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Article

Effect of Almond Residue Soil Amendments and Irrigation Regiment on Organic Acid Development and Transport in Soil

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ABSTRACT: Preplant soil disinfestation often relies on harmful soil fumigants; however, the efficacy of sustainable alternatives using biomass amendment fermentation is limited to tillage depths (0−15 cm). This soil column study evaluated whether increasing the irrigation frequency could promote anaerobic pest-suppressive conditions in deeper soils by leaching biocidal fermentation products (organic acids) from surface-applied amendments. Columns received either singular (standard) or weekly irrigation. Almond hulls, an agricultural byproduct, were either incorporated 0−15 cm into soil or applied as a surface mulch. Oxygen and organic acids were measured at 4−50 cm over 21 days, and the experiment was conducted in triplicate. Anaerobic conditions (3% O_2) were achieved after 5 days, corresponding to acetic acid accumulation below amended layers: maximum concentrations ranged from 42 to 93 mM at 19−50 cm depths. Additional irrigation further increased concentrations in the deepest layer (50 cm) by almost 50%, demonstrating that water management can enable strategies for depth-dependent soil pest control. This may be particularly valuable for soil disinfestation ahead of the establishment of deep-rooted crops.

KEYWORDS: *crop protection, biopesticides, waste valorization, soil transport, sustainable agriculture*

1. INTRODUCTION

Soil-borne pathogens present an enormous risk to agriculture worldwide as well as time and financial burdens to growers.[1] Management strategies for deep-rooted orchard crops are particularly challenging, as certain pathogens such as parasitic nematodes (*Meloidogyne* spp. and *Pratylenchus* spp.) can survive in soils as deep as 150 cm.[2] Volatile chemical fumigants such as 1,3-dichloropropene and chloropicrin can be injected into deep soil (>50 cm) where they diffuse quickly to ensure the control of the entire root zone,[3] potentially eliminating pests within days after application.[3] However, this volatility also increases acute and long-term inhalation risks for farmworkers and residents living near the application site.[4−8] Thus, there is increased interest in fumigation alternatives that can safely and effectively control nematodes in deep soil.

Traditional solarization in which soil is tarped with a clear plastic impermeable film can raise soil to lethal temperatures.[9] However, full pathogen control is limited by soil depth: while temperatures of solarized soil can reach 45−50 °C at 10 cm, temperatures may only rise to 38−45 °C at 20 cm.[10] Biosolarization, a preplant soil disinfestation process in which biomass is incorporated into soil before tarp application, has been used to improve the efficacy of solarization.[11−14] Irrigation and plastic tarping limit oxygen availability, while organic amendments introduce labile carbon into the soil. These factors promote the growth and activity of anaerobic bacteria (*Bacilli* spp. and *Clostridia* spp.)[15] that produce fermentative biopesticidal organic acids (OAs).[16−19] Since OA accumulation increases with soil biomass levels, biosolarization efficacy has previously been limited to tillage depths (15−20 cm).[20,15] However, studies have found that water-soluble biopesticides can dissipate more rapidly in saturated soils than aerated soils.[21] Increasing irrigation rates and frequencies during biosolarization could leach soluble compounds from the 15−20 cm deep amended layers and increase OA accumulation in deeper soil. Additionally, saturation could effectively maintain anaerobic conditions in deep soils, further enriching soils with OA-producing anaerobes.

The objective of this study was to determine the effects of irrigation frequency on the accumulation of water-soluble OAs as a function of depth and time. Soil columns were used to simulate field biosolarization conditions and permit repeated soil atmosphere (O_2) and water (OA) sampling at selected depths. All columns were initially drip irrigated until full column saturation was reached, and then two irrigation treatments were applied: columns received either no additional water inputs (standard method) or additional water inputs weekly. Residues from almond processing (hulls and shells) were selected as representative soil amendments due to high fermentable sugar content (over 22%)[22,23] and have been shown to produce OAs and pest suppression in previous biosolarization trials.[24] Additionally, almond residues are high-volume and low-cost waste products often produced near agriculturally productive areas, making these amendments logistically suitable for biosolarization. To better understand the role of amendment tillage depth on OA distribution, two application strategies were evaluated: the standard method of

