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Preplant Application of Allyl Isothiocyanate Controls Weeds and Pathogens in Eastern North Carolina Strawberry (*Fragaria ×ananassa* cv. Camarosa) with and without Addition of Soil-applied Steam

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Abstract. **Allyl isothiocyanate (AITC) is a colorless aliphatic oil that naturally occurs in many plants of the cabbage and mustard family (Brassicaceae). It has antimicrobial activity and is used as pesticide for a variety of applications. However, AITC as a soil disinfectant has exhibited inconsistent weed and pathogen control, mainly because of its higher viscosity and low vapor pressure (5 mmHg at 25 °C). Steam, however, effectively controls soil-borne pathogens if soil temperatures of 65 °C or more are reached for a minimum duration of 30 minutes. We hypothesized that steam applications targeting lower temperatures, when combined with soil-injected AITC, will provide sufficient weed and pathogen control. We further hypothesized that the combination of AITC and steam will lead to higher strawberry yields compared with either of the components on their own. Two strawberry (*Fragaria ×ananassa* cv. Camarosa) trials were conducted during two consecutive seasons (2020–21 and 2021–22). The trials were conducted at the Central Crops Research Station in Clayton, NC, USA, and the Horticulture Research Station in Castle Hayne, NC, USA. Eight treatments and a nontreated control were established in a randomized complete block design (four replicates each). The treatments were Pic-Clor 60, AITC, AITC followed by 60 minutes of steam injection, AITC followed by 30 minutes of steam injection, AITC followed by 10 minutes of steam injection, 60 minutes of steam injection, 30 minutes of steam injection, and 10 minutes of steam injection. Soilborne pathogen control efficacy was assessed using wet *Pythium* sp. plating assays. Weed control was assessed through weed seed/tuber germination assays. Our results showed that combining ATIC with steam did not reduce weed or pathogen levels or improve yield when compared with AITC alone or Pic-Clor 60. Moreover, treatment comprising steam alone did not provide sufficient control. However, AITC alone controlled weeds and pathogens as effectively as Pic-Clor 60 during both years and both locations of the study. These results showed that AITC alone could be a potential alternative soil disinfectant for Eastern North Carolina strawberry production.**

The strawberry fruit production farm gate value was estimated at $3.6 billion in 2022 (CDFA 2023; USDA NASS 2023). Strawberry fruit production in California had a farm gate value of approximately $3 billion in 2022 (CDFA 2023), followed by Florida with $500 million (USDA NASS 2023). However, strawberries are grown commercially in almost every state in the United States. Other states with large strawberry industries are North Carolina ($21.3 million) (USDA NASS 2018) and Oregon ($22 million) (USDA NASS 2017). Nearly all strawberries grown in the United States are grown in annual hill plasticulture systems (Samtani et al. 2019). A typical strawberry season in North Carolina begins in August, when beds are raised and fumigated. North Carolina strawberry growers rely mostly on short-day strawberry cultivars such as Camarosa, Chandler, Camino Real, Fronteras, or Ruby June. Then, plants are planted between late September and mid-October. They often reach dormancy during winter. Harvest begins in early April and ends in May or early June.

Preplant fumigation is a critical component of strawberry plasticulture systems to control weeds, soilborne pathogens, and other pests. Diseases such as *Verticillium* wilt, *Fusarium* wilt, and charcoal rot are caused by soilborne pathogens and negatively impact yield in California and other growing regions in the western United States (Holmes et al. 2020). However, southeastern strawberry production is impacted mostly by black root rot (Louws and Cline 2019), *Phytophthora* crown rot (Marin et al. 2018), or *Pestalotia* leaf spot and fruit rot (Baggio and Peres 2020). Black root rot is caused by multiple pathogens including, but not limited to, *Pythium* sp., *Rhizoctonia* sp., and *Pratylenchus penetrans* (Heald 1920; LaMondia 1999; Louws and Cline 2019; Nemec and Sanders 1970; Raski 1956).

Soil fumigants also have a crucial role in weed control during strawberry production. Despite control provided through plastic mulch, weeds frequently emerge from uncovered soil in the planting hole. Post-transplant herbicide options for strawberry are sparse (Melanson et al. 2023). Preplant soil fumigation is often the only solution a grower has to sufficiently control weeds during strawberry production, although it has become more common to integrate fumigation with preplant applications of herbicide (Melanson et al. 2023). However, even then, not all weed species can be controlled using those tools, and especially nutsedge species (*Cyperus* sp.) can emerge from tubers and pierce through plastic even after integrated weed control approaches, causing substantial economic damage (Santos et al. 2006).

Typical preplant fumigants for strawberry production in the United States are limited to a few chemical options, mostly 1,3-dichloropropene ($C_3H_4Cl_2$), chloropicrin (CCL_3NO_2), dazomet ($C_5H_{10}N_2S_2$), and metam sodium ($C_2H_4NNaS_2$). These chemicals can be effective on their own (Desaeger et al. 2017; Fennimore et al. 2003; Qiao et al. 2015) or when applied in combination with each other (Gerik and Hanson 2011; Kabir et al. 2005; Mao et al. 2019). However, regional regulations (O'Malley 2010; USEPA 2008a, 2008b) and limited availability, especially in the Southeast, restrict the use of many of these chemicals in the United States.

