American Journal of Applied Sciences

Original Research Paper

Experimental Investigation of Thermo-Physical Properties of Soil Using Solarisation Technology

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Article history
Received: 19-04-2017
Revised: 10-06-2017
Accepted:17-07-2017

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Abstract: Soil Thermo-Physical Properties (TPP) depend on heat transfer in the soil. This paper presents a study on different soil solarisation technologies influenced by soil TPP. This study evaluates three factors: The tillage depth for soil at three levels (15, 25 and 45 cm), the number of plastic film at three levels (single, double and without plastic film) and three cases of fertilizers (chemical fertilizer, organic fertilizer and without fertilizer). The parameters explored in this study include soil bulk density (Mg/cm^3), soil porosity (%), soil volumetric moisture content (cm^3/cm^3) and soil thermal diffusivity (m^2/sec). Data management and analysis were performed using SAS 9.1 statistical software and the spilt-plot under Randomized Complete Block Design (RCBD). The results show that soil Tillage Depth (TD) strongly influences TPP, as well as a significant effect on soil bulk density (ρ_b), porosity (Φ), volumetric moisture content (θ) and thermal diffusivity (D). The results also reveal that a tillage depth of 15 cm produces lower values of ρ_b, θ and D (1.25 Mg/cm^3, 0.131 cm^3/cm^3 and 1.24×10^{-6} m^2/sec, respectively) and a higher value of Φ (52.78%). In addition, the finding indicates that ρ_b is increased by increasing TD. There was a significant positive correlation between the number of plastic film and parameters studied. The soil double plastic film produced lower values of ρ_b and D for soil (1.253 Mg/cm^{3,} 7.76×10^{-7}m^2/sec). However, it recorded higher values for Φ and θ for soil (52.70% and 0.231 cm^3/cm^3, respectively). Furthermore, the current study shows significant differences between the types of fertilizers on ρ_b. Organic Fertilizer (OF) obtained a lower value of ρ_b (1.2 Mg/m^3), compared with chemical fertilizer and without fertilizer (1.28 and 1.31 Mg/m^3, respectively). In contrast, contrary to expectations, this study did not find significant differences between the types of fertilizer on D and θ for soil. A positive correlation was found in the interaction between the studied factors in the parameters. Furthermore, D increased with increasing soil bulk density (*pb)* and tillage depth.

Keywords: Soil Tillage Depth, Number of Plastic Film, Organic Fertilizer, Soil Bulk Density, Soil Thermal Diffusivity

Introduction

Soil Thermo-Physical Properties (TPP) are widely used parameters of soil physics in the field of agricultural and especially in applications concerning soil energy balance (Alrtimi *et al*., 2016; An *et al*., 2016; Andújar Márquez *et al*., 2016; Genesio *et al*., 2012; Logsdon *et al*., 2010; Rajeev and Kodikara, 2016; Ravazzani *et al*., 2015; Usowicz *et al*., 2016; Wu *et al*., 2017; Xiukang *et al*., 2015). Consequently, knowledge of TPP is required to accurately predict soil temperature (Hu *et al*., 2016). Soil Solarisation Technology (SST) is an important practical method of increasing soil temperature by using solar radiation, playing a key role in improving and controlling soil properties, including in crop fields (Keesstra *et al*., 2016; Moreno *et al*., 2016). SST is also the main factor for analysing Organic Matter (OM) in soil (Conant *et al*., 2011; Grunwald *et al*., 2017;

Li *et al*., 2016). Furthermore, SST overpowers weed growth (Kader *et al*., 2017; Mutetwa and Mtaita, 2014). SST strongly affects the establishment of microclimates that lead to increased fertilizer productivity in soil, reduces soil irrigation consumption (Cerdà *et al*., 2016; Jiang *et al*., 2017; Mahdavi *et al*., 2017; Wu *et al*., 2017; Zhou *et al*., 2017), affects soil temperature (Al-Shammary and Al-Sadoon, 2014; Al-Shammary *et al*., 2016) and improves the physical structure of soil (Dec *et al*., 2009).

Soil Thermo-Physical Properties (TPP) are soil thermal conductivity (*k*), volumetric heat capacity (C_v) and thermal diffusivity (*D*). They strongly depend on soil bulk density (ρ_b), porosity (Φ) and gravimetric water content (θ) for soil (Alrtimi *et al*., 2016; Levy and Schmidtm, 2016; Lu and Dong, 2015; Mondal *et al*., 2016; Ravazzani, 2017; Usowicz *et al*., 2013; Zhang *et al*., 2017). There are several studies in the literature that estimate TPP under different conditions.

Williams *et al*. (2016) observed that the relationship between soil tillage management and hydrothermal properties influences soil structure and increases crop production. In addition, Al-Shammary and Al-Sadoon (2014) reported a significant differences between tillage depth and soil thermal properties. Their results show that thermal conductivity (*K*) is increased with increasing soil depth. Consequently, increasing ρ_b and water content (*w)* with increasing TD.

Other studies Chaudhari *et al*. (2013); Li *et al*. (2017); Merante *et al*. (2017) have found that Organic Fertilizer (OF) can improve soil physical properties. OF has a positive effect on soil bulk density (*ρb)* and porosity (Φ) because improving soil biological fertility. Celik *et al*. (2010); Li *et al*. (2017) studied the effects of Organic Fertilizer (OF) on SPP. They noted that OF significantly reduced soil bulk density (*pb*). Therefore, OF can help improving soil structure as well as *ρb depend on* different factors, For example, compaction, consolidation and the amount of organic matter present in the soil. Furthermore, Pires *et al*. (2017); Alam and Salahin (2013) indicated that soil porosity (Φ) is influenced by the tillage system. They found that soil porosity decreases with soil depth.

