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Weed Management by In Situ Cover Crops and Anaerobic Soil Disinfestation in Plasticulture

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Abstract: Weeds negatively affect organic vegetable crop growth and profitability. Weed management is the greatest challenge for vegetable organic growers since control options are limited for organic vegetable production. Anaerobic soil disinfestation (ASD) is a novel non-chemical pest management technique that creates anoxic conditions in the topsoil layer for a limited time. ASD is primarily based on the addition of labile carbon sources to topsoil to promote anaerobic conditions driven by microorganisms in moist soil mulched with polyethylene film (polyfim). Field studies were conducted in the summer–fall of 2020 and 2021 to determine the efficacy of warm season cover crops used as carbon sources for ASD and their role in weed management. The study used a factorial experimental design with four cover crop residue treatments (sorghum-sudangrass, sunn hemp, both, or none) in two soil aeration conditions (aerated or non-aerated). Cover crops were grown for 75 days, incorporated into the soil, and sealed with totally impermeable film (TIF) clear mulch, followed by a 4-week ASD process. All incorporated cover crop treatments in non-aerated conditions generated moderate to higher anaerobic conditions (0–150 mV) and provided significantly higher ($p < 0.05$) weed control than all the other treatments tested or controls. Tomato plants transplanted in non-aerated, cover crops incorporated plots were more vigorous and produced higher yields than aerated plots. No phytotoxicity was observed on tomato plants following ASD treatment in any of the treatments tested. This study demonstrated that warm season cover crops could potentially serve as a carbon source for ASD in organic tomato production.

Keywords: organic weed control; organic tomato; non-chemical weed control; plastic mulch; yellow nutsedge control

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1. Introduction

Organic agriculture is the fastest growing sector of the U.S. food industry. More than 100,000 hectares are transitioning to organic production, and organic vegetable production has increased by 27% since 2017; however, 65% of organic farms reported production and management challenges [1]. The inability to control weeds is a major hindrance when transitioning from conventional to organic crop production. Weed management remains one of the most challenging, costly, and time-consuming aspects of crop production for most organic crop growers. Weed density and biomass were four times higher in organic systems than in conventional systems, and under standard weed management practices, organic systems had a 40% lower yield than the conventional system [2]. Increasing global demand for organic food, especially vegetables, necessitates the development of nonchemical methods of weed management.

Vegetable crops are highly susceptible to weed competition and require a weed-free environment during their early stages of growth. High rainfall and humidity in the Southeast of the United States are conducive for severe weed infestations, which can be disastrous for organic production. Weeds affect both vegetable yield and quality and market value [3].

If left unchecked, weeds can reduce yields by 30 % to 95 % in vegetable production systems [4,5] and this result in a loss of value of 8% to 13% for specific vegetables [6]. While plasticulture is effective against many weeds, some weeds, such as nutsedge species, are resistant to plasticulture because the sharp piercing nature of their leaf tips and strong midribs allow them to puncture plastic mulch. Weed control options are limited in organic vegetable production. Hand-weeding is impractical because it requires a substantial amount of labor, organic herbicides that provide weed control are non-selective and may cause crop damage, and other mechanical methods are unavailable; therefore, weed control strategies in the plasticulture system are complex in plasticulture. Other non-chemical techniques, such as solarization, have limitations that hinder commercial adoption, including long treatment processes (>2 months) and high-temperature requirements (36−60 °C) [7]. Biosolarization, a method modified from solarization, has been effective for weed control in organic production, which uses organic amendments and irrigation in addition to tarping with clear mulch [8]. Another promising non-chemical option is anaerobic soil disinfestation (ASD), which slightly differs from biosolarization and is not solely dependent on solar heat supply but on an oxygen-free soil environment.

ASD utilizes carbon-rich soil amendments, increases soil moisture and tarping with a completely impermeable film to rapidly create an anaerobic environment that kills a large proportion of oxygen-dependent plant pathogens and weeds [9,10]. Anaerobic conditions in the soil are typically maintained for 3 to 10 weeks in ASD. Several studies have found that the evolution of volatile organic compounds (VOC), shifts in microbial communities, lowered pH, and anaerobic conditions developed during the ASD period all contribute to pest mortality [9,11,12]. The application of ASD in commercial vegetable production systems has not yet gained widespread acceptance due to a lack of a standardized, cost-effective carbon source capable of providing multi-pest control [9]. Cover crops can potentially serve as a reliable carbon source for the implementation of ASD in South Carolina and other southeastern regions. During the summer fallow period, cover crops help suppress weeds, reduce weed control costs, and limit weed seed set. Later, in situ incorporation of cover crop residue can serve as an alternative to high-cost carbon inputs in ASD technology; this may provide season-long weed control in plasticulture vegetable production. Research is required to find suitable high-residue cover crop options for the ASD carbon source in organic or conventional vegetable cropping systems that provide effective weed control while maintaining crop yield in southeastern environmental conditions.