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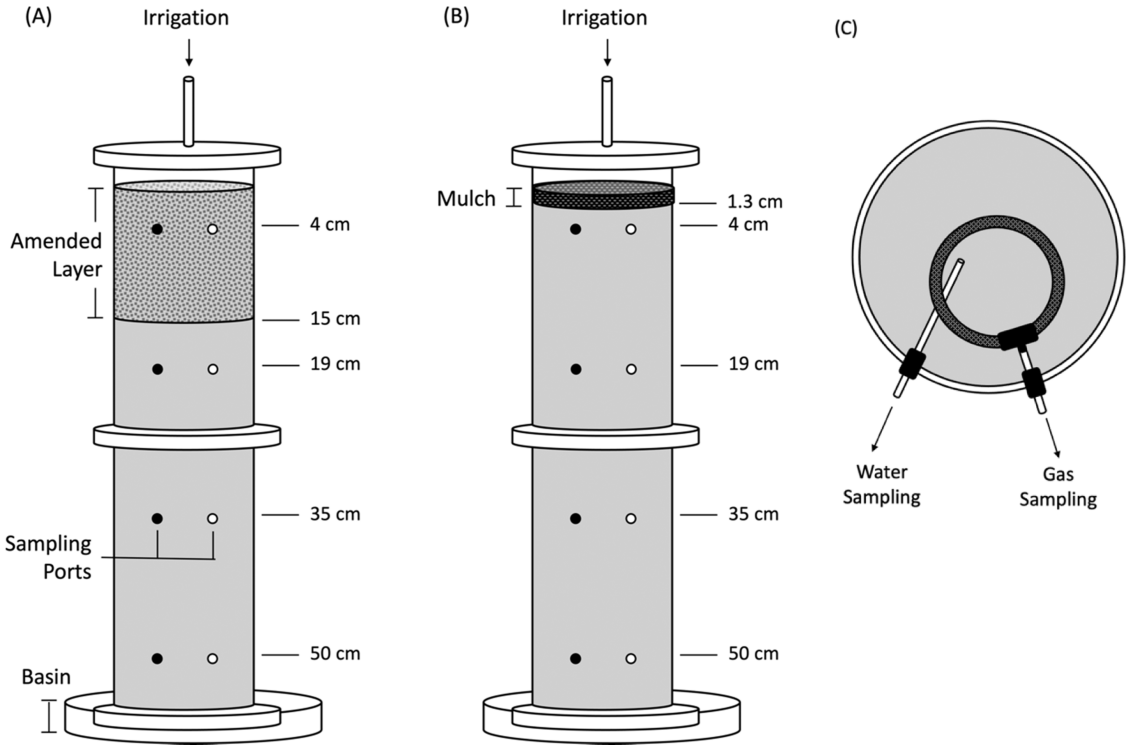

Figure 1. Soil column diagram. Soil and amendments were added to columns such that (A) 1.4% almond residues and 98.6% soil were mixed and incorporated on top of 15.2 cm and (B) residues were applied as an unincorporated 1.3 cm layer on top of the soil (mulched). Each column contained soil liquid (●) and gas (○) sampling ports at each of four depths: 4, 19, 35, and 50 cm. At each cross-sectional depth, (C) Macro Rhizons were embedded into the soil to allow for direct soil water sampling, and porous hosing tubes were embedded into the soil to allow direct atmosphere sampling. The base of the columns was submerged in a basin containing a thin layer of distilled water (~1 cm).

incorporating the residues in the first 15 cm of soil and an alternative method where residues were mulched in a single layer on the soil surface. Time-series data on oxygen and OA concentration were collected for 21 days at depths ranging from 4 to 50 cm. Results from this study can establish whether existing technology, drip irrigation, and amendment tillage can be strategically implemented to expand the use of fumigation alternatives.

2. MATERIALS AND METHODS

2.1. Materials. Air-dried soil was collected from the top 0−30 cm at a commercial almond orchard soil in Chico, CA (39.803°N, −121.903°W), sieved through a 4.0 mm mesh, and stored in an airtight container. Soil properties were previously described:[24] soil texture was a clay loam (36% sand, 36% silt, 28% clay), total carbon and nitrogen content were 1.5 and 0.12% dry weight (dw), and pH was 7.0. Dried almond hulls and shells from the nonpareil variety were obtained from North State Hulling (Chico, CA) from the 2016 growing season and ground to a particle size of 6.3 cm via a 1000 hp tub grinder (Morbark, Winn, MI). Residues had total carbon and nitrogen contents of 36% and 0.65% dw, respectively, neutral detergent fiber, starch, and sugar contents of 258, 3.9, and 267.4 g kg^{-1} dw, respectively, and a pH of 4.8 as previously described.[24,25]

2.2. Soil Column Construction and Preparation. Four cylindrical polyethylene columns were constructed with a height of 61.0 cm and a diameter of 16.5 cm (Figure 1). The lid of the column contained a single port connected to a T-shape connector to allow for irrigation via individual 3.0 reservoirs. The lid simulated soil tarping typically of biosolarization or ASD application, and the base of the column included an aluminum grate covered with mesh fabric to allow for the percolation of gravitational water. Columns included two ports at each of four depths to allow for sampling: 4, 19, 35, and 50 cm. One port was fitted with a Macro Rhizon sampler with an outer diameter of 4.5 mm and a pore size of 0.15 μm (SoilMoisture Equipment Corp, CA) used to extract soil water. The second port at each depth was fitted with a PE-50 plastic tube connected to a circular porous hosing used to extract samples of the soil atmosphere. Sampler outlets were each connected to a valve on the exterior of the column to control the flow of soil water and gas during sampling. Sealant tape and vacuum grease were applied to the fixtures to prevent gas leakage.

For two of the four columns, the air-dried soil was filled to a height of 42 cm. An incorporated mixture of soil and residues was then prepared, representing an amendment rate of 1.4% hulls and shells by dry weight. The amendment soil mixture was then added to the remaining 15.2 cm of the column, bringing the soil column to a final depth of 57.2 cm, a total soil weight of 15 kg, and an estimated bulk density of 1.2 g cm^{-1}. The remaining two columns were filled with soil to a height of 55.9 cm, and residues were then mulched on top of the soil to achieve a total depth of 57.2 cm (Figure 1).

