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Variation of the Soil Thermal Properties with Different Applications in Greenhouse Solarization

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Solarization technology allows for improving soil quality as well as crop productivity. The efficiency of this technique is closely linked to soil thermal properties. Therefore, this study investigated the effects of different applications (dry-ice application (CO_2), basaltic tuff (BT), various colored PE (VCPE), organic matter (OM)) on soil thermal properties. The research was conducted in greenhouses covered by three plastic types (normal PE – Greenhouse 1; UV+IR stabilized PE – Greenhouse 2; UV stabilized PE – Greenhouse 3) in the Çukurova region of Turkiye. Soil thermal diffusivity (D), a key heat transfer parameter that expresses the temperature gradient, was derived using soil temperature in the heat-amplitude equation. The means of the highest maximum soil temperatures at depths of 5, 20 and 30 cm were 54.3 °C (VCPE – Greenhouse 1), 46.2 °C (VCPE – Greenhouse 2) and 43.6 °C (BT – Greenhouse 2) for both years, respectively. The highest average values of $\overline{D}_{5\text{-}30cm}$ were 65 $cm^2\ h^{-1}$ with CO_2 application, followed by 47 $cm^2\ h^{-1}$ with BT, and 39.8 $cm^2\ h^{-1}$ under OM+CO_2. The $\overline{D}_{20\text{-}30cm}$ was higher than those of the upper layer. Notably, the increase in heat emission towards the sub-soil layers under BT and OM was significant ($P < 0.05$). OM, VCPE and BT treatments can be used successfully to increase the effectiveness of solarization. Additionally, Cv values increased in a linear relationship with the increase of soil water content. The thermal conductivity (K) increased as the soil water content approached field capacity and decreased when saturation levels were reached. This indicates that maintaining soil water content at saturation levels is not effective for solarization applications.
Keywords: Soil solarization,soil temperature, soil thermal properties, heat-amplitude equation, greenhouse.

INTRODUCTION

Global awareness on environmental issues has diversified the use of solar energy in agriculture. In intensive cultivation areas (such as greenhouses), soil fertility rapidly declines after the second year. This decline results from the biological imbalance of the soil due to the rapid reproduction of certain pests and microorganisms. Alongside organic farming practices, the ban on the use of pesticides *(MeBr and derivatives)* to combat these pests has led to a tendency to alert pest control programs or adopt new alternative application (Carrieri *et al*., 2013; Katan, 2017; Morra *et al*., 2018). In recent years, solarization a basic, integrated, non-toxic control method hav been widely used (Al- Shammary *et al*., 2016; Simmons *et al*.,2016; Jagtap *et al*., 2022; Wolie, 2024). Although pests cannot be completely eradicated in areas where solarization is applied; sufficient crop cultivation can be ensured by significantly reducing the number of pests within the plough layer (50-60 cm).

Soil solarization is an environmental friendly disinfestation treatment that has used in temperate regions during periods of high temperature to improve the subsequent yield and quality of vegetable crops, and reduce chemical use. It is a hydro-thermal process, as solar radiation is trapped in soil covered by a thin transparent plastic film, which uses direct sunlight to raise the soil temperature sufficiently to control soil-borne pests and pathogens (Martínez-Escudero *et al*., 2022). It is beneficial in terms of environmental sustainability and shows good synergism in combination with various organic amendments because of its effectiveness in controlling root-knot nematode in greenhouse vegetable crops, compared to single treatments (Oka *et al*., 2007). Organic matter is a crucial soil component in maintaining physical, chemical and

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biological equilibrium in soils, and can restore fertility in soils depleted of organic content.

The efficiency of solarization under various climate conditions is correlated with several factors, including the amount of radiant energy on plastic cover (PE), the thermal properties of the cover material, properties of organic materials added in soil, the duration of solarization, ambient temperature, soil-water content and variations in thermal conductivity and heat storage of the soil (Ioannou, 2000; D'Addabbo *et al*., 2010). Solarization efficiency is also influenced by nematodes, soil-borne disease factors and temperature-induced mortality rate of microorganisms. Solarization efficiency can be improved with new methods like incorporating organic materials into the soil to increase and retain heat.

Organic amendments increase soil heat and temperature (Komariah *et al*., 2011). Abu-Hamdeh and Reeder (2000) reported that adding turf into the soil decreased thermal conductivity. Several other researchers have studied the effects of water content and bulk density on thermal properties (Labance *et al*., 2006; Castello *et al*., 2017; Ahmed *et al*., 2017). Some model studies, effects of soil water contents altered thermal properties of the soil (Hu *et al*., 2016; Liang *et al*., 2017). To eradicate pests in deeper soil layers by increasing thermal sensitivity, soil-water content is maintained above field capacity. A novel approach of enriching CO_2 content in the environment and increasing heat flux into the soil has resulted in higher maximum soil temperatures, thereby shortening LD_{90} periods (Al-kayssi, 2009). On the other hand, it was found that the temperature of the soil top layer remained over 60.8 °C for different periods under solarization covers with good thermal properties (EVA, COE and BIO) due to advancements in mulch film properties; thus, the thermal regime was positively affected (Scopa *et al*., 2008).

Solarization efficiency of different applications should be analyzed in terms of how effectively they increase soil thermal conductivity. Thermal conduction is influenced by thermal conductivity (K) and thermal diffusivity (D) and when one of the parameters is known, the other can be easily determined using the formula $D(\theta) = K(\theta)/C_v(\theta)$. In this study, effects of various significant and new applications (dry ice (CO_2), basaltic tuff (BT), UV+IR reinforced cover material (VCPE), organic matter (OM), dry ice-supplemented organic matter ($OM+CO_2$)) on soil thermal diffusivity were investigated. To compare the effectiveness of this applications in improving solarization efficiency, thermal diffusivity (D) was determined under field conditions, and application activities were quantified numerically. Additionally, the relationships of thermal properties with soil water content and bulk density under solarization applications were examined.