Warm season cover crops fit well into existing vegetable production systems in the southeastern United States' environmental conditions. The key variables that influence weed management with cover crops are competition, allelopathy, physical effect, and cover crop biomass [13]. Sorghum-sudangrass (*Sorghum bicolor* ×*Sorghum bicolor var. sudanese*) and sunn hemp (*Crotalaria juncea* L.) are rapid-growing, heat- and drought-tolerant summer cover crops commonly adapted to the environmental conditions in the southeastern U.S. Both cover crops require low maintenance and require no attention after planting until incorporation into the soil. In addition, these cover crops are well known for their allelochemical properties, which inhibit weed growth [14,15]. Allelopathic suppression of weeds has been demonstrated to be a species-specific phenomenon [16,17]. Using a mixture of cover crops with allelopathic activity against diverse weed species may offer more effective weed management. Furthermore, if additive or synergistic effects are observed, combining the effects of in situ cover crop residue incorporation, solarization, and ASD could maximize weed control in plasticulture.

Previous efforts to develop cover crop-based ASD technology have produced variable results and had limited adoption [9]. Previous studies have evaluated ASD efficacy using cover crops as a carbon source in greenhouse conditions [9,18,19]. To our knowledge, no field studies using ASD technology have examined the weed control effects of in situ incorporation of sorghum-sudangrass and sunn hemp residues into polyethylene-mulched vegetable production. Two-year field research was conducted in South Carolina to evaluate the efficacy of two cover crops and their combination in polyethylene mulched tomato (*Lycopersicon esculentum* L.) production under organic conditions.

2. Materials and Methods

2.1. Experiment Location and Set Up

Field trials were conducted during the summer–fall of 2020 (Year one) and 2021 (Year two) at the Coastal Research and Education Center in Charleston, SC (32.7932165, −80.0710892, altitude 4.26 m) on adjacent field plots. Annually, this region receives an average precipitation of 130 cm with temperatures typically ranging from 2 °C to 32 °C. The field soil was Charleston loamy fine sand (thermic Aquultic Hapludalfs) with a pH of 6.9 and 0.9% soil organic matter. The cover crops evaluated in this study, sorghum-sudangrass (*Sorghum bicolor* ×*Sorghum bicolor var. sudanese*) and sunn hemp (*Crotalaria juncea* L.) are common summer cover crops adapted to the environment in the southeastern U.S. The experimental design was a randomized complete block design (RCBD) with four replications. Treatments were arranged as 4 × 2 factorial, 4 cover crop treatments (sorghum-sudangrass, sunn hemp, mix (sorghum-sudangrass + sunn hemp), none) and 2 soil aeration conditions (aerated and non-aerated). The experiment consisted of 8 treatments replicated 4 times in a total of 36 plots. Soil aeration conditions (aerated and non-aerated) were established after cover crop termination; before that, cover crops were seeded irrespective of aeration conditions. No cover crop, non-aerated and no cover, aerated treatments served as controls while in the ASD process. No cover crop, non-aerated control may also be termed as solarization. Plots were 6 m by 1.2 m in size in both growing seasons, and a 3 m buffer zone separated each plot. In both seasons, the cover crops were grown under rainfed conditions with no additional irrigation or fertilization.

2.2. Cover Crops Seeding, Growth and Termination

In both years, the field was mechanically disked to break down weeds and improve soil granulation and surface uniformity one day before cover crop seeding. In both years, certified organic seeds of cover crops with more than 80% germination were used. Sorghum-sudangrass seeds (High mowing organic seeds, Wolcott, VT, USA) were drilled at a rate of 78 kg ha^{-1} and sunn hemp seeds (Hancock seed Co., Dade City, FL, USA) were drilled at 67 kg ha^{-1} and for a mixture of both, sorghum-sudangrass and sunn hemp were seeded at a rate of 39.2 kg ha^{-1} and 33.6 kg ha^{-1}, respectively. Seed drilling was accomplished using a 2.2 m wide John Deere drill with 0.17-m row spacing and a ~2.5 cm seeding depth. Cover crops were sown on 28 April and 16 April in 2020 and 2021, respectively.

