Sustainability Research and Training Program

PUBLICATION SRTP-2016-02

Developing Co-Products from Anaerobic Digestion: Application of Composted Anaerobic Digestate to Soil to Enhance Sustainable Agriculture and Waste Management

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Suggested Citation:

Bayo, Jesus F., Toniato, J., Yazdani, R., Fadel, M., VanderGheynst, J., Simmons, C. (2016). Developing Co-Products from Anaerobic Digestion: Application of Composted Anaerobic Digestate to Soil to Enhance Sustainable Agriculture and Waste Management. SRTP-2016-02, Sustainability Research and Training Program, University of California, Davis, California.

Project: Developing co-products from anaerobic digestion: Application of composted anaerobic digestate to soil to enhance sustainable agriculture and waste management

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New strategies are needed to advance sustainable management of food, agricultural, and green wastes while promoting sustainable agriculture. Soil biosolarization is a relatively new green technology alternative to harmful chemicals that uses passive solar heating in conjunction with microbial production of volatile fatty acids (VFAs) in the soil to inactivate pathogens and weed seeds in agricultural soils on rural and urban farms. The soil microbial activity can be affected by the nature of the amendment applied and its degree of stability. Solid residues from anaerobic digestion (AD) of food waste are promising soil amendments for biosolarization due their bacterial load and organic matter content, which could induce VFA production and lead to nutrient mineralization to benefit crop growth. As a result, biosolarization may offer a novel application for AD solid residues that can divert them from landfills and add value to the AD process. Accordingly, our objectives are to assess the biosolarization effectiveness of food waste digestate from anaerobic digestion as indicated by weed seed inactivation and impact on soil quality.

Research objectives:

Objective 1. Determine how digestate compost properties affect efficacy of biosolarization

Outcomes: An assessment of the compatibility of composted solid anaerobic digestion residues with soil biosolarization was performed by simulating biosolarization in bioreactors. Bioreactors contained soil amended with solid two solid digestates from two anaerobic digesters with different operational conditions and different original feedstocks. A thermophilic digestate (TD) was acquired from the anaerobic digester located on the University of California, Davis (UC Davis) campus in Davis, CA. The UC Davis digester processes mixed organic waste (food, agriculture, and green wastes). The digester utilizes sequential thermophilic hydrolysis and methanogenesis (55°C) with a low solids loading (5-10% of total solids). The solid digestate was periodically separated from the liquid phase and dewatered by pressing. The Yolo County Landfill (Woodland, CA) provided a mesophilic digestate (MD) from anaerobic digestion of food, animal and green wastes. Digestion occurred under high solids loading (40-60% of moisture content) and mesophilic conditions (35°C). Both digestates were air-dried, ground and sieved (<2mm) after sampling. The properties of both digestates are summarized in Table 1.

The bioreactors mimicked the two soil conditions that may be found in the field during biosolarization: aerobic conditions near the surface and anaerobic conditions at lower depths. The microcosm set up for the aerobic and anaerobic treatments is described elsewhere (Achmon et al., 2016b). Briefly, batch anaerobic microcosms comprised of 250-mL glass media bottles fitted with modified caps connected to an in-line check valve (catalog #80103, Qosina, Edgewood, NY). These digesters permitted headspace gas to leave the digester without risk of oxygen contamination from retrograde airflow. The microcosms were loaded with 100 g (dry weight) of non-amended and amended soils. Four replicates were used. Following preparation, digesters were incubated at 55 °C Methane, hydrogen and carbon dioxide content of the biogas produced from each microcosm was measured via a MicroOxymax respirometry system (Columbus Instruments, Columbus, OH) that was run in anaerobic mode according to the manufacturer's instructions.

Table 1. Chemical content on dry weight basis of the soil and the thermophilic (TD) and mesophilic (MD) digestates

Digestate	**Total N**	**Total C**	**C/N**	**NH_4-N**	**NO_3-N**	**K**	**PO_4-P**
	%			**ppm**			
Soil	0.04	0.38	6.57	-	18.77	84	14.90
TD	1.48	47.10	31.75	373.33	<10	7500	8363.33
MD	1.03	41.53	40.19	150.00	<10	12200	760.00

The aerated bioreactors (250 mL) at air flow of 20 mL min^{-1} were filled with 100 g (dry weight) of the non-amended or amended soils were incubated at 55ºC for 190h. CO_2 concentrations in both reactor influents and effluents were measured using an infrared absorbance CO_2 sensor and the mass flow-rate through the reactors was measured using a mass-flow meter. CO_2 evolution rate (CER, mg day^{-1} g dry $soil^{-1}$) was calculated for each reactor based on mass balances of CO2 at each time point. Cumulative CO_2 evolution (cCER, g CO2 g dry $soil^{-1}$) was determined by integrating CER over time and fitting the observed data to a saturation model.

No significant release of CO_2 or CH_4 was observed for the anaerobic bioreactors. This shows that the microbial activity under these conditions and at this amendment ratio was either non-existant or below the detection threshold of the respirometer sensors. However, H_2 production was observed in 3 out of the four replicates of the reactors containing soil amended with TD (Figure 1). These samples showed a peak of H_2 production between the 2^{nd} and 5^{th} day of incubation. These data suggest anaerobic microbial activity in these samples.

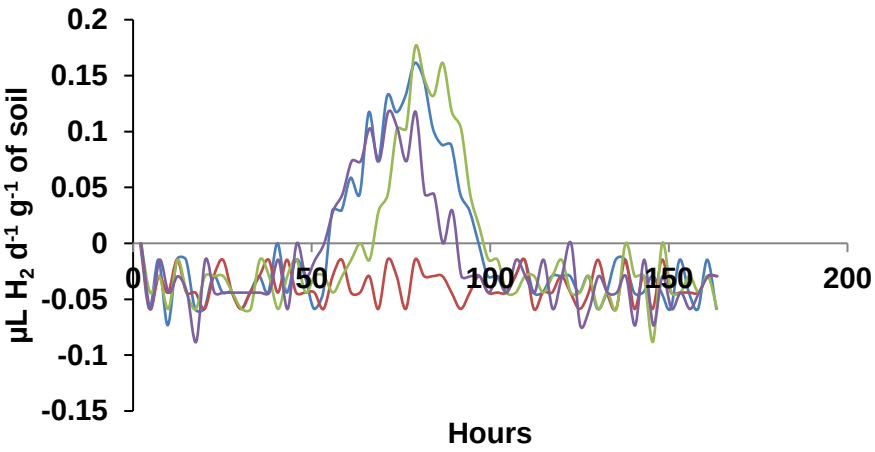

Figure 1. Rate of H_2 released in the reactors containing soil amended with TD under anaerobic conditions.