MATERIAL AND METHODS

Experiments were conducted over the agricultural fields of Agricultural Experimental Station, at Cukurova University, Adana located in southern Turkey (37º 00´ 50´´ N, 35º 21´ 18´´ E; 32 m altitude) during July and August of the years of 2008 and2009. The research area is 20 m above sea level.

The study area has a dominant Mediterranean climate, characterized by hot and dry summers and mild and rainy winters. The long-term average temperature is 18.8ºC, with August being the hottest month with 28.1ºC and January is the coldest month at 9.9ºC. Total precipitation is 649.5 mm, almost all of which is occurs during winter months. Relative humidity generally reaches high values in summer months due to increased temperatures and initiated irrigations of agricultural lands. Decreased relative humidity values are encountered in winter months. The long-term average relative humidity is approximately 66%. Long-term average wind speed is 1.7 m s^{-1}. The variation of the vapor-pressure deficit values throughout the year is similar with the relative humidity and temperature. The long-term annual potential evapotranspiration is 1572 mm.

A Davis-Vantage Pro2 mini meteorology station located in the experimental area was used to measure the meteorological data. Measurements included air temperature, wind speed and direction, precipitation, total radiation and relative humidity. Particularly during the summer of 2008, changes in indoor and outdoor air temperature of the greenhouse over approximately one month are presented in Table 1 as the average of daily average temperature values. The research involved greenhouses covered with three different types of cover materials: normal PE (Greenhouse-1), UV+IR stabilized PE (Greenhouse-2), and UV stabilized PE (Greenhouse-3). As shown in the One-way ANOVA test (Table 1), no significant temperature differences were observed in three greenhouses. Experimental treatments are provided in Table 2.

Table 1. ANOVA results for greenhouse temperatures

Source of variation	Degrees of freedom	Sum of squares	Mean square	F-value
Applications	3	1064.58	354.86**	140.93
Error	108	271.94	2.52	
Total	111	1336.52		
Multiple comparison				
Applications	Mean	Groups		
Out of greenhouse	32.564	b		
Greenhouse 1	39.179	a		
Greenhouse 2	40.393	a		
Greenhouse 3	39.211	a		

LSD: 0.83

** Significant at the 1% probability level

Table 2. Experimental treatments

Treatments	Description
CO_2	0.5 kg m^{-2} CO_2 (dry ice or gaseous)
BT	Basaltic tuff on soil (5 kg m^{-2}, <5mm)
VCPE	Covering with cover material of different color and thickness (UV+IR)
OM	OM addition (1.5 kg m^{-2})
OM+ CO_2	Equal addition of CO_2 and OM
PE	Normal solarization
Control	Soil temperature application to be monitored in the greenhouse.

During the solarization process, experimental plots were covered with a double leyer (40 microns) of 20-microns PE cover material for mulching. Additionally, UV+IR reinforced and yellow PE cover material were used for one of the plots. The plots were each 2 x 2 meters in dimension. The greenhouse soil was located in the transition zone of Arıklı and Menzilat series. Soil chemical and physical properties are provided in Tables 3a and 3b.

Gülez and Şenol, (2002) identified the Menzilat-Arık transition zone soils. To provide some information, transition zone soils are deep soils formed from A-C horizons, with the dominant texture up to the C horizon being clay, while in the C horizon, it is silty clay. The clay content is less than that of the Arık series. In the Menzilat series, the soils are flat, well-drained, with medium texture, and the stony surface layer makes the soil unworkable (soil tillage) and reduces its water-holding capacity. It is observed that the clay content of the study area soils is 43-44%, and the TK values of 27-30% (at 0.33 bar) are compatible (Tables 3b and 4).

While forming the plots, the soil was tilled to a depth of 30-35 cm before mulching. The soil surface was leveled (large land pieces and plant wastes were removed). Materials to be added to the plots were mixed into the soil and a drip system was installed. The plots were irrigated as to have the saturated soil depth of 30 cm. Afterwards, the mulching process was performed with PE cover (Katan and De Vay, 1991).

Soil temperatures were monitored by PT-100 temperature sensors in 5, 20 and 30 cm depth. The sensors were placed near the center of the plots for elimination of border effect. Cables were connected to three 32-channel Elimko scanner devices and measurements were recorded on a main computer at 15 minutes intervals. Soil-water content was monitored with a TDR (6050X3K1 Mini Trase Kit) device. When the water content decreased from saturation to field capacity, drip irrigation system was used to restore it to saturation. For this purpose, the basic hydro-physical properties of the soil were studied. The amount of water required to saturate the plots was determined using the soil water characteristic of the study area soils (Table 4) and considering the existing water content.

To monitor outdoor soil water contents, similar plots were also generated outdoor. They were saturated and covered with PE. During the outdoor solarization process, soil water content was measured with TDR and tensiometer devices that had been specifically calibrated for greenhouse soils.

During the study, soil temperatures, maximum and minimum temperatures in mentioned depths (5, 20 and 30 cm) and greenhouse indoor ambient temperatures were monitored.

