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Leveraging Tomato Crop Residues and Pomace for Biosolarization to Deplete Weed Seedbank in Tomato Fields

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Cite This: *ACS Agric. Sci. Technol.* 2022, 2, 22−31 Read Online

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ABSTRACT: The biomass from crops left in the field after harvest, or without harvest, could be manipulated to create a hostile environment for soil pests. To assess this potential, a field study was conducted to determine the differential impact of soil organic amendments using plant residue from tomato at two developmental stages (vegetative and fruit-set) and tomato pomace with or without solarization (with and without film) on weed seeds. Under a solarized soil condition, the organic amendments generally enhanced weed seed mortality, suggesting the importance of combining both organic amendment and solarization, i.e., biosolarization, as a viable technique for weed control. The greatest weed seed mortality (47%) was observed with biosolarization that utilized the tomato crop terminated at the fruit-set stage as the organic amendment, on redroot pigweed (*Amaranthus retroflexus*). Seed mortality caused by biosolarization was mainly attributed to increase soil temperature (6 °C increase), with an additive role of the soil pH and volatile fatty acid accumulation. This study suggested that tomato plant residue can be leveraged to promote weed seedbank depletion, thereby reducing weed pressure in subsequent crops.

KEYWORDS: *soil organic-amended, integrated weed management, volatile fatty acids, anaerobic soil disinfestation, weed seed mortality*

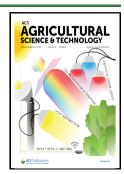
■ INTRODUCTION

Weed management in a conventional tomato production system relies on the use of herbicides for both preplant and in-season weed control.[1,2] The use of herbicides has contributed greatly to crop protection. However, the intensive use of herbicides has led to the development of herbicide-resistant weed species.[3,4] In addition, the negative environmental and health consequences of some herbicides and conventional fumigants such as methyl bromide are leading to restrictive regulation and necessitating the need for alternative weed management methods.[5] Integrated weed management practices have been recognized widely as the most viable approach to minimizing herbicide resistance and reducing the amount of pesticide residues in the environment. Thus, there is a need to identify additional strategies that can serve as components of an integrated weed management approach.

Biosolarization is a pest control practice that combines the use of elevated temperature along with biological activity developed by amending the soil with an organic matter to create a hostile environment for weed seeds and other pests in the soil.[6,7] The soil temperature is elevated due to the greenhouse effect promoted by covering moist soil with transparent plastic film, a process referred to as solarization. Exposure to high temperature has been effective in killing weed seeds. For instance, the exposure of weed seed (barnyardgrass [*Echinochloa crus-galli*], London rocket [*Sisymbrium irio*], annual sowthistle [*Sonchus oleraceus*], black nightshade [*Solanum nigrum*], tumble pigweed [*Amaranthus albus*], and common purslane [*Portulaca oleracea*]) to temperatures above 50 °C for several hours caused 100% mortality, whereas a temperature of 42 °C was lethal to only some species regardless of the duration.[8] Some of the major limitations to the adoption of solarization, such as the need for a long duration of treatment, high reliance on climatic conditions, and efficacy at only relatively shallow soil depths, can be addressed by biosolarization. In this process, supplemental organic amendments and water, in addition to transparent plastic film, promote soil microbial activity in the amended soil for lethal effect on weed seeds and other soilborne pests and diseases. The microbial activity along with the displacement of the air in the soil with water promotes an anaerobic soil environment.[9] Under these conditions, the fresh organic matter can be fermented, releasing, among other metabolites, volatile fatty acids (VFAs). These VFAs include acetic, formic, and butyric acids, which have been reported to promote weed control.[6] Although biosolarization typically includes elevated temperatures due to the transparent plastic film, the anaerobic conditions can have pest management impacts even without the solarization effect. This is termed anaerobic soil disinfestation (ASD) when opaque films are used and can be effective even when applied in colder climates or seasons where solarization potential is limited.[10]

Depletion of weed seeds in the soil (seedbank) by biosolarization is expected to reduce weed population during subsequent crop growing seasons, and this may reduce the need for the application of herbicides for preplant and in-crop weed control in agricultural production systems. Studies have shown that weeds varied greatly in their response to biosolarization

Received: April 2, 2021
Revised: January 8, 2022
Accepted: January 11, 2022
Published: January 21, 2022



https://doi.org/10.1021/acsagscitech.1c00074
ACS Agric. Sci. Technol. 2022, 2, 22−31

and/or solarization.[6,11] Using a plow down crop of sudex (*Sorghum bicolor* x *S. sudanense* = "sudex", cv. "Green Grazer V") as organic amendment, Stapleton et al.[12] reported 35−100% weed biomass reduction in six weed species. Achmon et al.[6] reported that biosolarization for a week with mature green waste compost and tomato pomace in the soil caused more than 95% mortality of black mustard (*Brassica nigra*) and black nightshade seeds. Meanwhile, results from a similar experiment using thermophilic and mesophilic digestates indicated that the microbial activity from these amendments was not sufficient to induce drastic seed mortality in black mustard and black nightshade.[13] Only the solarized soil amended with thermophilic digestate enhanced the mortality of black mustard seeds compared to the soil with the same amendment but without solar heating. Soil solarization in Mediterranean-like regions such as the Central Valley in California controlled field bindweed (*Convolvulus arvensis*), redroot pigweed (*Amaranthus retroflexus*), barnyardgrass, annual sowthistle, and winter annual grasses, while sweet clover (*Melilotus officinalis*) was poorly controlled.[11]

Biosolarization is usually conducted by adding large inputs of organic materials such as green waste, tomato pomace, almond hulls, or grape pomace to the system.[14−16] In crops where a significant amount of biomass is left in the field after harvest or in instances where a crop is destroyed without harvest, this crop biomass has the potential to serve a similar purpose. Although crop destruction is not common, it does occur occasionally due to missed market windows, poor crop quality due to environmental conditions, or the presence of quarantine pests such as branched broomrape.[17] Under these scenarios, crop residues already being destroyed could be utilized as the organic amendment for soil biosolarization. Tomato pomace has been reported to be effective in promoting anaerobic microbial activity and VFA production with soil solarization, with a moderate duration of phytotoxicity in the soil after use.[6] In this study, our aim was to determine if there is a differential impact of soil organic amendment on weed seeds using industrial processing tomato pomace, as well as plant residue from tomato, simulating a scenario where a quarantine pest is detected at the vegetative stage and/or reproductive stage of a processing tomato crop. This effect was tested with or without solarization/biosolarization to assess the importance of elevating soil temperature using transparent films. To the best of our knowledge, the use of tomato plant residue as soil organic amendment to promote weed control has not been reported. To understand the changes in soil conditions that were associated with weed seed control, we documented the soil pH, moisture, temperature, and volatile fatty acids (VFAs) in the soil during the treatments.

