A comparison of different solarisation systems and their impacts on soil thermal characteristics—an application in cultivated soils close to Baghdad, a highly populated city in Iraq

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Abstract

Solarisation application by mulching the soil with a polyethene plastic film has a significant influence on soil thermal characteristics (TCs), which, in turn, show a strong impact on soil energy balance and agricultural productivity. In countries like Iraq with highly populated cities, such as Baghdad, that need large quantities of agriproducts, this kind of clean energy should play a key role in sustainable agricultural production. However, little is known about the effects of different soil solarisation systems in specific cultivated fields for this country characterised by an arid climate and silty clay soils. Therefore, an experimental study was conducted to investigate changes in soil TCs under different soil solarisation systems (black and clear plastics) at three different soil depths in a two-factor factorial design. Also, both the black and clear plastic plots were compared with a control (without mulch) plot treatment.

Three different soil TCs were assessed, namely soil thermal flux (q_h), soil thermal conductivity (k), and soil volumetric heat capacity (C_v). The results of this study indicated that the soil solarisation application had a significant influence on soil TCs. Soil q_h decreased with increasing soil depth, while k and C_v exhibited an opposite trend. The black plastic mulch treatment produced higher soil q_h , k , and C_v values than both the clear plastic and the control treatments. Moreover, high diurnal variability of the TCs was also registered, and the clear plastic conserved a higher temperature than the black one during the night hours. During daylight, the black mulch reached a maximum temperature of 70 °C. It is recommended that more research should be conducted to get new insights on the interplay of the different seasons, and different crops and soil types.

Keywords

Soil energy balance
Solarisation
Plastic mulch
Soil thermal characteristics
Agricultural management system
Urban areas

Introduction

A drastic increase in population and globalisation has called for the redesign of agricultural management systems to increase food production without harmful effects on soil quality (Milligan and O’Keeffe 2018; Brevik et al. 2019). Due to these demographic and economic changes, renewable energies and their combination with sustainable agricultural management systems should play a vital role for designing efficient land management plans, and achieving land degradation neutrality (Keesstra et al. 2018; Griggs et al. 2013).

The combination of renewable energies and sustainable agricultural management systems should be mandatory for urban areas which experience the highest demand for food and energy (Godfray et al. 2010). One example of renewable energy is thermal energy, which should be considered a high priority in

underdeveloped arid and semi-arid countries characterised by highly populated cities (da Silva et al. 2018; Steinmetz et al. 2016). However, in an extensive review conducted by Kasirajan and Ngouajio (2012), the applications and studies of sustainable plastic mulches and their impacts on soil thermal characteristic (TCs) are devoid of environmental and agronomic perspectives.

Thermal energy, being able to modify soil properties, has been studied as an important parameter of soil systems (Wilhelm and Bockheim 2016; Mengistu et al. 2017). TCs show a key influence on soil energy balance and soil temperature (Pramanik et al. 2015). It is well-known that thermal energy can be transferred by convection and conduction. However, soil TCs in cultivated fields are dynamic because they are primarily dependent on the effects of certain mechanical human alterations such as tillage, and inherent natural conditions such as soil bulk density and moisture content (Hu et al. 2016; Wilhelm and Bockheim 2016; Alrtimi et al. 2016).

Knowing the positive and negative effects of solarisation techniques on soil properties, and when and where these practices have started, is very useful. The implementation of solarisation technology has been assessed by many investigations under different soil management systems and environmental conditions in more than 60 countries (Gamliel and Katan 2005), particularly in arid and semi-arid climates (e.g. J Katan et al. 1976; Pullman et al. 1979; Shi et al. 2018; Al-Shammmary and Al-Sadoon 2014a). Solarisation increases crop productivity by modifying some key soil properties such as increasing the soil porosity and conserving soil moisture content as a result of the reduction in evaporation (Zribi et al. 2015). Some authors have also highlighted that soil aggregation can be improved (Kader et al. 2017) and soil salinity can be reduced (M. Zhang et al. 2018) by solarisation application. However, recent research has confirmed that solarisation may show some negative impacts on soil quality. The drastic variation of soil temperature and moisture content could destroy some beneficial soil microbial communities, such as Bacilli and Gammaproteobacteria, Actinobacteria, Alphaproteobacteria, and Acidobacteria (Kanaan et al. 2018).