2.3. Termination of Cover Crops and Initiation of Anaerobic Soil Disinfestation

Cover crops were grown for 75 days in both years. Cover crops were flail mowed (to maximize maceration) and the residue was incorporated into the top 20 cm of the soil profile using a tractor-mounted rototiller on 16 July and 7 July in 2020 and 2021, respectively. Then, to start ASD, a tractor-mounted plastic bedder and drip tape implement were used to re-bed the field plots and seal them with clear plastic mulch and two drip lines. Assigned non-aerated plots were covered and entirely sealed with a totally impermeable film (TIF) clear polyethylene mulch (30 µm). The aerated plots were covered but there were punched holes on both sides of beds at 0.6 m spacings. The study included punched holes to compare the effects of ASD versus non-ASD plots because punching holes in the polyfilm cover allows gas exchange to occur in the cover crop residue treated plot and the atmosphere, thereby preventing the formation of anaerobic conditions. The holes were punched using circular wooden sticks with a 2 cm diameter. Immediately after bed formation, irrigation was applied to facilitate anaerobic soil disinfestation (ASD) in the soil. Same-day certified organic tomato cultivar Galahad F1 (High Mowing Organic Seeds, Wolcott, VT, USA) seeds were seeded into 72-cell trays (Johnny Selected Seeds, Fairfield, ME, USA) and allowed to germinate and grow for 4 weeks.

Oxidation Reduction Potential (ORP) probes/sensors (Pt combination electrodes, Ag/AgCl reference; Sensorex, Garden Grove, CA, USA) were installed in each plot at a 15 cm depth under the mulch. A data logging system (CR-1000X with AM 16/32 multiplexers, Campbell Scientific, Logan, UT, USA) was used to record the outputs from the sensors, which monitored readings every 30 s and averaged them hourly. Later, irrigation was applied based on moisture and redox potential measurements throughout the trial. ASD was performed for 4 weeks, and holes were poked on both sides of all the plastic sealed beds and left undisturbed for one week to regain aerobic conditions. The clear plastic beds were painted with white spray at a 1:7 paint to water dilution to avoid the high solar heat effects on the crop. ASD was terminated after 4 weeks in both years.

2.4. Tomato Transplantation and Management

After ASD termination, tomato plants were transplanted on 22 August and 15 August in 2020 and 2021, respectively. Tomato cultivar Galahad F1 was transplanted and selected based on its tolerance to the environmental conditions in the southeastern U.S. All plots with 24 cm in-row spacing had 10 plants per plot. The transplants were irrigated and fertilized daily through the drip tape connected to the centrally controlled irrigation system based on 2020 Southeastern Vegetable Growers Handbook recommendations [20]. After 2 weeks of crop transplantation, staking was completed by installing 1.82 m wooden stakes and tying the plants with strings adopting the Florida weave stacking method [21]. Plants were checked daily during active growth and tied to the stakes depending on the growth.

2.5. Data Collection

Cover crops plant density, height, and aboveground biomass data were collected. The cover crop plant population was measured by counting the number of seedlings in 0.18×0.18 m^2 quadrats, randomly placed at five locations within each plot 75 days after planting (DAP), and the quadrat was placed in the center to avoid edge effects. For aboveground cover crop biomass, plants within a 0.18×0.18 m^2 quadrats in each plot were clipped, weighed for fresh biomass, and then oven-dried in a general protocol oven (Heratherm™, Thermo Scientific, Waltham, MA, USA) at 70 °C for 72 h and weighed for dry weight. ASD effects on weed control were estimated by counting weeds that emerged on the whole bed (0, 45, and 90 DAT). Weeds were identified as yellow nutsedge and grasses (crabgrass, goosegrass, or barnyardgrass). To check crop response, tomato plant vigor was estimated at two different time intervals of 14 and 28 days after transplantation. Plant vigor was visually accessed with a score of 1 to 10 (where 1 is the least vigorous plot and 10 is the most vigorous plot, which was determined based on plant height and leaf number). The plots were harvested weekly or biweekly according to the crop harvest conditions. Crop yield was graded and sorted following USDA guidelines [22].

2.6. Statistical Analysis

All data were subjected to analysis of variance using a mixed model methodology (JMP ver. 14; SAS Institute Inc., Cary, NC, USA). Cover crop, soil aeration, and their interaction effects were considered fixed, while replication was considered random. Data sets were pooled when there was no treatment by year interaction, otherwise they were presented separately. Cover crop fresh biomass, dry biomass, plant population, redox potential and plant vigor data sets were pooled for both years. All data were examined for normal distribution with the Shapiro–Wilk and Anderson Darling tests. When necessary, either square root, log, or arcsine square root transformation was used to normalize the data. The weed control and plant vigor data were transformed. The transformed data were used for statistical interpretation, but the back-transformed data were presented. The plant vigor evaluations conducted after 14 and 28 DAT were similar; therefore, only the 28 DAT ratings are presented. Means were separated using Fisher's protected least significant difference procedure ($p \leq 0.05$).

3. Results and Discussion

3.1. Weather Conditions at the Field Experimental Site

The daily average air temperatures ranged from 16.7 to 27.1 °C with an average of 21.9 °C in 2020 and from 16.9 to 27 °C with an average of 21.4 °C in 2021 (Figure 1). The experimental site received 29 cm of precipitation in 2020 and 32 cm in 2021 during the cover crop growth period. In 2021, the experimental site received higher precipitation during the ASD period (27 cm) than in 2020 (14 cm); the peaks in the graphs are shown (Figure 1b). Throughout the experiment, total precipitation was 110 cm in 2020 and 118 cm in 2021.