■ MATERIALS AND METHODS

Field Setup. A field study was conducted in a tomato field at the Plant Sciences Field Facility of the University of California, Davis (38.5391° N, −121.7833° W) during the summer of 2019. The experimental soil of the area is described as a loamy alluvial land (mixed Xerofluvents) with a clay, silt, and sand content of 12.5, 19.6, and 67.9%, respectively (soilweb: https://casoilresource.lawr.ucdavis.edu/gmap/). The field was fallow for a year before establishing the biosolarization study. The experiment was laid out as a randomized complete block design in a split plot arrangement with six replicates. The experiment consisted of two factors: organic amendments (main plot treatments) and solarization (subplot treatments). The organic amendment treatments were residues from a tomato crop terminated at a late vegetative stage (53 days after transplanting; 2.93 ton/ha dry weight), a tomato crop terminated at a fruit-set stage (71 days after transplanting; 11.06 ton/ha dry weight), tomato pomace (11.06 ton/ha dry weight), and no organic amendment (Table 1). The solarization treatments included solarized (with film) and not solarized (without film) conditions. The treatment combinations of organic amendment and solarization (eight treatments in total) were evaluated to determine their impact on weed seed mortality. The treatment combinations (Table 1) included nonamended soil without film (CNT, as control) or covered with film (CBS), incorporated plant residue from tomato terminated at the vegetative stage without film (YNT) or covered with film (YBS), incorporated plant residue from tomato terminated at the fruit-set stage without film (ONT) or covered with film (OBS), and incorporated tomato pomace without film (TPNT) or covered with film (TPBS).

Table 1. Treatment Combinations in a Study That Evaluated the Impact of Organic Amendment Source and the Use of Film on Weed Seed Mortality[a]

treatment combination[b]	organic amendment[c]	solarization
CNT	none	none
CBS	none	TIF[d]
YNT	53 days old plant at the vegetative stage	none
YBS	53 days old plant at the vegetative stage	TIF
ONT	71 days old plant at the fruit-set stage	none
OBS	71 days old plant at the fruit-set stage	TIF
TPNT	tomato pomace	none
TPBS	tomato pomace	TIF

[a]Experiment was conducted at the field research facility, Plant Sciences Department, University of California, Davis, in 2019. [b]Nonamended soil without film (CNT) or covered with film (CBS), amended soil with plant residue from tomato terminated at the vegetative stage without film (YNT) or covered with film (YBS), amended soil with plant residue from tomato terminated at the fruit-set stage without film (ONT) or covered with film (OBS), and amended soil with tomato pomace without film (TPNT) or covered with film (TPBS). [c]Application rates of plant at the vegetative stage, fruit-set stage, and pomace were 2.93, 11.06, and 11.06 ton/ha dry weight, respectively. [d]Totally impermeable film.

The experimental layout consisted of six beds, which were 67 m long and 1.5 m wide established in May 2019. Each bed had two subsurface drip lines, spaced 15.2 cm apart from the center of the bed, and buried 20 cm deep. Logistical limitations related to field setup and farm operations required plants with the same targeted development stage to be grown in the same row. Thus, whole rows were set with either late vegetative tomato plants, fruit stage tomato plants, or bare soil (for nonamended and tomato pomace-amended plots). Beds with tomato plants (four out of the six beds) were planted with a single row of tomato transplants in the center of the bed between the two drip lines. Tomato seedlings, 10 cm tall, were transplanted on May 30 and June 17, 2021. Tomato plants from both planting dates were terminated on August 9 when they were at the fruit-set stage or still in a vegetative stage, respectively. The other two rows were left with bare soil to integrate the nonamended and the tomato pomace-amended plots.

Representative tomato biomass in the two tomato planting dates was determined on the 5th of August (4 days before the termination of plants to obtain residue). All of the above-ground plant biomass was collected in two 1 m by 1.5 m sections in each of the planted beds totaling four replicates per planting stage. The measured dry weight biomass was 2.93 and 11.06 ton/ha for the plants that were terminated at vegetative and fruit-set stages, respectively. Vegetative stage, fruit-setting stage, and pomace amendments were equivalent to 0.2, 0.7, and 0.7% application rates (dry weight basis; w/w), respectively, relative to soil weight estimated for a depth of 10 cm (equivalent to the incorporation depth of the plant debris during rototilling).

https://doi.org/10.1021/acsagscitech.1c00074
ACS Agric. Sci. Technol. 2022, 2, 22−31

Tomato plants were terminated by mowing with a tractor-mounted flail mower in all plots. Fresh tomato pomace (64% moisture content) consisted of tomato seeds and skins. Pomace was obtained from a nearby tomato processing facility (Campbell Soup Supply Company, Dixon, CA) 3 days before the beginning of the experiment and kept in the field in 75 L totes with lids until incorporated in the field. Tomato pomace was evenly spread manually from 5 gal buckets on the soil surface of the designated experimental plots in the two beds without tomato plantings. The same beds also contained the nonamended experimental plots. All beds were then mechanically rototilled to incorporate the plant debris or pomace to a depth of 10 cm. To have consistent experimental plot sizes, experimental unit plots of 3.7 m long and 1.5 m wide were delimited to have six replicates of each treatment. Due to inadequate tomato pomace biomass, the tomato pomace treatments only had five replicates. A buffer zone of at least 1.8 m separated each experimental plot in the same bed to reduce the potential movement of tomato residues between experimental plots during rototilling. After biomass incorporation, two weed seed bags (made with meshed cotton fabric) of each species were buried in each plot (see the following section).

Temperature data loggers (Thermochron iButtons model 1922L, Embedded Data Systems, Lawrenceburg, KY) were placed at a depth of 10 cm in three replicates of each treatment. Loggers were set to record temperature values every 30 min. In the same day, loggers were buried and beds were mechanically covered with a totally impermeable transparent plastic film (Soltif Transparent, Solplast S.A, Murcia, Spain). After the plastic film was installed over the entire row, it was cut and removed from the nonsolarized experimental plots (Table 1). Following film installation, the drip irrigation system was run for 18 h. This time was estimated to be sufficient to bring soil to field capacity in the area between the drip tape and the surface. Visually, plots were homogeneously wet at the soil surface. No further irrigation water was applied during the experiment. Temperature loggers and weed seed bags were retrieved 13 days after the film installation.

Weed Seed Mortality Study. The weed species evaluated in this study included common lambsquarters (*Chenopodium album*), field bindweed, and redroot pigweed. These species are among the predominant weeds at the location of the study and are common in California tomato fields.[18] For each weed species, there were two cloth bags (∼0.3 L in size) containing 100 seeds each. Sand was added to the bags to reduce seed-to-seed contact that can inflate mortality. The bags had a string with a tag for the ease of recovery from soil. The bags were buried at a depth of about 10 cm in each plot, following the incorporation of plant residue but prior to plastic film installation. The seed bags were collected 13 days after burial for seed viability tests. The viability of the seeds was evaluated by placing the collected seeds in a 9 cm Petri dish containing a filter paper (Whatman, Grade 2, Sigma-Aldrich Inc., Missouri) moistened with 2 mL of water. Each Petri dish was covered with a semitransparent, flexible, thermoplastic (Parafilm, Sigma-Aldrich Inc., Missouri) to minimize water loss. The Petri dishes were randomly placed in a growth chamber (Conviron CMP 6010, Winnipeg, Canada) under 16/8 h of light/darkness at 25 °C. After 14 days in the growth chamber, the total germinated seeds were recorded. The nongerminated seeds were subjected to a crush test as a standard method for these weeds.[19] This method is used to indirectly test seed viability for weed seedbank studies in which many samples are assessed. The crush test was conducted by placing seeds on a white paper sheet and then applying pressure to each seed using forceps (redroot pigweed and common lambsquarters) or a light (0.05 kg) hammer (field bindweed). Seeds were considered viable if the seed interior appeared creamy and oily, and seeds were considered nonviable if the seed content was powdery and/or dark. The number of germinated seeds plus the crush test-based number of viable seeds were considered as total viable seeds. The weed seed mortality was calculated as the percentage of the difference between the total seeds in the experimental bag and total viable seeds.