2.3. Biosolarization Irrigation Treatment. Each batch of the four columns' treatments was conducted in triplicate, beginning with the initial drip irrigation and ending after 21 days of incubation at 30 °C (the average 15−20 cm biosolarized soil temperature).[26] All columns received the same initial irrigation treatment of 5.1 ± 0.3 L of deionized water, and irrigation was stopped after 3.5 days when the wetting front reached the column base, with an average rate of 1.7 ± 0.5 L per day. The infiltration rate was monitored by measuring the depth of the wetting front in the soil at different times (Figure S1), which reached depths of 4, 19, 35, and 50 cm after an average of 1, 6, 22, and 63 h, respectively. The bottom of the columns was submerged in a thin layer of distilled water (~1 cm) in a basin at the base of each column to prevent oxygen contamination.

In each batch, two of the four columns received subsequent aliquots of water such that gravitational water just began to percolate from the base, equivalent to 670 ± 130 mL. These events occurred 9 and 16 days from the start of the first irrigation to simulate weekly irrigation periods during biosolarization and ASD. After each

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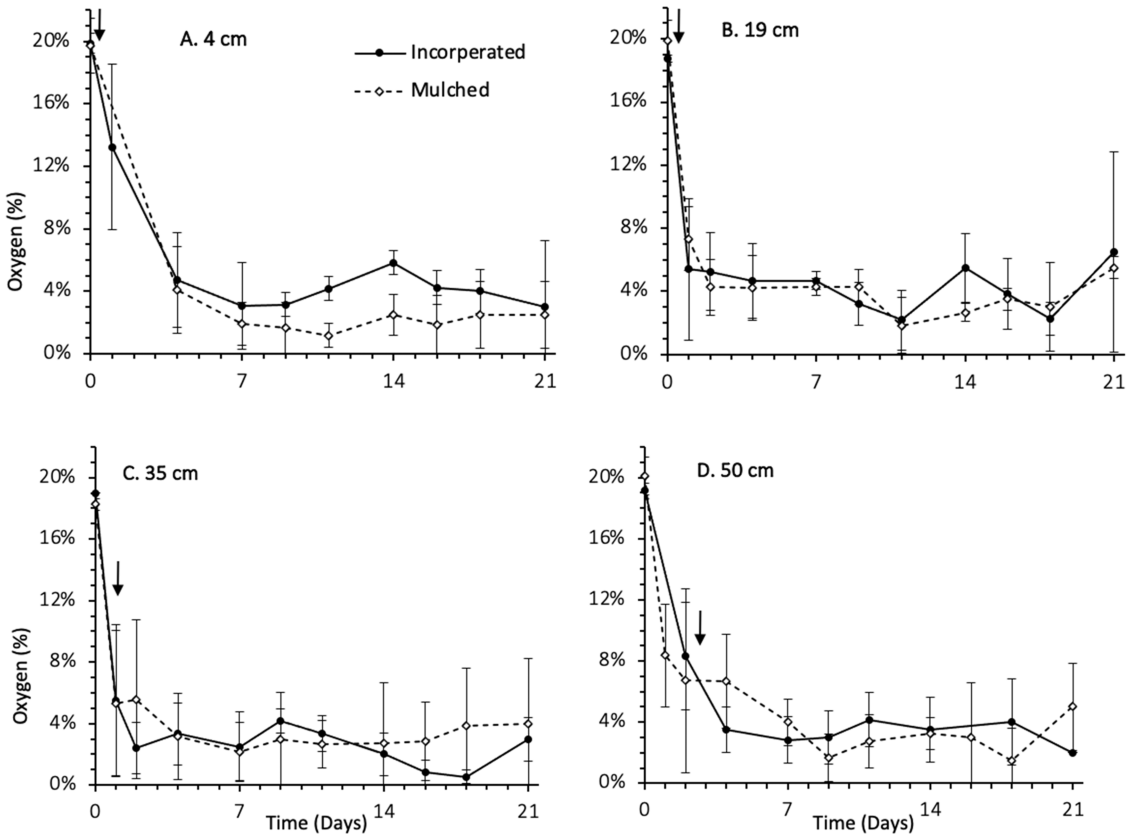

Figure 2. Soil oxygen content over 21 days of incubation. Oxygen content (%) at 4 (A), 19 (B), 35 (C), and 50 cm (D) was measured by GC-TCD for soils incorporated with almond residues down to 15.2 cm or mulched in a single 2.5 cm top layer. Arrows (↓) indicate the time at which the wetting front reached the respective soil depth. All points shown represent columns that received a single initial irrigation with error bars showing standard deviation (n = 3).

irrigation event, the water input port was sealed to prevent air contamination in the soil.

2.4. Oxygen Measurements in the Soil Column Gas Phase. Oxygen was measured as previously described.[26] Soil atmosphere ports were first purged via a 3 mL syringe, and gas was then collected from each of four depths using a 1 mL syringe with three-way stopcocks to prevent air leaks. Immediately following sampling, 100 μL of air in each 1 mL syringe was taken up with a glass gastight syringe and injected into the gas chromatograph inlet. Gas analysis was performed with an Agilent 6890 N GC equipped with a 12.2 m (40 ft) HayeSep, packed stainless steel, 3.18 mm (1/8 in.) OD column. The inlet, oven, and detector temperatures were 120, 30, and 120 °C, respectively, and the helium flow rate was set at 20 mL/min. ChemStation software was used for collecting the data and integration. Oxygen sampling occurred at each of the four depths at 0, 1, 2, 3, 4, 7, 9, 11, 14, 16, 18, and 21 days following irrigation initiation.

