Hindawi Publishing Corporation
International Journal of Agronomy
Volume 2012, Article ID 368654, 7 pages
doi:10.1155/2012/368654

Research Article

Enhanced Soil Solarization against *Fusarium oxysporum* f. sp. *lycopersici* in the Uplands

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Received 28 March 2011; Accepted 11 November 2011

Academic Editor: David Clay

Soil solarization tests against *Fusarium oxysporum* f. sp. *lycopersici*, the causal agent of tomato Fusarium wilt, were conducted for seven weeks through July and August 2008 and 2009 in the climatic conditions of Al-Aroub Agricultural Experimental Station, located in the southern mountains of the West Bank, Palestine. Double polyethylene (DPE) sheets, regular polyethylene (PE) sheets, and virtually impermeable films (VIF) were compared to examine their effects on soil temperature, disease severity, and plant growth. Results showed that in comparison to the control, PE, DPE, and VIF treatments increased the mean maximum soil temperatures by 10.2, 14.1, and 8.8°C, respectively, in 2008 and by 10.2, 12.6, and 8.3°C respectively, in 2009. The longest length of time recorded for temperature above 45°C under DPE sheets were 220 hours in 2008 and 218 hours in 2009. The treatments reduced the pathogen population by 86% and the disease by 43% under the DPE treatment in 2009 and to a lesser extent by the other treatments. Increases of up to 94% in fresh plant weight and up to 60% in plant dry weight were evident under the same treatment. The treatments also increased soil organic matter, both nitrogen forms, and major cations.

1. Introduction

Soil solarization is a natural hydrothermal process of disinfesting soil of plant pests and pathogens that is accomplished through passive solar heating. Solarization is commercially practiced mainly in areas which are characterized by high summer air temperatures such as the Mediterranean, deserts, and tropical areas and is affected by several factors, including solar irradiation intensity, air temperature, plastic color and type, soil moisture, soil properties, and other factors [1, 2]. The most well-known function of solarization is reduction of soilborne inoculum of plant pathogens including fungi, bacteria, and nematodes by direct thermal inactivation which is achieved at soil temperatures ranging from 40°C to more than 60°C [3]. In addition, soil solarization increases the release of soluble nutrients (inorganic N forms, extractable P, and K, available cations, and dissolved organic matter) due to soil heating, and consequently results in improved plant growth and yield increases [3–8].

Solarization's major drawbacks are its dependence on climate and its ineffectiveness in controlling heat tolerant soilborne pathogens such as *Fusarium oxysporum* f. sp. *lycopersici*, the causal agent of tomato wilt. Many efforts are being made to improve solarization efficiency in controlling soilborne pathogens including integration with a biological control agent, lower dosages of chemical fungicides, organic amendments (composts, plant residues, and green and animal manures), and physical methods (plastic mulch type, and double-layer mulch) [2, 9]. Using a double layer of polyethylene sheets makes soil solarization more feasible in areas with cooler climates and increases soil temperatures 2–5°C more than a single layer [10].

Tomato wilt disease caused by *Fusarium oxysporum* f. sp. *lycopersici* is a serious disease which causes heavy crop losses worldwide. Several management options have been suggested to control the disease, including soil solarization [11, 12]. In Palestinian agriculture, Fusarium wilt is a serious disease of greenhouses and open field crops. Various fungicides and soil fumigants are being used to control the disease, but because of the concern regarding the toxicity and cost of these compounds, there are strong efforts to reduce the amounts applied to soil and to use more environmentally

friendly and cost-effective control options including soil solarization.

The present study aimed to improve the efficiency of soil solarization by using double layers of regular polyethylene sheets compared with regular polyethylene, and virtually impermeable films that contain ethylene vinyl alcohol against *Fusarium oxysporum* f. sp. *lycopersici* populations, and Fusarium wilt severity on tomato planted in the Southern Palestinian Uplands.