Table 3a. Soil chemical properties

Depth (cm)	Organic matter (%)	pH (1:1)	Salinity (%)	Lime (%)
0-10	1.72	7.72	0.058	38.5
10-20	1.79	7.68	0.055	38.6
20-30	1.66	7.66	0.052	38.6

Table 3b. Soil physical properties

Depth	Clay	Silt	Sand	Texture class	Bulk density	Hydraulic conductivity	Porosity (%)		
(cm)		%			(g cm^{-3})	(cm sa^{-1})	Total	Micro	Macro
0-10	44.3	37.8	17.9	C	1.26	0.15	51.57	27.79	23.78
10-20	43.4	36.5	20.1	C	1.27	0.14	50.16	28.52	21.64
20-30	43.3	36.6	20.1	C	1.30	0.13	48.02	30.26	17.76

Table 4. Soil water characteristics

Depth (cm)	0.01	0.1	0.33	0.5	0.75	1	15
				(bar)			
0-10	51.57	31.03	27.79	26.88	26.18	25.66	18.68
10-20	50.16	31.08	28.52	27.53	26.99	26.30	18.57
20-30	48.02	33.22	30.26	29.25	28.53	27.83	19.02

Thermal properties (thermal diffusivity, thermal conductivity and volumetric heat capacity) and temperature amplitude were calculated. Mathematical equations including sine curve solution of soil temperature were used to define various properties related to heat transfer of soil and the thermal properties of the soil were determined.

Theoretical considerations:

The equation describing heat transport in soils is given as,

$$\frac{\partial T}{\partial t} = D\frac{\partial^2 T}{\partial z^2} \qquad (1)$$

where D is the thermal diffusivity ($cm^2.sa^{-1}$), T is the temperature (°C), z is the soil depth (cm) and t is the time (h) (Kirkham and Powers, 1972). The equation is valid for the following conditions:

1. Soil profile is uniform,
2. Both thermal diffusivity and conductivity are assumed to be constant.

Solution of Eqn. (1) for the following initial and boundary conditions

$$T_{(z,t)} = A \sin \omega t \quad z = 0,\ t \geq 0 \qquad (2)$$

$$lim_{z\to\infty} T(z,t) = 0 \quad t \geq 0 \qquad (3)$$

is given as

$$T_{(z,t)} = \overline{T}_{(z)} + A\, exp^{-z\left(\frac{\omega}{2D}\right)^{1/2}} \cdot sin\left[\omega t - \left(\left(\frac{\omega}{2D}\right)^{1/2} z\right) - \pi/2\right] \qquad (4)$$

Amplitude of temperature changes for different soil depths can be deduced from Eqn. (4) as

$$A(z=0) = A_0$$

$$A(z=z_1) = A_1 = A\, exp^{-z_1\left(\frac{\omega}{2D}\right)^{1/2}}$$

$$A(z=z_2) = A_2 = A\, exp^{-z_2\left(\frac{\omega}{2D}\right)^{1/2}}$$

The ratio of the amplitudes at two different depths (z_1 and z_2)

$$\frac{A_1}{A_2} = \frac{\exp^{-z_1\left(\frac{\omega}{2D}\right)^{1/2}}}{\exp^{-z_2\left(\frac{\omega}{2D}\right)^{1/2}}}$$

yields the equation

$$D = \frac{\omega}{2}\left[\frac{z_2 - z_1}{ln\left(\frac{A_1}{A_2}\right)}\right]^2 \qquad (5)$$

which can be used for calculation of soil thermal diffusivity (Kırda and Sarıyev, 2002). In the equation $A_1 = T_{max,1} - \overline{T}(z_1)$; $A_2 = T_{max,2} - \overline{T}(z_2)$, $T_{max,1}$ and $T_{max,2}$ are the amplitudes at depths z_1 and z_2 , respectively.

Later thermal conductivity λ ($cal.cm^{-1}.°C^{-1}$) was calculated using the equation

$$\lambda = C_v.D \qquad (6)$$

where C_v is volumetric heat capacity ($cal.cm^{-3}$ °C) which is a function of soil water content (θ) and soil mineral matter (X_m), soil organic matter content (X_o) as was shown in the equation $C_v = 0.46 * X_m + 0.60 * X_o + \theta$ (Hanks and Ashcroft, 1980).

Differences between temperature and thermal diffusivity values obtained from the treatments were determined with LSD (Least Significant Difference) test at a 5% significance level, with the aid of One-way ANOVA test and Minitab statistics package.

RESULTS

***Soil temperature*:** Cumulative values of mean soil temperatures were used to find the differences between experimental treatments. In 2008, the most efficient temperature increase was observed in OM plots (Table 5). BT, VCPE, OM+CO_2 and PE treatments were also found to be effective. However, effects of CO_2 treatments were lower in most cases, though it was high in control plots. This application improved the daily maximum temperature rise within first 5 cm of soil only in Greenhouse-1; it did not have the same effect in sub layer depths (Figure 1).

In 2009, consistent with the data of the previous year, OM, VCPE and BT treatments had the highest temperature increases. Cumulative temperature values at 20 and 30 cm soil depths under BT application ($OM_{20\ cm}$: 1291 °C< $BT_{20\ cm}$: 1293 °C and $OM_{30\ cm}$: 1245 °C< $BT_{30\ cm}$: 1252 °C) were found to be more successful than other applications. Statistically, they all were included into the same group (Table 5). The success order of applications related to accumulated

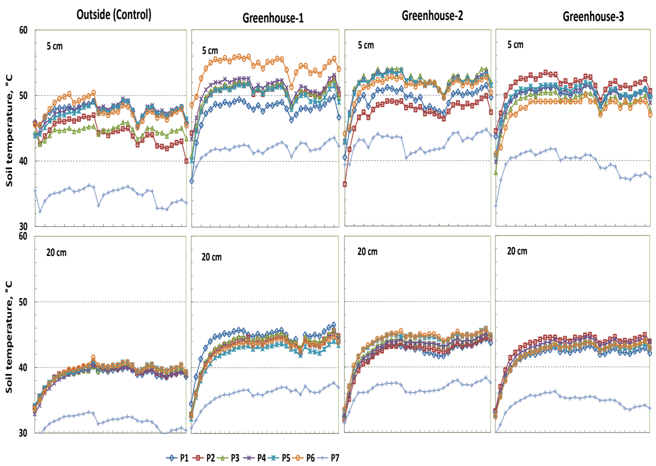
Table 5. Cumulative average temperature values of experimental treatments