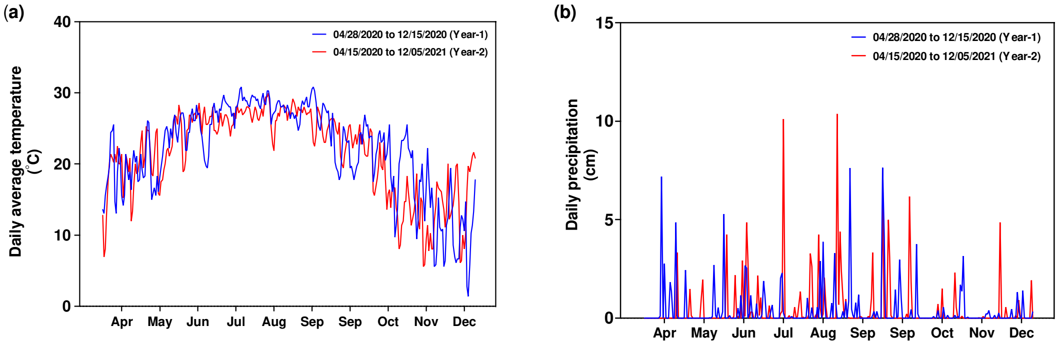

Figure 1. Daily average temperature (**a**) and precipitation (**b**) from cover crop seeding to harvest of the tomato crop. Data were obtained from the Climatology Office of the South Carolina State Department of Natural Resources.

3.2. Cover Crop Biomass and Plant Population

Plant fresh biomass, dry biomass, and plant population for each cover crop treatment were pooled for both years, because there was no cover crop by year interaction. The data indicated that significantly higher fresh (~56472 kg ha^{-1}) and dry biomass (~11357 kg ha^{-1}) production for sorghum-sudangrass was obtained in both years, which was approximately 1.3 times higher compared to sunn hemp and the mixture of both (sorghum-sudangrass + sunn hemp) (Table 1). The plant populations were similar in all cover crop treatments in both years (Table 1). Average plant heights were 65 cm and 70 cm for sorghum-sudangrass and sunn hemp, respectively, for both years of field trials. Both cover crops are used extensively as soil improvement or green manure crops in the tropics because of their ability to produce large amounts of biomass in a short period. Our findings are nearly consistent with previous studies, which showed that sunn hemp produced 13,000 kg ha^{-1} of dry biomass [23] and sorghum-sudangrass produced 8000 kg ha^{-1} [24]. Summer cover crop residues are traditionally integrated into the soil via primary cultivation prior to crop planting in organic production [14,24–26]. Incorporating cover crop residue into the soil before planting vegetable crops provides numerous environmental benefits, improving soil health and weed suppression, which helps organic growers to maintain yield without reliance on chemical fertilizers and herbicides [27].

3.3. Soil Redox Potential

Throughout the 4-week ASD period, hourly soil redox potential readings were recorded and averaged to quantify typical anaerobic conditions. The redox potential value (<200 mV) is selected as the anaerobic threshold for the soil [28,29]. The decrease in redox potential (200 mV) implied oxygen consumption and the creation of anaerobic conditions in the soil. [10,28,29]. Redox potential data were pooled for both year field trials, because there was no treatment by year interaction. All the non-aerated, cover crop amended plots in both years remained anaerobic (Eh < 200 mV) during the ASD period. All aerated treatments had average redox potential readings greater than 200 mV. In both years, redox potential in the sorghum-sudangrass amended, non-aerated plots remained below 200 mV throughout the ASD 4-week period and reduced to an average of 110 mV (Figure 2). Similar to sorghum-sudangrass amended, non-aerated plots, the decreased average redox potential was observed in the sunn hemp (95 mV) and mix (128 mV) amended, non-aerated plots (Figure 2). The average redox potential value was >200 mV in all aerated treatments, and increased to 220 mV in the no cover crop non-aerated plots and 329 mV in the no cover crop amended, aerated plots (Figure 2). In both years, a significant difference in average redox potential was observed between cover crop amended, non-aerated plots compared to no cover crop amended, non-aerated plots (Figure 2). According to the previous research, higher levels of anaerobic conditions are a significant indicator of effective weed control [30]. In this experiment, all cover crop amended, non-aerated plots had higher anaerobic soil conditions compared to all aerated plots. Redox reactions occurring in such anaerobic conditions result in the production of VOC, methane, changes in microbial communities, and a decrease in soil pH, which are all lethal to weed species [9,11,31].

Table 1. Fresh biomass, dry biomass and plant population of cover crops grown for 75 days in 2020 and 2021 field experiments conducted at the organic research farm, Clemson University Coastal Research and Education Center (CREC), Charleston, SC, USA [1].