Liang *et al*. (2017) Qin *et al*. (2015); Xiukang *et al*. (2015); Jabran *et al*. (2016) ; Wu *et al*. (2017); Ingman *et al*. (2015) all found that Soil-Mulching Systems (SMS) had a positively influence on soil heat transfer and soil evaporation. As a result, *SMS* was more useful for reducing soil moisture losses. They observed also that SMS reduces the temperature of the soil.

Soil thermal conductivity (*K*) depends on (*ρb*), (Φ) and (θ) (Łydżba *et al*., 2016; Tokoro *et al*., 2016), as well as Soil Mineral Composition (SMC) and texture (Tokoro *et al*., 2016). Usowicz *et al*. (2013); Pramanik *et al*. (2015) found that Soil Solarisation Technology (SST) had a positively impact on soil temperature because It influenced the soil thermal regime by controlling for radiation balance and soil thermal conductivity (*K*), as well as volumetric heat capacity (C_v) in soil.

Ingman *et al*. (2015); Merante *et al*. (2017); Roxy *et al*. (2014); Gan *et al*. (2012) demonstrated that the *K* and C_v of soil are significantly impacted by soil moisture content. Furthermore, the results of their study identified increased *K* and C_v with soil depth. Jabro *et al*. (2016); Chaudhari *et al*. (2013) demonstrated that soil Tillage Depth (TD) has an influence on soil physical properties. They found that *ρb* was significantly increased by soil TD. In contrast, other studies presented the contradictory result that tillage depth made no significant difference to *ρb* (Jabro *et al*., 2016; Karuma *et al*., 2014).

Gnatowski (2009); Levy and Schmidt (2016) found that soil thermal diffusivity (*D*) is a fundamental property for studying the thermal process of soil. The results of their study indicate that *D* depends on moisture content because *D* is increased by increasing volumetric moisture content in soil. Tong *et al*. (2017) argued that *D* is related to soil temperature changes. Their results indicated that *D* depended on soil thermal conductivity (*K*). Miyajima *et al*. (2015); Usowicz *et al*. (2016); Roxy *et al*. (2014) showed that soil thermal diffusivity (*D*) is amplified by increasing the soil bulk density and moisture content. However, Makarychev and Bolotov (2017) observed that soil thermal diffusivity (*D*) is decreased by increasing moisture content. Levy and Schmidt (2016) discovered that soil thermal diffusivity (*D*) significantly increased with increasing soil depth.

The objective of this study is to investigate the effect of soil solarisation technology on soil thermal diffusivity. Furthermore, the study examines the influence of soil tillage depth, number of plastic films and fertilizer type son soil bulk density, soil volumetric moisture content and soil porosity.

Materials and Methods

The field experiment involved studying a soil solarisation technology influenced by some soil thermal-physical properties: Soil bulk density (*ρb*), porosity (Φ), gravimetric water content (θ) and soil thermal diffusivity (*D*) for Silty Clay (SIC). Soil specifications are shown in Table 1. The research procedure involved several steps. Firstly, the field allocated to the study experiments was cleared of plant waste and then soil samples for silty clay were used to blend the tissue from the continuous field with a three depths (0-15, 15-25 and 25-45 cm) after smoothing and passing it through a 2 mm diameter sieve and drying it under the sun. Several models were used to analyse the physical and chemical properties of the soil, Soil Mechanical Analysis has classified under (Triangular diagram) according to the "Modern American Classification "the procedure used by (Vogt *et al*., 2015), Soil texture was determined by hydrother meter method and the Electric Conductivity (EC) was done according to the procedure of (Krishna, 2016), Ph soil was prepared according to the procedure used by (Vogt *et al.*, 2015), Organic matter by (Kroetsch and Wang, 2007). For the experiments, three factors were selected: (i) Three soil depths for tillage systems (15,25 and 45 cm), (ii) Three levels for number of plastic films(single, double and without-plastic film) and (iii) Three fertilizer types (chemical fertilizer type [0.07 kg/2m^2 Triple Superphosphate TSP added, equivalent to 350 kg/ha], organic fertilizer [0.05 kg/2m^2 humic acid added, equivalent to 250 kg/ha] and without fertilizer). Each treatment area was 2 m^2, making a total experiment area of 162 m^2. The experiment included 27 treatments ×3 replicates, making a total of 81 experimental treatment units, as shown in Fig. 1. The procedures of this study were tested by analysis of variance and least significant differences were compared averages at a probability the 5% level using a split-split plot under the randomized Complete Block Design (RCBD). In addition, the study used a tractor Same Explorer 85 DT and Disc Plough for the purpose of ploughing to three level depths (15, 25 and 45 cm) and then disc harrows to smooth the soil as shown (Appendix 2 and 3). In the next step, the experimental field was irrigated to full capacity (100%) by using surface Irrigation method. The experimental field unit was covered with plastic films (single, double) after 48 h from irrigation process. Transparent polyethylene film was used for soil solarisation technology, which was 0.5 mm thick, 600 mm width. It is proven by the polyethylene film with the soil surface, it has been properly rolled so that it is perfectly attached to the soil surface purpose increasing solarisation efficiency and Wear plastic straps at least two places to prevent dusting. Finally, calculations of soil bulk density (Mg/m^3), soil porosity (%), soil volumetric moisture content (cm^3/cm^3) and soil thermal Diffusivity (*D*) were carried out after removing the covers from all three treatment areas. Analysis of Variance (ANOVA table) for parameter studied represented by mean square error (appendix 1).