	2008			2009		
Application	**5 cm**	**20 cm**	**30 cm**	**5 cm**	**20 cm**	**30 cm**
CO_2	1281 c	1225 b	1177 b	1336 b	1275 a	1224 b
BT	1312 ab	1249 a	1208 a	1365 ab	1293 a	1252 a
VCPE	1311 ab	1248 a	1211 a	1375 a	1287 a	1245 a
OM	1320 a	1246 a	1203 a	1374 a	1291 a	1245 a
OM+ CO_2	1302 b	1235 ab	1202 a	1367 ab	1283 a	1243 ab
PE	1310 ab	1248 a	1206 a	1362 ab	1291 a	1246 a
Control	1060 d	1027 c	1007 c	1140 c	1084 b	1059 c
$LSD_{0.05}$	14.69	16.48	13.08	33.8	28.7	20.0

Different letters in a column indicate significant differences (P < 0.05) in LSD test.

temperature values was as follows: OM > VCPE > BT > PE > OM+CO_2 > CO_2 > Control.

***Highest and mean daily maximum temperatures*:** Maximum temperatures achieved in applications and the mean daily maximum temperatures were found to differ according to greenhouse environment. The maximum temperatures recorded in all greenhouse environments and at the specified soil depths were as follows; 55 °C (Greenhouse-1, OM), 47.7 °C (Greenhouse-2, OM+CO_2) and 45.4 °C (Greenhouse-2, PE) for 5, 20 and 30 cm, respectively. In this study, mean daily maximum temperatures were 53-54 °C at a 5 cm soil depth and 47-48 °C outside the greenhouse (Figure 1).



P1: + *CO_2* P5: + *OM+ CO_2*
P2: + *Basaltic tuff* P6: + *Different colored cover materials*
P3: + *PE* P7: *Control*
P4: + *OM*

Figure 1. Daily maximum temperatures recorded during solarization (17.07-16.08.2009) at 5 and 20 cm depth

Although higher temperatures were obtained in the greenhouse environment, temperatures detected in open-air solarization applications were found to be sufficient for the solarization efficiency in the Cukurova region. Recorded temperature values were 44-46 °C in 20 cm and 42-43 °C in 30 cm. The mean maximum temperature levels obtained in 20 and 30 cm soil depths can increase the mean temperatures on sub layers which should be lower (37-38 °C) by 4-5 °C through these applications thus potentially improving the method for combating diseases on sub layers. It was found that the mean temperature in 2009 was 2 °C lower as compared to 2008. In 2009, significant differences were seen between temperature levels of some treatments ($P<0.05$). For example, the mean maximum temperature and maximum temperature at 5 cm depth under VCPE in Greenhouse-1 were 54.3±0.3 °C (Figure 2.) and 55.9 °C (Figure 1.), respectively. In present study, the highest and average maximum temperature values at 5 cm depth for VCPE (Various color and size cover material (UV+IR) were similar to the values previously mentioned (Greenhouse-1, 55.9 °C and 54.3. ±0.3 °C). Additionally, BT subject was found to be significant (Greenhouse-3, 5 cm) and is notable for achieving the highest values with 53.4 °C and 51.5±0.3 °C (Figure 1 and Figure 2). As shown in Figure 2, the average maximum soil temperatures during the solarization period (2008 and 2009) for 5, 20 and 30 cm soil depths were, respectively; 54.3 ± 0.3 °C (VCPE-greenhouse 1-2009), 46.2 ± 0.2 °C (VCPE-greenhouse 2-2008) and 43.6 ± 0.4 °C (BT-greenhouse 2-2008). At the same time, the average maximum temperatures measured under different applications at 5, 20 and 30 cm soil depths were found to be higher than the control by 9-11.5 °C, 6-8.5 °C and 5.5-8 °C, respectively.

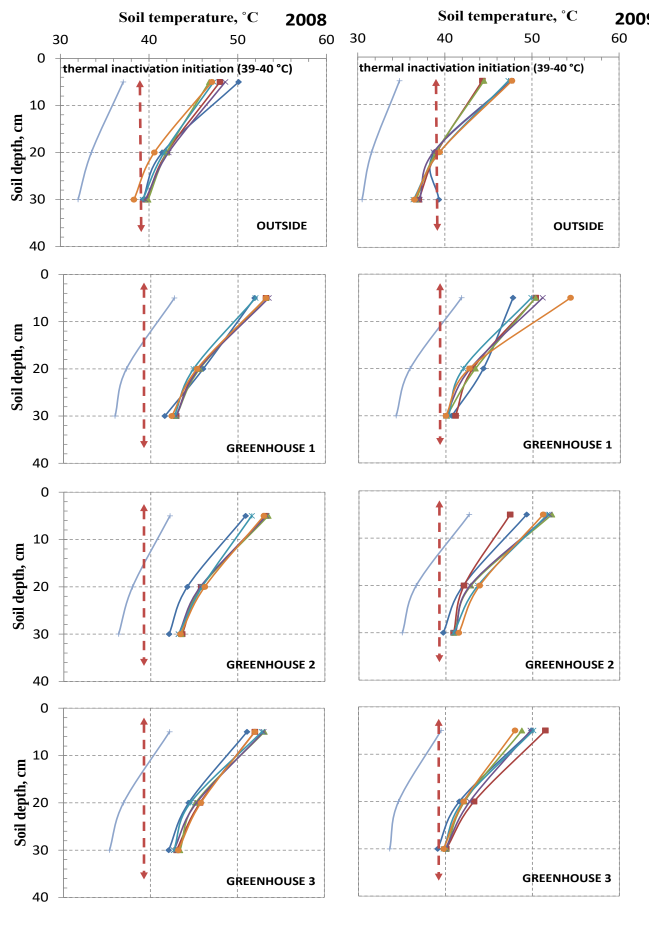


Figure 2. Average daily maximum temperatures at depths of 5, 20 and 30 cm during solarization exceed the thermal damage limit (39–40 °C) for many mesophilic organisms in the region.