Allyl isothiocyanate (AITC; C_4H_5NS) is naturally found in the cabbage and mustard family (Brassicaceae) (Morra and Kirkegaard 2002) and is available as a synthetically produced soil fumigant in the state of Florida under the trade name Dominus®. It has been reported that AITC effectively controls pathogens and weeds in vitro (Bangarwa and Norsworthy 2015, 2016; Bangarwa et al. 2017; Baysal Gurel et al. 2019; Brown and Morra 1997; Gao et al. 2021; Kim et al. 2020; Ren et al. 2018; Vandicke et al. 2020). However, at 25 °C, AITC is an oily substance with very low vapor pressure; therefore, it has a low tendency to disperse in the soil (Almasri et al. 2019). This has frequently led to ineffective control after soil applications, especially in areas with cooler climates such as the California central coast. An alternative method for organic production, especially in California, is anaerobic soil disinfestation, which incorporates organic material and aims to change microbial conditions before planting (Butler et al. 2012; Muramoto et al. 2014; Rosskopf et al. 2015; Shennan et al. 2017; Shrestha et al. 2016).

Steam has been shown to improve the efficacy of weed and pathogen control if combined with AITC in microplot studies (Kim et al. 2020). Generally, soil disinfestation through heat can occur through soil solarization, steam application, or the combination of both (Daugovish et al. 2016; Samtani et al. 2017). Soil solarization uses the application of clear plastic and solar energy to heat the soil (Baysal-Gurel et al. 2019; Israel et al. 2005; Stapleton and DeVay 1986). Steam has been used for decades to disinfest soil and can effectively control soilborne pests, weeds, and pathogens (Baker 1962). Steam has been used successfully in greenhouse settings through stationary application methods (Fenoglio et al. 2008; van Loenen et al. 2003). Field-based steam application methods can be either stationary or mobile (Dabbene et al. 2003; Fennimore et al. 2014; Peruzzi et al. 2011; Yang et al. 2019). Steam stand-alone treatments, applied with mobile prototype steam applicators, effectively control weeds and soilborne pathogens in strawberry production systems if target temperatures are reached and maintained (Fennimore et al. 2014; Hoffmann et al. 2017, 2020; Kim et al. 2022; Samtani et al. 2017).

There are questions regarding whether AITC in combination with steam will lead to improved pathogen and weed control in strawberry under plasticulture field conditions. In this study, we assessed pathogen and weed control efficacy of AITC combined with steam. Strawberry ('Camarosa') field trials were conducted in two locations in eastern North Carolina over the course of two seasons. We hypothesized that the combination of steam and AITC will increase strawberry yield and control soilborne *Pythium* sp. And weeds more effectively than the components by themselves.

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Materials and Methods

Field trial design. Eight treatments and a nontreated control were established in a randomized complete block design (4 replicates, 20 plants per replicate). A complete list of application conditions is provided in Table 1. Application dates are provided in Table 2. The following application were made: chloropicrin plus 1,3-D (Pic-Clor 60); 60 min of steam injection (Steam60); 30 min of steam injection (Steam30); 10 min of steam injection (Steam10); AITC only (AITC); AITC followed by 60 min steam of steam injection (AITC60); AITC followed by 30 min of steam injection (AITC30); and AITC followed by 10 min of steam injection (AITC10) (Table 1). Research was conducted at the Central Crops Research Station (CCRS) in Clayton, NC, USA, and the Horticultural Crops Research Station (HCRS) in Castle Hayne, NC, USA, over the course of two strawberry growing seasons (2020–21 and 2021–22).

Four 61-m-long beds were used at each location during both years of the trial. Each plot comprised a 3-m × 1.5-m block within each bed, and each replicate was separated by a 3-m-long buffer zone. Buffer zones did not include strawberry plants. In addition, there was a 4.6-m-long buffer zone on both ends of each bed. The field used at CCRS comprises a Norfolk sandy loam, and the soil at HCRS comprises Seagate fine sand. Before bed shaping and fumigation, preplant N–P–K fertilizer (6–6–18) was applied at a rate of 67.2 kg N ha^{-1}.

Fumigation. At the start of each season, beds were raised and overlain with black plastic, and fumigants were applied at a depth of 15.2 cm with two shanks (Table 1). Fumigation dates are listed in Table 2. A total of 158 m^2 of treated area was shank-injected with AITC, and 56 m^2 of treated area was injected with Pic-Clor 60 at both locations during both years of the trial. We purchased AITC from TriEst Inc. under the trade name Dominus® in a pressurized cylinder. Dominus® does not have an organic label. Application rates were lower in 2020–21 because of a malfunction of one of the shanks.

Steam injection. Steam injection occurred after fumigation, bed shaping, and plastic laying, and before strawberry planting (Table 2). In AITC treatments that were combined with steam (AITC60, AITC30, AITC10) (Table 1), steam was applied 21 d after AITC application. Steam was generated using the Sioux® Steam-Flo 25L Boiler (Beresford, SD, USA). A 51-m hose with 18-cm spikes spaced 30 cm apart was attached to the boiler. The spikes poked through the plastic along the area where strawberries would eventually be planted. The spikes were 18 cm long and had small holes at their tips, where steam was released (Fig. 1).