Mathematical Calculations

Soil Bulk Density, Porosity and Volumetric Moisture Content

Soil bulk density (*ρb*) was measured by the volumetric cylinder method. With this method, a cylindrical metal sampler with a removable sample cylinder that fits inside it was pressed into the soil to depths of 15, 25 and 45 cm and carefully removed to preserve a known volume of soil in the cylindrical sample with a height of 7 cm and a diameter 5 cm. The soil sample was dried at 105°C for 24 h and then weighed. Bulk density (*ρb*) is the oven-dried mass (m_s) divided by the field volume of the sample (v_t), as shown in the following equation (Smith, 2000):

$$Bulk\,density\,(\rho b) = \frac{M_s\,(M_g)}{V_t\,(m^3)}$$

where, M_s is the oven dry weight of soil (*Mg*) and V_t is the volume of soil sample (m^3).

Total porosity (*Φ*) is defined as the percentage of the bulk volume not occupied by solids, calculated by the following equation (Smith, 2000):

$$Porosity\,(\phi) = 1 - \frac{\rho p\left(\frac{M_g}{m^3}\right)}{D_p\left(\frac{M_g}{m^3}\right)}$$

where, *ρb* is soil bulk density (Mg/m^3) and D_P is soil particle density (Mg/m^3).

Furthermore, the volumetric moisture content (cm^3/cm^3) was calculated by gravimetric methods (p_w) of field soil at a depth of 0-45 cm. This involved first weighing the wet samples of all treatments and then oven-drying the samples at 105°C for 24 h. The moisture percentage in the soil samples (p_w) on a wet-dry mass basis was obtained by dividing the difference between the wet and dry samples and multiplying by 100. Where the bulk density (*ρb*) of a sample is known, the volume–basis water content (*θ*) may be obtained by the following equation (Smith, 2000):

$$Volumertic\,moisture\,content\,(\theta) = \frac{p_w * p_b}{p_w}$$

where, θ is the volumetric moisture content (cm^3/cm^3), ρ_w is the moisture content by weight (%), ρ_b is the soil bulk density (Mg/m^3) and ρ_w is the water density (Mg/m^3).

Soil Thermal Diffusivity (m^2/sec):

Soil Thermal Conductivity (W/mk)

The soil thermal conductivity (*K*) of silt clay was calculated by using the following equation (Kersten, 1949):

$$K = [0.9\log w - 0.2]10^{0.01\gamma d}$$

where, *w* is the moisture content (%) and γ is the dry density (*gm*/*cm*^{3}).

Soil Volumetric Heat Capacity (J/m^{3}k)

The soil volumetric heat capacity (C_v) was calculated with reasonable accuracy from the volumetric water content (*θ*) and soil bulk density (*ρb*) (Evett *et al.*, 2012):

$$Cv = \frac{2.01\times10^6\,p_b}{2.65 + 4.19\times10^6\,\theta}$$

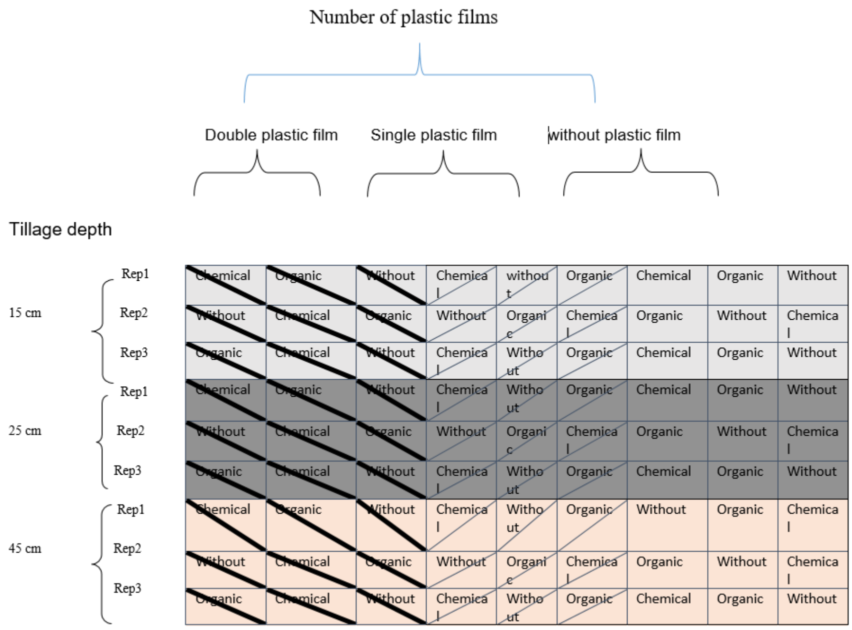

Fig. 1. Schematic diagram of the experimental field design

Table 1. Characterization of soil profile.

	Soil properties									
	Physical					Chemical				
			Soil mechanical analysis Silty Clay (SIC)							
Depth of soil (cm)	Bulk density (Mg/cm^3)	Porosity (%)	Silt gm/kg	Clay gm/kg	Sand gm/kg	ph	EC ds/m	N Mg/kg	P Mg/kg	K Mg/kg
0-15	1.31	50.49	407	468	125	6.90	2.63	30.63	7.54	407.20
15-25	1.33	49.66	408	454	138	6.82	3.82	27.50	10.00	420.40
25-45	1.38	47.88	426	412	162	6.58	3.95	25.56	10.00	430.50

Soil Thermal Diffusivity (m^2/sec)

Soil diffusivity is defined as the ratio of thermal conductivity to volumetric heat capacity (Hillelm, 1998):

$$D = \frac{K}{C_v}$$

where, D is the soil thermal diffusivity (m^2/sec), K is the thermal conductivity (W/mK) and C_v is the volumetric heat capacity (J/m^{3}k).