***Thermal Diffusivity*:** Considering both years of the study, the highest average $\overline{D}_{5\text{-}30\ cm}$ values were obtained from CO_2 treatments with 65 $cm^2\ sa^{-1}$ under Greenhouse-1 conditions, while the lowest values were observed in VCP plot with 20.6 $cm^2\ sa^{-1}$. As compared to the control, the data from 2008 showed that OM+CO_2 was effective both outside the greenhouse and Greenhouse-1 and Greenhouse-2, with the highest thermal diffusivity calculated outdoor (39.8 cm^2 sa^{-1}). In 2009, the BT application clearly emerged as the most effective under Greenhouse-1 and Greenhouse-2 conditions ($P<0.05$) (Figure. 3). Furthermore, no significant difference found between solarization applications in terms of thermal conductivity both inside and outside the greenhouse. Different applications were highlighted in various environments in 2009. The CO_2 application achieved the highest thermal diffusivity alone in Greenhouse-1 environment. The next highest success was obtained in BT treatment, which had the best $\bar{D}_{5\text{-}30\ cm}$ value of 47 cm^2 sa^{-1} in Greenhouse-2 environment (UV+IR reinforced PE). In Greenhouse-3, the VCPE treatment was found to be successful, with a $\bar{D}_{5\text{-}30\ cm}$ value of 39.4 cm^2 sa^{-1}. Additionally, the highest $\bar{D}$ values varied across different treatments depending on the greenhouse conditions and years.

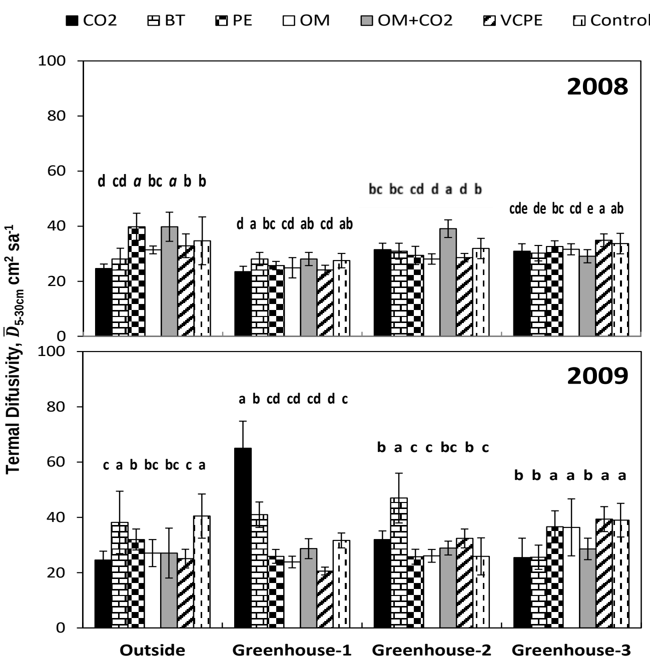


Figure 3. $\bar{D}$ **5-30 cm values calculated by the amplitude method; Y-axis represents the thermal diffusivity in 5-30 cm soil depth, (cm^2 h^{-1}), while the X-axis indicates the conditions (Outdoor, Greenhouse-1, Greenhouse-2, Greenhouse-3). Error bars indicate the standard error as mean ± SD and the bars with the same letter are not significantly different according to the LSD test at P ≤ 0.05.**

DISCUSSION

***Effects of experimental treatments on soil temperature*:** In present study, the most effective temperature rise at each soil depth was observed in the OM plots in 2008. This can be attributed to the fact that the organic material added to the soil surface absorbed high levels of solar energy due to its darker color. Moreover, the heat and carbon-dioxide released from the fermentation of organic matter (compost fertilizer) contributed to higher temperatures. It was assumed that penetration of carbon-dioxide into the soil would be limited by carbonic acid (H_2CO_3) from the reaction between carbon-dioxide and water when the soil-water content was at saturated level. Subsequently, CO_2 content was increased with dry ice applied to the air between PE cover and the soil surface aiming to create a greenhouse effect. However, the application of CO_2 with 0.5 kg m^{-2} of dry ice to the soil surface only achieved the highest temperature at 5 cm depth and was not effective at the subsoil depth. In contrast, Al-Kayssi (2009) increased carbon-dioxide content by injecting pure CO_2 into 0.10 m using a method described by Okada *et al.* (2001). This approach resulted in maximum temperature levels and accumulation at sub-layers of soil.