2.5. Organic Acid Measurements in the Soil Column Liquid Phase. Prior to collecting each water sample, water in each Macro Rhizon port was purged using a 3 mL syringe. To directly sample soil water, needles were fixed to each sample port and used to piece the septa of 10 mL vacutainers (BD, Franklin Lakes, NJ), and soil water was collected via vacuum pressure. A volume of 1 mL of each extract was filtered through a 0.2 μm filter (Thermo Fisher Scientific Inc., San Diego, CA) into a 2 mL HPLC autosampler tube. Water sampling occurred at each of the four depths at 0, 1, 2, 3, 4, 7, 9, 11, 14, 16, 18, and 21 days following irrigation initiation. OAs were analyzed as previously reported:[24] succinic, lactic, formic, acetic, propionic, isobutyric and butyric acid contents in soil extracts were analyzed by high-performance liquid chromatography (HPLC model UFLC-10Ai, Shimadzu, Columbia, MD; Aminex HPX-87H column; 300 mm × 7.8 mm, Bio-Rad, Hercules, CA) coupled to a UV detector set to 210 nm (SPD-20A Prominence, Shimadzu, Columbia, MD). Peaks were integrated to determine molar concentrations in the soil solution.

2.6. Organic Acid Extraction in Soil Water after Treatment. After the 21-day treatment period, soil columns were destructively sampled for the measurement of residual organic acids. Each of the four continuously sampled depths was used for analysis (4, 19, 35, 50 cm), as well as the surface soil (1 cm) and the residual mulched biomass when applicable. OAs and pH were measured in 1:1 (w/w) deionized water extracts, as reported in Section 2.5, and molar concentrations for each compound were calculated based on the water content measured for each soil sample.

2.7. Data Analysis. Stepwise regression was performed via R studio software (version 1.1.423) using oxygen levels and OA concentrations as response variables. Due to the inconsistency of soil water sampling systems (Macro Rhizons), three replicate measurements were not observed at all treatments and time points: the number of measurements for each treatment, depth, and time are reported (Table S1). For linear regression of OA concentration, time course data were subdivided into two phases: the initial 0−9 day period where all columns received identical water inputs (n = 2 for each amendment treatment) and the subsequent 9−21-day period after half of the columns received additional water inputs (n = 1 for each amendment and irrigation treatment). For OA concentration and pH values obtained from soil extracts after the experiment, ANOVA and Tukey's honestly significant difference test were used to compare different treatments at each depth. The significance level was set at 0.05. A Shapiro−Wilk test was performed to test for the normality of the residuals. It was necessary to perform square root transformations on organic acid data to satisfy the requirement for the normality of residuals.

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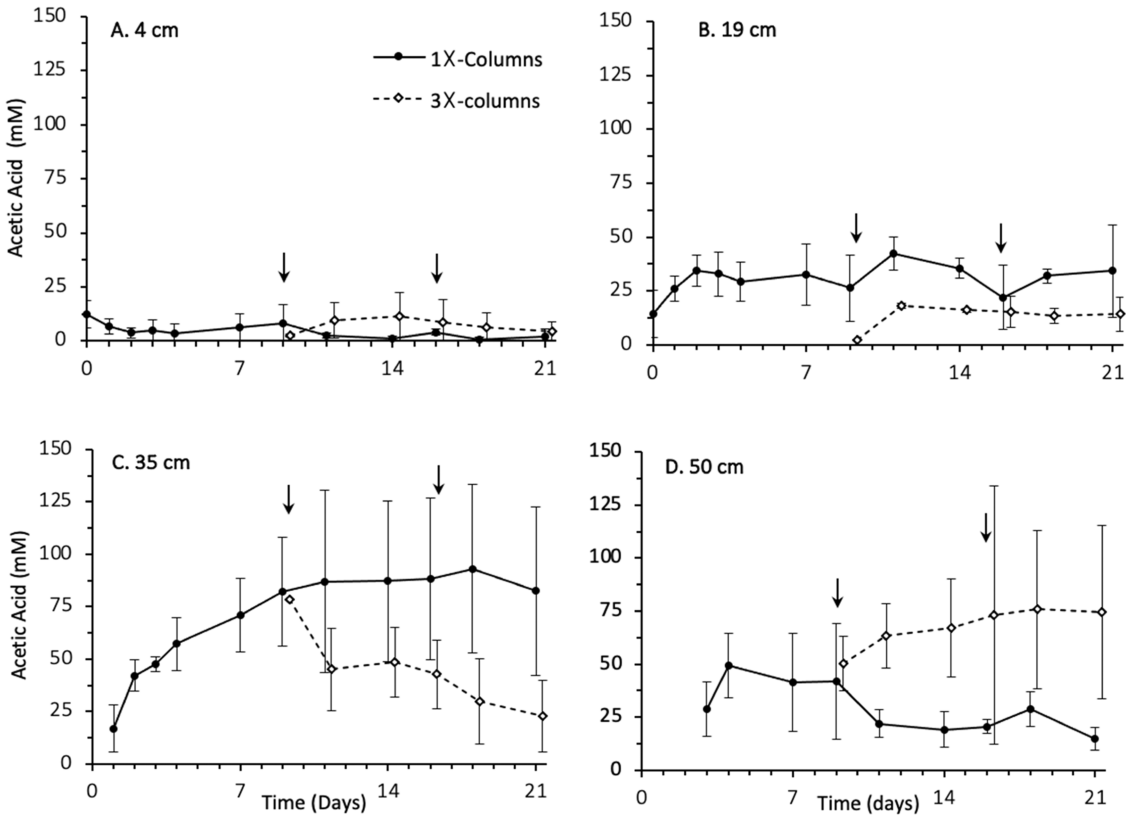