Cover Crop	Fresh Biomass (kg ha^{-1})	Dry Biomass (kg ha^{-1})	Plant Population (Plants m^{-2})
Sorghum-sudangrass	56,472 ± 4134 a	11,357 ± 657 a	65 ± 3 a
Sunn hemp	39,232 ± 2631 b	8466 ± 840 b	69 ± 4 a
Sorghum-sudangrass + Sunn hemp	42,282 ± 3004 b	8507 ± 645 b	68 ± 6 a
	p Values		
Cover crop	<0.001 *	<0.001 *	0.12
Cover crop * Year	0.673	0.737	0.971

[1] Means within the column followed by the same letter are not significantly different based on least significant difference (LSD) test ($p < 0.05$); (*) in text indicate interaction and on *p* values indicate significant effects.

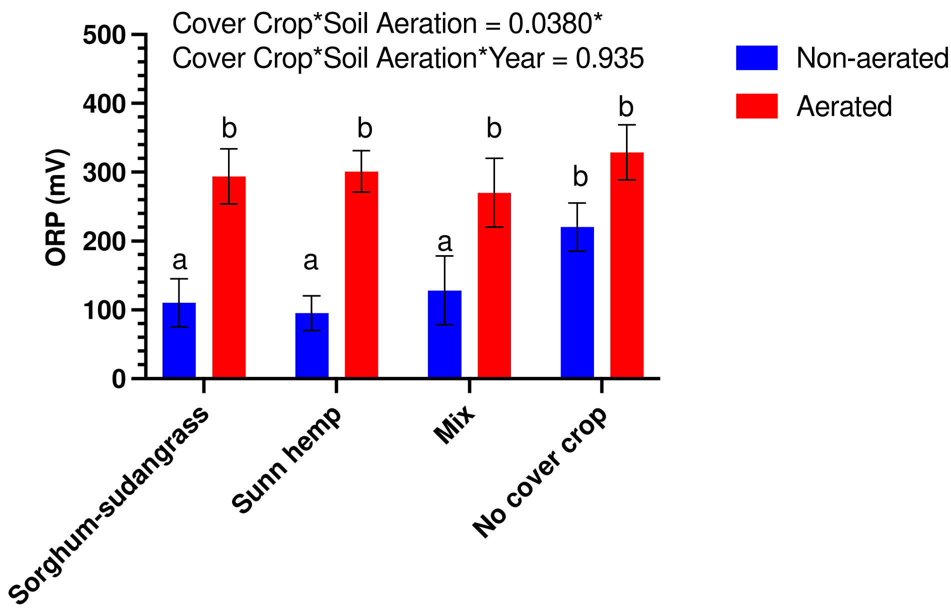

Figure 2. Average soil ORP (oxidation-reduction potential) in 2020 and 2021 field trials over a 4-week ASD period in field plots amended with cover crops [sorghum-sudangrass, sunn hemp, mix (sorghum-sudangrass + sunn hemp)] in two soil conditions (non-aerated or aerated). Data are pooled for both years because there was no cover crop*soil aeration*year interaction; (*) in text indicate interaction and on *p* values indicate significant effects. Data are expressed as mean ± SD (n = 8); bars with the same letter indicate the means are not significantly different based on the least significant difference (LSD) test ($p < 0.05$). The experiment was conducted at the organic research farm, Clemson University Coastal Research and Education Center (CREC), Charleston, SC, USA.

3.4. Weed Control

Both years' field studies were conducted on heavily yellow nutsedge-infested certified organic field plots. Each year, weed control duration was determined by monitoring the in-crop yellow nutsedge and grasses population from the entire bed (6 × 1.2 m) at transplant (0 DAT), mid-season (45 DAT), and at the end of harvest (90 DAT). The number of weeds that emerged on the whole bed by puncturing plastic mulch and tomato planting holes was counted.

Yellow nutsedge population: due to a significant ($p < 0.05$) interaction between treatment and year, the weed count data for both years are presented separately (Tables 2 and 3). Cover crop and soil aeration significantly affected yellow nutsedge shoot counts at all three observation timings in both year field trials ($p < 0.05$), and their interactions were marginally significant in 2020 at all three observation times (Tables 2 and 3). At 90 DAT, all non-aerated cover crop amended plots had a similar reduced number of yellow nutsedge plants counted in both years, which were reduced at least two times compared to the aerated control (no cover crop amended) plot. These findings imply that the ASD with cover crop may provide yellow nutsedge control in plasticulture tomato production. In this experiment, anaerobic soil conditions were significantly higher in cover crop amended, non-aerated plots than in no cover crop amended or all aerated plots. The observed lower yellow nutsedge populations in cover crop amended, non-aerated or ASD plots in this field study could be attributed to phytochemicals produced by anaerobic microbes during the ASD process. In addition, this study used clear plastic mulch, so soil solarization effects combined with ASD and cover crop, could also be responsible for the enhanced control of yellow nutsedge, which is also supported by the enhanced weed control in cover crop amended, non-aerated plots in comparison to no cover crop, non-aerated and no cover, aerated treatments. A few studies report the effects of ASD + solarization on weed control [9] and conclude that future research is warranted in this area. Our results are parallel to previous research associated with ASD and cover crops; a study conducted in Tennessee observed that adding ASD to a mustard/arugula cover crop significantly decreased the number of weeds compared to untreated control [32]; the authors concluded that the increased control was caused by the chemical properties of the amendments, specifically with the release of isothiocyanates from the mustard. In this study, weed control may result from the combined effects of allelochemicals produced by the breakdown of the cover crop, lowered pH, anaerobic conditions, and solarization. Other variables that could have influenced weed control in this experiment include cover crop competition, allelopathy, physical effect and cover crop biomass [14].