The success of BT treatments can be attributed to two main factors. First, the low albedo (reflection) value due to black-like color of soil surface results in higher absorption of solar energy, which increases soil temperature by 1-3 °C. Second, the latent temperature rise is associated with the increasing hydration capacity of basaltic tuff which has a high-porous structure that enhances heat transfer towards sub layers. The effects of organic matter addition on solarization were studied by Kaşkavalcı (2007). It was indicated that the benefit of organic matter was only marginal and addition of poultry litter increased maximum soil temperature from 40.9 °C to 41.2 °C at a depth of15 cm during solarization. In another study, (Gelsomino *et al.*, 2006) found that the temperature at an 8 cm depth increased up to 55 °C with the use of farm manure. Komariah *et al.* (2011) reported that rice meals used as an organic additive raised the mean and maximum temperatures within the 0-30 cm soil depth to very high levels (77 °C). These studies suggest that plastic mulch effective in regulating soil temperature has significant material characteristics apart from its optical properties. The higher soil temperatures observed with organic amendment applications might be due to the fermentation process of the organic materials upon contact with soil, as also noted by Komariah *et al.* (2008) when using cassava bagasse as organic amendment. Chellemi *et al.* (1999) investigated various solarization film optical properties and found that the most successful film application was TIR (PE absorbing thermal infrared energy). They reported mean soil temperatures of 49.3 °C, 44.5 °C and 38.6 °C at depths of 5, 10 and 25 cm, respectively with this film. Conversely, Scopa *et al.* (2008) investigated the thermal behavior patterns of biodegradable plastic solarization films and found that soil temperatures exceeded 60 °C at depths close to the soil surface (0-2 cm). The most effective plastic film was BIO (20 mm thickness, polyesterammide biodegradable), which Resulted in temperatures of 51-60 °C at 10 cm depth and 40-50 °C at 20 cm depth.

Solarization is one of the best alternatives in terms of environmental sustainability for controlling weeds and pests in soils (Carrieri *et al*., 2013; Katan, 2017; Morra *et al*., 2018). Soil temperature can reach between 40 °C and 50 °C near the soil surface during the day when the soil is covered by plastic mulch during the summer seasons in semi-arid and arid areas. While the soil-based pest eradication activity in the open field and greenhouse environment during solarization is very successful in the surface soil, its effectiveness decreases with depth. Consequently, direct thermal inactivation of soil-borne pathogens and diseases is the most important goal in solarization. Thermal damage too many mesophilic organisms in the soil begins around 39–40 °C (Stapleton and DeVay, 1995).

Effects of experimental treatments on soil thermal diffusivity: In soil solarization activities, the primary goal is to transfer heat to sub-regions. Thermal diffusivity (D) values, which reflect the amount and duration of thermal energy required to raise the ambient temperature to a target level, are dependent on thermal conductivity. Basaltic tuff increased air-filled pore volume with its porous structure and expansion property. This allows for better heat dissipation due to the effective bonding of good conductor mineral particles with less conductive liquid phases in the appropriate water content range (around field capacity or above), while minimizing contact with poorly conductive gaseous phases. On the other hand, there is a close correlation between thermal properties of organic substances and water content. Thermal properties differ by thermal absorption capacities in interfused soils, different specific heats and proportional amounts. It was assumed that organic material would reduce thermal conductivity by decreasing soil bulk density. However, OM+CO_2 application significantly increased thermal diffusivity (39.8 cm^2 sa^{-1}). In a related study, the hydration capacity of soil fertilizer mixture (compost fertilizer) was found to be 80% with thermal conductivity under saturated conditions calculated as 4.07-18.51 cm^2 sa^{-1} and 7.40 cm^2 sa^{-1} respectively (Ahn *et al*., 2009). The highest thermal diffusivity $\overline{D}_{5\text{-}30}$ values in 2008 and 2009 were recorded under OM+CO_2 and BT treatments, respectively. The high $\overline{D}_{5\text{-}30}$ value related to OM+CO_2 treatment can be explained by increase in heat flow and chemical reactions resulting from the fermentation of organic substances and by the fact that CO_2 under PE decreased radiative cover effect with convective adjustments and the loss in absorbed infrared radiation amounts and thus kept the heat inside soil system. The increased effect of CO_2 on heat gain when combined with OM can be supported by findings that rising CO_2 content in open-top chambers impact bacterial diversity, microbial population, mycorrhizal networks and metabolic activity (Morten *et al*., 2002; Ebersberger *et al*., 2003). D values of soil are above 15 cm^2 sa^{-1} in high temperature levels (25-30 °C) (Hanks and Ashcroft, 1980). Sesveren (2007) calculated $\overline{D}$ related to 5-20 and 20-30 soil depths on plots where CO_2 was applied in clayed soil as 18 and 18.5 cm^2 sa^{-1} through amplitude method. The data and $\overline{D}$ values calculated at 45-60 °C levels are consistent, indicating that the solarization activity was analyzed accurately. The lower thermal diffusivities may be as a result of lower bulk density and higher porosity which could make more heat to be dispersed (An *et al*., 2016). It results from particularly water content and complex tendencies with volume weight apart from the interaction with thermal conductivity, volume weight, volumetric thermal capacity (Yang *et al*., 2002).

Interactions of volumetric water content (Θ) with volumetric heat capacity (Cv) and thermal conductivity (K): Daily changes in soil temperature are influenced by soil properties, soil cover materials and the intensity of solar radiation. Plastic covers, mulches effect both soil temperature and soil water condition. The presence of water enhances thermal conductivity, heat transfer and heat penetration into the soil, thereby increasing solarization efficiency (Gamliel and Katan, 2005; Al-Shammary and Al-Sadoon, 2014). Consequently, soil water content is elevated to saturation before solarization begins and maintained at a high level with additional irrigation during the progress of solarization (Al-Karaghouli and Al-Kayssi, 2001). To support this, the basic hydro-physical properties of the study area soil were examined. Also, in 2009, the relationships between thermal properties and soil water content (particularly between volumetric heat capacity, thermal conductivity and soil water content) were investigated.