Figure 3. Soil acetic acid concentration over 21 days of incubation. The concentration was measured for acetic acid at each of four soil depths: 4 cm (A), 19 cm (B), 35 cm (C), and 50 cm (D). Soils receiving either one single initial irrigation (1X) or two additional irrigation (3X) days are shown, with arrows (↓) indicating the time at which columns received additional irrigations. Measurements of different amendment strategies (mulched vs incorporated) were pooled ($n \leq 6$). Error bars indicate the standard deviation at each sampling time; data points are staggered for clarity.

3. RESULTS

3.1. Oxygen Depletion. Infiltration depth after the initial irrigation event (0 h) was logarithmic with respect to time (Supplementary Figure 1): the wetting front reached the 4, 19, 35, and 50 cm sampling ports after 1, 6, 22, and 63 h, respectively. Across depths, soil oxygen content decreased exponentially with time ($P < 0.001$), from 20 ± 1% to an average of 7 ± 3% after 1 day and 5 ± 1% after 4 days (Figure 2). For the first 3 days post irrigation, the oxygen content was significantly affected by depth, in which deeper soils (19−50 cm) had significantly lower oxygen content than the shallow 4 cm soil at days 0, 1, and 3 ($P = 0.001$ for all), but this effect was not observed for later time points. Average oxygen content for all treatments and depths reached a combined average of 3 ± 1% 5 days post irrigation, and these levels were maintained for the full 21-day incubation. It should be noted that as treatment time progressed (9−18 days), oxygen content in mulched (MUL) columns was on average 45% lower than those of incorporated (INC) soils at the shallowest sampling port ($P = 0.001$), but there were no significant differences between MUL and INC columns below 4 cm.

3.2. Organic Acid Concentration. To allow the assessment of the effects of subsequent irrigation, data recovered from the soil solution were divided into two phases: (1) the time period after initial irrigation (days 0−9) in which all columns received the same 5 L water inputs and (2) the time period after which columns received either additional 0.7 L water inputs at 9 and 16 days (3X), or no additional water inputs (1X; Figure 3). The major products identified in the soil extracts throughout the treatment duration were acetic acid (AA) and propionic acid (PA), making up 70 ± 20% and 11 ± 10% of total OAs, respectively. Other products included butyric, formic, succinic, and isobutyric acids, which made up 9, 4, 3, and 4% of total OAs, respectively. Regression analysis found that the amendment application strategy had no significant effect on either AA ($P = 0.853$) or PA ($P = 0.211$) concentrations, so OA data from INC and MUL were pooled.

During phase 1, OAs' accumulation was not evenly distributed throughout the soil profile: significant interacted effects were observed between incubation time and sampling depth ($P < 0.001$). OA concentrations at 4 cm were the lowest of all sampling depths and decreased from an average of 12.3 mM to 8.4 mM between days 0 and 9 ($P = 0.013$). In contrast, OA concentrations at all deeper soil depths (19−35 cm) significantly increased with incubation time ($P = 0.001$).

Initial AA concentrations measured after water percolated to each given depth (0, 1, and 3 days post irrigation for 19, 35, and 50 cm, respectively) were 14.2, 16.8, and 28.8 mM, respectively. Nine days post irrigation, concentrations at 19, 35, and 50 cm increased to 26.3, 82.2, and 41.8 mM, respectively, although this increase was only significant at 35 cm ($P < 0.001$). Similar soil profiles were observed with PA (Figure 4): at day 9, concentration minimums were measured at 4 cm (<2 mM), maximums were measured at 35 cm (6.9 mM), and intermediate levels were measured at 19 and 50 cm (4.5 and 2.2 mM, respectively).