2. Materials and Methods

2.1. Soil Preparation and Treatments. Two soil solarization field experiments were conducted for seven weeks from July 6 to August 22, 2008 and from July 1 to August 17, 2009 in Al-Aroub Agricultural Experimental Station of the Faculty of Agriculture, Hebron University, Hebron-Palestinian Authority. The solarized soil was classified as clay soil (28% sand, 13% silt, and 59% clay; pH_{H_2O} 7.3; $EC_{1:2.5}$ (25°C) 0.4 ms cm^{-1}; 22% $CaCO_3$; 2.1% organic matter; 5.2 mg kg^{-1} NH_4^+; 28 mg kg^{-1} NO_3^-; 20.1 mg kg^{-1} P; 2203 mg kg^{-1} Ca^{+2}; 399 mg kg^{-1} Mg^{+2}; 195 mg kg^{-1} K^+; 74 mg kg^{-1} Na^+; 30 mg kg^{-1} Fe^{+3}). The soil was deeply plowed (30 cm) two weeks before starting the experiment and rotovated before mulching. Experimental plots were then irrigated to be 60% water-filled pore space two days before the start of the solarization period. The experimental design was a randomized complete block design with three replicates (plots, 3×4 m) for each treatment. Four treatments were involved: nonsolarized soil (CK), solarized soil using regular polyethylene (PE) sheets (50 μm thick), solarized soil using double polyethylene sheets separated by 2 cm (DPE), and solarized soil using virtually impermeable films that contain ethylene vinyl alcohol (VIF). Two sets of inoculum bags of *Fusarium oxysporum* f. sp. *lycopersici* were incorporated at 20 and 30 cm depths. The treated plots were mulched with PE, DPE, and VIF sheets, while the control plots were left uncovered. After solarization, three soil subsamples were randomly collected from the middle of each plot to a depth of 20 cm. After removing the top 2-3 cm of soil, the subsamples were combined into one composite sample. One set of inoculum bags was sampled 3 weeks after solarization, and the second set was sampled at the end of the solarization period.

2.2. Preparation of F. oxysporum Inoculum. The isolate of *Fusarium oxysporum* f. sp. *lycopersici* used in the experiment was isolated from diseased tomato stem. Diseased stem was sectioned into 3-4 mm pieces, surface-sterilized by immersion in 1% sodium hypochlorite solution for 4 min, and rinsed three times with sterile-distilled water. Two thin pieces of diseased samples were placed in 90 mm Petri dish containing selective peptone pentachloronitrobenzene (PCNB) agar medium [13]. The peptone PCNB agar medium ingredients were 15 g Difco peptone; 1 g KH_2PO_4; 0.5 g $MgSO_4 \cdot 7H_2O$; 20 g agar; 1 g pentachloronitrobenzene (PCNB, 75% WP); 1 mL Lactic acid; 0.5 g Chloramphenicol; 1 L distilled water. The ingredients were mixed and dissolved, and the pH was adjusted to 4.5, and the medium were autoclaved. Seven-day-old growing fungal hyphae were further subcultured on potato dextrose agar (PDA) medium amended with 300 mg L^{-1} chloramphenicol. A single-conidium culture was prepared and subcultured, and one of the growing colonies was used to inoculate further Petri dishes. Petri dishes were then incubated for 40 days in the growth chamber at 25°C, with 12 hours photoperiods. The dried paste made of the fungal growth in the growing media was used to prepare the chlamydospore inoculum. Forty days were enough for most of the mycelial cells to develop into chlamydospores. The chlamydospore inoculum was ground and mixed in dry sandy soil and propagules measured as CFU g^{-1} using the dilute plate technique: 2.5 g of previously prepared soil inoculum were placed in 23 mL distilled water (1 : 10), and 0.2 mL of the suspension were spread on each of the six Petri dishes containing 15 mL of selective peptone-PCNB agar medium prepared earlier. The Petri dishes were then incubated at 25°C under darkness for three days and under natural room light for 4 days. The numbers of *Fusarium* colonies were counted and the mean inoculum concentration was calibrated to 1260 CFU per 1 g of the dry inoculum-sandy soil mixture. Twenty grams of prepared soil inoculum were placed in each muslin bag. Small muslin bags containing the inoculum were closed with plastic silks and incorporated in experimental plots at a depth of 20 and 30 cm (as mentioned earlier) in both seasons experiments [14].