Cryopak iMini temperature loggers (Part #MX2ES8L; Cryopak, Edison, NJ, USA) recorded soil temperature in the center of the bed. Each logger recorded temperature at the 18-cm depth. The maximum and average temperatures recorded during steaming were collected (Tables 3 and 4).

'Camarosa' plug plants were planted (planting dates in Table 2) with 0.3-m spacing between plants in a double row, which is common for strawberry plasitculture in North Carolina.

Harvest. Harvest occurred twice weekly at CCRS from 19 Apr to 27 May 2021, and from 2 Apr to 26 May 2022. Harvest occurred twice weekly at HCRS from 12 Apr to 27 May 2021, and from 31 Mar to 19 May 2022. Once harvest began, 4–0–8 liquid fertilizer was applied at a rate of 5.6 to 7.8 kg N ha^{-1} per week. Marketable and nonmarketable yields were assessed twice per week. Fruit was determined as nonmarketable because of deformities, disease symptoms, water damage, and weight less than 5 g per berry.

Pythium sampling and media preparation. Ten soil samples (diameter, 2.5 cm; depth, 18 cm) were collected from the strawberry planting holes in each replicate. Soil samples were collected on the day of strawberry planting. Soil samples were placed in labeled paper bags, mixed, and left to air-dry for 1 week. Once the soil dried, samples were transferred to sterile plastic containers and kept in the refrigerator at 7 °C. Samples were analyzed for *Pythium* propagules per gram of soil (ppg) using a wet plating assay according to Klose et al. (2007). Corn meal agar (17 $g \cdot L^{-1}$; Sigma-Aldrich, St. Louis, MO, USA) was autoclaved at 121 °C for 20 min on a liquid/slow cycle using a Sterilmatic® autoclave (Market Forge Industries, Inc., Everett, MA, USA). After autoclaving, Tween 20 (1 $mL \cdot L^{-1}$; Thermo Fisher Scientific, Waltham, MA, USA) was added to the solution. Once the agar cooled to ~50 °C, antifungal and antibiotic solutions were added at the following rates: 25 $mg \cdot L^{-1}$ rose bengal (Fisher Chemical, Fair Lawn, NJ, USA); 250 $mg \cdot L^{-1}$ ampicillin (Fisher Bioreagents, Fair Lawn, NJ, USA); 22 $mg \cdot L^{-1}$ benomyl (Sigma-Aldrich, St. Louis, MO, USA); 10 $mg \cdot L^{-1}$ rifampicin (Fisher Chemical); and 50 $uL \cdot L^{-1}$ of 2.5% aqueous pimaricin stock solution (Sigma-Aldrich). Afterward, the agar was poured into 100-mm × 15-mm petri dishes (FisherBrand, Fair Lawn, NJ, USA). The prepared petri dishes were left in the dark at room temperature for 72 h before plating soil solutions.

A 0.5-g soil sample was measured and placed into a 50-mL plastic screw cap tube. Under a sterile flow hood, 20 mL of sterile deionized water was added to each 50 mL tube and placed on a vortex. Then, 0.5 mL of solution was plated across five petri dishes. This process was replicated three times for each soil sample. The solution was spread across the agar using a sterile cell spreader (VWR International, Radnor, PA, USA). Plates were left in the dark at room temperature. *Pythium* ppg were counted 48 h and 72 h after plating. Then, the average number of ppg per gram of soil was calculated.

Weed germination assay. Ten soil samples (diameter, 2.5 cm; depth, 18 cm) were collected

Table 1. Chemical fumigant application rates, steam pressure, and water usage for at the Central Crops Research Station (CCRS) and the Horticultural Crops Research Station (HCRS) during the 2020–21 and 2021–22 growing seasons. Technical issues with the shank application system in 2020 led to differences in application rates between years.

		AITC rate ($kg \cdot ha^{-1}$ [ii])		Pic-Clor 60 rate ($kg \cdot ha^{-1}$)		Steam pressure (psi[iii])		Water ($L \cdot ha^{-1}$ [iv])		Propane ($L \cdot ha^{-1}$)	
Location	Treatment[i]	2020–21	2021–22	2020–21	2021–22	2020–21	2021–22	2020–21	2021–22	2020–21	2021–22
CCRS	NTC										
	Pic-Clor 60			157	325						
	Steam60					5–7	5–7	244,448	148,541	1,822	1,314
	Steam30					5–7	5–7	122,224	74,271	911	657
	Steam10					5–7	5–7	40,074	24,756	304	219
	AITC	168	210								
	AITC60	168	210			5–7	5–7	244,448	148,541	1,822	1,314
	AITC30	168	210			5–7	5–7	122,224	74,271	911	657
	AITC10	168	210			5–7	5–7	40,074	24,756	304	219
HCRS	NTC										
	Pic-Clor 60			244	523						
	Steam60					5–7	5–7	141,591	213,164	1,822	1,636
	Steam30					5–7	5–7	70,796	106,582	911	818
	Steam10					5–7	5–7	23,599	35,172	303	273
	AITC	130.1	343.0								
	AIT60	130.1	343.0			5–7	5–7	141,591	213,164	1,822	1,636
	AITC30	130.1	343.0			5–7	5–7	70,796	106,582	911	818
	AITC10	130.1	343.0			5–7	5–7	23,599	35,172	304	273

[i] Treatments: NTC = nontreated control; Pic-Clor 60 = chloropicrin + 1,3-dichloropropene; Steam60 = 60-min steam application; Steam30 = 30-min steam application; Steam10 = 10-min steam application; AITC = allyl isothiocyanate; AITC60 = allyl isothiocyanate + 60-min steam application; AITC30 = allyl isothiocyanate + 30-min steam application; AITC10 = allyl isothiocyanate + 10-min steam application.