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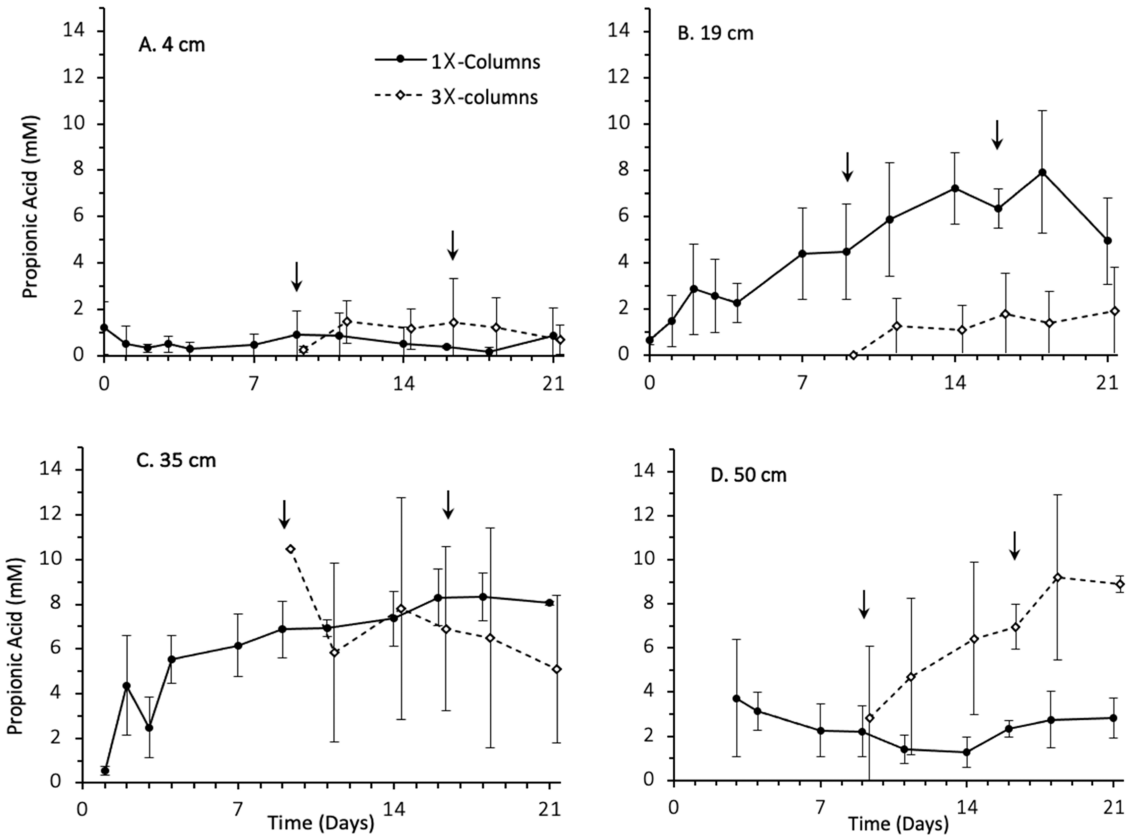

Figure 4. Soil propionic acid concentrations over 21 days of incubation. The concentration was measured for propionic acid at each of four soil depths: 4 cm (A), 19 cm (B), 35 cm (C), and 50 cm (D). Soils receiving either one single initial irrigation (1X) or two additional irrigation (3X) days are shown, with arrows (↓) indicating the time at which columns received additional irrigations. Measurements of different amendment strategies (mulched vs incorporated) were pooled ($n \leq 6$). Error bars indicate the standard deviation at each sampling time; data points are staggered for clarity.

During phase 2, the OA profile of undisturbed 1X columns was consistent with concentrations measured at end phase 1 (day 9): AA concentrations at 35 cm remained significantly higher than at any other depth ($P = 0.035$), averaging 83.8−91.4 mM between days 9−21. This was followed by intermediate AA concentrations at 19 cm (25.8−40.5 mM) and 50 cm (15.9−26.2 mM). Finally, AA concentrations at 4 cm remained the lowest (0.8−3.5 mM). Similarly, PA levels in 1X columns did not significantly change with time after day 9, regardless of depth: PA concentrations were highest at 35 cm (7.0−8.4 mM), followed by 19 cm (5.9−7.7 mM), 50 cm (0.2−2.7 mM), and 4 cm (<1 mM).

Irrigation frequency significantly affected the concentration and distribution of ($P < 0.001$) of OAs. After 21 days, AA concentration in 3X columns decreased to 14.2 mM at 19 cm and 22.9 mM at 35 cm, representing a 46 and 72% decrease from day 9 levels, respectively. In contrast, increasing irrigation frequency significantly increased OA concentrations in the 50 cm soil layer ($P < 0.001$), with average AA concentrations from 50.3 mM at day 9 days to a peak of 74.5 mM at 21 days, a 48% increase. AA levels at 4 cm remained low (5.4−10.6 mM) and did not significantly change with time. Irrigation treatment had a similar effect on PA: concentrations at 19 cm were on average 2.5-fold lower than those in 1× columns (1.7−3.5 mM), and PA concentrations at 50 cm significantly increased from 2.2 mM at 9 days to a peak of 8.9 at 21 days ($P < 0.001$).

3.3. Soil Extractions. Soil OA levels measured in soil extracts after the 21-day treatment followed trends similar to those of direct soil solution measurements (Figure 5). Again, AA and PA made up 72 ± 24 and 12 ± 10% of total OAs, respectively. Regardless of treatment, OA concentrations were lowest in surface layers (1−4 cm soil and mulch layer) with ≤10 mM AA and ≤1 mM PA. Overall, the amendment strategy had little effect on OA distribution, with the exception of the 1X-MUL treatment. Soil extraction measurements found that the combination of mulching and low irrigation resulted in extremely low AA (<5 mM) and PA (<1 mM) concentrations compared to any other treatment at 50 cm.