2.3. Estimation of F. oxysporum Population after Solarization. The population of *F. oxysporum* in the muslin bags buried earlier in solarized and nonsolarized plots in both seasons were assessed after 3 weeks of solarization and at the end of the solarization period. The pathogen population in the muslin bags was measured as CFU g^{-1} by using the dilute plate techniques on selective peptone-PCNB agar medium [13]. Soil dilutions were prepared by taking 2.5 g of soil in 23 mL of sterilized distilled water (1 : 10); 0.2 mL of the suspension was spread on each Petri dish. Petri dishes were incubated at 25°C under darkness for three days and under natural room light for 4 days. The number of propagules grown was counted and calculated as CFU per gram soil. The experimental design was completely randomized with five replicates (Petri dishes) seeded with dilutions of soil sampled earlier at 20 and 30 cm depths.

2.4. Disease Severity. Fusarium wilt (%) of tomato plants growing in solarized and nonsolarized soils was evaluated after 3 weeks of solarization and at the end of the solarization period (7 weeks). Under each experimental plot, three soil subsamples were randomly collected to a 20 cm depth and mixed thoroughly to make one composite sample. Seventeen grams of the inoculum bags were added to the respective soil sample taken from each plot for each sampling period. Each 500 g composite soil sample amended with the inoculated soil from bags from each experimental plot was divided into 5 small planting pots, each containing 100 g of soil. In each pot, a plastic grid was placed in the bottom to keep the soil in and a 20 mL of autoclaved perlite were added to permit excess water to drain. Tomato seeds (3–5) were then seeded in each pot and a layer of autoclaved perlite

was added to cover the top. After emergence, the number of seedlings was reduced to two per pot. Plants were then incubated in a growth chamber at 25°C, with 15 hours photoperiods. Plants were irrigated regularly with deionized water. The number of wilted plants was recorded weekly from week 3 to week 10 after sowing. The accumulated number of wilted plants was documented and the percentage of wilt was calculated. A completely randomized design was used with five replicates. The same parameters were measured in the same manner for the second solarization experiment.

2.5. Plant's Growth Evaluation. Three soil subsamples were randomly collected from the upper 20 cm of each experimental plot. After removing the top 2-3 cm of soil, the subsamples were mixed thoroughly to make one composite sample. Each composite soil sample (1 kg) was incorporated in 5 pots (replicates). Tomato seeds (3–5) were then seeded in each pot. After emergence, the number of seedlings was reduced to 1 per pot. Plants were then incubated under greenhouse conditions at 25°C for two months. Plants were irrigated daily and the plant's fresh and dry weights were evaluated at the end of the experiment. A completely randomized design was used with five replicates (pots).

2.6. Soil Temperature. The soil temperature was recorded by HOBO data loggers (Onset Computer Corporation, Bourne, USA) during the two solarization periods. The loggers were set to take a reading every 40 minutes during the solarization period at the depth of 15 cm in the middle of all experimental plots. The loggers were removed at the end of the period, and the data downloaded using the BOXCar version 3.7 software (Onset Computer Corporation, Bourne, USA).

2.7. Soil Analysis. Composite soil samples (1000 g) were collected from the center of experimental plots at the end of the experiment. Soil samples were oven dried at 105°C for 24 h. Dry soil samples were then sieved (2 mm) and the fine soil was used for chemical analysis (pH_{H_2O}, $EC_{1:2.5}$, $CaCO_3$, organic matter, NH_4^+, NO_3^-, P, Ca^{+2}, Mg^{+2}, K^+, Na^+, and Fe^{+3}). The soil pH and EC were evaluated in water extracts (1 : 2.5, w/v) by pH meter (pH meter 3305, Jenway, UK) and conductivity meter (4010 conductivity meter, Jenway, UK). Calcium carbonate was evaluated using a calcimeter (Calcimeter, Eijkelkamp, Germany). The organic matter was evaluated by acidic wet oxidation with potassium dichromate according to the Walkley-Black wet combustion method [15]. The exchangeable ammonium and nitrate were evaluated according to the methods described by Keeney and Nelson [16]. Available phosphorus was measured by using the molybdate ascorbic acid method [17]. Exchangeable calcium, magnesium, sodium, and potassium were evaluated by the neutral ammonium acetate (pH = 7) method. Air-dry soil samples were ground and sieved using a 20-mesh sieve; 2.5 g of soil were placed in 125 mL Erlenmeyer flasks and 25 mL of 1 N ammonium acetate, pH 7 were then added. Flasks were shaken for 15 min, and the solutions were filtrated and analyzed by flame atomic absorption (A Analyst 100, Perkin Elmer). The concentrations of cations were calculated using standard curves as mg kg^{-1} [18].