The aerobic incubation of the non-amended soil in bioreactors at 55°C for 60h showed cCER values of 0.20±0.01 mg CO_2 g $soil^{-1}$. After 190h of incubation, the cumulative CO_2 released by the TD- and MD- amended soil was 2.87±0.31 and 1.83±0.41 mg CO_2 g $soil^{-1}$ (Figure 2). When the results were fitted to the saturation model, the $cCER_{max}$ values in the TD-amended samples (5.69±2.19 mg of CO_2 g $soil^{-1}$) were significantly ($P<0.05$) higher than MD-amended soil (2.59±0.65 mg of CO_2 g $soil^{-1}$). The amended soils had significantly higher ($P<0.05$) values for $cCER_{max}$ compared to the non-amended soils (0.37±0.04 mg of CO_2 g $soil^{-1}$). Previous lab studies incubating soil amended with 2% of compost plus 5% of tomato pomace or 5% of white wine grape wastes showed values for cCER of 40 and 10 mg of C-CO_2 g $soil^{-1}$ after 10 d, respectively. This produced an increase in the temperature in the bioreactors of up to 2ºC (Achmon et al., 2016b). The lab incubation of our samples showed a lower respiration rate compared to other studied biosolarization amendments, indicating that the digestates were comparatively less labile and thus induced less biological heating of the soil during biosolarization.

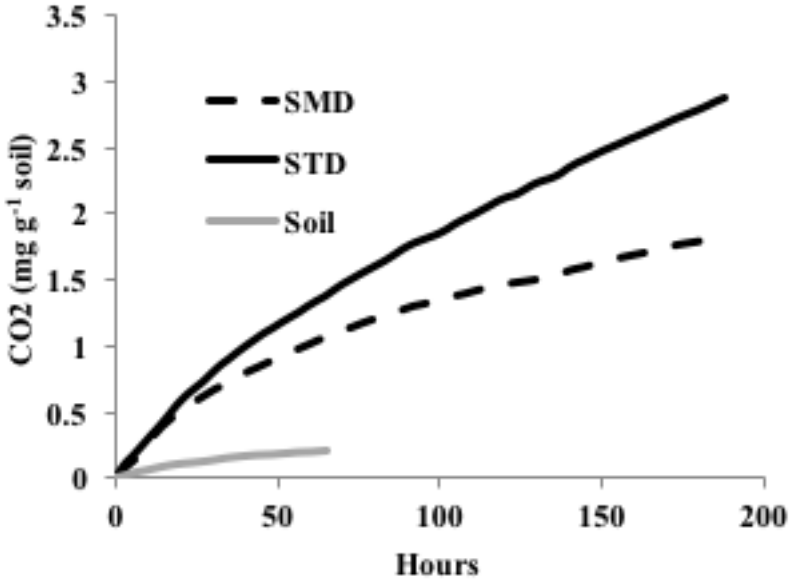

Figure 2. Mean cumulative CO_2 evolution in soil amended with mesophilic (SMD) and thermophilic (STD) digestates in aerobic conditions at 55ºC (n=3)

The pH values of the amended samples before the incubations were close to 7. No significant differences in the pH values were observed after the incubations under anaerobic or aerobic conditions. Likewise, all treatments save for one showed no significant accumulation of volatile fatty acids (VFA) in the soil. Soil amended with TD incubated under anaerobic conditions was the sole treatment to exhibit VFA production. These samples showed a concentration of acetic acid of 87.18±26.32 µg/g of soil. This agrees with the gas evolution data, where only the anaerobic TD treatment yielded H_2 production. H_2 is often a byproduct of acetic acid fermentation.

Overall, these data show that AD solid digestates can perform differently in biosolarization and that such differences may stem from the AD conditions used to generate digestate. These data were used to inform design of the subsequent field study.

Objective 2. Measure soil quality and nutrients after biosolarization with digestate compost.

Outcomes:

Soil mesocosms (Figure 3) served as experimental units in field studies using the same soil amendment treatments described in objective 1. Soil mixtures were wetted to their respective field capacities and allowed to equilibrate overnight at 4°C. Equilibrated soil mixtures were packed into 3.8 L black plastic grow bags (17.8 cm diameter and 22.5 cm height, neHydro, Southampton, MA) with drainage holes to facilitate moisture and gas

exchange with the surrounding soil. Compact temperature sensors and data loggers (Thermochron iButtons model 1922L, Embedded Data Systems, Lawrenceburg, KY) were embedded in the center of each mesocosm at 15 cm depth.

Field preparations and plot arrangements at the Kearney Agricultural Research and Extension Center (Parlier, CA) followed a previously described protocol (Simmons et al., 2013). Five replicate plots were prepared with randomized mesocosm positions in each plot. Mesocosms were buried in field plots, sprinkler irrigated and then covered with clear plastic tarp ('Huskey Film Sheeting'; Poly-America, Inc., Grand Prairie, TX) to initiate biosolarization. An identical set of mesocosms without temperature loggers were prepared and incubated in parallel at room temperature (RT, 22-27ºC). They were loosely covered with plastic tarp to avoid water loss. After 8 days of treatment, the mesocosms were extracted from the field and divided into three sections representing different soil depths (H=0-7.5 cm, M=7.5-15 cm and L=15-22.5 cm depth). Incubation of control mesocosms at RT ceased at the same time. The contents of control mesocosms were thoroughly mixed as no depth effect was expected due to the absence of solar heating. Samples were stored at -20ºC for further analysis. Various physico-chemical properties were analyzed in mesocosm soil samples as described below.