Soil volumetric heat capacity (Cv) can be defined as the amount of heat required to increase the temperature of a unit volume of soil by 1 °K (Hillel, 2003) and depends on the volumetric water content (Θ) and bulk density (ρb) (Evett *et al*., 2012). In addition, Cv is greatly affected by the instant available soil water content (μ) and soil depth (O'Kelly and Sivakumar, 2014). Cv varied as a function of mineral, organic matter and soil water content related to the research soil is given in Figure 4. According to the calculations, Cv values increased with rising Θ, showing a linear relationship with Θ and bulk density.

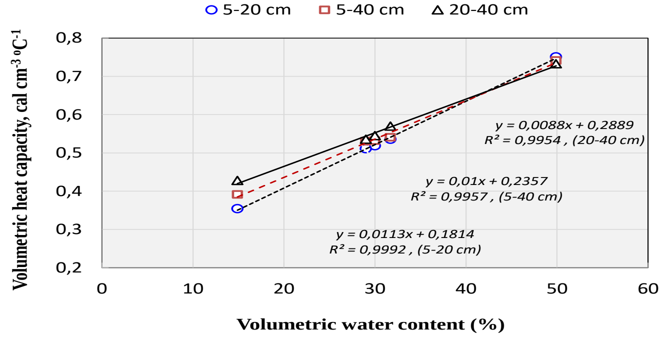
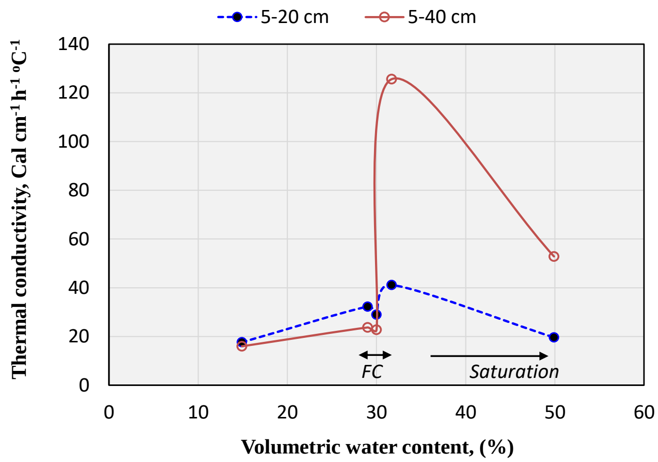


Figure 4. Changes in C_V with the volumetric θ for different solarized soil depths

Abu-Hamdeh (2003) stated that water content and volumetric heat capacity showed a linear relationship, and this linear relationship was clearer (certainty) in clay soils. In clay soils, Cv increases as a result of the increase in the contact surfaces of solid particles in unit volume and the decrease in porosity. Similar relationships between Cv and ϴ have been reported by other researchers. (Bristow, 1998; Chandrakanthi *et al*., 2005; Sesveren *et al*., 2006; Opoku *et al*., 2006). In addition, several studies have documented a linear increase in all soil thermal properties with an increase in soil temperature (Ts) (Lamond and Pielert, 2006; Sun *et al*., 2016 Mengistu *et al*., 2017). Ochsner *et al*. (2001) suggested that air-filled porosity and volumetric water content had an effect on the thermal properties of the soil. Theoretically, this situation can be predicted because the thermal conductivity and volumetric heat capacity of water (0.6 W m^{-1} $°C^{-1}$, 4,18 MJ m^{-3} $°C^{-1}$) are greater than those of air (0,025 W m^{-1} $°C^{-1}$, 0,001 MJ m^{-3} $°C^{-1}$) (Holman, 2002; Labance *et al*., 2006). Due to increasing water-filled part of the pore space with increasing water content and decreasing with increasing bulk density, the reduced volume fraction of air, which has a relatively lower thermal conductivity and volumetric heat capacity than water and solid materials, causes this difference. In addition, modern solarization applications, compost materials containing organic matter are used to increase the solarization efficiency of the soil. In this regard, the thermal properties of compost materials often display specific trends related to particle size, bulk density and water content. Ahn *et al.* (2009) developed first-order regression models that accurately represented the relationship between saturation degree and volumetric heat capacity (r = 0.95-0.99) and thermal conductivity (r = 0.84-0.99).

Soil thermal conductivity (K) depends on bulk density (ρb), porosity (P) and volumetric water content (ϴ) since heat transfer in the soil depends on the solid phase and mineral composition (Tokoro *et al*., 2016; Łydżba *et al*., 2017). In addition, k value increases with soil depth due to the increase in soil bulk density (Abu-Hamdeh, 2000; Merante *et al*., 2017). Soil K value is affected by soil temperature in most soil types, as changes in heat flow due to movement in the water content in the soil, increase in soil temperature (Ts) with solarization application, and cause a change in the available water state (Usowicz *et al*., 2017).

As shown in Figure 5, the thermal conductivity increased up to the level of the field capacity of the soil, and then decreased as the water content reached saturation. This significant result is confirmed by various studies (Kırda and Sarıyev, 2002; Sarıyev *et al*., 2007; Mang and Christiana, 2019). Ekwue *et al*., (2006) demonstrated that clay soils exhibited lower thermal conductivity values at higher water contents as compared to sandy and loamy soils. It was also reported that the impact of changes in soil water content on thermal conductivity is greater than the effects of soil bulk density and soil particle size.



FC: Field capacity

Figure 5. Relationship between *K* and *ϴ* under solarization application.