[ii] $kg \cdot ha^{-1}$ = kilogram per hectare.

[iii] psi = pounds per square inch.

[iv] $L \cdot ha^{-1}$ = liters per hectare.

from each plot. Samples were taken from the planting holes on the same day as planting, just before strawberries were planted. The 10 soil cores were mixed together and used for the weed seed survival analysis. In the greenhouse, 12.7-cm × 12.7-cm × 5.0-cm plastic containers were lined with a paper towel, labeled, and filled with 10 g of soil medium. Then, 400 g of the soil sample was measured and placed on top of the soil medium to reach container capacity. Samples were hand-watered every other day. Soil medium was tested for potential weed contamination by using additional containers to assess potential germination. Weed seedlings were identified and counted as they germinated. Soil samples were mixed 30 d after establishment. Seedlings that were too difficult to identify at an early stage were collected and grown in large pots to ensure accurate identification.

Statistical analysis. Data were analyzed using a two-way analysis of variance ($\alpha \leq 0.05$; factors: year and treatment) using RStudio (RStudio Desktop version 2022.07.02, Boston, MA, USA) with R 3.3.3. When appropriate, treatment effects were analyzed separately for each year. Fisher's least significant difference post hoc test was performed when necessary ($\alpha \leq 0.05$). *Pythium*, weed germination, and yield were data-tested for normal distribution (Shapiro-Wilk, $\alpha \leq 0.05$) beforehand. *Pythium* data were $\log_{10}$-transformed before further analysis.

Results

Pythium control. During both years and at both locations, shank-injected AITC alone showed similar *Pythium* control compared with shank-injected Pic-Clor 60 (Table 5). Additional steam injections (AITC60, AITC30, and AITC10) did not enhance *Pythium* control compared with AITC alone or Pic-Clor 60 (Table 5). Steam-alone treatments did not effectively control *Pythium* sp. (Table 6).

Weed seed germination. During both years and at both locations, AITC alone and AITC60 controlled weeds in a manner similar to Pic-Clor 60 (Table 7). All weed species identified in the weed germination assay were effectively controlled by AITC alone (Table 7). Steam alone did not effectively control weeds; AITC in combination with steam (AITC60, AITC30, AITC10) did not enhance weed control above AITC alone (Table 8). However, AITC combined with steam (AITC60, AITC30, AITC10) improved weed control compared with steam-alone treatments. At CCRS, *Cyperus* sp. germination was significantly lower in AITC10 compared with Steam10. At HCRS, AITC10 had significantly less *Spergula* sp., *Cyperus* sp., and *Portulaca* sp. germination compared with Steam10. AITC30 had significantly less *Cyperus* sp. and *Trifolium* sp. germination compared with Steam30. Additionally, AITC60 had significantly less *Spergula* sp., *Cyperus* sp., *Trifolium* sp., and *Portulaca* sp. germination, compared with Steam60 (Supplemental Table 1).

Strawberry yield. During both years and at both locations, marketable yields of the AITC alone treatment were similar to those of the Pic-Clor 60 treatment (Tables 9 and 10). Steam-alone treatments did not increase yields compared to the NTC (Table 10). The highest yield of 1001 g/plant was achieved with AITC followed by 60 min of steam injection (AITC60) during the 2021–22 season at HCRS.

The AITC treatments combined with steam had higher yields compared with steam alone (Supplemental Table 2). During the 2020–21 season at CCRS, AITC10 and AITC30 had significantly higher yields compared with Steam10 and Steam30, respectively. During the 2021–22 season at HCRS, AITC10, AITC30, and AITC60 had higher yields compared with Steam10, Steam30, and Steam60, respectively ($\alpha \leq 0.05$) (Supplemental Table 2).

Table 2. Fumigation application, steam application, and strawberry planting dates at the Central Crops Research Station (CCRS) and Horticultural Crops Research Station (HCRS) during the 2020–21 and 2021–22 growing seasons.

Location	Season	Fumigation application date	Steam application date	Strawberry planting date
CCRS	2020–21	10 Sep 2020	30 Sep and 1 Oct 2020	26 Oct 2020
CCRS	2021–22	15 Sep 2021	5–6 Oct 2021	27 Oct 2021
HCRS	2020–21	22 Sep 2020	8–9 Oct 2020	23 Oct 2020
HCRS	2021–22	29 Sep 2021	12, 14, and 19 Oct 2021	22 Oct 2021

Fig. 1. Steam generator and field application. (**A**) Sioux® Steam-Flo 25L Boiler (Beresford, SD, USA). (**B**) Spikes injecting steam into a raised bed. (**C**) Spike hose applied on both sides of the raised plastic bed.