Results and Discussion

Influence of the Studied Factors on Soil Bulk Density (Mg/m^3)

Table 2 shows the influence of soil Tillage Depth (TD), number of Plastic Films (PF) and Fertilizer Type (FT) on the soil bulk density (ρb). The results show a significant difference in tillage depth in soil bulk density. The soil bulk density increased from 1.25 to 1.27 Mg/cm^3 when increasing soil TD from 15 to 25 cm. The increasing rate was 16.8%. ρb also increased to 1.31 Mg/cm^3 at an increasing rate of 36% and an increasing tillage depth of 45 cm. This result may be due to the gradual increase in soil bulk density with increasing soil depth. These results match those observed by (Bennett *et al*., 2017; Keesstra *et al*., 2016; Tamminen and Starr, 1994; Romaneckas *et al*., 2009).

The number of Plastic Films (PF) caused significant variation in ρb. The double-plastic films treatment produced the lowest soil bulk density (1.25 Mg/cm^3) compared with the single-plastic films and without plastic films treatments (1.27, 1.31 Mg/m^3, respectively). The reason for this result may be twofold: the increasing soil temperature at the soil surface and the decomposition of organic fertilizer by microorganisms, which would decrease soil bulk density compared with single-plastic films and without plastic films. This finding is in agreement with (Conant *et al*., 2011; Al-Shammary *et al*., 2016; Li *et al*., 2016; Grunwald *et al*., 2017).

Table 2. Effect of tillage depth, number of plastic films and fertilizer type on bulk density (Mg/cm^3)

		Average ρ_b (Mg/m^3) on interaction triple Fertilizer Type (FT)			
Tillage Depth (cm) (TD)	Number of Plastic Films (PF)	Chemical	Organic	Without	Interaction tillage depth and number of plastic films
15	Single	1.25	1.22	1.26	1.24
	Double	1.24	1.20	1.25	1.23
	Without-plastic film	1.28	1.26	1.29	1.27
	Single	1.28	1.26	1.30	1.28
25	Double	1.25	1.23	1.30	1.26
	Without-plastic film	1.28	1.26	1.30	1.28
45	Single	1.28	1.27	1.36	1.27
	Double	1.24	1.24	1.32	1.25
	Without-plastic film	1.37	1.37	1.38	1.31
Average of fertilizer type		1.27	1.25	1.30	LSD 0.05
Tillage Depth (cm) (TD)	Fertilizer Type (FT)	Average ρ_b (Mg/m^3) on Interaction Tillage Depth and Fertilizer Type	Average ρ_b (Mg/m^3) on Tillage Depth (TD)		Tillage depth = 0.025, Number of plastic Films = 0.025, Fertilizer Type = 0.025 Tillage depth X
15	Chemical	1.25		1.25	Number of plastic
	Organic	1.22			Films = 0.018
	Without	1.26			Tillage depth X
25	Chemical	1.27		1.27	Fertilizer = 0.018
	Organic	1.25			Number of plastic Films X fertilizer
	Without	1.30			Type = 0.026
45	Chemical	1.30		1.31	Tillage depth X
	Organic	1.29			Number of plastic
	Without	1.35			Films X Fertilizer
					Type = 0.006
Number of Plastic Films (PF)	Fertilizer Type (FT)	Average ρ_b (Mg/m^3) on Interaction of the number of Plastic Films (PF) and fertilizer type		Average ρ_b (Mg/m^3) on the Number of Plastic Films (PF)	
Single	Chemical	1.27	1.27		
	Organic	1.25			
	Without	1.30			
Double	Chemical	1.24	1.25		
	Organic	1.22			
	Without	1.29			
Without-plastic Film	Chemical	1.31	1.31		
	Organic	1.29			
	Without	1.32			

A significant difference in soil bulk density (*ρb*) is obtained for fertiliser types. The soil with Organic Fertilizer (OF) showed a lower value of *ρb* (1.25 Mg/m^3) compared with Chemical Fertilizer (CF) and no Fertilizer (WF) (1.27 and 1.30 Mg/m^3, respectively). The reason for this result might be that the application of organic fertilizer normally reduces *ρb* of soil due to the higher organic matter content of the soil. These results agree with the findings of (Celik *et al*., 2010; Li *et al*., 2017), who reported the relevance of the application of organic matter to the improvement in physical and chemical properties of the soil. The interaction between Tillage Depth (TD) and number of Plastic Films (PF) showed a positive correlation in *ρb* values, with the lowest value of *ρb* showing at TD15 cm + double-plastic films at 1.23 Mg/cm^3. In contrast, the highest *ρb* value (1.31 Mg/m^3) was obtained by TD 45 cm + without-plastic films treatment. Further analysis showed that there was a significant difference in the interaction between TD and FT on soil bulk density (*ρb)*. The lower average *ρb* (1.22 Mg/m^3) was obtainedforTD15 cm and Organic Fertilizer (OF) type, while the highest average *ρb* (1.35 Mg/m^3) was obtained for TD 45 cm and Without Fertilizer (WF) type. The results, as shown in Table 2, indicate a significant difference in the interaction between the number of Plastic Films (PF) and Fertilizer Type (FT) on soil bulk density (*ρb)*. The lower value of *ρb* (1.22 Mg/m^3) was obtained between the double-plastic films and the Organic Fertilizer (OF) type, while the higher value of *ρb* (1.32 Mg/m^3) was obtained without-plastic films and Without Fertilizer (WF) type. Another important finding was that interactions between Tillage Depth (TD), number of Plastic Films (PF) and Fertilizer Type (FT) showed significant differences between treatments on *ρb*. The lowest average for value *ρb* (1.20 Mg/m^3) was obtained at the interaction between TD 15 cm, double-plastic film and organic fertilizer, while the highest average value of *ρb* (1.38 Mg/m^3) was obtained at TD 45 cm, without-plastic films and without fertilizer type.