Soil Moisture, pH, Electrical Conductivity, and Volatile Fatty Acids. Soil samples were taken from each experimental plot before installing the plastic film (T0), after 5 days (T5), and at the end of the experiment (T13) using 2.5 cm diameter core samplers down to 10 cm. Three core samples per experimental plot were taken and pulled together in a plastic bag. The sampling at T5 only had two subsamples per plot to minimize the disruption of the anaerobic conditions. During the T5 sampling, in the plastic-covered plots, a small area was isolated with sandbags to reduce oxygen contamination while extracting the samples. After soil samples were collected, the hole was sealed with transparent tape and the sandbags were removed.

The electrical conductivity (EC) and pH of soil were determined using a pH meter and conductivity meter (Mettler Toledo, Columbus, OH) by creating 1:1 (w/w) mixtures of soil and distilled water, equilibrated for 30 s in a vortex. For VFA analyses, the same extracts were then centrifuged for 10 min at 10 000 g. An aliquot of the supernatant was filtered through a 0.2 μm filter (Titan-3, 17 mm filter blue 0.2 μm PTFE membrane, Thermo Fisher Scientific Inc., San Diego, CA) into a high-performance liquid chromatography (HPLC) vial. Lactic, acetic, propionic, formic, butyric, and isobutyric acids were measured using an HPLC-UFLC-10Ai (Shimadzu, Columbia, MD) equipped with an Aminex HPX-87H (300 × 7.8 mm^2) column (Life Science Research, Education, Process Separations, Food Science, Hercules, CA) and an SPD-M20A diode array detector set at 210 nm. The HPLC conditions are described elsewhere.[16] Total organic matter was estimated as the volatile solid (VS) content by measuring the weight lost in samples that were first dried at 105 °C for 24 h and then combusted in a muffle furnace for 4 h at 600 °C. The initial VS in the nonamended soil and soil amended with the fruit-setting stage, tomato pomace, and vegetative stage amendments were 4.54 ± 0.24, 4.69 ± 0.25, 5.31 ± 0.81, and 4.58 ± 0.38%, respectively.

Data Analysis. The temperature data was used to determine mean temperature, cumulative $h > 30$ °C, cumulative $h > 40$ °C, and degree-day. The degree-day values were calculated using the trapezoidal rule to approximate the integral of soil temperature versus time data using 0 °C as baseline in *R* (Version 0.98.1103; Boston, MA).[20]

Analysis of variance (ANOVA) was conducted to test for the significant effects ($P \leq 0.05$) of the factor film (yes/no), type of organic amendment (none, tomato pomace, and fruit-set and vegetative stage plant biomass), and their interactions on the weed seed mortality. Statistical *T*-test was used to evaluate significant differences between treatments with film (solarized/biosolarized) and without film. Tukey's honestly significant difference (HSD) test was used to compare means where more than two treatments were involved. Correlation analysis was performed to determine the relationship between weed seed mortality and changes in soil conditions after treatment application. Statistical analysis was conducted using *R* and JMP 15.0 (100 SAS Campus Drive, Cary, NC).

RESULTS AND DISCUSSION

Weed Seed Mortality. *Common Lambsquarters Seed Mortality.* Common lambsquarters mortality was affected by both organic amendment and film factors ($P = 0.024$ and $P < 0.001$, respectively; Table 2). The organic amendments increased the common lambsquarters seed mortality, which

Table 2. *P*-Values of the Analysis of Variance (ANOVA) of the Weed Mortality (%) Determining the Significance of Organic Amendment (None, Tomato Pomace, Fruit-Set Plant Biomass, and Vegetative Stage Plant Biomass), Film (Yes/No), and Their Interactions[a]

factors	common lambsquarters	field bindweed	redroot pigweed	overall mortality
amendment	0.024	0.004	<0.001	<0.001
film	<0.001	0.006	0.047	<0.001
amendment × film	0.747	0.991	0.944	0.920

[a]A *P*-value ≤ 0.05 suggests significant effect. Experiment was conducted at the field research facility, Plant Sciences Dept, University of California, Davis, in 2019.

https://doi.org/10.1021/acsagscitech.1c00074
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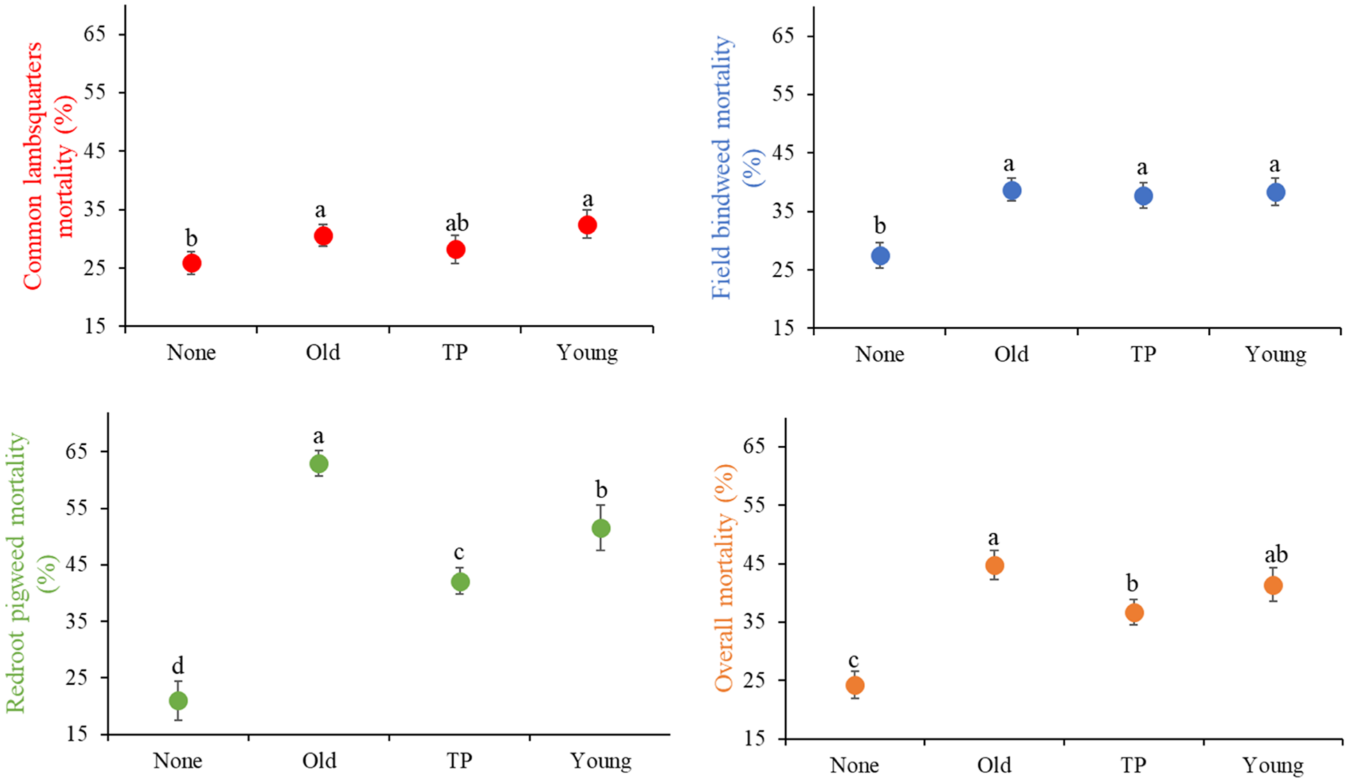