Discussion

Pathogen and weed control. Our results showed that shank-injected AITC can sufficiently control *Pythium* sp. and weeds (*Spergula arvensis*, *Cyperus esculentus*, *Trifolium repens*, *Portulaca amilis*, and *Lolium multiflorum*) to some extent in eastern North Carolina strawberry production. This could be consistently observed through both field sites and in both application years, regardless of fumigant application rates. Furthermore,

Table 3. Average soil temperature at a depth of 18 cm in the center of the raised bed during steam application at the Central Crops Research Station (CCRS) and Horticultural Crops Research Station (HCRS) during the 2020–21 and 2021–22 strawberry seasons.

		Avg soil temp					
		10-min steam[i]		30-min steam[ii]		60-min steam[iii]	
Location	Season	AITC10	Steam10	AITC30	Steam30	AITC60	Steam60
CCRS	2020–21	22.84	28.16	22.34	35.89	46.92	48.86
CCRS	2021–22	26.94	34.72	33.33	28.62	30.76	25.87
HCRS	2020–21	25.76	28.16	41.23	44.38	27.96	29.61
HCRS	2021–22	21.33	20.99	44.38	34.55	23.09	25.09

[i] AITC10 = AITC + 10-min steam; Steam10 = 10-min steam.
[ii] AITC30 = AITC + 30-min steam; Steam30 = 30-min steam.
[iii] AITC60 = AITC + 60-min steam; Steam60 = 60-min steam.

Table 4. Maximum soil temperature at a depth of 18 cm during steam application at the Central Crops Research Station (CCRS) and Horticultural Crops Research Station (HCRS) during the 2020–21 and 2021–22 strawberry seasons.

		Maximum soil temp					
		10-min steam[i]		30-min steam[ii]		60-min steam[iii]	
Location	Season	AITC10	Steam10	AITC30	Steam30	AITC60	Steam60
CCRS	2020–21	22.93	35.25	25.10	50.21	69.92	54.43
CCRS	2021–22	27.90	35.1	36.57	29.85	33.90	28.50
HCRS	2020–21	26.04	28.42	48.57	52.61	32.53	35.17
HCRS	2021–22	21.40	21.15	32.33	26.75	23.8	26.5

[i] AITC10 = AITC + 10-min steam; Steam10 = 10-min steam.
[ii] AITC30 = AITC + 30-min steam; Steam30 = 30-min steam.
[iii] AITC60 = AITC + 60-min steam; Steam60 = 60-min steam.

Table 5. Average *Pythium* ppg·g^{-1} soil for the allyl-isothiocyanate (AITC) treatments. Data are from the Central Crops Research Station (CCRS) and Horticultural Crops Research Station (HCRS) during the 2020–21 and 2021–22 strawberry seasons. Means (n = 4 reps) followed by different lowercase letters within the same row and within the same steam time indicate significant differences (α ≤ 0.05) according to Fisher's least significant difference test.

		Pythium ppg·g^{-1} Soil[i]					
Location	Season	NTC[ii]	CD	AITC	AITC10	AITC30	AITC60
CCRS	2020–21	2406 ± 1486 a	60 ± 29 ab	1213 ± 1092 ab	60 ± 29 ab	820 ± 698 ab	20 ± 6 b
CCRS	2021–22	6067 ± 3592 a	427 ± 409 ab	527 ± 526 ab	0 ± 0 b	61 ± 60 ab	67 ± 58 ab
HCRS	2020–21	4740 ± 1268	853 ± 448	1460 ± 577	1413 ± 589	907 ± 297	6560 ± 2598
HCRS	2021–22	8493 ± 2955 a	2907 ± 2326 abc	87 ± 27 bc	3787 ± 3778 ab	7 ± 6 c	2060 ± 931 abc

[i] Data were analyzed using $\log_{10}$ transformation, but data are displayed as the original value (ppg·g^{-1} soil).
[ii] NTC = nontreated control; Pic-Clor 60 = chloropicrin +1,3-dichloropropene; AITC = allyl isothiocyanate; AITC10 = AITC + 10-min steam; AITC30 = AITC + 30-min steam; AITC60 = AITC + 60-min steam.

AITC is a potent pesticide, able to decrease *Fusarium graminearum* and *Fusarium poae* (Vandicke et al. 2020). A field study found that AITC controlled *Fusarium* sp., *Pythium* sp., and *Phytophthora* sp., as well as, or in some years better than, chloropicrin (Ren et al. 2018). Additionally AITC (183–275 kg·ha^{-1}) controlled *Fusarium oxysporum* as well as Pic-Clor 60 (337 kg·ha^{-1}), and AITC significantly decreased *F. oxysporum* colony-forming units when it was applied at a rate of 367 kg·ha^{-1} (Yu et al. 2019).

Shank-injected AITC has shown successful control of large crabgrass (*Digitaria sanguinalis*) and yellow nutsedge when applied as a preplant fumigant (Devkota et al. 2013; Ren et al. 2018). Moreover, AITC has effectively controlled purple nutsedge (*Cyperus rotundus*) in tomato production (Yu et al. 2019) and palmer amaranth (*Amaranthus palmeri*) in bell pepper production (Bangarwa et al. 2011).