2.8. Statistical Analysis. The data were statistically analyzed using one-way repeated analysis of variance (ANOVA). Fishers LSD test ($P \leq 0.05$) was used for mean's separation (Sigma Stat 2.0 program, SPSS Inc., USA).

3. Results

3.1. Soil Temperature. Soil temperature was greatly increased in solarized soil treatments compared with the control (Table 1 and Figure 1). The means of maximum soil temperatures (°C) recorded during the solarization period were 32.6, 42.8, 46.7, and 41.4 during 2008 and 35.3, 45.5, 47.9, and 43.6 during 2009, under the control, PE, DPE, and VIF treatments, respectively. The means of maximum soil temperatures increased by 10.2, 14.1, and 8.8 during 2008 and by 10.2, 12.6, and 8.3 during 2009 under the same treatments, respectively, compared with the unsolarized control treatment. The double layer treatment (DPE) increased the mean of maximum temperature by 3.9 and 2.4°C during 2008 and 2009, respectively, compared to the one layer regular polyethylene sheet treatment (PE) and by 5.3 and 4.3°C during the 2008 and 2009, respectively, compared to the VIF sheet treatment. The number of hours recorded for the sublethal temperature class (45–50°C) were 220 h (19.1%) and 218 h (18.9%); 17 h (1.4%) and 28 h (2.4%); 5 h (0.4%) and 36 h (3.1%) under the DPE, PE, and VIF sheet treatments during 2008 and 2009 seasons, respectively, compared to the total solarization time. The absolute maximum soil temperatures measured during the solarization periods were 50.1°C and 49.3°C recorded under the DPE sheets in the summers of 2009 and 2008, respectively.

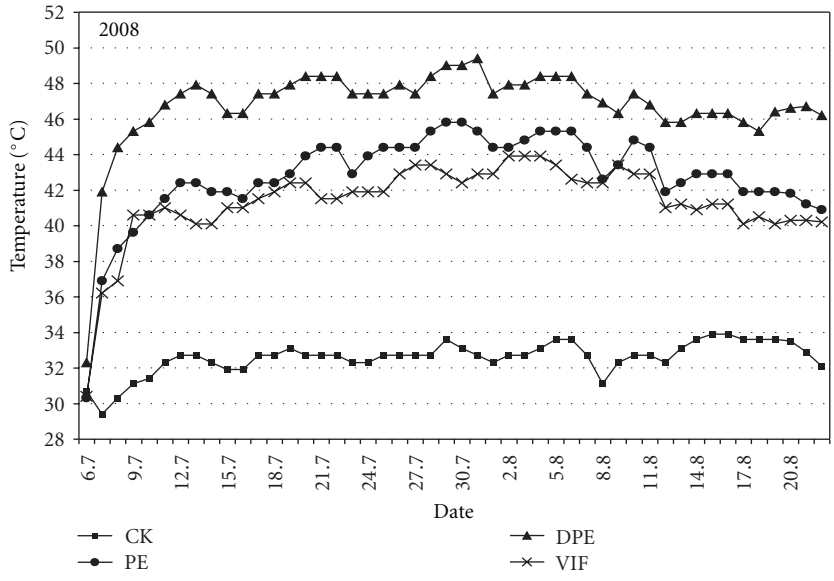
3.2. Pathogen Population and Disease Severity. After seven weeks of solarization, the population of *F. oxysporum* (CFU) in soil was reduced significantly at the depth of 20 cm by 44%, 53%, and 43% in 2008 and by 61%, 86%, and 60% in 2009 when PE, DPE, and VIF solarization sheets were used, respectively, compared with the control (Table 2). The highest reduction of pathogen population at both soil depths was obtained under DPE sheets during 2009 after 7 weeks of solarization.

Three weeks of soil solarization was not significantly effective in reducing Fusarium wilt (%) in either year. However, the disease was reduced significantly by 32%, 39%, and 25% during 2008 and by 30%, 43%, and 30% during 2009 when PE, DPE, and VIF sheets were used, respectively, compared with the control after seven weeks of solarization. The double polyethylene sheet recorded the highest disease reduction compared to control after seven weeks of solarization (Table 3).