Figure 1. Weed seed mortality in soil amended with residue from a tomato crop terminated at the fruit-set stage (old), tomato pomace (TP), and a tomato crop terminated at the vegetative stage (young) compared with no amendment (none), irrespective of film treatments. Data with different letters suggests significant difference ($P \leq 0.05$; $N = 9$) based on Tukey's test. Experiment was conducted at the field research facility, Plant Sciences Dept, University of California, Davis, in 2019.

was up to 34% mortality with the use of tomato plants, compared to 24% mortality in nonorganically amended soil (Figure 1). In a solarized soil, the average mortality was 41% compared to nonsolarized soil where mortality was 18% (Figure 2). Analyses

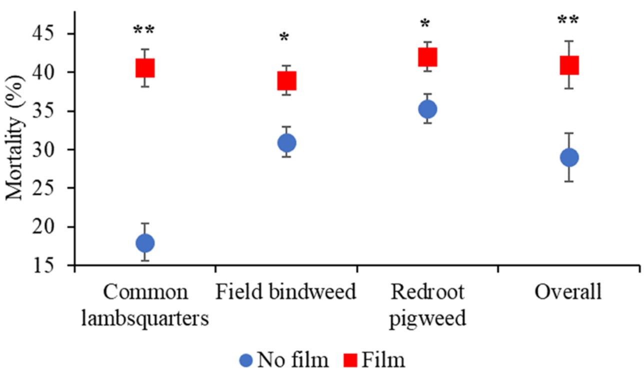

Figure 2. Weed seed mortality in a nonsolarized (no film) and solarized (with film) soils. These were averaged across organic amendments. Asterisk suggests significant difference based on *t*-test (*$P \leq 0.05$; ** $P \leq 0.001$; $N = 12$). Experiment was conducted at the field research facility, Plant Sciences Dept, University of California, Davis, in 2019.

among individual treatment combinations (Figure 3) suggest that biosolarization treatments (OBS, TPBS, and YBS) provided a similar level of weed seed mortality, ranging from 30 to 32%. This mortality was reduced to 19% when solarization occurred with no organic amendment.

Field Bindweed Seed Mortality. Field bindweed was affected by organic amendments ($P = 0.006$; Table 2) and film factors ($P = 0.009$; Table 2). In nonamended soils, the average seed mortality was 27%, which was lower ($P < 0.05$) than the mortality in any of the soils with organic amendment, showing up to 41% seed mortality (Figure 1). In solarized plots, the average mortality of field bindweed seeds was 39% compared to nonsolarized soil with an average of 31% seed mortality (Figure 2). Analyses of individual treatment combinations showed that seed mortality among biosolarized samples was not different (17−19% mortality; Figure 3) but significantly higher than the solarized sample (8%).

Redroot Pigweed Seed Mortality. Redroot pigweed seed viability was affected by the film and the amendment type ($P < 0.05$; Table 2). There was a significant difference between the effect of solarized and nonsolarized soils on the mortality of redroot pigweed seeds ($P = 0.05$); however, this difference was the least among the evaluated weed species. The solarized soil caused an average of 47% mortality, compared to a 41% average mortality in a nonsolarized soil (Figure 2). The average nonamended soil seed mortality was 21%. The use of tomato pomace caused 36% mortality, and this mortality increased to 53−64% when soils were amended with residue from plants terminated at vegetative and fruit-set stages, respectively (Figure 1). Analyses among individual treatment combinations (Figure 3) showed that seed mortality was higher in the solarized and nonsolarized samples amended with vegetative and fruit-setting tomato plant residues than the rest of the treatments. The lowest seed mortality was observed in soil that was merely solarized (CBS) or just amended with tomato pomace with no solarization (TPNT).

Overall Weed Seed Mortality. Overall mortality was significantly affected by both amendment and film treatments

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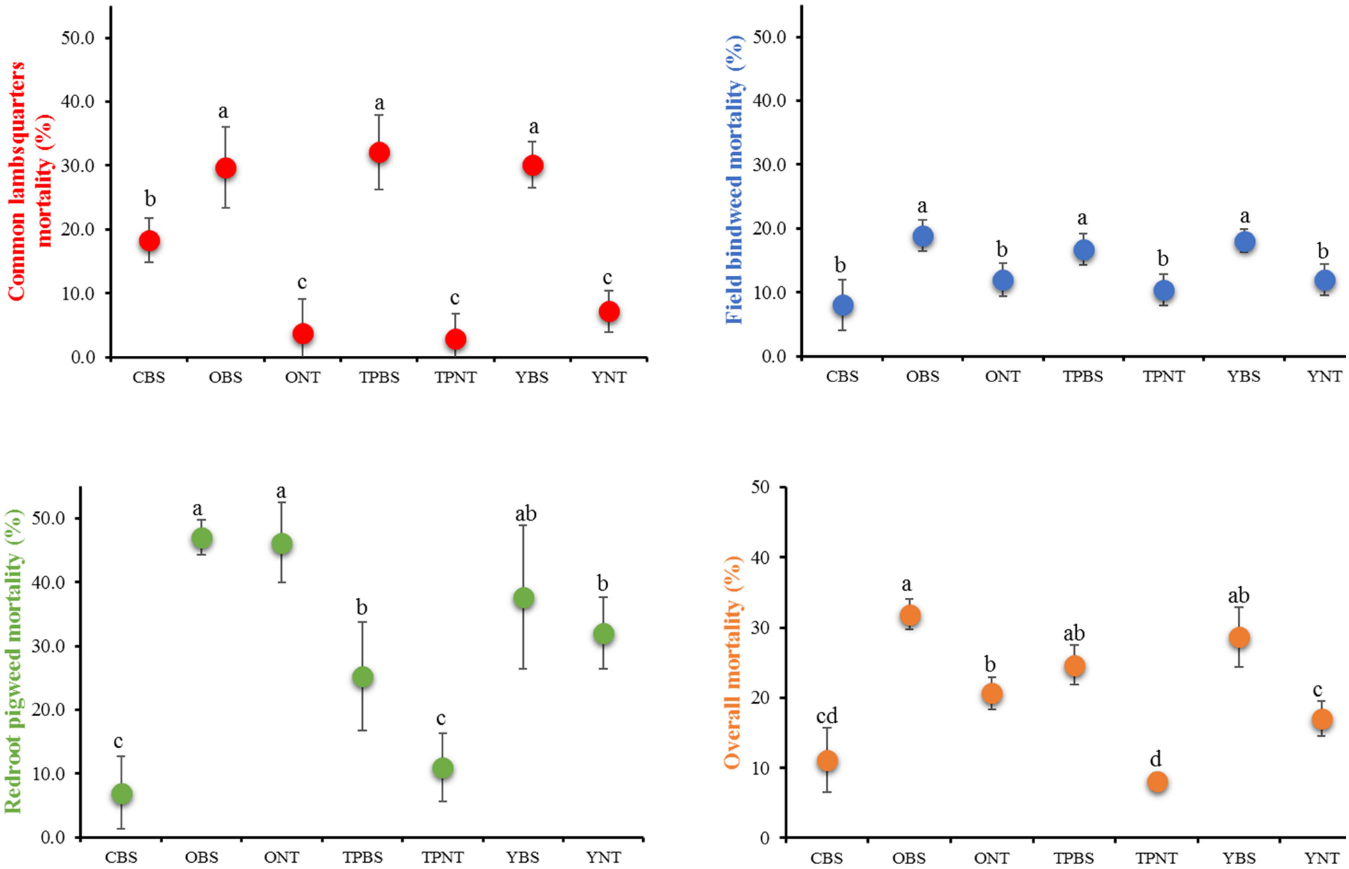