Figure 3. Images of the soil mesocosms (left) and the plot where the microcosms where buried under the plastic tarp

Effect of incubation on pH, volatile fatty acids content (VFAs), electrical conductivity (EC)

TD addition significantly increased ($P<0.001$) the soil pH from 7.21±0.03 in the non-amended soil to 7.69±0.03 (Table 3). The MD did not significantly affect the pH of the soil (7.13±0.11). In general, after incubation at RT or solarization, the pH values did not change drastically although some significant differences were observed (Table 2). Soil pH did not show a significant trend with depth following solarization (Table 2). VFAs were detected in two of the analyzed samples. The lowest layer of the solarized soil

amended with TD (15-22.5 cm) indicated acetic acid and propionic acid accumulation (160.98±85.78 and 13.24±10.03 µg/g of soil, respectively).

Table 2. Mean and standard deviation (n=5) of the EC and pH of non-amended soil and soil amended with thermophilic solid digestate (STD) and mesophilic solid digestate (SMD) prior to biosolarization (T=0), after incubation at room temperature (RT) and after solarization at 3 different depths.

	Sample	**pH mean±std**	**EC (µS/cm) mean±std**
Soil non-amended	Control	7.21^{b}±0.03	308.33^{cd}±20.40
STD	T=0	7.69^{ab}±0.03	337.00^{bc}±15.28
	RT	7.92^{a}±0.05	347.60^{bc}±24.45
	0-7.5cm	7.75^{ab}±0.39	263.40^{d}±20.51
	7.5-15cm	7.29^{ab}±0.06	261.80^{d}±15.12
	15-22cm	7.27^{ab}±0.75	301.20^{cd}±34.63
SMD	T=0	7.13^{b}±0.11	594.20^{a}±28.05
	RT	7.77^{a}±0.07	385.40^{b}±30.88
	0-7.5cm	7.67^{a}±0.10	306.00^{cd}±11.25
	7.5-15cm	7.31^{b}±0.31	325.80^{c}±21.53
	15-22cm	7.79^{a}±0.16	324.60^{c}±22.41

Different letters indicate significant differences ($p<0.05$)

Soil amended with MD incubated at room temperature also presented quantifiable amounts of acetic, propionic and butyric acid production (153.98±8.63, 110.30±6.56 and 77.35±9.40 µg/ g of soil), respectively. TD addition to soil did not significantly increase the EC compared to the non-amended soil (Table 2). Likewise, a slight significant decrease was observed at the top layer of the TD-amended solarized soil from 337.00±15.28 µS cm^{-1} at the initial time to 263.40±20.51 µS cm^{-1} and 261.80±15.12 µS cm^{-1} in the top and medium layers of the solarized soil, respectively ($P<0.001$). The addition of the MD amendment significantly increased the EC of the soil from 308.33±20.40 µS cm^{-1} to 594.20±28.05 µS cm^{-1} ($P<0.001$, Table 3). Incubation at RT decreased the EC, but it was still significantly higher than the non-amended soil (385.40±30.88 µS cm^{-1}, $P=0.002$). After solarization, these MD-amended soils presented no significant differences in the EC values with regard to the non-amended soil.

Soil water retention capacity

Water retention of samples at field capacity (FC), the wilting point (WP) and the plant available water (PAW) were compared in the original non-amended soil and the middle layer of the digestate-amended soil mesocosms after solarization (Table 3). After

solarization, both, the FC and PAW significantly increased ($p<0.001$) with amendment addition. MD digestate increased PAW by 11% whereas the thermophilic digestate increased it by 17%.

Table 3. Water retention characteristics of the non-amended soil and the medium layer (7.5-15 cm depth) of soil amended with thermophilic solid digestate (STD) and mesophilic solid digestate (SMD) after solarization. Values represent the mean and standard deviation (n=5) of the % of water (wet basis) observed at the Field Capacity (FC), Wilting Point (WP) and Plant Available Water (PAW)

	FC (%)		**WP (%)**		**AW (%)**	
	Mean	**Std**	**mean**	**Std**	**mean**	**Std**
S	10.8^{a}±0.3		2.7^{a}±0.2		8.0^{a}±0.2	
STD	12.6^{c}±0.2		3.2^{b}±0.1		9.4^{c}±0.3	
SMD	11.9^{b}±0.3		3.1^{b}±0.1		8.8^{b}±0.3	

Different letters indicate significant differences ($p<0.05$)

Total C and N

The total N of the non-amended soil was 0.04±0.00% (dry weight basis). In the TD-amended soil the total N was 0.05±0.01% (Figure 4). After the experiment, the values remained similar to the non-amended soil. On the other hand, the thermophilic digestate significantly increased ($P<0.001$) the C level from 0.38±0.01% in the non-amended soil to 1.07±0.24% in the amended soil. The C level decreased in the samples incubated at RT and as well as in the solarized samples but this decrease was only significant for the upper layer of the solarized soil (STD-H=0.65±0.06%, $P<0.001$). The C/N ratio increased from 6.57±1.99% in the non-treated soil to 20.11±2.92% due to TD addition (Figure 4, left axis). The significant decrease in C in the upper solarized layer also resulted in a significant decrease in the C/N to 14.10±2.15.

The addition of the mesophilic digestate also did not affect the total N of the soil (0.05±0.00%) and no significant differences were observed due to incubation at RT or solarization. The total C contribution of the mesophilic digestates increased the C level to 0.93±0.06%. As for the solarized soil amended with TD, these values decreased during solarization and incubation at room temperature. Again, this decrease was only significant for the upper layer of the solarized soil (0.66±0.09%, $P=0.005$). Finally, the C/N ratio of the MD-amended soil was 19.49±0.52 initially and it only decreased significantly to 14.28±1.89 for the upper layer of the solarized mesocosms ($P=0.003$).