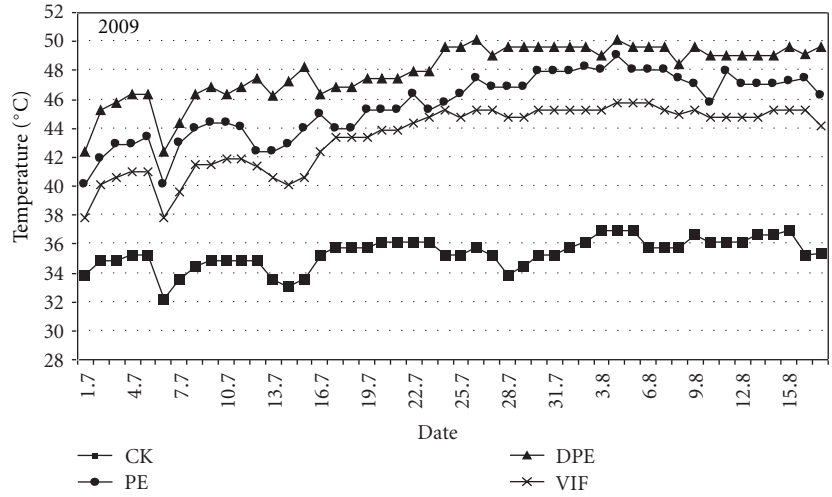
3.3. Plant's Growth. Soil solarization significantly increased fresh and dry weights of tomato plants in both seasons. Fresh

Table 1: Number of hours for different temperature classes recorded under solarization treatments (control (CK), regular polyethylene (PE), double regular polyethylene (DPE), and virtually impermeable films (VIF)) during July 6-August 22, 2008 and July 1-August 17, 2009 in Al-Aroub Agricultural Research Station, South of the West Bank.

Temperature class	Number of hours (2008)				Number of hours (2009)			
	CK	VIF	PE	DPE	CK	VIF	PE	DPE
<30°C	730	47	67	41	670	200	103	22
30–35°C	422	401	430	328	383	384	457	408
35–40°C	0	410	362	296	99	310	289	262
40–45°C	0	289	276	267	0	222	275	242
45–50°C	0	5	17	220	0	36	28	218
Total (hours)	1152	1152	1152	1152	1152	1152	1152	1152
Min (°C)	20.9	26.1	23.1	23.7	20.5	23.2	24	23.6
Max (°C)	33.1	43.9	45.8	49.3	36.6	49.6	45.8	50.1
Average of Max.	32.6	41.4	42.8	46.7	35.3	43.6	45.5	47.9



(a)



(b)

Figure 1: Maximum temperatures recorded under solarization treatments, regular polyethylene (PE), double regular polyethylene (DPE), virtually impermeable films (VIF), and nonsolarized soil (CK) from July 6-August 22, 2008 and July 1-August 17, 2009 in Al-Aroub Agricultural Research Station, South of the West Bank.

Table 2: Effect of solarization with regular polyethylene (PE), double regular polyethylene (DPE), and virtually impermeable films (VIF) on population of *Fusarium oxysporum* f. sp. *lycopersici* in soil.

Treatments	2008				2009			
	Solarization period (weeks)							
	3		7		3		7	
	20 cm	30 cm	20 cm	30 cm	20 cm	30 cm	20 cm	30 cm
CK	1233* ab	1563 ab	1242 a	1270 a	1132 a	1249 a	1176 a	1209 a
PE	923 b	1067 b	694 b	628 bc	766 ab	877 ab	458 bc	804 b
DPE	950 b	940 b	582 bc	528 bc	642 ab	603 b	161d	174 d
VIF	1150 b	1050 bc	708 b	644 bc	804 ab	1078 ab	470 cd	679 c
	LSD = 534				LSD = 514			

* Values are means of *F. oxysporum* f. sp. *lycopersici* (CFU/g soil) of 3 soil sub-samples, each planted on five Petri dishes.

Table 3: Effect of solarization with regular polyethylene (PE), double regular polyethylene (DPE), and virtually impermeable films (VIF) on Fusarium wilt (%) caused by *Fusarium oxysporum* f. sp. *lycopersici*. (LSD = 11).