Figure 3. Weed seed mortality relative to control (CNT; no film and no organic amendment) caused by individual treatments. Treatments were nonamended soil covered with film (CBS), amended soil with residue from tomato plant terminated at the vegetative stage without film (YNT) or covered with film (YBS), amended soil with residue from tomato plant terminated at the fruit-set stage without film (ONT) or covered with film (OBS), and amended soil with tomato pomace without film (TPNT) or covered with film (TPBS). Experiment was conducted at the field research facility, Plant Sciences Dept, University of California, Davis, in 2019. Data with different letters within a weed species suggests significant difference between treatment ($P \leq 0.05$; $N = 6$, $N = 5$ for TPNT and TPBS) based on Tukey's HSD test.

Table 3. Mean and Standard Deviation of the Number of $h > 30$, >40 °C, the Degree-Day, and the Mean Temperature (°C) Provided by Each Treatment ($n = 3$) at a 10 cm Depth[a]

treatment[b]	hours > 30 °C	hours > 40 °C	degree-day (°C)	mean (°C)
CNT	145.17 ± 3.82B	13.33 ± 23.09B	392.5 ± 5.10B	30.24 ± 0.39B
CBS	233.5 ± 20.61A	84.00 ± 29.05A	465.2 ± 16.14A	35.83 ± 1.24A
ONT	75.17 ± 15C	0 ± 0B	351.16 ± 6.81C	27.06 ± 0.52C
OBS	258.17 ± 30.99A	71 ± 15.22A	455.52 ± 263.41A	35.16 ± 1.14A
TPNT	161.50 ± 7.47B	4.83 ± 8.37B	397.92 ± 6.92B	30.66 ± 0.53B
TPBS	273.00 ± 24.74A	83.00 ± 20.97A	468.82 ± 15.61A	36.11 ± 1.20A
YNT	115.00 ± 26.04BC	0 ± 0BC	368.02 ± 212.48BC	28.95 ± 1.04BC
YBS	246.33 ± 11.27A	85.33 ± 10.79A	465.35 ± 7.02A	35.84 ± 0.54A
	p-value	*p*-value	*p*-value	*p*-value
amendment	<0.001	0.602	0.003	0.002
film	<0.001	<0.001	<0.001	<0.001
amendment × film	<0.001	0.854	0.065	0.066

[a]Different letter indicates significant differences within treatments using Tukey's honestly significant difference (HSD) test ($P < 0.05$). *P*-values of the analysis of variance (ANOVA) of the effect of film, amendment type, and their interaction are also added. Experiment was conducted at the field research facility, Plant Sciences Dept, University of California, Davis, in 2019. [b]Nonamended soil without film (CNT, as control) or covered with film (CBS), amended soil with plant residue from tomato terminated at the vegetative stage without film (YNT) or covered with film (YBS), amended soil with plant residue from tomato terminated at the fruit-set stage without film (ONT) or covered with film (OBS), and amended soil with tomato pomace without film (TPNT) or covered with film (TPBS).

(Table 2; $P < 0.05$). In nonamended soils, the overall weed seed mortality averaged 24%, which was lower than the overall weed seed mortality of 35, 42, and 45% in soil amended with tomato pomace, vegetative plant, and fruit-setting plant residue, respectively (Figure 1; $P < 0.05$). The average weed seed mortality in nonsolarized soil was 28% compared to 43% mortality in a solarized soil (Figure 2). The trend in the level of overall seed mortality provided by these organic amendments was consistent when film was used (Figure 3). In general, CBS and TPNT were the least effective treatments for reducing weed seed mortality.

Soil Conditions. Soil temperature recorded at 10 cm followed a daily cycle. These daily changes between maximum and minimum temperatures were of ∼18 °C in the solarized plots and ∼10 °C in the nonsolarized plots. As expected, solarizing the soil had a significant effect ($P < 0.05$) on the number of $h > 30$, >40 °C, degree-day, and mean temperature (°C). The organic amendment also had a significant effect ($P < 0.05$) on the number of $h > 30$ °C, degree-day (°C), and mean temperature (°C). This significant interaction effect could be attributed to different phenomena that were not measured in this study (i.e., higher heat retention due to higher water holding capacity of the amended soils, darker color on amended soil due to the darker color of the degraded organic matter, or heat release attributed to the higher microbial activity in the amended soils, as previously observed).[21] During the treatment period, weed seeds under film were subjected to at least 71 h with temperatures >40 °C, whereas without film, the maximum period of time above this temperature was 13 h (Table 3). The mean temperature in the nonsolarized soil was 30.2 °C, significantly lower than the mean temperature in solarized soil (35.8 °C).