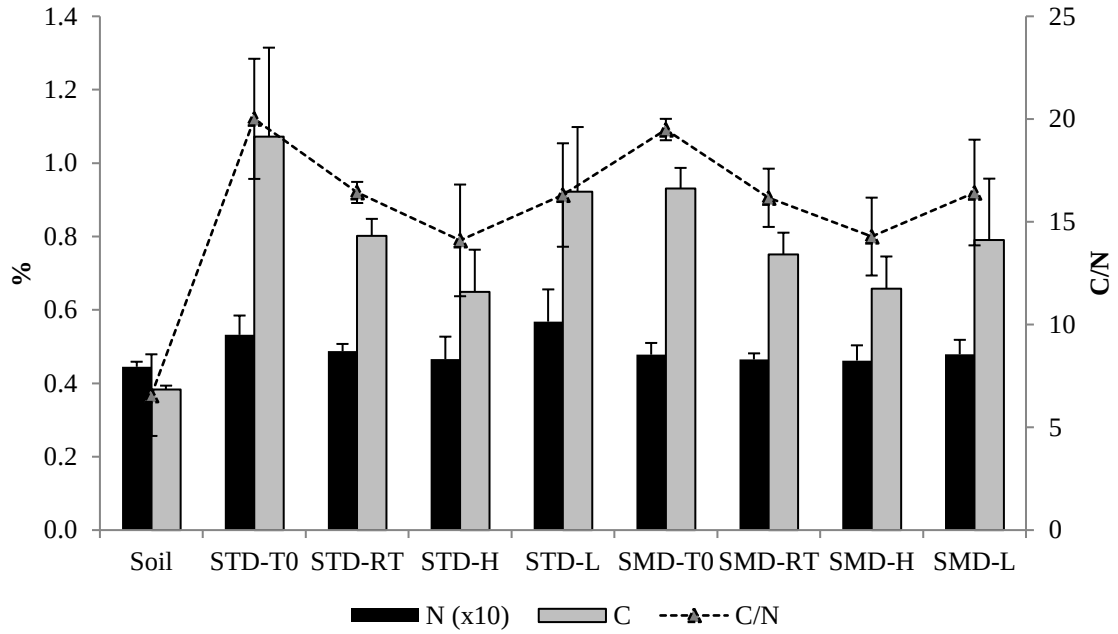

Figure 4. Total C and N content and C/N ratio of the non-amended soil and soil samples amended with thermophilic (STD) and mesophilic (SMD) digestates at the beginning of the experiment (T0), after incubation at room temperature (RT) and after solarization at different depth (S-H=0-7.5cm and S-L=15-22cm). Bars represent the standard deviation of the mean (n=5). For visual reasons the total N values in the figure are ten times higher than the measured value

Extractable NH_4-N, NO_3-N, P and K

The non-amended soil presented a NO_3-N level of 18.77±0.47 μg g^{-1} (Figure 5). The addition of the thermophilic digestate significantly decreased this level to 2.77±0.95 μg g^{-1} ($P<0.001$). After solarization or incubation at RT, this concentration dropped to <1 μg g^{-1}. The non-amended soil presented a NH_4-N level of 3.96±0.03 μg g^{-1}. The addition of the thermophilic digestate did not significantly change this level (2.77±0.95 μg g^{-1}). After incubation at RT, the NH_4-N level did not change significantly, whereas after solarization a significant accumulation of NH_4-N was observed in both upper and lower layers of the TD-amended soil (7.13±1.63 and 6.45±1.57 μg g^{-1}, respectively, $P<0.05$). Regarding extractable P, the TD amendment showed a significant increase from 14.90±0.24 μg g^{-1} in the non-amended soil to 27.14±0.55 μg g^{-1} in the TD-amended sample ($P<0.001$). After incubation at RT and solarization, it significantly dropped to 22.08±1.62 μg g^{-1} ($P<0.001$) only in the upper layer of the solarized microcosm (STD-H, Figure 5). Regarding extractable K, a slight increase due to the TD addition was observed from 84.67±9.99 μg g^{-1} in the original soil to 98.60±2.30 μg g^{-1} after TD addition. After the experiment, this amount slightly increased for the samples incubated at RT and the bottom (STD-L) and medium (STD-M) layers of the solarized mesocosms (Figure 4). On the other hand, the K concentration at the top layer of the solarized soil decreased slightly, although significant differences ($P<0.001$) were only found between this layer

(91.60±7.47 µg g^{-1}) and the lower layers (107.20±1.64 µg g^{-1} and 107.40±2.30 µg g^{-1}, at 7.5-15 and 15-22 cm depths, respectively) in the solarized samples.

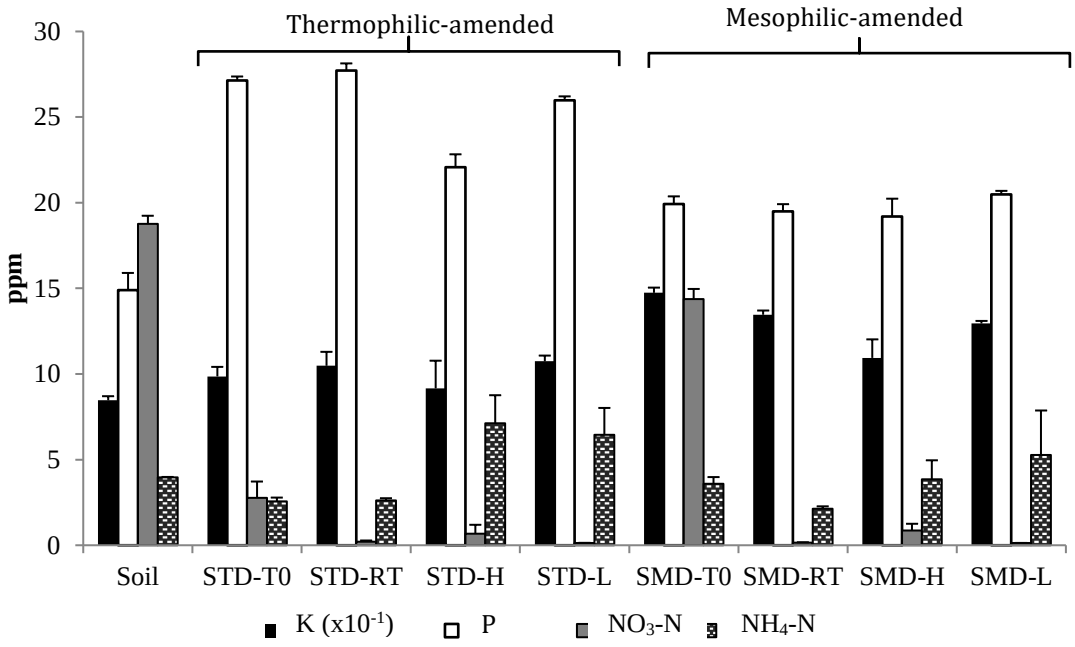

Figure 5. Extractable NH_4-N, NO_3-N, P and K content of the non-amended soil and the amended samples with thermophilic (STD) and mesophilic (SMD) digestates at the beginning of the experiment (T0), after incubation at room temperature (RT) and after solarization at different depths (S-H=0-7.5cm, and S-L=15-22cm). Bars represent the standard deviation of the mean (n=5). For visual reasons the K values in the figure are ten times lower than the measured value