Although AITC controlled *Pythium* in the present study, the pathogen control efficacy of AITC may vary based on environmental conditions. For examples, AITC alone did not sufficiently control *V. dahliae* beyond its injection point compared with chemical fumigants in California strawberry production (Kim et al. 2020). Another study in California found poor control of *P. ultimum* in cut flower production (Hoffmann et al. 2020). However, it is likely that low soil temperatures and heavier soils negatively affected the belowground distribution at those trial locations. Kim et al. 2020 conducted their trial in June in Salinas, CA, USA, where average temperatures are 7 to 8 °C lower than those in September in Clayton and Castle Hayne, NC, USA (US Climate Data 2023), when these studies were conducted. Presumably, higher soil temperatures during and after AITC application could lead to conditions that will favor dispersion of AITC through the soil profile (National Library of Medicine 2023). Additionally, it is very likely that dispersion of AITC through the soil profile is further facilitated by sandy soils with high porosity, as used in this study (USDA, Natural Resources and Conservation Service 2019).

Soil-applied steam can control weeds if soil temperatures of 70 °C are reached for 15 min. Steam injections control most pathogens if soil temperatures are 65 °C for 30 min (Baker and Roistacher 1957; Fennimore et al. 2014; Hoffmann et al. 2017). The highest temperature reached in this study

Table 6. Average *Pythium* ppg·g^{-1} soil for the steam-alone treatments. Data are from the Central Crops Research Station (CCRS) and Horticultural Crops Research Station (HCRS) during the 2020–21 and 2021–22 strawberry seasons. Means (n = 4 repetitions) followed by different lowercase letters within the same row and within the same steam time indicate significant differences (α ≤ 0.05) according to Fisher's least significant difference test.

		Pythium ppg·g^{-1} soil[i]			
Location	Season	NTC[ii]	Steam10	Steam30	Steam60
CCRS	2020–21	2406 ± 1486	2893 ± 1347	2714 ± 1768	3540 ± 2433
CCRS	2021–22	6067 ± 3592	2740 ± 1243	2700 ± 1028	1740 ± 955
HCRS	2020–21	4740 ± 1268	2067 ± 1366	4044 ± 2824	3607 ± 3070
HCRS	2021–22	8493 ± 2955	5947 ± 1476	3333 ± 1845	5580 ± 2464

[i] Data were analyzed using $\log_{10}$ transformation, but data are displayed as the original value (ppg·g^{-1} soil).
[ii] NTC = nontreated control; Steam10 = 10-min steam; Steam30 = 30-min steam; Steam60 = 60-min steam.

Table 7. Average weed seeds germinated during a 2-month assay for the 2021–22 season at the Central Crops Research Station (CCRS) and the Horticultural Crops Research Station (HCRS). Data shown are from allyl-isothiocyanate (AITC) treatments. Means (n = 4 repetitions) followed by different lowercase letters within the same row and within the same steam time indicate significant differences (α ≤ 0.05) according to Fisher's least significant difference test.

		Weed seed germination					
Location	Weed species[i]	NTC[ii]	Pic-Clor 60	AITC	AITC10	AITC30	AITC60
CCRS	*Spergula arvensis*	2.75 a	0 b	0.75 ab	0 b	0 b	0 b
	Cyperus esculentus	7.25 a	0.5 b	0.5 b	0 b	0 b	0 b
	Trifolium repens	2.5	1.75	1.75	2.5	1.5	1.75
	Portulaca amilis	0.75	0	0	0	0	0
	Lolium multiflorum	0	0.25	0	0	0	0
	Combined	13.25 a	2.5 b	3 b	2.5 b	1.5 b	1.75 b
HCRS	*Spergula arvensis*	21.75 a	0 b	0.5 b	0 b	0 b	0 b
	Cyperus esculentus	37.25 a	7 b	17 ab	0.5 b	3.25 b	0.25 b
	Trifolium repens	14.5 a	0 b	1 b	0 b	0 b	0 b
	Portulaca amilis	4.25 a	0.5 b	0.5 b	0 b	0 b	0 b
	Lolium multiflorum	3.5 a	0 b	0.75 b	0 b	0 b	0 b
	Combined	81.25 a	7.5 b	19.75 b	0.5 b	3.25 b	0.25 b

[i] *Spergula arvensis* = corn spurry; *Cyperus esculentus* = yellow nutsedge; *Trifolium repens* = white clover; *Portulaca amilis* = Paraguayan purslane; *Lolium multiflorum* = annual ryegrass.
[ii] NTC = nontreated control; Pic-Clor 60 = chloropicrin +1,3-dichloropropene; AITC = allyl isothiocyanate; AITC10 = AITC + 10-min steam; AITC30 = AITC + 30-min steam; AITC60 = AITC + 60-min steam.

Table 8. Average weed seeds germinated from during a 2-month assay for the 2021–22 season at the Central Crops Research Station (CCRS) and the Horticultural Crops Research Station (HCRS). Data shown are from steam-alone treatments. Means (n = 4 repetitions) followed by different lowercase letters within the same row and within the same steam time indicate significant differences (α ≤ 0.05) according to Fisher's least significant difference test.