Soil moisture content was affected by the amendment type, film, time of observation, and their interactions ($P < 0.05$; Figure 4 and Table S1). Soil moisture content was initially higher in all

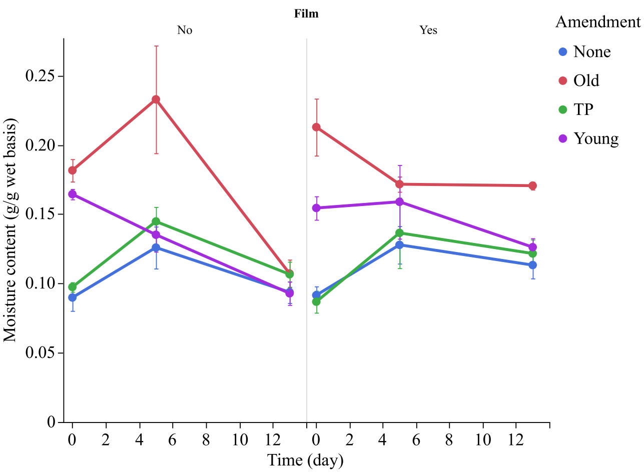

Figure 4. Mean and standard error ($n = 6$, except for the tomato pomace treatment that only had five replicates) of soil moisture content (0−10 cm) with (yes) and without film (no) plots measured for each organic amendment treatment: no amendment (none), amended with residue from tomato plant terminated at the fruit-set stage (old), amended with tomato pomace (TP), and amended with residue from tomato plant terminated at the vegetative stage (young). On days 0 and 13, three core samples and on day 5 two soil cores were taken randomly within the experimental plot and then pooled. Experiment was conducted at the field research facility, Plant Sciences Dept, University of California, Davis, in 2019.

plots with tomato plant residue than in the control and tomato pomace-amended plots ($P < 0.05$). This was attributed to the crop irrigation of the beds before the termination of tomato plants since the T0 soil samples were collected after film installation but before the initial irrigation. After 12 days of incubation, the moisture of the soil samples with residue from plants terminated at the fruit-set stage under film showed significantly higher moisture content than the other solarized plots ($P < 0.05$).

The soil pH was significantly affected by the amendment, film, and the interaction between amendment and film, and between amendment and time of observation ($P < 0.05$; Table S1). After 5 days of treatment, the pH was not significantly different among the organic amendments in the nonsolarized soil, whereas in the solarized soil, the plots with tomato plant residue showed significantly higher pH values than those with tomato pomace (Figure 5; $P < 0.05$). After 12 days of treatment, the solarized soil

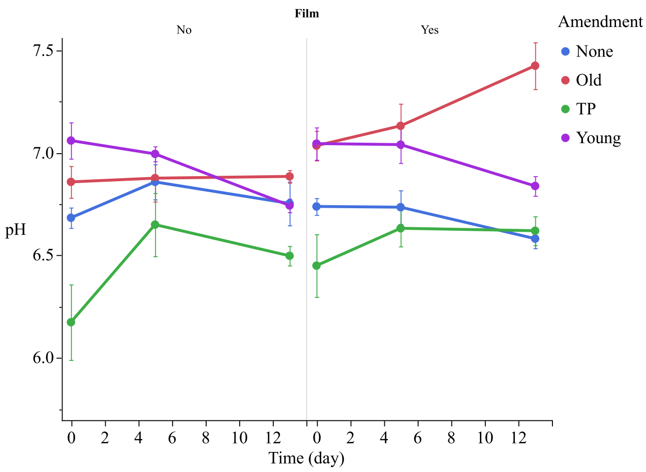

Figure 5. Mean and standard error ($n = 6$, except for the tomato pomace treatment that only had five replicates) of soil pH (0−10 cm) with (yes) and without film (no) plots measured for each organic amendment treatment: no amendment (none), amended with residue from tomato plant terminated at the fruit-set stage (old), amended with tomato pomace (TP), and amended with residue from tomato plant terminated at the vegetative stage (young). On days 0 and 13, three core samples and on day 5 two soil cores were taken randomly within the experimental plot and then pooled together. Experiment was conducted at the field research facility, Plant Sciences Dept, University of California, Davis, in 2019.

had a significantly greater pH level in plots treated with fruit-setting plants, than any other amendment sources ($P < 0.05$).

The EC was affected by the time of observation and the interaction between the amendment and film ($P < 0.05$; Table S1). Initially, the EC was significantly higher in the tomato pomace-amended, nonsolarized plots than in both plots with tomato plant residue ($P < 0.05$; Figure 6). These differences were not observed in the solarized plots. After 5 days, EC was statistically similar in all treatments. After 12 days of treatment, the EC of the soil with fruit-setting plant residue was significantly higher than the rest of the nonsolarized treatments.

The amendment type had a significant effect on lactic acid and total VFA concentration ($P < 0.05$). None of the monitored VFAs were observed in the control samples. Lactic acid was mainly observed in the samples from plots amended with tomato pomace (Figure 7) without showing significant changes throughout the experiment in both solarized and nonsolarized plots. Formic acid was initially detected in the plots with tomato plant residue (Figure 7) in both solarized and nonsolarized soils, whereas, after 12 days of treatment, it was only detected in nonsolarized soil amended with plants terminated at the fruit-set stage. In the solarized plots, formic acid dissipated faster compared to nonsolarized plots. Similar to lactic acid, acetic acid was mainly observed in the tomato pomace-amended soils and

https://doi.org/10.1021/acsagscitech.1c00074
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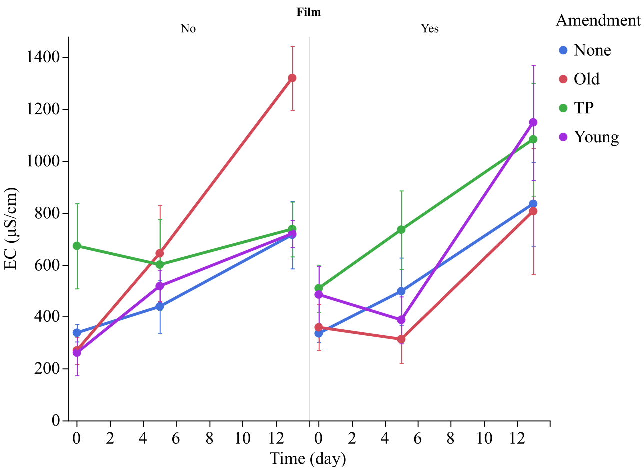

Figure 6. Mean and standard error ($n = 6$, except for the tomato pomace treatment that only had five replicates) of soil electrical conductivity (0−10 cm) with (yes) and without film (no) plots measured for each organic amendment treatment: no amendment (none), amended with residue from tomato plant terminated at the fruit-set stage (old), amended with tomato pomace (TP), and amended with residue from tomato plant terminated at the vegetative stage (young). On days 0 and 13, three core samples and on day 5 two soil cores were taken randomly within the experimental plot and then pooled together. Experiment was conducted at the field research facility, Plant Sciences Dept, University of California, Davis, in 2019.

disappeared in all of the treatments after 12 days of treatment. Samples from tomato pomace-amended soils had the greatest accumulation of total VFAs. At the beginning of the experiment, the total VFA concentration was significantly higher in the tomato pomace-amended plots than in plots amended with tomato plant residue ($P < 0.05$). At the same time, the nonsolarized tomato pomace-amended (TPNT) treatment showed significantly higher VFA concentration than the treatment with plants terminated at the vegetative stage (YNT) in the nonsolarized treatments. These statistical differences between TPNT and YNT were observed in the nonsolarized samples after 12 days of treatment. The solarized plots did not show statistical differences in total VFA among the organic amendments at the end of the experiment.

Mechanisms Inducing Weed Mortality. To understand the changes in the soil induced by the treatment, which could be responsible for weed seed mortality, a pairwise correlation between weed seed mortality and the temperature, pH, or VFA concentration was evaluated (Table 4). Correlation analysis for moisture content was not included due to the possible confounding effect of irrigation during the experiment.