Grasses population: overall, the grass weed population was comparatively lower than the yellow nutsedge population in this study. For both years, there was no significant main effect of cover crop or soil aeration by cover crop interaction for grass counts at any observation time (Tables 2 and 3); however, the main effect of soil aeration had a significant impact on grass counts at 0 DAT in 2020 (Table 2), and 0 and 30 DAT in 2021 (Table 3). The lower population of grass weed in this study could be the function of solarization in all treatments considering the fact that we utilized transparent plastic mulch. Furthermore, previous research found some grasses to be more resistant to the effects of ASD, which could be another factor for lower control in this study [9]. Considering the lack of other weed control options, it is challenging to eradicate weeds completely in organic cultivation; however, integrating numerous available strategies may target weed seed banks, which could provide short and long-term weed management benefits dependent on different weed species and agro-environments.

Table 2. Treatment effect on weed control at 0, 45, and 90 days after treatment (DAT) of anaerobic soil disinfestation (ASD) in the 2020 field experiments conducted at the organic research farm, Clemson University Coastal Research and Education Center (CREC), Charleston, SC, USA [1].

Cover Crop	Soil Aeration	Weed Population Per Plot (6 × 1.2 m)					
		Yellow Nutsedge			Grasses		
		0 DAT	45 DAT	90 DAT	0 DAT	45 DAT	90 DAT
Sorghum-sudangrass	Non-Aerated	1 C	5 D	12 E	0 C	3 A	8 A
	Aerated	10 B	12 BC	21 BC	1 BC	4 A	10 A
Sunn hemp	Non-Aerated	1 C	5 D	14 DE	0 C	5 A	11 A
	Aerated	14 B	17 B	24 B	3 AB	6 A	12 A
Sorghum-sudangrass + sunn hemp	Non-Aerated	0 C	6 D	13 E	0 C	5 A	9 A
	Aerated	10 B	11 C	18 CD	1 C	4 A	10 A
No Cover crop	Non-Aerated	1 C	7 CD	16 CDE	0 C	5 A	10 A
	Aerated	21 A	26 A	32 A	3 AB	5 A	11 A
		p Values					
Cover Crop		0.039 *	0.005 *	0.003 *	0.1549	0.485	0.363
Soil Aeration		<0.001 *	<0.001 *	<0.001 *	0.005 *	0.461	0.390
Cover crop * Soil Aeration		0.057	0.0091 *	0.0715	0.1549	0.616	0.959

[1] Means within the column followed by the same letter are not significantly different based on least significant difference (LSD) test ($p < 0.05$); (*) in text indicate interaction and on *p* values indicate significant effects.

Table 3. Treatment effect on weed control at 0, 45, and 90 days after treatment (DAT) of anaerobic soil disinfestation (ASD) in the 2021 field experiments conducted at the organic research farm, Clemson University Coastal Research and Education Center (CREC), Charleston, SC, USA [1].

Cover Crop	Soil Aeration	Weed Population Per Plot (6 × 1.2 m)					
		Yellow Nutsedge			Grasses		
		0 DAT	45 DAT	90 DAT	0 DAT	45 DAT	90 DAT
Sorghum-sudangrass	Non-Aerated	1 C	4 C	9 D	1 BC	2 B	4 A
	Aerated	10 B	11 B	19 BC	2 ABC	4 A	7 A
Sunn hemp	Non-Aerated	2 C	3 C	17 C	1 BC	2 B	5A
	Aerated	11 B	15 B	21 BC	3 A	4 A	6 A
Sorghum-sudangrass + sunn hemp	Non-Aerated	3 C	7 C	10 D	1 BC	5 A	5 A
	Aerated	10 B	14 B	21 BC	3 AB	5 A	6 A
No Cover crop	Non-Aerated	9 B	13 B	22 B	2 AB	4 A	7 A
	Aerated	20 A	23 A	30 A	3 AB	5 A	5 A
		p Values					
Cover Crop		<0.001 *	<0.0001 *	<0.001 *	0.199	0.001 *	0.991
Soil Aeration		<0.001 *	<0.001 *	<0.001 *	0.005 *	0.002 *	0.173
Cover crop * Soil Aeration		0.459	0.458	0.176	0.241	0.465	0.288

[1] Means within the column followed by the same letter are not significantly different based on least significant difference (LSD) test ($p < 0.05$); (*) in text indicate interaction and on *p* values indicate significant effects.

