value	NS	NS	NS	NS	*	NS	NS	NS	*	*	NS	NS	*	*	NS	NS	*	*	NS	NS	**	NS
Sandea																						
Without	2.9	3.0 a	1.1	7.0 a	7.0	11.6	6.9	25.5 a	8.0 a	15.6	14.5	38.1 a	8.2	17.7	25.5	51.4 a	8.2	17.9	31.3	57.4	15.8	73.2
With	2.2	1.9 b	0.8	4.9 b	6.5	9.0	5.8	21.3 b	7.3 b	12.3	12.9	32.5 b	7.5	14.5	24.5	46.5 b	7.5	14.7	30.1	52.3	16.3	68.6
<i>p</i> value	NS	*	NS	*	NS	NS	NS	*	NS	NS	NS	*	NS	NS	NS	*	NS	NS	NS	NS	NS	NS
Interaction																						
<i>p</i> value	*	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	**	NS

XL: Extra-large fruit (diameter > 70.0 mm); L: Large fruit (63.5 < diameter < 70.0 mm); M: Medium fruit (57.2 < diameter < 64.3 mm); TMY: Total

marketable yield; TY: Total yield. CSF: Chemical soil fumigation control with Pic-Clor 60; ASD0.5: Anaerobic soil disinfestation with 6.9 m³ ha⁻¹ of molasses and 11 Mg ha⁻¹ of composted poultry litter; ASD1.0: Anaerobic soil disinfestation with 13.9 m³ ha⁻¹ of molasses and 22 Mg ha⁻¹ of composted poultry litter.

** indicates significant difference at $p \leq 0.01$, * indicates significant difference at $p \leq 0.05$, NS indicates not significantly different at $p \leq 0.05$.

^x Means within the same column for soil treatment or Sandea application followed by the same letter were not significantly different by Fisher's LSD test at $p \leq 0.05$.

Table 9

Effects of soil treatment and Sandea application on tomato yield components^x of accumulative and total fruit harvests in Immokalee.

Treatment	1 st harvest (Mg ha ⁻¹) ^x				1 st + 2 nd harvest (Mg ha ⁻¹) ^x				Total season harvest (Mg ha ⁻¹) ^x					
	XL	L	M	TMY	XL	L	M	TMY	XL	L	M	TMY	Culls	TY
Soil treatment														
CSF	8.0 b	0.7	0.1	8.8 b	22.1 b	4.5	0.9	27.5 b	28.6 c	10.7 a	4.5 a	43.8 b	5.2 b	49.0 b
ASD0.5	18.1 a	0.6	0	18.7 a	34.3 a	3.9	0.4	38.6 a	37.1 b	6.8 b	2.1 b	46.0 b	8.4 a	54.4 b
ASD1.0	18.5 a	0.5	0	19.0 a	38.5 a	4.2	0.5	43.2 a	44.3 a	8.0 b	3.0 b	55.3 a	10.0 a	65.3 a
<i>p value</i>	**	NS	NS	**	**	NS	NS	**	**	**	*	*	*	**
Sandea														
Without	15.4	0.7	0.1	16.2	32.0	4.2	0.6	36.8	36.5	8.4	3.2	48.1	7.2 b	55.3
With	14.3	0.5	0.0	14.8	31.3	4.2	0.6	36.1	36.9	8.6	3.1	48.6	8.6 a	57.2
<i>p value</i>	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	**	NS
Interaction														
<i>p value</i>	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

XL: Extra-large fruit (diameter > 70.0 mm); L: Large fruit (63.5 < diameter < 70.0 mm); M: Medium fruit (57.2 < diameter < 64.3 mm); TMY: Total marketable yield; TY: Total yield. CSF: Chemical soil fumigation control with Pic-Clor 60; ASD0.5: Anaerobic soil disinfestation with 6.9 m³ ha⁻¹ of molasses and 11 Mg ha⁻¹ of composted poultry litter; ASD1.0: Anaerobic soil disinfestation with 13.9 m³ ha⁻¹ of molasses and 22 Mg ha⁻¹ of composted poultry litter.

** indicates significant difference at $p \leq 0.01$, * indicates significant difference at $p \leq 0.05$, NS indicates not significantly different at $p \leq 0.05$.

^x Means within the same column for soil treatment or Sandea application followed by the same letter were not significantly different by Fisher's LSD test at $p \leq 0.05$.

Table 10

Effects of soil treatment and Sandea application on tomato fruit quality attributes^x in Citra and Immokalee.

Treatment	Color	Firmness	pH	Total soluble solids (°Brix)	Dry matter content (%)
Citra					
Soil treatment					
CSF	30.66	19.63	4.37	3.6	4.43
ASD0.5	30.95	19.36	4.35	3.7	4.49
ASD1.0	30.77	20.03	4.39	3.8	4.63
<i>p value</i>	NS	NS	NS	NS	NS
Sandea					
Without	30.85	19.43	4.37	3.7	4.47
With	30.74	19.91	4.37	3.8	4.56
<i>p value</i>	NS	NS	NS	NS	NS
Interaction					
<i>p value</i>	*	NS	NS	NS	NS
Immokalee					
Soil treatment					
CSF	5.4	3.10	4.14	3.2	2.62
ASD0.5	5.4	3.04	4.07	3.1	2.50
ASD1.0	5.3	2.84	4.11	3.2	2.51
<i>p value</i>	NS	NS	NS	NS	NS
Sandea					
Without	5.3	3.01	4.09	3.2	2.61
With	5.4	2.97	4.13	3.2	2.47
<i>p value</i>	NS	NS	NS	NS	NS
Interaction					
<i>p value</i>	NS	NS	NS	NS	NS

^x In Citra, fruit color was measured using a portable chroma meter, and a* values indicating redness-greenness were used to indicate fruit red color; fruit firmness was measured using a texture analyzer, and the maximum force (N) required to compress the fruit by 2 mm was recorded. In Immokalee, fruit color was determined using a 1 to 6 tomato ripening scale where 1 = green and 6 = red, fruit firmness was measured as fruit deformation (mm) using a portable digital firmness tester.

CSF: Chemical soil fumigation control with Pic-Clor 60; ASD0.5: Anaerobic soil disinfestation with 6.9 m³ ha⁻¹ of molasses and 11 Mg ha⁻¹ of composted poultry litter; ASD1.0: Anaerobic soil disinfestation with 13.9 m³ ha⁻¹ of molasses and 22 Mg ha⁻¹ of composted poultry litter.

* indicates significant difference at $p \leq 0.05$, NS indicates not significantly different at $p \leq 0.05$.