Soil temperature parameters (except the variable hours >30 °C) were positively correlated with the mortality of common lambsquarters seeds and overall weed seed mortality (Table 4; $P \leq 0.05$).

The pH measured in the experiment was positively correlated with the overall weed seed mortality, field bindweed mortality,

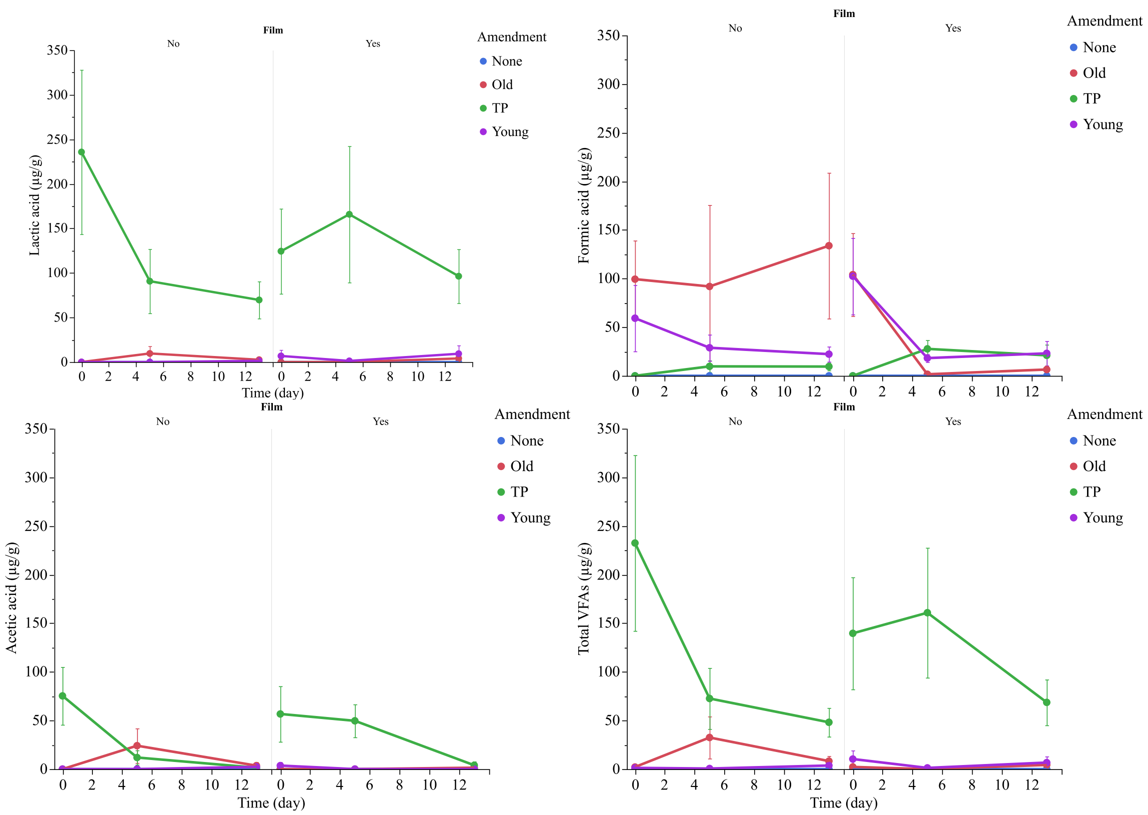

Figure 7. Mean and standard error ($n = 6$, except for the tomato pomace treatment that only had five replicates) of lactic, acetic, formic, and total volatile fatty (total VFAs) acids with (yes) and without film in the soil (0−10 cm) for each organic amendment treatment: no amendment (none), amended with residue from tomato plant terminated at the fruit-set stage (old), amended with tomato pomace (TP), and amended with residue from tomato plant terminated at the vegetative stage (young). On days 0 and 13, three core samples and on day 5 two soil cores were taken randomly within the experimental plot and then pooled together. Experiment was conducted at the field research facility, Plant Sciences Dept, University of California, Davis, in 2019.

https://doi.org/10.1021/acsagscitech.1c00074
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Table 4. Pearson's Correlation Coefficients (r) and Significance (P-Value) of the Correlations between Weed Seed Mortality and Temperature (Degree-Day, Mean, h > 40 °C), pH, or Total Volatile Fatty Acid (Total VFA) in the Soil[a]

	redroot pigweed		common lambsquarters		field bindweed		overall	
	r	P-value	r	P-value	r	P-value	r	P-value
Temperature								
degree-day	0.20	0.37	0.61	<0.05	0.32	0.14	0.46	<0.05
mean (°C)	0.22	0.33	0.57	<0.05	0.30	0.17	0.46	<0.05
hours> 30 °C	0.12	0.60	0.56	<0.05	0.26	0.25	0.38	0.08
hours> 40 °C	0.37	0.09	0.58	<0.05	0.34	0.12	0.57	<0.05
pH	0.42	<0.05	0.20	0.68	0.32	<0.05	0.46	<0.05
total VFA[b]	−0.50	<0.05	−0.16	0.51	−0.37	<0.05	−0.37	<0.05

[a]Number of samples ranged from 34 to 46. Experiment was conducted at the field research facility, Plant Sciences Dept, University of California, Davis, in 2019. [b]Total VFA was analyzed using $\log_{10}$-transformed concentration data.

and redroot pigweed mortality (P < 0.05; Table 4). The $\log_{10}$-transformed concentration of the total VFAs measured in all of the treatments was negatively correlated with the overall, field bindweed and redroot pigweed mortality (P < 0.05).

DISCUSSION

Solarization and biosolarization have been reported to control redroot pigweed and field bindweed;[11,22] however, no research applying these practices to control common lambsquarters was found. In our study, we found that soil solarization, organic amendment, and biosolarization provided varying levels of seed mortality in the three weed species tested. The variation in seed mortality in response to the treatment-induced changes in the soil environment highlights the species differential tolerance and the complexity of the mechanisms involved in inactivating weed seeds. From two growth chamber studies, Dahlquist et al.[8] reported that a soil temperature at 50 °C for 4−113 h was required to cause 100% seed mortality of six weed species; at 42 °C, three out of the six species had 100% seed mortality after 96−384 h; and at 39 °C, only one species (annual sowthistle) had complete seed mortality but after 672 h of exposure. A study by Candido et al.[23] showed that with a temperature range of 40−50 °C, which lasted for 8 days (192 h), solarization resulted in 100% control of redroot pigweed and field bindweed. Tanveer et al.[24] also observed 100% mortality of field bindweed in a germination study at 45 °C for 14 days. In addition, Dahlquist et al.[8] estimated that an average soil temperature of 46 °C that lasted 13 days (312 h) caused 100% seed mortality of tumble pigweed (*Amaranthus albus*), a close relative of redroot pigweed. These past studies suggest that the average 80 h above 40 °C recorded with the use of film in our study could have increased mortality. The large difference in the mortality of common lambsquarters between the solarized and nonsolarized plots (Figure 2) along with the significant correlation with temperature highlights the sensitivity of this weed to the temperature ranges measured in this study. Such a large effect was not directly observed in field bindweed or redroot pigweed. In general, the mortality levels recorded were low (39−47%) due to the short duration of the study (13 days). This duration was selected to appreciate differences among treatments. An experimental duration of 4−6 weeks (a time typically applied for solarization) might have achieved full control in most of the treatments but would not allow an understanding of the mechanisms involved in the inactivation of each species.