The addition of the mesophilic digestate also significantly decreased the level of NO_3-N (14.36±0.60 µg g^{-1}, P<0.001), although to a lesser extent than the TD-amended soil. Again, incubation at RT and solarization led to a decrease in NO_3-N, with final levels being less than 1 µg g^{-1}. Similar to the TD-amended soils, MD addition did not significantly change the levels of NH_4-N (3.60±0.38 µg g^{-1}). The incubation at RT did not affect these levels (2.14±0.14 µg g^{-1}); however, an accumulation of NH_4-N was observed at the lower layer of the solarized samples (5.28 ±2.59 µg g^{-1}) that was significantly higher that the ammonium level at RT (P=0.008). MD amendment also increased the extractable P (19.92±0.30 µg g^{-1}), but to a lower extent than the TD. This level did not change significantly during the experiment. Finally, the contribution of MD digestate to the extractable K was larger than that observed for TD (147.40±4.51 µg g^{-1}). This value significantly decreased during the incubation in all the samples (P<0.05) and this decrease was more significant in the upper layer of the solarized soil (109.40 µg g^{-1}, P<0.001).

Despite the low application rate used in this experiment, the positive effect of both digestates on soil quality was evident. Their increase of the PAW is of great importance for crops of arid regions. The addition of liquid digestates from agricultural waste to soil has already been shown to provide a long term increase in the moisture retention capacity of soil (Garg et al., 2005). In addition, this study shows that soil biosolarization does not impact PAW benefits imparted by the digestate amendments. Another concern surrounding soil amendment with digestate is the potential phytotoxicity due to soluble salts present in the digestates (Alburquerque et al., 2012b; Rombolà et al., 2015). The EC was used as an indirect method to measure soluble salts. Only the addition of the MD presented a significant increase in EC at the beginning of the experiment, nonetheless, the levels reduced to those observed in non-amended soil levels after the experiment. The higher decrease of the EC level on the upper layer of the biosolarized samples could be attributed to leaching of salts from the mesocosms due to irrigation at the onset of biosolarization. Greater microbial activity at this level would also consume organic acids or nutrients, which contribute to EC. This is supported by the significant decrease in total C observed at the top layer of both amended-solarized soils (Figure 4).

The selected digestates had an initial C/N ratio higher than usual values (5-20) typical for stable organic materials (Gutser et al., 2005; Sellami et al., 2008). The higher C/N ratio of solid digestates is attributed to the liquid-solid separation step where most of the available N remains in the liquid fraction (Moller et al., 2010). Therefore, the solid digestate addition had a greater impact on the C content of the soil and a lower impact on the total N. The primary available form of N in the digestate was NH_4-N (Table 1). Contrary to the accumulation of NO_3-N found in other solarization and biosolarization studies (Flores et al., 2007), the lack of NO_3-N during the experiment indicates that nitrification was inhibited during the experiment. This may have been due to a lack of nitrifying bacteria and/or their sensitivity to high temperatures (Gelsomino et al., 2006). In addition, disappearance of N-NO_3 may be related to immobilizing inorganic-N via sequestration in microbial biomass (Alburquerque et al., 2012a). Despite their high N-NH_4 content, the addition of the amendments did not increase the soil N-NH_4 significantly. The solarization process has also been reported to promote the accumulation of N-NH_4 (Gelsomino et al., 2006). This accumulation was only significant for the TD-amended samples. Ammonium accumulation can contribute to higher pest inactivation in amended soils (Gamliel et al., 2000; Bailey and Lazarovits, 2003; Gelsomino et al., 2006; Rombolà et al., 2015).

Solarization studies have also reported an increase in extractable P and no impact on the extractable K after solarization without amendments (Stapleton et al., 1985). The high K and P content of the solid digestates provide opportunities for digestates to serve as fertilizers suitable for crops that require relatively high amounts of P and K, such as leguminous plants or crops at the reproductive or blooming phase

(Nkoa, 2014). These elements seem to be depleted during solarization at the top layer. As for the decrease of the EC, a possible explanation could be biological fixation due to higher microbial activity in this layer.

Objective 3. Confirm efficacy of biosolarization with digestate compost in field trials.

Outcomes:

The same field set up described in objective 2 was used in objective 3. To assess the pest inactivation efficacy of biosolarization, temperature and weed seed inactivation were measured in mesocosms. To assess weed seed inactivation, two permeable nylon mesh packets of weed seeds were buried proximal to temperature loggers within each mesocosm at 15 cm depth. Each seed packet contained either 30 seeds of *Brassica nigra* (black mustard) or 50 seeds of *Solanum nigrum* (black nightshade) and 2.46 mL of the appropriate soil mixture to provide direct contact with seeds (Kroeker et al., 2012). After biosolarization, weed seed packets were removed from the mesocosms and the weed seed inactivation was analyzed via germination and vital staining assays as previously described (Achmon et al., 2016a).

Temperature evolution

For the non-amended soil and the TD- and MD-amended soils, similar trends in temperature evolution were observed at 15 cm depth (Figure 6). Temperature fluctuated daily with increasing daily peak temperatures during the treatment period. This was attributed to the initially (and uncharacteristically) cool weather conditions at the onset of the experiment followed by a warming trend over the duration of the experiment. On the last day of treatment, the maximum mean temperatures observed at 15 cm depth were 9 ºC higher than the air temperature (36.11 ºC 32). The cumulative temperature of the samples in degree-days reached 273ºC-day in all the samples (Table 2). No significant differences ($P>0.05$) in degree-days between the unamended and the digestate-amended samples were observed, indicating that solar heating was primarily responsible for elevated soil temperatures as opposed to biological heating from microbial respiration.