In deeper soil layers (19−35 cm), OA profiles were significantly affected by irrigation. In agreement with direct column extracts at day 21, peak OA levels were detected at 35 cm when columns received a single initial irrigation: averaged across amendment treatments, concentrations were significantly higher in 1X than 3X columns at 35 cm for both AA (56.4 vs 24) and PA (6.8 vs 5.1). Similarly, concentrations were significantly higher for 1X columns than those for 3X columns at 19 cm for AA (18.8 vs 4.6) and PA (5.0 vs 0.6). Finally, soil extracts confirmed that increasing irrigation frequencies resulted in OA concentrations that increased linearly with depth ($P < 0.001$), peaking at 50 cm. Averaged across amendment treatments, AA concentrations in 3X columns were significantly higher than 1X columns at 50 cm (56.4 vs 24.0 mM), and the same was true for PA (5.6 vs 1.9).

Soil treatment and depth had little effect on soil pH, with the exception of the mulched layer derived from 1X-MUL treatment (Figure 6). Whereas nonmulched soils had a

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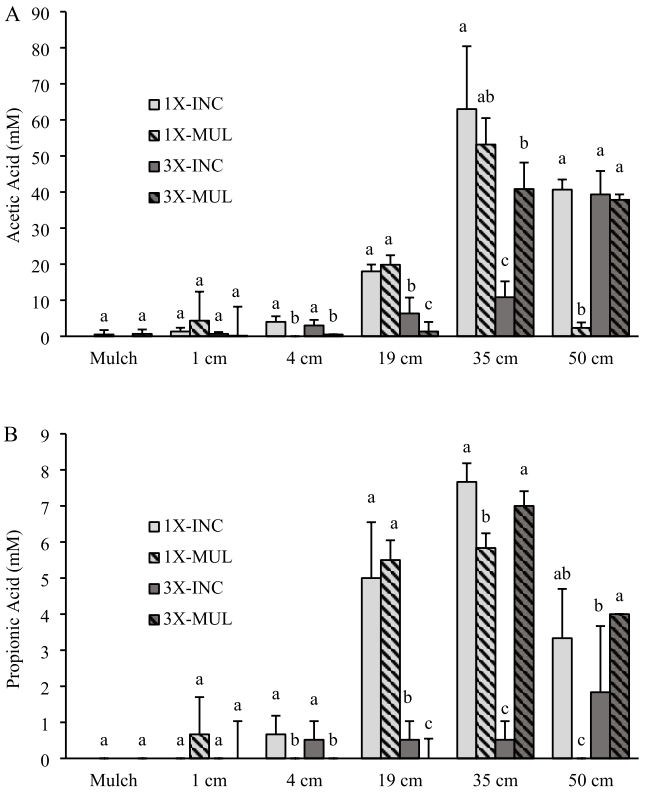

Figure 5. Soil organic acid concentrations extracted after 21 days of incubation. Acetic acid (A) and propionic acid (B) were measured in 1:1 soil extracts for the mulched layer and at five soil depths (1, 4, 19, 35, and 50 cm). Four distinct treatments are shown: columns receiving a single initial irrigation (1X) or two additional irrigations (3X) and almond residues incorporated down to 15.2 cm (INC) or mulched in a single top layer (MUL). Error bars represent the standard deviation of the duplicate measurements. Lowercase letters indicate the results of a one-way ANOVA and Tukey's HSD conducted at each depth.

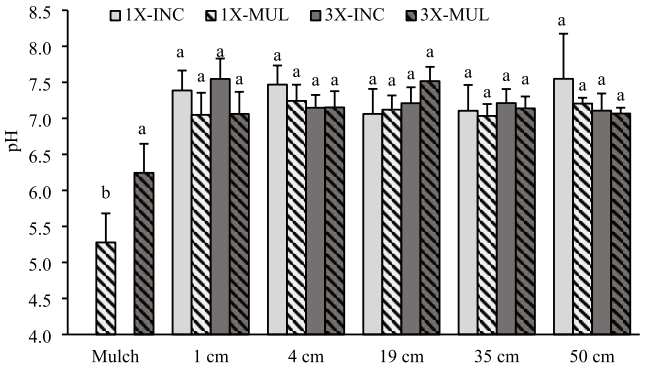

Figure 6. Soil pH after 21 days of incubation. Values were measured in 1:1 soil extracts for the mulched layer and at five soil depths (1,4, 19, 35, and 50 cm). Four distinct treatments are shown: columns receiving a single initial irrigation (1X) or two additional irrigations (3X) and almond residues incorporated down to 15.2 cm (INC) or mulched in a single top layer (MUL). Error bars represent the standard deviation of duplicate measurements. Lowercase letters indicate the results of one-way ANOVA and Tukey's HSD conducted at each depth.

combined average pH of 7.2 ± 0.2, extracts from the pure residue were significantly more acidic, with a pH of 5.3 ± 0 ($P < 0.001$).