Past studies have demonstrated that the impact of soil organic amendments on weed seed mortality varied with the species and source of organic matter.[6,8] Our study indicated that soil organic amendment using tomato plant residue increased the seed mortality of common lambsquarters, field bindweed, and redroot pigweed, compared to that of tomato pomace where increased mortality was only found in field bindweed and redroot pigweed (Figure 1). On the overall weed seed mortality, there was no difference in the level of mortality in plots amended with tomato plant residue derived from the two developmental stages; however, the use of tomato plant terminated at the fruit-set stage caused greater mortality compared to the use of tomato pomace. All organic-amended treatments that were solarized generally provided improved weed seed mortality when compared to mere solarization with no amendment (Figure 3). However, the lack of statistically significant interactions between the film and amendment highlights that biosolarization efficacy may depend on the susceptibility of the specific species being tested. Longer treatment times or greater biomass could have resulted in more profound differences. This confirms the importance of understanding the mechanisms of biosolarization to improve weed control.

The amendment rate applied in the field has a significant role in the efficacy of weed control. For instance, the tomato pomace rate (0.7% w/w) used in our study did not promote weed seed mortality above 35% after 13 days of treatment. Achmon et al.[6] reported that amendment rates of tomato pomace of 2.5 and 5% caused 100% mortality of *B. nigra* and *Solanum nigrum* seeds after 8 days of treatment. In this study, the use of biomass from a tomato crop terminated at an advanced developmental stage (with higher amendment rate, 0.7% w/w) only showed significantly increased mortality than those terminated at an earlier stage (with lower amendment rate, 0.2% w/w) for redroot pigweed. This lack of consistency in increasing mortality with increasing rate may be attributed to the generally low amendment rates applied in this study (≤0.7% w/w) combined with the relatively low heat or other mechanisms inducing mortality.

Similar to the scenario presented in this study, cover crops, which potentially provide organic amendments to the soil, have been applied as a carbon source for soil biofumigation of different soilborne pathogens.[25,26] Some commonly used cover crops used for disease control include *Brassica* spp. as *Brassicaceae* plants are known to have glucosinolates in their tissues. The hydrolysis of these compounds by the myrosinase enzyme can release biocidal volatile compounds, principally isothiocyanates.[27] The studies using cover crops are generally focused on soilborne pests and diseases instead of weeds, and results are inconsistent. Rodriguez-Molina et al.[26] did not observe benefits of using cover crops to the control of *Phytophthora nicotianae* and attributed the higher control of the studied pathogen to high temperatures. On the other hand, McCarty et al.[25] observed that pathogen levels of *Rhizoctonia solani* were lowest and equivalent to the positive control for samples treated with anaerobic soil disinfestation (ASD) + cereal rye (*Secale cereale*) and ASD + mustard/arugula (*Sinapis alba*/*Eruca sativa*) treatments. They concluded that, as anaerobic conditions and pH were similar across treatments, the increased control was due to other amendment chemical properties including the release of isothiocyanates in the mustard/arugula cover crops. Cover crops have a direct effect on weed suppression, although this is achieved by more than a single action whereby competition, physical impediment, and allelopathy have been assumed as main mechanisms.[28,29]

Biosolarization is expected to change the soil conditions or properties with direct lethal impacts on weed seeds. Our study showed significant changes due to biosolarization in soil conditions such as temperature, total VFA accumulation, and pH that could explain some of the mechanism of weed seed mortality. VFAs have been suggested to play a key role in weed seed mortality[6,7] and other soilborne pathogens.[30] Acetic acid, a VFA, has been used in herbicide formulations to control weeds.[31,32] However, this study measured concentrations of acetic acid lower (<150 μg/g of soil) than those reported in other studies where partial (35% of control at concentrations of acetic acid >240 μg/g of soil) or full control of *S. nigrum* and *B. nigra* was observed (100% of control at concentrations of acetic acid >12 000 μg/g of soil). Only field bindweed showed some positive interaction effect between total VFAs and temperature (measured as the number of $h > 40$ °C). This may indicate higher sensitivity of this weed to temperature when VFAs are present in the soil. The lack of positive correlation between VFAs and weed seed mortality in our study may be due to the low concentration of VFAs, which were further hindered by the heat. This lack of effect may be particularly important in the case of common lambsquarters.

VFAs and isothiocyanates are not the only compounds known to have negative effects on weed germination. Allelochemicals from cover crops (benzoxazolin-2-one [BOA], 2,4-dihydroxy-1,4-benzoxazin-3-one [DIBOA], DIBOA-glucoside, and 2,2′-oxo-1,1′-azobenzene [AZOB]) have been reported to control weeds.[33] In addition, it has also been described that aqueous extracts from tomato leaves, roots, and whole plant have potential allelopathic effects due to compounds such as tannic acid, hydroquinone, *p*-hydroxybenzoic acid, vanillic acid, and ferulic acid.[34] This allelopathic effect may support the higher mortality observed for redroot pigweed in samples amended with tomato plant residue with or without solarization. This also agrees with other greenhouse and field experiments that observed that redroot pigweed showed greater mortality than common lambsquarters in soil under cereal rye mulches, suggesting relatively higher sensitivity of redroot pigweed to allelochemicals in soils.[29]

CONCLUSIONS

The level of weed seed mortality caused by biosolarization depends on the weed species, the materials used for organic amendment, and the amount of heat generated. Our study showed that in a commercial scenario where tomato plants must be destroyed due to pest infestation and/or quarantine regulation, an incorporation of these plants into the soil as a carbon source for biosolarization could promote the depletion of weed seedbank. This effect was more evident when incorporating tomato plants with advanced growth stages. Nevertheless, the level of biomass reached by a tomato crop may not be enough to promote a drastic change in soil properties and increase efficacy in weed management as it has been observed in previous studies where 100% control was observed in only 8 days using tomato pomace at a 5% amendment rate.[6] Allelopathic mechanisms involved in weed seedbank depletion can compensate for low tomato plant biomass. In general, this depletion in seedbank is expected to reduce weed density during the subsequent crop growing season and can serve as a component of an integrated weed management strategy in crop production systems. We suggest further study to determine seed germination over a much longer time frame after biosolarization treatments and model how the populations of the studied species may be affected in future generations due to different susceptibilities (i.e., if certain proportions of the viable seeds were killed in the current generation). Furthermore, this study can be further extended to leverage other postharvest residues in the field to control weeds and soilborne pathogens and diseases.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsagscitech.1c00074.

Regression model estimates for treatments (Table S1); and ANOVA table for soil measurements (Table S2) (PDF)

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All authors contributed equally to this work.

Funding

This study was funded by California Tomato Research Institute (CTRI) and the California Department of Food and Agriculture Specialty Crop Block Grant Program (CDFA-SCBG No. 43408).

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors thank Solplast S.A. for the donation of the plastic film and Campbell Soup Supply Company for providing the tomato pomace used in the experiment.

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