Treatments	2008		2009	
	Solarization period (Week)			
	3	7	3	7
CK	58 a	65 a	56 a	63 a
PE	46 a	33 c	51 a	33 bc
DPE	46 a	26 cd	40 ab	20 d
VIF	50 a	40 b	46 ab	33 bc

weights (%) increased by 37, 94, and 56, while dry weights (%) increased by 38, 60, and 57 under PE, DPE, and VIF treatments, respectively, compared to control in 2008. In 2009, plant fresh weights (%) increased by 46, 77, and 61, while dry weights increased by 46, 76, and 60 in PE, DPE, and VIF treatments, respectively, compared to the control (Table 4). The highest increase in plant growth was recorded under the DPE treatment and significant variation between solarization treatments was not observed.

3.4. Soil Chemical Properties. The solarization treatments significantly affected the soil pH, EC, organic matter, available ammonium, nitrate, calcium, magnesium, and potassium. Calcium carbonate, phosphorus, and iron were not affected (Table 5). The solarization treatment PE, DPE, and VIF slightly increased the pH by 4.1%, 5.5%, and 4.1% during 2008 and by 8.2%, 6.8%, and 4.1% during 2009, respectively, compared to the control. In addition, the solarization treatments increased the EC values by 50%, 200%, and 75% during 2008 and by 125%, 225%, and 250% during 2009, respectively, compared to the control.

The PE, DPE, and VIF solarization treatments stimulated the decomposition of organic matter and reduced the percentage of organic matter in soil by 19, 42, 33 percentage during 2008 and by 32, 45, 45 percentages during 2009 respectively, compared to the control. In addition, the available ammonium increased significantly by 2-3-fold and the nitrate by 1-2-fold during the solarization treatment in both seasons.

At the same treatments, available calcium (%) increased by 65, 67, and 76% during 2008 and by 65, 69, and 62% during 2009 respectively, compared to the control. Available magnesium was increased by 12, 13, and 14%, respectively, during 2008 and by 10 and 14% under DPE and VIF, respectively; the PE treatment has not affected Mg^{+2}. Available potassium in the treated soils, increased by 100, 112, and 125% during 2008 and by 103, 120, and 111%, during 2009, respectively, under the three solarization treatments.

4. Discussion

Soil solarization is considered a relatively mild heating treatment for disinfesting soils where the population of soilborne pathogens including *Fusarium oxysporum* f. sp. *lycopersici* is reduced. The results showed significant reduction in pathogen population at the soil depths of 20 and 30 cm after seven weeks of two solarization periods under all treatments compared with the control; the highest reduction was observed under DPE treatment mainly during the 2009 solarization. In addition, tomato wilt was significantly (LSD = 11, $P \leq 0.05$) reduced after seven weeks of solarization, but was not affected after three weeks using all types of solarization sheets in both seasons. Both pathogen population and disease reduction were negatively correlated to soil temperatures recorded under solarization treatments. The mean maximum temperature increase over the control was in the range of 8.8–14.1°C in 2008 and 8.3–12.6°C in 2009. In addition, the number of hours recorded for temperatures above 45°C under VIF, PE, and DPE was 5, 17, and 220 hours for the 2008 season and 36, 28, and 218 hours, for the 2009 season, respectively. Similar results were obtained by Tamietti and Valentino, [12] in which significant reduction in Fusarium wilt of melon (*Fusarium oxysporum*

Table 4: Effect of solarization with regular polyethylene (PE), double regular polyethylene (DPE), and virtually impermeable films (VIF) on tomato plant fresh and dry weights (g plant^{-1}).

Treatments	2008		2009	
	Weight (g plant^{-1})			
	Fresh	Dry	Fresh	Dry
CK	88.1* c	11.6 b	97.6 b	13.2 b
PE	121.2 b	16 a	143 a	19.3 a
DPE	171.7 a	18.6 a	172.7 a	23.3 a
VIF	138.2 a	18.2 a	157.1 a	21.2 a
LSD ($P \leq 0.05$)	37.2	4.8	45.3	6.1

* Data are means of fifteen replicates; means followed by the same letter in colums are not significantly different according Fisher LSD test at ($P \leq 0.05$).

Table 5: Effect of solarization with regular polyethylene (PE), double regular polyethylene (DPE), and virtually impermeable films (VIF) on chemical properties of soil.