Influence of the Studied Factors on Soil Porosity (%)

Table 3 shows the experimental data for soil Tillage Depth (TD), number of Plastic Films (PF) and Fertilizer Type (FT) on soil porosity (*Φ*).The results showed a significant difference between TD on *Φ*. The highest value of *Φ* (52.78%) was obtained at TD15 cm in comparison withTD25 and 45 cm, which showed the values of 51.86 and 50.30%, respectively. The reason for this result might be the reduced soil porosity for increased bulk density when increasing tillage depth. This finding is in agreement with the result obtained by (Alam and Salahin, 2013). There was a significant positive correlation between numbers of Plastic Films (PF) and soil porosity (*Φ*). The highest value of *Φ* (52.70%) was obtained with the double-plastic films in comparison with the single-plastic films and without plastic films, which showed the values of 51.82 and 50.43% respectively. The reason for this finding may be that the soil of the double-plastic film has the lowest *pb* compared with the soil of the single-plastic films and without plastic films. Another reason could be that the soil of the double-plastic film had high temperature storage for soil, which led to the decomposition of the organic fertilizer by microorganisms. This would have decreased soil bulk density and increased soil porosity, compared with other treatments, a finding that is in agreement with (Merante *et al*., 2017; Keesstra *et al*., 2016). Further analysis showed a significant difference in the effect of fertilizer type son soil porosity (*Φ*). The higher value of *Φ* (52.57%) was obtained with Organic Fertilizer (OF) in comparison with Chemical Fertilizer (CF) and Without Fertilizer (WF) (51.73 and 50.64%, respectively).The reason for this result may be that the soil with organic fertilizer has a lower soil bulk density (*pb*), which leads to increased porosity (*Φ*). These results agree with the findings of (Li *et al*., 2017; Merante *et al*., 2017), in which the increasing organic matter of the soil led to decreased bulk density (*pb*) with increased porosity (*Φ*). The results in Table 3 show that there were significant differences in the interaction between Tillage Depth (TD) and the number of Plastic Films (PF) on the soil porosity(*Φ*). The TD15 cm and double-plastic film showed the highest *Φ* (53.70%); the lowest value of *Φ* (48.92%) was obtained at TD 45 cm and without-plastic film. Furthermore, there was a strong evidence of interaction between TD and FT on *Φ*, which showed the highest value of *Φ* (53.58%) at TD15 cm and Organic Fertilizer (OF), while the lowest value of *Φ* (48.04%) was obtained at TD 45 cm and Without Fertilizer (WF). Also, the results show that the interaction between the number of Plastic Films (PF) and Fertilizer Types (FT) was significantly different. The highest value of *Φ* (53.83%) was obtained for the interaction of the double-plastic film and Organic Fertilizer (OF), while the lowest *Φ* (49.95%) was obtained for without-plastic film and Without Fertilizer (WF). Furthermore, the interaction between soil Tillage Depth (TD), number of Plastic Films (PF) and Fertilizer Type (FT) showed significant differences among treatments on *Φ*, interaction between TD15 cm, the soil of the double-plastic film and organic fertilizer showed the highest value of *Φ* (54.71%), while the lowest *Φ* (47.92%) was obtained at TD45 cm, from the soil without-plastic film and two levels of fertilizer types Without Fertilizer (WF) and Organic Fertilizer (OF).

Influence of the Studied Factors on Soil Volumetric Moisture Content (cm^3/cm^3)

Table 4 presents the summary statistics for the influence of soil Tillage Depth (TD), number of Plastic Films (PF) and Fertilizer Types (FT) on the soil volumetric moisture content (*θ)*. It can be seen that the Tillage Depth (TD) had a significant effect on *θ*. TD 25 cm was obtained at a higher value of *θ* (0.196 cm^3/cm^3), compared with TD 45 and 15 cm, which show the values of 0.184 and 1.250 cm^3/cm^3, respectively The reason for this result might be that the soil volumetric moisture content (*θ*) is multiplied by the soil depth and because the obtained tillage depth of 25 cm had high moisture content compared with tillage depths of 45 cm and 15 cm. The results obtained show significant differences between the numbers of Plastic Films (PF) in *θ*. The soil of the double-plastic film resulted in a higher value of *θ* (0.231 cm^3/cm^3) and a lower value of 0.103 cm^3/cm^3 with the without-plastic film. The reason for this finding might be that the soil of the double-plastic film exhibited higher moisture content compared with other treatments because double-plastic film reduces the amount of water lost from evaporation compared with single-plastic film and without-plastic film. Surprisingly, no differences were found between fertilizer types on volumetric moisture content (*θ*). Statistical significance was evaluated at $p \leq 0.05$.