3.5. Tomato Crop Performance and Yield

Following ASD treatment, tomato plants were transplanted to evaluate the potential impact of the cover crops on tomato plant growth and to assess any risk of plant stunting or phytotoxicity. Plant vigor data were pooled for both years of the field trials, because there was no treatment by year interaction. Cover crop and soil aeration significantly ($p < 0.001$) affected plant vigor in both years field trials. At 28 DAT, tomato plants in non-aerated plots amended with cover crops were more vigorous than in controls (aerated or non-aerated, no cover crop treatment) (Figure 3). Plants were similarly vigorous in all non-aerated treatments in both years. The substantial nitrogen or other nutrients' input by sunn hemp and sorghum-sudangrass, as well as weed control, may account for the increased tomato plant vigor in non-aerated cover crop treatments. Previous research reported that phytotoxicity after ASD is a matter of concern for growers when using allelopathic carbon sources [10,28]. However, in this study, no symptoms of plant stunting or phytotoxicity were observed in any of the treatments tested. Based on these findings, the negative effects of ASD and cover crop treatments on soil fertility and plant nutrition are unlikely, which is consistent with previous studies [18].

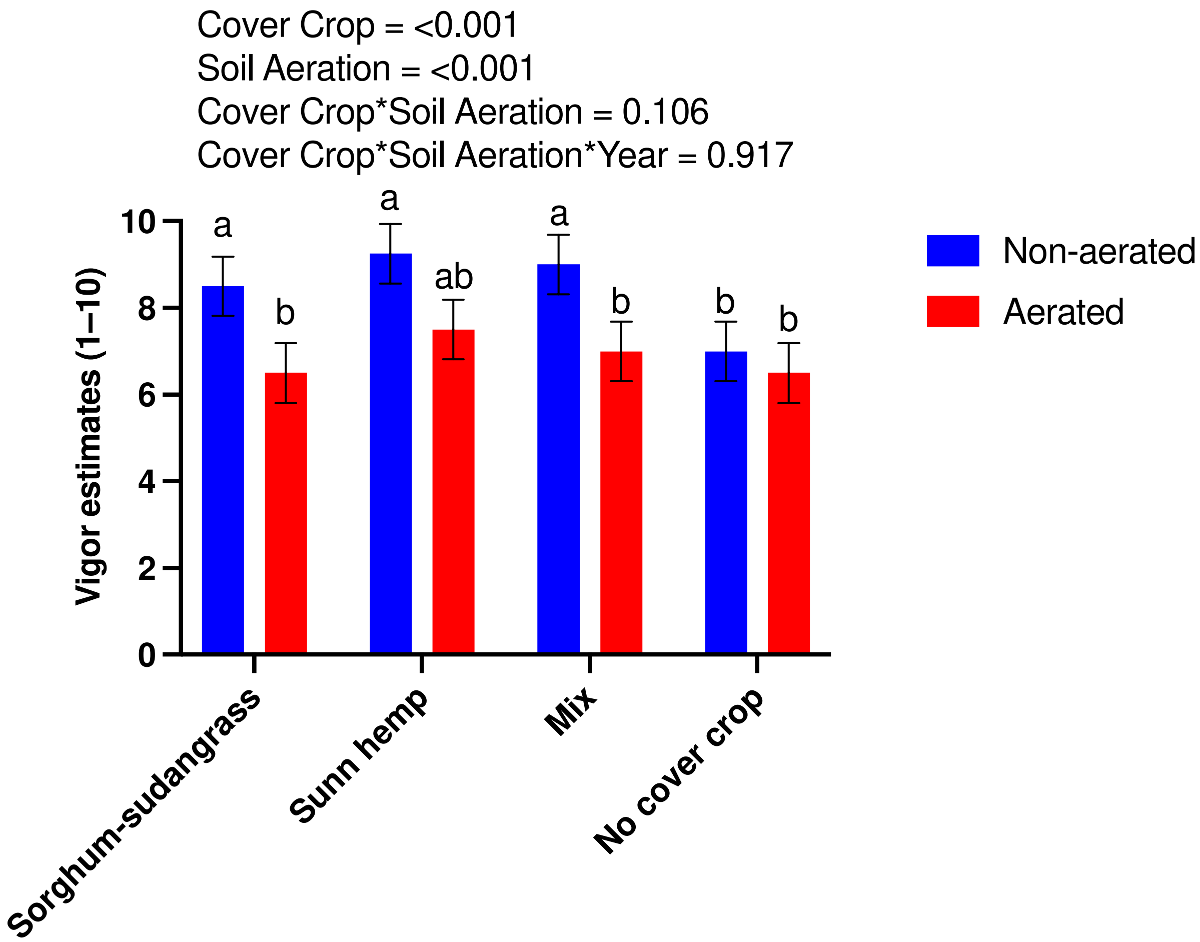

Figure 3. Tomato plant vigor (1–10) estimates taken after 28 DAT (days after transplantation) in 2020 and 2021 field plots amended with cover crops [sorghum-sudangrass, sunn hemp, mix (sorghum-sudangrass + sunn hemp)] in two soil conditions (non-aerated or aerated). Data are pooled for both years because there was no cover crop*soil aeration*year interaction; (*) in text indicate interaction and on p values indicate significant effects. Data are expressed as mean ± SD (n = 8); bars with the same letter indicate the means are not significantly different based on the least significant difference (LSD) test ($p < 0.05$). The experiment was conducted at the organic research farm, Clemson University Coastal Research and Education Center (CREC), Charleston, SC, USA.

The total marketable yield of tomato fruit for the years 2020 and 2021 is shown in Table 4. Due to a significant ($p < 0.05$) year effect, the marketable yield for both years is presented separately. Marketable yield was significantly influenced by factor soil aeration ($p < 0.05$) for both years and by cover crop ($p = 0.05$), in 2021. In 2020, tomato fruit yields were significantly higher in non-aerated plots amended with sunn hemp (18.66 t ha^{-1}), sorghum (15.56 t ha^{-1}), and mix (15.34 t ha^{-1}) as compared to all other treatments (Table 4). Similarly, in 2021, non-aerated plots amended with sunn hemp (12.87 t ha^{-1}) and mix (18.26 t ha^{-1}) had higher yields than all other treatments. Whereas, in the no cover, aerated/control treatment, the yield was (10.87 t ha^{-1}) and (6.47 t ha^{-1}) in the years 2020 and 2021, respectively. In both years, total marketable yield in sunn hemp amended, non-aerated treatment was significantly higher than no cover crop, non-aerated treatment. A similar yield was observed in all aerated treatments in both years (Table 4). Our findings are consistent with those of a previous study; when considering the increased weed control, crop biomass, and nutrient uptake in cover crop amended, non-aerated plots, the yield may have increased [9,18].