AQ2

Soil tillage plays an important and recognised role in soil management practices in agricultural fields by modifying soil physical properties (Al-Kaisi et al. 2005; Bogunovic et al. 2017b), or by enhancing soil and water mobilisation (Alliaume

et al. 2014; Martínez-Casasnovas and Sánchez-Bosch 2000). However, its impact is different at distinct soil depths that need to be assessed. Accordingly, tillage depth also affects solarisation effectivity because of gains and losses of soil heat transfer energy throughout the soil profile as a result of changes in colour, compaction, moisture, organic matter, and porosity, among others.

There has been an increasing amount of literature on soil TCs under different environmental conditions. Recently, the main TCs considered are the thermal flux (q_h), soil thermal conductivity (k), and soil volumetric heat capacity (C_v) (Łydźba et al. 2016; Li et al. 2016; Alrtimi et al. 2016; Levy and Schmidt 2016). These TCs are strongly dependent on soil mineral composition, bulk density (ρ_b), moisture content (μ), and soil texture (Łydźba et al. 2016). However, the effectiveness of a soil solarisation system, and its impact on TCs, also varies with the type of mulch used. For example, Li et al. (2016) studied the impact of plastic mulch on soil flux density. They found that plastic mulch reduced soil evaporation, which influences soil TCs, and had a significant influence on soil q_h . A recent study conducted by Levy and Schmidt (2016) in Antarctic soils demonstrated that soil k and C_v are dependent on μ , and both increase with soil depth. Furthermore, studying the effects of soil ρ_b , μ , and organic matter on soil thermal conductivity, they discovered that k increases with soil ρ_b and μ . Alrtimi et al. (2016) investigated the differential impacts of soil porosity (Φ) and volumetric moisture content (θ) on soil k . They found a relationship between soil k , Φ , and θ , and that soil ρ_b increases soil k . Dong et al. (2016) evaluated soil μ and thermo-hydraulic properties by estimating soil temperature at different depths. They demonstrated that soil's hydraulic properties significantly influenced soil μ because of their impact on soil heat transfer. Furthermore, they established that soil TCs can be estimated from soil hydraulic properties and soil condition.

In arid and semi-arid areas close to big populated urban areas with an elevated number of sunny hours, the variations of TCs along the soil profile is not well-known. However, this knowledge will allow farmers to decide on a more sustainable and effective mulch type. Therefore, an experimental study was conducted to investigate changes in soil TCs under two different soil solarisation systems (black and clear plastics) at three different soil depths in a two-factor factorial design. Both solarisation systems plots were compared with a control

plot without any mulch. Three different soil TCs were assessed, namely soil thermal flux (qh), soil thermal conductivity (k), and soil volumetric heat capacity (C_v). A field experiment was conducted on experimental plots in the highly populated city of Baghdad, Iraq, with a representative soil type cultivated with the wheat crop.

Materials and methods

Study area

The experimental field (33° 13' 59.8" N, 44° 27' 52.6" E) is located in the Al-Rabyaa station which belongs to the Agriculture Ministry in Zafaraniah/Baghdad, Iraq, and is in a slightly undulating area. The experimental procedure was carried out during summer (from June 1, 2015 to September 1, 2015) in order to get the maximum solar energy, and also to avoid problems of excessive rainfall since summer months are generally dry. The experimental plot is characterised by the subtropical aridity of the Arabian Desert and the subtropical humidity of the Arabian Gulf, experiencing a mean annual rainfall of 160 mm (Alzubaydi and Alamar 2016; Al-Shammary et al. 2016). The climate is characterised by a long, hot, and dry summer with an average relative humidity of 26.9%, and an average temperature of 34.6 °C. The parent material belongs to the lithological group of sedimentary rocks with an average depth of groundwater higher than 150 cm (Almahmood 2010).

AQ3

Prior to establishing the crops, seeds of *Alhagim aurorum* (a legume species), *Cynodon dactylon* (a grass species), and *Imperata cylindrical* (a grass species) were spread to serve as cover crops. According to the US Department of Agriculture Soil Survey Staff (1975) classification system, the soils are silty clay because of the high contents of clays (> 40%) and silts (> 40%) (Table 1). The soils are cultivated with wheat and barley which are under surface irrigation with water sourced from the Tigris River.