Location	Weed species[i]	Weed seed germination			
		NTC[ii]	Steam10	Steam30	Steam60
CCRS	*Spergula arvensis*	2.75	1.75	0.75	0.25
	Cyperus esculentus	7.25	4.25	13.5	3
	Trifolium repens	2.5	3	2.25	2.75
	Portulaca amilis	0.75	0	0.5	0
	Lolium multiflorum	0	0	0	0
	Combined	13.25	9.00	17.00	6.00
HCRS	*Spergula arvensis*	21.75	8.00	16.75	20.00
	Cyperus esculentus	37.25 c	98.50 a	92.00 ab	57.25 bc
	Trifolium repens	14.50	12.75	20.75	20.25
	Portulaca amilis	4.25	5.25	4.50	7.75
	Lolium multiflorum	3.50	2.50	4.00	4.50
	Combined	81.25 b	127.00 a	138.00 a	109.75 a

[i] *Spergula arvensis* = corn spurry; Cyp*erus esculentus* = yellow nutsedge; *Trifolium repens* = white clover; *Portulaca amilis* = Paraguayan purslane; *Lolium multiflorum* = annual ryegrass.

[ii] NTC = nontreated control; Steam10 = 10-min steam; Steam30 = 30-min steam; Steam60 = 60-min steam.

Table 9. Average cumulative yield per plant for AITC treatments. Data shown are from the Central Crops Research Station (CCRS) and Horticultural Crops Research Station (HCRS) during the 2020–21 and 2021–22 seasons. Means (n = 4) and *SE* followed by different lowercase letters within the same row and within the same steam time indicate significant differences (α ≤ 0.05) according to Fisher's least significant difference test.

Location	Season	Cumulative yield (g/plant)					
		NTC[i]	CD	AITC	AITC10	AITC30	AITC60
CCRS	2020–21	226 b	274 ab	377 a	350 a	353 a	360 a
CCRS	2021–22	513	586	532	536	542	588
HCRS	2020–21	599	723	636	641	603	617
HCRS	2021–22	649 c	788 b	894 bc	956 c	960 c	1001 c

[i] NTC = nontreated control; Pic-Clor 60 = chloropicrin +1,3-dichloropropene; AITC = allyl isothiocyanate; AITC10 = AITC + 10-min steam; AITC30 = AITC + 30-min steam; AITC60 = AITC + 60-min steam.

was 48.86 °C over the course 60 min. Our aim was to improve AITC dispersion in a strawberry bed; our aim was not to control weeds and pathogens with a steam-alone treatments. Typical commercial and prototype mobile soil steam applicator prototypes raise soil temperatures to 70 to 80 °C (Fennimore et al. 2014; Guerra et al. 2022; Hoffmann et al. 2017; Kim et al. 2020). Heat transfer through steam application varies depending on soil type (Miller et al. 2014), soil depth (Gelsomino et al. 2010), distance from steam application (Hoffmann et al. 2017), steam application speed (Huh et al. 2020), and application method (Miller et al. 2014).

Application methods that shank-apply steam and simultaneously mix the soil have been proven to be more effective for heat transfer compared with stationary steam application (Fennimore et al. 2014; Kim et al. 2021; Miller et al. 2014). Field-based steam application has also controlled *Pythium* sp. and weeds in lettuce production (Guerra et al. 2022). In addition, mobile steam systems in combination with exothermic substances have effectively controlled pathogens (Luvisi et al. 2006; Triolo et al. 2004). Stand-alone steam applications have also effectively controlled pathogens (Fennimore et al. 2014; Hoffmann et al. 2017). However, these steam applications are predicted to be costly and time-intensive (Fennimore and Goodhue 2016; Michuda et al. 2021).

Efforts to combine AITC with steam applications have been successfully evaluated by Kim et al. (2020). However, our study did not support those results for raised plasitculture beds using lower-than-effective steam temperatures. Pathogen control and weed control as well as yield did not improve when steam was combined with AITC compared with AITC alone under the field conditions of this study. Naturally occurring conditions in the Southeast (sandy soils, high temperatures when fumigating) could have contributed to better distribution of AITC in a raised bed compared with cooler climates such as those in most strawberry production regions in California. However, these assumptions will require additional research and could not be answered during this study.

Table 10. Average cumulative yield per plant for steam-alone treatments. Data shown are from the Central Crops Research Station (CCRS) and Horticultural Crops Research Station (HCRS) during the 2020–21 and 2021–22 seasons. Means (n = 4) and *SE* followed by different lowercase letters within the same row and within the same steam time indicate significant differences (α ≤ 0.05) according to Fisher's least significant difference test.

Location	Season	Cumulative yield (g/plant)			
		NTC[i]	Steam10	Steam30	Steam60
CCRS	2020–21	226	202	226	286
CCRS	2021–22	513	486	478	558
HCRS	2020–21	599	539	685	632
HCRS	2021–22	649	668	753	771

[i] NTC = nontreated control; Steam10 = 10-min steam; Steam30 = 30-min steam; Steam60 = 60-min steam.

Conclusion

Our study showed that shank-applied AITC was as effective as shank-applied Pic-Clor 60 to control soilborne pathogens and weeds and produced similar marketable yields. The addition of spike-injected steam did not enhance the efficacy of AITC. These results showed the potential for shank-applied AITC as a preplant fumigant alternative in eastern North Carolina strawberry production. However, further research needs to be conducted to develop tangible application guidelines for North Carolina and the Southeast.