Table 4. Tomato yield in the 2020 and 2021 field experiments conducted at the organic research farm, Clemson University Coastal Research and Education Center (CREC), Charleston, SC, USA [1].

Cover Crop	Soil Aeration	Marketable Yield (t ha^{-1})	
		2020	2021
Sorghum-sudangrass	Non-Aerated	15.56 a	11.99 ab
	Aerated	10.27 b	7.29 b
Sunn hemp	Non-Aerated	18.66 a	12.87 a
	Aerated	11.11 b	7.02 b
Sorghum-sudangrass + sunn hemp	Non-Aerated	15.34 a	18.26 a
	Aerated	9.82 b	9.85 b
No Cover crop	Non-Aerated	11.22 b	7.24 b
	Aerated	10.87 b	6.45 b
		p Values	
Year		0.002 *	
Cover Crop		0.430	0.051
Soil Aeration		0.007 *	0.012 *
Cover Crop * Soil Aeration		0.456	0.529

[1] Means within the column followed by the same letter are not significantly different based on the least significant difference (LSD) test ($p < 0.05$); (*) in text indicate interaction and on *p* values indicate significant effects.

4. Conclusions

Our findings highlight the potential benefits of incorporating summer-cover crops in ASD for weed management in organic vegetable production. The results indicate that the cover crops may fit well into the ASD program in South Carolina in terms of biomass production and weed control in plasticulture tomato production. Cover crops used in this study produced moderate anaerobic conditions, with improved weed control and no phytotoxicity observed on tomato plants after ASD. However, additional research is needed to improve consistency and understand the weed control mechanism. More research is required to determine whether ASD kills weed seeds/tubers permanently or induces weed seed dormancy in the soil, as well as the effects of ASD, solarization and cover crops on soil health.

Cover crops and ASD are of interest to organic vegetable growers; however, scale-appropriate technology and equipment are required to promote these practices to the increasing proportion of organic farm operations. Cover crops in the ASD program, along with other carbon sources such as molasses, may aid in the development of chemical pesticide alternatives by attaining high levels of anaerobic conditions. Small-scale organic growers generally lack the equipment and tools to incorporate high-biomass cover crops into plasticulture production, which is one of the significant limitations of integrating cover crops into ASD. To maximize ASD adoption, research in the agricultural mechanization sector is required to streamline the ASD process while utilizing in situ cover crop incorporation. Future research should be focused on more detailed investigations of using cover crop treatments with ASD in fields at various locations with different soil types.

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