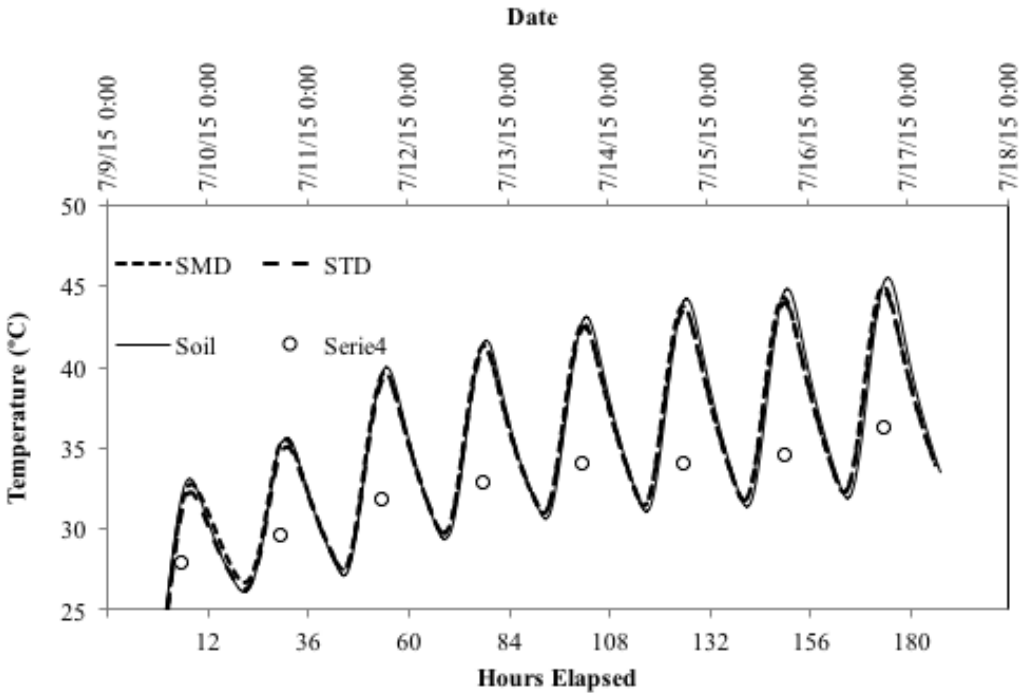

Figure 2. Mean temperature evolution (°C) for solarized mesocosms. Points are related to the maximum air temperature registered in the closest meteorological station (n=5 for S and SMD, n=4 for STD)

Weed inactivation analysis

B. nigra seeds in the solarized soil without amendment yielded mortality of 40.33±20.81% (mean±standard deviation, Figure 6). The Tukey HSD post-hoc analysis showed significantly higher mortality ($P<0.05$) in the solarized soil, amended with TD (71.33±26.42%), when compared to the same sample incubated at RT (31.65±22.03%), to the solarized MD-amended samples (22.32±7.34%) and to the MD-amended samples incubated at RT (19.00±11.88). A two-way ANOVA of the effect of the amendment type (non-amended, TD-amended and MD-amdended) and temperature of incubation (solarization vs room temperature) and their interaction on *B. nigra* inactivation only found significant positive effect of the solarized TD-amended treatment ($P=0.025$).

The *S. nigrum* seeds exhibited high mortality in the non-amended-solarized soil (81.42±11.80%). Mortality was lower in both amended and non-amended samples incubated at room temperature, as well as in solarized amended soil. In fact, samples incubated at RT amended with TD (48.50±13.65%) and with MD (55.71±9.73%) presented significantly lower mortality ($P=0.003$ and $P=0.036$, respectively). The non-amended, non-solarized sample showed lower mortality as well (67.45±18.07%) but differences were not significant. Contrary to *B. nigra*, a two-way ANOVA of the effect of the amendment type and temperature of incubation and their interaction on *S. nigrum*

inactivation showed a positive effect of the solarization in the *S. nigrum* inactivation (P=0.011).

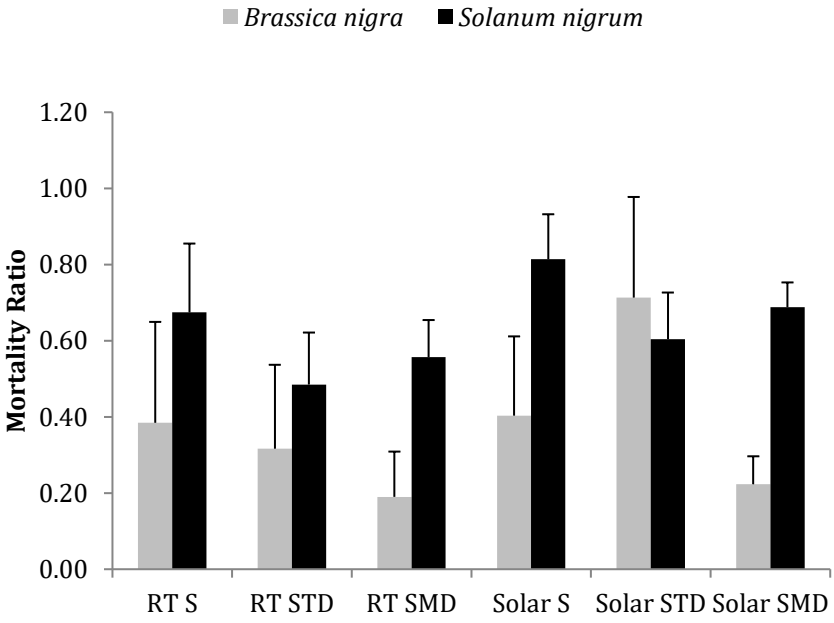

Figure 6. Seeds mortality fraction of *B. nigra* and *S. nigrum* in the non-amended solarized soil (S), the TD-amended solarized soil (STD), the MD-amended solarized soils (SMD), soils incubated at room temperature (RT) or solarized (Solar). Bars represent the standard deviation of the mean (n=5). Different letters indicate significant differences between the samples for the same weed