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Supplemental Table 1. Average weed seeds germinated during a 2-month assay for the 2021–22 season at the Central Crops Research Station (CCRS) and the Horticultural Crops Research Station (HCRS). Means (n = 4) followed by different lowercase letters within the same row and within the same steam time indicate significant differences (α ≤ 0.05) according to Fisher's least significant difference test.

		Weed seed germination								
		No steam[i]			10-min steam[ii]		30-min steam[iii]		60-min steam[iv]	
Location	Weed species	NTC	Pic-Clor	AITC	AITC	Steam	AITC	Steam	AITC	Steam
CCRS	*Spergula* sp.	2.8 ± 1.9	0.0 ± 0.0	0.8 ± 0.8	0.0 ± 0.0	1.8 ± 1.1	0.0 ± 0.0	0.75 ± 0.5	0 ± 0	0.3 ± 0.3
	Cyperus sp.	7.3 ± 4.2	0.5 ± 0.5	0.5 ± 0.5	0.0 ± 0.0 b	4.3 ± 1.3 a	0.0 ± 0.0	13.50 ± 10.6	0 ± 0	3.0 ± 1.7
	Trifolium sp.	2.5 ± 0.7	1.8 ± 0.3	1.8 ± 0.8	2.5 ± 1.9	3.0 ± 1.7	1.5 ± 0.9	2.3 ± 1.0	1.8 ± 0.6	2.8 ± 1.1
	Portulaca sp.	0.8 ± 0.8	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.5 ± 0.3	0.0 ± 0.0	0.0 ± 0.0
	Lolium sp.	0.0 ± 0.0	0.3 ± 0.3	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
HCRS	*Spergula* sp.	21.8 ± 5.4 a	0.0 ± 0.0 b	0.5 ± 0.5 b	0.0 ± 0.0 b	8.0 ± 2.9 a	0.0 ± 0.0	16.8 ± 9.6	0.0 ± 0.0 b	20.0 ± 6.9 a
	Cyperus sp.	37.3 ± 11.7	7.0 ± 4.5	17.0 ± 12.3	0.5 ± 0.5 b	98.5 ± 6.6 a	3.3 ± 1.4 b	92 ± 19.5 a	0.3 ± 0.3 b	57.3 ± 11.8 a
	Trifolium sp.	14.5 ± 6.5 a	0.0 ± 0.0 b	1.0 ± 0.8 b	0.0 ± 0.0	12.8 ± 5.8	0.0 ± 0.0 b	20.8 ± 8.2 a	0.0 ± 0.0 b	20.3 ± 7.9 a
	Portulaca sp.	4.25 ± 1.7 a	0.5 ± 0.5 b	0.5 ± 0.3 b	0.0 ± 0.0 b	5.3 ± 1.9 a	0.0 ± 0.0	4.5 ± 2.6	0.0 ± 0.0 b	7.8 ± 2.2 a
	Lolium sp.	3.5 ± 1.3 a	0.0 ± 0.0 b	0.8 ± 0.5 b	0.0 ± 0.0	2.5 ± 1.4	0.0 ± 0.0	4.0 ± 1.9	0.0 ± 0.0	4.5 ± 2.6

[i] NTC = nontreated control; Pic-Clor = chloropicrin +1,3-dichloropropene; AITC = allyl isothiocyanate.

[ii] AITC10 = AITC + 10-min steam; Steam10 = 10-min steam.

[iii] AITC30 = AITC + 30-min steam; Steam30 = 30-min steam.

Supplemental Table 2. Average cumulative yield per plant at Central Crops Research Station (CCRS) and Horticultural Crops Research Station (HCRS) during the 2020–21 and 2021–22 seasons. Means (n = 4) and *SE* followed by different lowercase letters within the same row and within the same steam time indicate significant differences (α ≤ 0.05) according to Fisher's least significant difference test.

		Cumulative yield (g/plant)								
		No steam[i]			10-min steam[ii]		30-min steam[iii]		60-min steam[iv]	
Location	Season	NTC	Pic-Clor	AITC	AITC10	Steam10	AITC30	Steam30	AITC60	Steam60
CCRS	2020–21	226 ± 64	274 ± 31	377 ± 28	350 ± 34 a	202 ± 28 b	353 ± 34 a	226 ± 24 b	360 ± 32	286 ± 50
CCRS	2021–22	513 ± 66	586 ± 31	532 ± 43	536 ± 28	486 ± 24	542 ± 16	478 ± 52	588 ± 41	558 ± 62
HCRS	2020–21	599 ± 100	723 ± 37	636 ± 34	641 ± 117	539 ± 35	603 ± 30	685 ± 69	617 ± 53	632 ± 54
HCRS	2021–22	649 ± 22 b	788 ± 66 ab	894 ± 25 a	956 ± 47 a	668 ± 94 b	960 ± 42 a	753 ± 70 b	1001 ± 41 a	771 ± 51 b

[i] NTC = nontreated control; Pic-Clor = chloropicrin +1,3-dichloropropene; AITC = allyl isothiocyanate.

[ii] AITC10 = AITC + 10-min steam; Steam10 = 10-min steam.

[iii] AITC30 = AITC + 30-min steam; Steam30 = 30-min steam.

[iv] AITC60 = AITC + 60-min steam; Steam60 = 60-min steam.