The results also showed that there was a significant positive correlation between Tillage Depth (TD) and number of Plastic Films (PF) with volumetric moisture content (*θ*). TD 25 cm and soil of the double-plastic film obtained the highest value of *θ* (0.242 cm^3/cm^3); while the lowest value of 0.026 cm^3/cm^3resulted from the interaction between TD 15 cm and the without -plastic film.

Table 3. Effect of tillage depth, number of plastic films and fertilizer type on porosity (%)

Tillage depth (cm)	Number of Plastic Films (PF)	Average Φ (%) on interaction triple Fertilizer Type (FT) Chemical	Organic	Without	Interaction the tillage Depth and number of plastic films
15	Single	52.83	53.96	52.45	52.57
	Double	53.2	54.71	52.83	53.70
	Without-plastic film	51.69	52.45	50.90	52.06
	Single	51.32	52.45	50.94	51.82
25	Double	52.83	53.58	50.94	52.82
	Without-plastic film	52.83	53.58	50.94	50.94
45	Single	51.69	52.45	48.67	50.81
	Double	52.83	53.20	50.18	51.19
	Without-plastic film	48.3	47.92	47.92	48.92
Average of fertilizer		51.73	52.57	50.64	LSD 0.05
Tillage depth (cm)	Fertilizers Type (FT)	Average Φ (%) on Interaction tillage depth and fertilizer type		Average Φ (% on the Tillage Depth (TD)	Tillage depth = 0.855, Number of plastic films = 0.889 Fertilizer type = 0.936
15	Chemical	53.08		52.78	Tillage depth × number
	Organic	53.58			of plastic film = 0.646
	Without	51.68			Tillage depth × fertilizer
25	Chemical	51.57		51.86	Type = 0.823
	Organic	52.57			Number of plastic film ×
	Without	51.57			Fertilizer type = 0.869
45	Chemical	50.81		50.3	Tillage depth × number
	Organic	52.07			of Plastic film × fertilizer
	Without	48.04			Type = 0.369
Number of Plastic Films (PF)	Fertilizer Type (FT)	Average Φ (%) on interaction the number of plastic films and fertilizer type		Average Φ (%) on the number of plastic films	
Single	Chemical	51.94		51.82	
	Organic	52.94			
	Without	50.68			
Double	Chemical	l52,95		52.70	
	Organic	53.83			
	Without	51.31			
Without-plastic film	Chemical	50.31		50.43	
	Organic	51.06			
	Without	49.95			

In addition, it can be seen from the data in Table 4 that the interaction TD 25 cm and Without Fertilizer (WF) type obtained the highest value of θ (0.203 cm^3/cm^3), lowest value (0.124 cm^3/cm^3) when interaction TD 15 cm and Without Fertilizer (WF) type. The interaction between number of Plastic Films (PF) and Fertilizer Type (FT) showed significant differences between a combination of double-plastic and Without Fertilizer (WF) to other treatments, obtained the highest value of θ (0.238 cm^3/cm^3); while the lowest value of θ showed at interaction between soil without-plastic film and without fertilizer type (0.085 cm^3/cm^3).

Furthermore, this finding confirms that triple interaction causes significant difference in the value of θ. The obtained interaction between TD 25 cm, soil of the double-plastic film and Without Fertilizer (WF) type at the highest value (0.262 cm^3/cm^3) and the lowest value (0.006 cm^3/cm^3) resulted in triple interaction TD 15 cm, soil of the without-plastic film and Organic Fertilizer (OF) type.

Influence of the Studied Factors on Soil Thermal Diffusivity (m^2/sec)

Table 5 shows the results obtained from the preliminary analysis of the influence of soil Tillage Depth (TD), number of Plastic Films (PF) and Fertilizer Type (FT) on soil thermal diffusivity (*D*). The results showed a significant effect of TD on the *D*. The highest value of *D* (1.94×10^{-6} m^2/sec) was obtained at TD 45 cm in comparison with the others (25 and 15 cm), which showed the values 9.65×10^{-7} and 1.24×10^{-6} m^2/sec, respectively.

Table 4. Shows the effect of tillage depth, number of plastic films and fertilizer type on soil volumetric moisture content (cm^3/cm^3)

Tillage Depth (cm) (TD)	Number of Plastic Films (PF)	Average θ (cm^3/cm^3) on Interaction triple Fertilizer Type (FT) Chemical	Organic	Without	Interaction the tillage depth and x number of plastic films
15	Single	0.137	0.156	0.116	0.136
	Double	0.251	0.222	0.216	0.229
	Without-plastic film	0.033	0.006	0.040	0.026
	Single	0.199	0.209	0.208	0.205
25	Double	0.227	0.238	0.262	0.242
	Without-plastic film	0.129	0.152	0.141	0.140
45	Single	0.226	0.147	0.193	0.188
	Double	0.210	0.218	0.238	0.222
	Without-plastic film	0.166	0.121	0.142	0.143
Average of fertilizer	0.177	0.160	0.172		LSD 0.05
Tillage Depth (cm)	Fertilizer Types (FT)	Average θ (cm^3/cm^3) on interaction tillage depth and fertilizer type		Average θ (cm^3/cm^3) on the tillage depth	Tillage depth = 0.035 Number of plastic Films = 0.025 Fertilizer type = N.S
	Organic	0.128			Tillage depth × number of plastic films = 0.018
	Without	0.124			Tillage depth × fertilizer Type = 0.040
25	Chemical	0.192		0.196	Number of plastic films x Fertilizer = 0.025
	Organic	0.192			
	Without	0.203			Tillage depth x number of plastic films x Fertilizer types = 0.019
	Chemical	0.200		0.184	
45	Organic	0.162			
	Without	0.191			
Number of Plastic Films (PF)	Fertilizer Type (FT)	Average θ (cm^3/cm^3) interaction number of plastic films and fertilizer type		Average θ (cm^3/cm^3) on the number of plastic films	
	Chemical	0.187		0.176	
Single	Organic	0.170			
	Without	0.172			
Double	Chemical	0.229		0.231	
	Organic	0.226			
	Without	0.238			
Without-plastic film	Chemical	0.108		0.103	
	Organic	0.117			
	Without	0.085			