4. DISCUSSION

Low soil oxygen levels are crucial to sustaining high organic acid concentrations during biosolarization, especially in soil depths where solar heating alone may be insufficient for pest control.[20] This study confirmed that combining almond residue amendments with managed irrigation could reduce soil oxygen at 4−50 cm depths. Oxygen depletion occurred rapidly post irrigation, with initial ambient oxygen content reducing to an average of 3% of the soil atmosphere after 4 days of incubation. Previous studies found that oxygen content below 5% was sufficient for the enrichment of facultative and obligate anaerobes, including *Bacillus* and *Clostridia*,[26,27] and subsequent organic acid fermentation.[28] Restricting oxygen can also reduce the viability of obligate aerobic pathogens such as parasitic nematodes;[29] moderate soil heating (30−35 °C) has been shown to augment this low-oxygen stress,[30] suggesting the increased efficacy of solarization and biosolarization in deeper soil as long as low oxygen levels are maintained. Significantly, the low oxygen levels measured 4 days post irrigation were maintained through the final 21-day time point, whereas previous biosolarization studies observed oxygen contamination either in shallow soils (<7.5 cm)[31] or 8 days post irrigation.[26]

These anaerobic conditions, combined with the high-sugar almond residue inputs, were sufficient for organic acid accumulation at certain time points and depths of the soil columns. The major products identified in this study—acetic and propionic acid—are indicators of soil disinfestation due to their biopesticidal properties. For instance, previous studies on soil amendments found that acetic acid concentrations as low as 40−60 mM could suppress a variety of soil pathogens.[32] Propionic acid has been shown to be particularly nematicidal, with concentrations as low as 13 mM causing at least 90% mortality to various nematode species.[33] With the exception of the shallow 4 cm layer, the levels of acetic acid observed in this study could be as high as 42−78 mM, depending on depth and treatment.

In general, acetic and propionic acid levels increased over the first 9 days after irrigation, but this trend was not uniform across the soil profile. Regardless of the residue application method, the shallowest soils measured (4 cm) had particularly low acid levels that declined as the irrigation progressed, whereas organic acid accumulation peaked at the 35 cm layer. This may be a result of residue-derived soluble sugars leaching from shallow amended layers and accumulating in deeper soils, where fermentation occurs under suppressed oxygen conditions. Additional irrigation periods at 9 and 16 days had a notable shift in organic acid distribution throughout the column. Concentrations in intermediate soil depths (19 and 35 cm) decreased, whereas concentrations at the deepest sampling depth increased (50 cm), demonstrating the value of increasing irrigation in increasing the depth biopesticides can reach. Despite the 4 cm soil layer having consistently low levels of biopesticide accumulation, the high efficacy of solarization typically eliminates the need for this additional mechanism of pest suppression in shallow spoils.[34] This positions biosolarization as an effective pest control strategy in soils down to at least 50 cm, where previously it had been seen as being unfeasible. This should expand the range of systems this fumigation alternative is considered for to include trees and other deep-rooted crops.

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Peak organic acid accumulation depended on the frequency of irrigation as opposed to the method of amendment: whether almond residues were mulched on the surface or incorporated into the top 0−15 cm corresponded to similar organic acid profiles. This is a departure from previous studies, which found that fermentation products typically accumulate in amended soil layers. This has economic implications, as it demonstrates that the soil amendment application strategy may be flexible to desirable or available techniques. For instance, mulching amendments can coincide with decreased energy application costs: tilling soil is estimated to be over 2.5 times as energy intensive per acre as mulching, where mulching is only slightly more energy intensive than no-until productions.[35] Importantly, using irrigation to leach residual biopesticides from the surface soil can reduce nontarget phytotoxic effects on crops,[36] thus avoiding long remediation times.

Other potential cobenefits of these soil conditions should be a focus of future studies. For instance, current research is exploring the effect of these biosolarization conditions on soil nitrogen transformation, such as increasing ammonification and organic nitrogen enrichment from almond processing residues. While not directly measured in this study, understanding the mobility of the preferred sugar substrate would be applicable when evaluating other fruit processing byproducts (i.e., date paste) as soil amendments. While this study shows the potential for irrigation strategies to influence organic acid eluviation and the concentration of biopesticides by depth, these processes are influenced by different soil textures, horizon structures, and electrical conductivity from field-applied irrigation that may be found in agricultural systems. Future studies using field conditions would facilitate the translation of this research to commercial application. Finally, a greater economic understanding of the impact of mulch as opposed to traditional tilling, as well as deep irrigation, should be conducted on biosolarization systems.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsagscitech.4c00133.

Table S1. Number of samples of soil solution taken for organic acid measurements for each amendment strategy, time, and depth. Figure S1. Infiltration rate of soil columns. Soil wetting front as a function of time period was plotted and used to fit the logarithmic regression model. Each point represents a mean of four measurements. The best fit line indicates the equation depth = 15.0 log(day + 0.1) + 34.9 (PDF)

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Notes

The authors declare no competing financial interest.

■ ABBREVIATIONS USED

OA	organic acids
AA	acetic acid
PA	propionic acid
INC	soil with almond residues incorporated down to 15.2 cm (1.4% dw)
MUL	soil with almond residues mulched with a single 2.5 cm top layer
1X	soil irrigated with 5 L of water at day 0
3X	soil irrigated with 5 L of water at day 0 and 0.7 L at days 9 and 16
1X-INC	soil with residues incorporated 0−15.2 cm, irrigated with 5 L of water at day 0
1X-MUL	soil with 2.5 cm mulched residues, irrigated with 5 L of water at day 0
3X-INC	soil with residues incorporated 0−15.2 cm, irrigated with 5 L of water at day 0 and 0.7 L at days 9 and 16
3X-MUL	soil with 2.5 cm mulched residues, irrigated with 5 L of water at day 0 and 0.7 L at days 9 and 16

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