Chemical propreties	2008					2009				
	Treatments					Treatments				
	CK	PE	DPE	VIF	LSD	CK	PE	DPE	VIF	LSD
pH_{H_2O}	7.3* b	7.6 a	7.7 a	7.6 a	0.21	7.3 c	7.9 a	7.8 ab	7.6 b	0.26
EC (ms)	0.4 c	0.8 b	1.2 a	0.7 b	0.25	0.4 c	0.9 b	1.3 a	1.4 a	0.14
$CaCO_3$ (%)	22 NS***	23 NS	23 NS	22.3 NS		22 NS	23 NS	23 NS	22.3 NS	
O.M (%)	2.1 a	1.7 ac	1.2 b	1.4 bc	0.38	2.2 a	1.5 b	1.2 b	1.2 b	0.42
NH_4^+	5.2 b	13.1 a	14 a	14.4 a	4.41	5.3 b	10.7 a	12.2 a	12.1 a	4.24
NO_3^-	28 b	48 a	48 a	49 a	9.88	27 b	42 a	46 a	47 a	11.2
P	20.1 NS	20.7 NS	24.3 NS	23.1 NS		20 NS	20 NS	21 NS	21 NS	
Ca^{+2}	2203 b	3642 a	3694 a	3890 a	396	2136 b	3542 a	3627 a	3470 a	667
Mg^{+2}	399 b	449 a	450 a	455 a	44.5	399 b	415 b	439 b	455 a	30.6
K^+	195 b	390 a	413 a	439 a	109	191 b	388 a	421 a	403 a	80.9
Na^+	74 b	146 b	311 a	162 b	100	78 b	160 b	280 a	154 b	117
Fe	30 NS	32 NS	38 NS	36 NS		32 NS	30 NS	36 NS	33 NS	

* Data are means of three replicates; means followed by the same letters in rows are not significantly different according Fisher LSD ($P < 0.05$).
**The concentrations of NH_4^+, NO_3^-, P, Ca^{+2}, Mg^{+2}, K^+, Na^+ and Fe are in mg kg^{-1}.
***NS: not significant.

f. sp. *melonis*) was negatively correlated with the number of hours of soil temperatures above 40°C; the number of hours recorded for the temperatures above 40°C was 234 hours at the depth of 25 cm. The reduction in pathogen population may be due to increased temperature killing the pathogen directly or due to increased temperatures weakening the pathogen with sublethal heat, rendering it in capable of inducing crop damage [10].

Furthermore, it was evident that solarization stimulated fresh and dry weights of tomato plants in both seasons. Fresh weights increased by 37–94% and dry weights by 38–60% in 2008 and 2009, respectively, compared to control. The highest increase was recorded under the DPE treatment. The stimulation of tomato plant growth may be related to the decomposition of organic matter and the increase of available ammonium and nitrate and available calcium, magnesium, and potassium in solarized soils. Increases in mineral nutrients such as ammonium and nitrate can be attributed to the decomposition of organic components of soil during treatment, while other minerals, such as calcium, magnesium, and potassium may have been virtually cooked of the mineral soil particles undergoing solarization. Similar increased growth responses (IGRs) of several plant systems grown under solarized soils have been observed in other studies [3–8, 19]. In addition, Stapleton and DeVay [20] reported that the concentrations of NH_4 and NO_3 in the top 15 cm of solarized soil were increased and the concentrations of other soluble mineral nutrients, including calcium, magnesium, phosphorus, potassium, and others increased, but less consistently. IGR can be attributed to a number of mechanisms, including the increase in nutrient levels in soil solution, stimulation of beneficial microorganisms, and the control of minor pathogens [3, 4].

Solarization treatments slightly increased soil pH during both seasons, compared with nonsolarized soils. The light increases in soil pH may be due to an increase in the concentrations of some mineral nutrients such as calcium, magnesium, and potassium which are released from the mineral soil particles undergoing solarization and have alkaline buffering action. On the other hand, some studies reported that solarization can decrease pH [3, 19]. In addition, solarization significantly increased the EC of soil extract, probably due to the increase in nutrient minerals after solarization.

In conclusion, double layers of polyethylene sheets enhanced the positive effect of solarization in terms of disease reduction and plant growth improvement, which was only possible by a better elevation of soil temperature during the solarization period. This enhancement will definitely open doors for a wide use of the technique in regions characterized with lower average temperatures than those traditionally used for solarization over the years.

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