The reason for this result might be because the TD 45 cm exhibited higher bulk density *ρb,* compared with TD 25 and 15 cm, *D* is increased by increasing *ρb*. This finding agrees with the findings of (Levy and Schmidt, 2016; Miyajima *et al*., 2015; Usowicz *et al*. 2016). The number of Plastic Films (PF) showed significant differences in *D*. The soil of the without-plastic films showed the highest value of *D* at 4.44×10^{-6} m^2/sec in comparison with soil covered by single-plastic films and double-plastic film, which showed the values 1.90×10^{-6} and 7.76×10^{-7} m^2/sec, respectively. The reason for this finding might be because the soil in the without-plastic film presented higher bulk density (*ρb*),which led to increased *D*, one of the most common factors to impact on soil thermal diffusivity. These results support the findings of (Tong *et al*., 2017).

The results showed no significant difference between Fertilizer Types (FT) on soil thermal diffusivity (*D*). From the data in Table 5, strong evidence of *D* was found at the interaction between the Tillage Depth (TD) and the number of soil- plastic film on the soil thermal diffusivity (*D*). The TD15 cm and without-plastic film showed the higher value of *D* (1.09×10^{-5} m^2/sec) and the lower value *D* (5.86×10^{-7} m^2/sec) was obtained at the interaction of TD 15 cm and the double-plastic film. Furthermore, it can be seen from the data that there was a significant positive correlation between Tillage Depth (TD) and Fertilizer Type (FT), indicating interaction at TD 45 cm and Organic Fertilizer (OF) obtained the highest *D* of 1.09×10^{-6} m^2/sec. The lowest value (9.63×10^{-7} m^2/sec) resulted from interaction at TD 25 cm and Chemical Fertilizer (CF) type. Interaction between the number of Plastic Films (PF) and Fertilizer Types (FT) on soil thermal diffusivity (*D*), the single-plastic film and the Organic Fertilizer (OF) type showed the highest value of *D* (1.00×10^{-6} m^2/sec)and the lowest value (8.27×10^{-7} m^2/sec) obtained at soil double-plastic film and without Fertilizer Type (WF).

Table 5. Effect of depth tillage, number of plastic films and fertilizer type on soil thermal diffusivity (m^2/sec)

Tillage Depth (cm) (TD)	Number of Plastic Films (PF)	Average *D* (m^2/s) on interaction triple Fertilizer Type (FT)			Interaction the tillage depth and number of plastic films
		Chemical	Organic	Without	
15	Single	1.14×10^{-6}	1.01×10^{-6}	1.20×10^{-6}	1.12×10^{-6}
	Double	7.90×10^{-8}	8.10×10^{-7}	8.70×10^{-7}	5.86×10^{-7}
	Without-plastic film	4.56×10^{-6}	2.48×10^{-5}	3.47×10^{-6}	1.09×10^{-5}
	Single	9.50×10^{-7}	9.00×10^{-7}	9.40×10^{-7}	9.30×10^{-7}
25	Double	8.50×10^{-7}	8.11×10^{-7}	8.29×10^{-7}	8.30×10^{-7}
	Without-plastic film	1.09×10^{-6}	1.16×10^{-6}	1.16×10^{-6}	1.13×10^{-6}
45	Single	8.83×10^{-6}	1.10×10^{-6}	1.05×10^{-6}	3.66×10^{-6}
	Double	9.80×10^{-7}	8.60×10^{-7}	9.00×10^{-7}	9.13×10^{-7}
	Without-plastic film	1.16×10^{-6}	1.33×10^{-6}	1.25×10^{-6}	1.24×10^{-6}
Average of fertilizer type		2.18×10^{-6}	3.64×10^{-6}	1.29×10^{-6}	LSD 0.05
Tillage Depth (cm) (TD)	Fertilizers Types (FT)	Average *D* (m^2/s) on interaction tillage (m^2/s) on the depth and fertilizer types		Average *D* tillage depth	Tillage depth = 2.677×10^{-6} Number of plastic films = 2.641×10^{-6} Fertilizer
15	Chemical	1.92×10^{-6}		1.24×10^{-6}	Types = N.S
	Organic	8.83×10^{-6}			Plastic films = 2.44×10^{-6}
	Without	1.85×10^{-6}			Tillage Depth X Fertilizer
25	Chemical	9.63×10^{-7}		9.65×10^{-7}	Types = 2.811×10^{-6}
	Organic	9.56×10^{-7}			Number of plastic films X
	Without	1.84×10^{-7}			Fertilizer types = 2.770×10^{-6}
	Chemical	3.65×10^{-6}		1.94×10^{-6}	Tillage Depth X Number of
45	Organic	1.09×10^{-6}			Plastic Films X Fertilizer
	Without	1.06×10^{-6}			Types = 6.28×10^{-9}
	Chemical	3.64×10^{-6}			
Number of Plastic Films (PF)	Fertilizer Types (FT)	Average *D* (m^2/s) on interaction number of plastic films and fertilizer types		Average *D* (m^2/s) on the number of plastic films	
Single	Chemical	3.64×10^{-6}		1.90×10^{-6}	
	Organic	1.00×10^{-6}			
	Without	1.06×10^{-6}			
Double	Chemical	6.36×10^{-7}		7.76×10^{-7}	
	Organic	8.27×10^{-7}			
	Without	1.96×10^{-6}			
Without-plastic film	Chemical	2.27×10^{-6}		4.44×10^{-6}	
	Organic	9.09×10^{-6}			
	Without	1.96×10^{-6}			