Conclusions

The soil temperatures reached in our study were relatively mild and we only showed a significant increase in inactivation of *B. nigra* seeds when TD amendment and solarization were combined. There are several possible explanations for the lack of inactivation with MD amendment and for *S. nigrum*. Firstly, temperatures were mild during the first days of the experiment. A thunderstorm occurred in the area on the first day of the experiment and caused the maximal air temperature to drop from 32ºC to 27ºC (UCIPM, 2015). Moreover, the digestate-amended mesocosms did not show higher temperatures associated with biological heating from soil microbial activity. Previous lab studies incubating soil amended 2% of compost plus 5% of tomato pomace or 5% of white wine grape wastes showed values for cCER of 40 and 10 mg of C-CO_2 g $soil^{-1}$ after 10 d. This produced an increase in the temperature in the bioreactors of up to 2ºC (Achmon et al., 2016b). The lab incubation of our samples showed a lower respiration rate compared to other amendments (Figure 3), indicating a low quantity of labile organic matter in the digestates. The low degree of temperature stress could have

contributed to the low weed seed inactivation of *B. nigra* in the MD-amended samples. For instance, lab studies have shown that seeds of *B. nigra* were inactivated when they were exposed to 50ºC for 16 h (Tuell-Todd et al., 2009) but the maximum temperature recorded was during the experiment was 45.57ºC (Table 2). A significant temperature effect was observed for *S. nigrum* as mortality in the solarized samples was significantly higher than in the samples incubated at RT. *S. nigrum* has been shown to be completely inactivated after 16 days of incubation at 42ºC. (Dahlquist et al., 2007)

Secondly, the slight drop in pH and the low concentration of VFAs detected in the amended soils may also explain the lack of weed seed inactivation in many of the amendment treatments. For instance, it has been observed that immature compost extracts with acetic acid concentrations of between 2474 and 1776 mg kg^{-1}, delayed and reduced the germination percentage of important economic weed species.(Ozores-Hampton et al., 1999) In a companion study, using tomato pomace as a source of unstable organic carbon and compost microorganisms as inoculum, a significant correlation was shown between soil VFA levels and inactivation of *B. nigra* and *S. nigrum.*(Achmon et al., 2016a) Moreover, the appearance of VFAs at a similar depth as the weed seed on the experiment in the TD-amended soil support the higher weed inactivation observed. However, the applied digestates did not seem to be unstable enough to produce VFAs at a level significantly increasing weed inactivation.

Educational objectives:

Objective 1. Develop solarization online training materials for urban and rural growers. Online tutorials and lessons will be created to communicate the importance of sustainable agriculture and show how to properly solarize soil.

An engineering activity directly related to soil biosolarization has been done, per-reviwed and published in digital library TeachingEngineering (https://www.teachengineering.org/activities/view/ucd_soil_solarization_lesson01_activity1). In summary, over the course of three sessions, students act as agricultural engineers and learn about the sustainable pest control technique known as soil biosolarization in which organic waste is used to help eliminate pests during soil solarization instead of using toxic compounds like pesticides and fumigants. Student teams prepare seed starter pots using a source of microorganisms (soil or compost) and "organic waste" (such as oatmeal, a source of carbon for the microorganisms). They plant seeds (representing weed seeds) in the pots, add water and cover them with plastic wrap. At experiment end, students count the weed seedlings and assess the efficacy of the soil biosolarization technique in inactivating the weed seeds. An experiment-guiding handout and pre/post quizzes are provided.

In addition, a didactic video describing the field trial of objectives 2 and 3 has been developed and loaded on line. This video shows how to set up a field experiment to assess weed seed inactivation through soil biosolarization.

https://www.youtube.com/watch?v=RzrEy7aAvX4.

Objective 2. Develop solarization and soil science lecture materials for graduate students that can be translated to Excellence Center in the Sustainable City. These lectures will expose graduate students to the fundamental concepts and techniques of soil analysis related to solarization, plant health, pest inactivation, soil microbiology, and sustainability.

Outcomes: Materials are being developed to educate both the general public and STEM graduate students on the fundamental principles and benefits associated with solarization and sustainable soil management. These materials will be delivered as slideshows and video vignettes that can be used both in the classroom and posted online to maximize reach. Figure 4 provides an example of some of these learning materials.

A lecture demonstrating some of the common performance metrics for biosolarization can be accessed at: https://ucdavis.box.com/s/diapw26xxg74kljzcmfvi1mh1yyr1hgj