Present findings and other research revealed that soil water content should not be maintained at saturation levels in solarization applications. This can be explained by the following relationship: While the incoming energy raises the temperature of the upper part of the soil when it is saturated, the process of transferring this energy to the lower regions is relatively less effective because most of the energy is stored at the soil surface. For example, increasing the temperature of the solid part requires approximately 5 times less energy than water (while the specific heat capacity of the solid is 0.20 cal g^{-1} $°C^{-1}$, water is 1 cal g^{-1} $°C^{-1}$). Therefore, although saturating the upper part of the soil raises the temperature of the water, effective heat transfer to the lower part cannot be achieved unless there is a high temperature gradient. Furthermore, while the temperature of the upper part of the soil increases, the transfer of energy to the lower part in a balanced manner can be best managed with the energy-mass flow. In other words, to increase the temperature by 1 °C for very wet soil, additional solar radiation absorption is required. As a result, wet soil will warm much more slowly than dry soil, and transmission of heat will be slower in the lower part of the soil.

***The limitations of study*:** The effects of soil heating on nutrient dynamics and microbial population depend on the temperature reached, its duration, and depth of heat penetration. The effects of biotic and abiotic stress on soil organisms can be measured such as changes in the biological activity, microbial biomass, soil respiration and enzyme activities (Palese *et al*., 2004).

When examining the results of microbiological analyses in the three greenhouses where solarization was performed, as well as in the outdoor environment, the CO_2 and DHA values, along with the microorganism count data compared to the control plot, indicate that microbial activity decreases significantly with increasing soil temperature. While this situation is considered a significant development for harmful microorganisms, it poses a disadvantage for beneficial ones.

These perturbations will also be decreased when micro and macrofauna are concerned, because most soil pathogens or pests are mesophilic or unable to survive at temperature above 37 °C for long periods. Long-term soil solarization effects have been investigated mostly on soil-borne fungal pathogens in open fields, but little information is available on the residual effects of solarization in greenhouse vegetable crop cultivation. Many studies provided evidence that the soil parameters are influenced by solarization treatments (Bonanomi *et al*., 2008).

Therefore, by mixing some clean zone soil (for example, from under a forest) into the solarized soil, a balanced environment can be quickly established for beneficial microorganisms. This issue is important for reopening a controversial topic for discussion. For instance, research indicates that even in stubble-burned soils, the balance of microorganisms, along with factors such as soil structure, moisture, temperature, organic matter content, soil cultivation (including tillage), and the influence of meteorological conditions, can stabilize over varying periods of time. It is important to evaluate the long-term effects, due to single or repeated solarization treatments (for two and three years) applied in different years, on microbial biomass, enzymatic activity, soil respiration and agronomic traits of soil solarization in greenhouse and open fields. In addition, future studies should involve more frequent sampling of microorganism populations and their balance. It is also recommended to evaluate parameters such as biomass, carbon to assess biological productivity in solarized soils.

The conductive and convective processes influence the soil thermal properties which are also dependent on factors related to the soil type such as texture, organic matter content, mineralogical composition and soil physical structure affect and control the transfer of heat in field conditions under mulching properties and climatic conditions. In some studies, D and K values were calculated at different depths, environmental conditions, and soil types (Wang *et al*., 2005; Otunla *et al.*, 2013; An *et al*., 2016). Considering the results from various authors, it appears that the values estimated in this research align with the literature. However, conducting the study within a single soil type may be a potential limitation. Therefore, examining the effects of the applications in medium-textured and sandy soils would be beneficial for assessing solarization effectiveness. Additionally, further investigation into soil thermal characteristics is needed to accurately predict soil temperature.

The mathematical approaches to describe heat flux in a porous and heterogeneous medium are very complex. In many cases, mathematical equations that are valid for homogeneous media, although not realistic, are used to describe heat flux in soil. Generally, soil thermal diffusivity is numerically estimated using the classical heat equation for solids, which includes a term representing the vertical gradient of soil diffusivity related to soil water content. These results are compared with the Amplitude and Phase Shift analytical methods. The relationship between thermal properties and soil water content is evaluated through the calibration of empirical models. It is well understood that these properties mainly vary with soil texture, water content, and bulk density; however, few models are available to accurately quantify this relationship. A specific model was not used in this study.

***Conclusions*:** This study aimed to determine effects of various cultural applications on increasing solarization efficiency. To compare applications, among heat conduction parameters under field conditions, thermal diffusivity was determined through amplitude method, its compatibility was tested and application activities were presented numerically. According to statistical assessment of the study results, it was determined that apart from the most effective OM, different color PE and basaltic tuff applications, other subjects (normal PE application, CO_2 application, OM+CO_2) can be used for solarization as well. Thermal diffusivity was determined with the approach on thermal properties. The expected additional greenhouse effect from carbon-dioxide application did not materialize and sufficient temperature rises were not observed. A significant temperature rise was found only in 5 cm depth of soil. The lack of this effect towards sub layers should be analyzed in terms of interactions with factors such as $CaCO_3$ content and CO_2 production of microorganisms. Moreover, while saturated conditions increased water temperature on top soil layers; however, effective thermal conduction was not found in sub regions unless temperature gradient was high. The most successful thermal diffusivity was obtained with OM+CO_2 and BT applications between 5 and 30 cm of soil. This finding suggested that good thermal conductor mineral substances which are interfused in soil improved physical and hydraulic properties of soil and thus positively contributes to increase microbial activity balance and transfer thermal towards sub layers. Also, no weeds were present in the plots treated with BT. This observation should be taken into consideration and investigated further in future studies. Cv values increased in a linear relationship with the increase of soil water content. The K value increased as the soil water content reached the field capacity and decreased as the saturation level were reached. This indicates that soil water content should not be maintained at saturation levels for effective solarization.

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***Author contributions*:** All authors designed the study; data was collected by YT and analyzed by AS, SS, YT, KD and MA; and SS prepared the first draft. All authors have read and agreed to the published version of the manuscript.

***Conflicts of Interest*:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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