Interestingly, the triple interaction was observed at soil thermal diffusivity (*D*). The highest value of *D* at 2.48×10^{-5} m^2/se cw as obtained as a result of interaction of TD 15 cm, without- plastic film and Organic Fertilizer (OF) type, while the lowest value (7.90×10^{-8} m^2/sec) was obtained as a result of interaction of TD 15 cm, double-plastic film and Chemical Fertilizer (CF) type

Conclusion

This study presented an experimental investigation of soil solarisation technology on soil thermo-physical properties. The results show significant differences in the following factors: Soil bulk density (ρb), porosity (Φ) and gravimetric water content (θ) and soil thermal diffusivity (*D*). The results of this investigation show that the tillage depth of 15 cm produces lower values of *pb*, θ and *D* (1.25 Mg/cm^3, 0.131 cm^3/cm^3 and 1.24×10^{-6} m^2/sec, respectively) and a higher value of Φ (52.78%). Furthermore, *D* and *pb* are directly proportional. There was a significant positive correlation between the number of plastic film and parameters studied, the soil double plastic film was obtained lower values of *pb* and *D* for soil (1.253 Mg/$cm^{3,}$ 7.76×10^{-7} m^2/sec). However, it recorded higher values for Φ and θ for soil (52.70% and 0.231 cm^3/cm^3, respectively). Furthermore, It was also shown that significant differences between the types of fertilizers on *pb*. Organic fertilizer obtained a lower value of *pb* (1.256 Mg/m^3), compared with chemical fertilizer and without fertilizer (1.277 and 1.307 *Mg/m^3*, respectively). On the other hand the results of this study indicate no significant differences in the fertilizer type on *D* and *θ*. A positive correlation was found in the interaction between the studied factors in the parameters. Furthermore, *D* increased with increasing soil bulk density (*pb)* and tillage depth. Also, soil thermal diffusivity (*D*) was observed to increase with increasing *ρb* and TD.

Acknowledgment

We thank Will Gates (Institute for Frontier Materials, Deakin University. Melbourne, Australia) for comments that greatly improved the manuscript.

Author's Contributions

Ahmed Abed Gatea Al-Shammary: Participated in all experiments, coordinated the data-analysis and contributed to the writing of the manuscript.

Abbas Kouzani: Participated in coordinated the data-analysis and contributed to the writing of the manuscript.

Akif Kaynak, Sui Yang and Michael Norton: Participated in writing of the manuscript

Ethics

This article is original and contains unpublished material. All of the authors have read and approved the manuscript and no ethical issues involved.

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Appendix 1 Analysis of Variance (ANOVA table) for parameter studied

	Source of parameters	Variation	Df	Mean Anova SS	F. squares	Value	R- Square F.pr	Coefficient of variation
Soil bulk density	TD	2	0.0220	0.0110	17.19	<0.0001		
	PF	2	0.0231	0.0065	10.24	0.0009	0.792	1.979
	FT	2	0.0138	0.0069	10.80	0.0007		
Soil porosity	TD	2	28.644	14.322	12.70	0.0003		2.051
	PF	2	17.676	8.8380	7.84	0.0031	0.744	
	FT	2	19.533	9.7660	8.66	0.0020		18.627
Volumetric	TD	2	0.0218	0.0100	10.85	0.0006	0.8276	
moisture content	PF	2	0.0742	0.0370	36.82	<0.0001	0.2270	205.030
	FT	2	0.0007	0.0036	0.37	0.6980		
Soil	TD	2	4.74×10-11	2.37×10-11	1.02	0.3770		
thermal	PF	2	6.58×10-11	3.29×10-11	1.42	0.2640		
diffusivity	FT	2	2.34×10-11	1.17×10-11	0.51	0.6100		

DOI: 10.3844/ajassp.2017.649.661

Appendix 2. Shows specifications of the tractor used

Specifications	Explorer 85 DT
Mark	Same
Make	Italy
Engine type	Diesel
Number of cylinder/Capacity No/cc	4/4000
Max. engine speed (rated) rpm	1,400-1,600
Max. Torque Nm	257
Fuel tank capacity litres	150
Engine powerkW/hp	61/83
Standard rear tyres	420/85R30"

Appendix 3. Shows specifications of implements

Specifications	Disc plough	Disc harrow
Make	Turkey	Turkey
Width of cut m	0.95	1.5 m
Number of units	3	7*2
Tractor power requirement kw	50-60	50-60

Nomenclature

Thermo-Physical Properties	TPP
Soil Physical Properties	SPP
Soil Solarisation Technology	SST
Soil-Mulching Systems	SMS
Soil Mineral Composition	SMC
Randomized Complete Block Design	RCBD
Tillage Depth	TD
Plastic Films	PF
Soil bulk density	*Pb*
Soil porosity	Φ
Soil volumetric moisture content	θ
Soil thermal diffusivity	*D*
Soil thermal conductivity	D
Soil volumetric heat capacity	C_v
Organic Fertilizer	*OF*
Fertilizer Type	*FT*