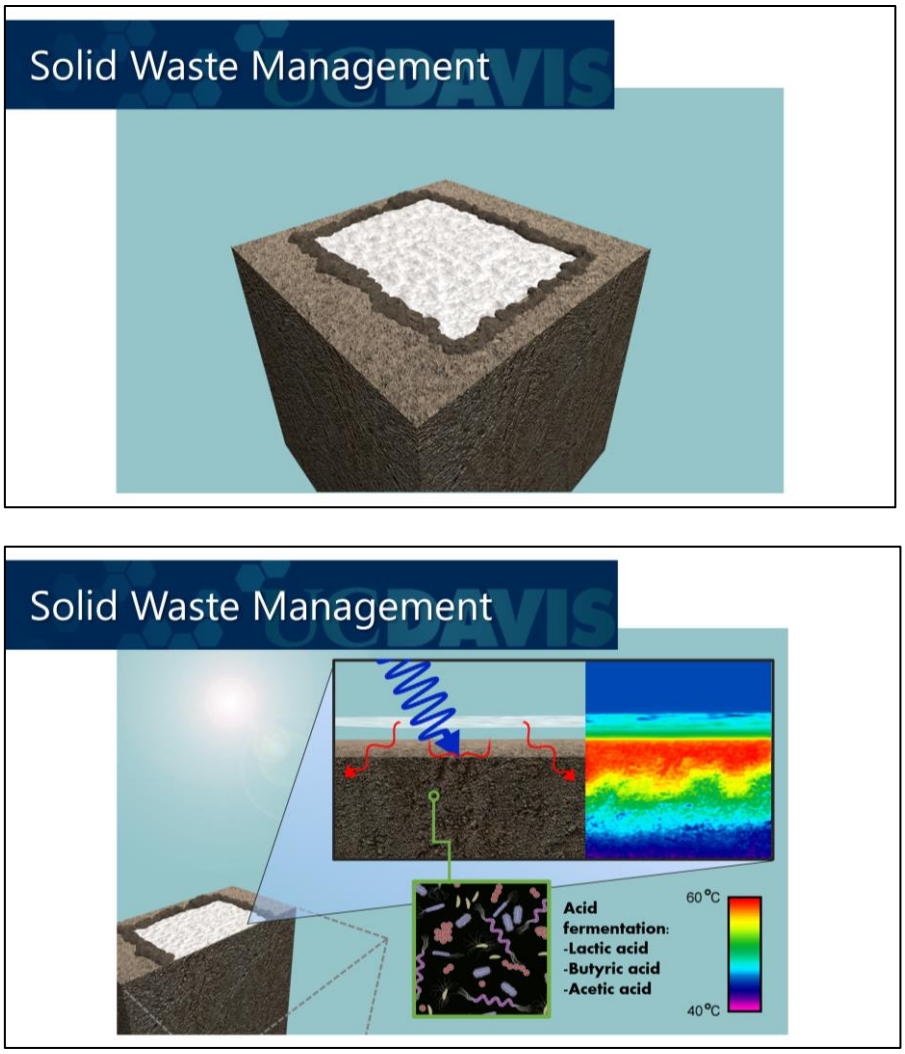

Figure 7. Graphical learning materials to communicate the basic elements and principles behind solarization.

Sustainable City focus:

As part of this work, the composition of the food waste collected at the Tadweer Waste Treatment Facility was considered. Composition data provided by Al Hoty Stranger Laboratories were used (Appendix). The data show that the food waste contains 2% total N, 0.15% P, and 0.50% K (dry weight basis). Although further research is needed to determine how these properties translate to digestates, it can be reasonably assumed that the P and K will be concentrated in the digestate solids as carbon is removed through biogas production. The food waste phosphorus content already exceeds the levels measured in the mesophilic digestate used in this project. As a result, the Tadweer waste digestate should at least deliver the soil P elevation observed in the present study. Furthermore, if the waste K is concentrated by a factor of 1.5 to 2.4 in the digestate, the levels would be comparable to the digestates used in the present study and similar

changes to soil K content would be expected following soil amendment. The translation of the total N in the food waste to the digestate is more difficult to predict since the final digestate level depends on the net effect of concentration of mineralized N versus nitrogen loss via ammonia emissions or denitrification. As the Tadweer food waste total N level is only slightly greater than the total N in the digestates used for the biosolarization study, it is possible that the Tadweer waste digestate will yield similar results to those observed in the present work.

Appendix

AL HOTY - STANGER LABORATORIES

مختبرات الحوطي ستانجر

TEST REPORT

CLIENT **TADWEER WASTE TREATMENT**

CHEMICAL ANALYSIS OF FOOD WASTE

Report date: 29/06/13

Report number	:	D13-158775-1	Source	:	Not given
Project name	:	Quality Assurance	Sample location	:	Not given
Client ref./request no.	:	Not given	Sampled by	:	Client
Sample description as identified by the client	:	Food waste	Sampling date/time	:	Not given
			Sampling method	:	Not given
			Sample delivered by	:	Client
Sample size	:	2 kg	Date/time sample received	:	18/06/13 – 1000 Hrs.
Lot number	:	Not given	Date tested	:	20/06/13 – 25/06/13
Lot size	:	Not given	Tested by / location	:	VK / DXB
Test method	:	Standard Methods of Chemical Analysis by F.J. Welcher			

Results:

PARAMETERS	UNITS	RESULTS
Total Solids	% by weight	41.27
Volatile Solids	% by weight	29.4
Ash Content (on dry basis)	% by weight	34.0
Protein (on dry basis)	% by weight	12.3
Fat Content (on dry basis)	% by weight	9.9
Crude Fiber (on dry basis)	% by weight	6.77
Carbohydrates (on dry basis)	% by weight	37.0

Remarks: None

Test method variation: None

Result relates only to the delivered items tested (if sampling was not carried out by testing laboratory).

Sandeep P.K.
For Al Hoty Stanger Laboratory

O. Mathew, Laboratories Manager
For Al Hoty Stanger Laboratories

CHEM/G/01/02/REV.02

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TEST REPORT

CLIENT **TADWEER WASTE TREATMENT**

CHEMICAL ANALYSIS OF FOOD WASTE

Report date: 31/12/13

Report number	:	D13-169066-1	Source	:	Tadweer Waste Treatment
Project name	:	Quality Assurance	Sample location	:	Aweer
Client ref./request no.	:	Not given	Sampled by	:	Client
Sample description as identified by the client	:	Food waste	Sampling date/time	:	28/12/13 – Not given
			Sampling method	:	Not given
			Sample delivered by	:	Client
Sample size	:	3 kg	Date/time sample received	:	28/12/13 – 1530 Hrs.
Lot number	:	Not given	Date tested	:	29/12/13 – 30/12/13
Lot size	:	Not given	Tested by / location	:	VK / DXB
Test method	:	Standard Methods of Chemical Analysis by F.J. Welcher			

Results:

PARAMETERS	UNITS	RESULTS
Total Solids	% by weight	45.6
Volatile Solids	% by weight	29.8
Ash Content (on dry basis)	% by weight	34.7
Protein (on dry basis)	% by weight	12.5
Fat Content (on dry basis)	% by weight	10.3
Crude Fiber (on dry basis)	% by weight	8.3
Carbohydrates (on dry basis)	% by weight	34.2
Phosphorus (P)	% by weight	0.07
Total Nitrogen (TN)	% by weight	0.91
Potassium (K)	% by weight	0.23

Remarks: None

Test method variation: None

Result relates only to the delivered items tested (if sampling was not carried out by testing laboratory).

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CHEM/G/01/02/REV.02

O. Mathew, Laboratories Manager
For Al Hoty Stanger Laboratories
cc

ALHOTY-STANGER LABORATORY

ISO 9001

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