Table 1

The average physical and chemical properties of the studied soils

Soil depth (cm)	BD (g/cm ³)	SM (%)	SOM (%)	PSD (%)			EC (ds/m ⁻¹)	CO ₃ ⁻²	HCO ₃ ⁻¹	Cl ⁻
				Clay	Silt	Sand				

Soil depth (cm)	BD (g/cm ³)	SM (%)	SOM (%)	PSD (%)			EC (ds/m ⁻¹)	CO ₃ ⁻²	HCO ₃ ⁻¹	Cl ⁻
				Clay	Silt	Sand				
0–10	1.21	31	8.0	47	41	12	2.06	0	7	13
10–20	1.24	32.6	4.8	45	41	14	1.70	0	9	8
20–30	1.29	38	4.0	41	43	16	1.34	0	10	3

BD, bulk density; *SM*, soil moisture; *SOM*, soil organic matter; *PSD*, particle size distribution

Experimental design and data analysis

Field experiments were conducted to investigate the impact of soil solarisation technology, using two different types of plastic mulch, examining three soil characteristics of thermal flux (q_h), thermal conductivity (k), and volumetric heat capacity (C_v) at different soil depths. For the experimental design and management of treatments, the variables were selected in a two-factor factorial design. The first factor was the soil tillage depth at three different levels of 10, 20, and 30 cm. The second factor was the mulching type being clear plastic mulch (CM), black plastic mulch (BM), and the control without mulch (WM) (Fig. 1). In the current study, the soil field was ploughed by a disc plough (DP) followed by a spring disk using a tractor (Same Explorer 85 DT). Three replications were considered, each replica consisting of nine (3 types of soil management $\times$ 3 soil depths) experimental plots of 2×2 m (Fig. 1). The experimental field was irrigated to 100% field capacity by surface irrigation, and the mulched experimental field plots were covered with a 0.5-mm-thick polyethene film after 48 h. The field was monitored from June 25, 2015 to August 7, 2015. The polyethene film was carefully unrolled and perfectly attached to the soil surface to increase the solarisation efficiency (Jaacov Katan and DeVay 1991). Plastic straps were also installed in at least two places to prevent blowing of dust underneath.

Fig. 1

Schematic diagram of the experimental field layout. Ti represents soil treatments of replication i ; shaded circles with crosses represent the thermocouple location at 10 cm (blue), 20 cm (orange), and 30 cm (green) depths

In the next step, a thermocouple-type (K) thermometer (MT-4011) was installed at each of the three soil depths, as well as between the mulch and soil surface, for hourly measurements of soil temperature from 9:00 to 15:00 h (24-h clock format). Finally, on August 7, 2015, calculations of the soil bulk density (g cm^{-3}), porosity (%), volumetric moisture content ($\text{cm}^3 \text{cm}^{-3}$), thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$), volumetric heat capacity ($\text{J m}^{-3} \text{K}^{-1}$), and thermal flux (W m^{-2}) were carried out after removing the covers from the treatment units.

Soil heat flux density, q_h it is q_h please format

h (W/m²), is a single-valued function of soil thermal conductivity, k (W/m K) and was calculated as (Evet et al. 2012):

$$q_h = -k \frac{dt}{dx} \quad 1$$

where dt is the difference in soil temperature (K) between two depths, and dx is the vertical distance between the depths (m).

Soil thermal conductivity (k) was estimated using Eq. 2 (N. Zhang and Wang 2017):

$$k = 0.1442 [0.9 \log \mu - 0.2] 10^{0.01pb} \quad 2$$

where μ is soil moisture content by weight (%) and ρ_b is soil bulk density (g/cm³). Then, the soil bulk density was calculated as (Smith 2000):

$$\rho_b = \frac{M_s}{V_t} \quad 3$$

where M_s is the oven-dried soil weight (g) and V_t is the soil volume (cm³).

Finally, the volumetric heat capacity, C_v (J/m³ K), was calculated considering Eq. 4 (Evet et al. 2012):

$$C_v = \frac{2.01 \times 10^6 pb}{2.65 + 4.19 \times 10^6 \theta} \quad 4$$

where θ is the volumetric moisture content (cm³/cm³), which was calculated as (Smith 2000):

$$\theta = \frac{p_w \times \rho_b}{d_w} \quad 5$$

where p_w is moisture content by weight (%) and d_w is water density (g/m³).

The main descriptive statistics of the average, standard deviation, maximum, and minimum were calculated and presented in tables and depicted in box plots. The

interaction effects of the experimental factors among treatments were obtained using a two-factor ANOVA. The main goal was to confirm whether the variables (factors) are significant, either separately (namely main effects) or in combination (via an interaction), and which is the included effect of the two analysed factors on soil thermal characteristics. Equal variance and Shapiro-Wilk tests were also carried out to confirm if the results follow a normal distribution. However, all the data showed no normal distribution. Therefore, the Tukey test was applied in order to assess differences among the plots. When significant differences were found, a post hoc test was used. Finally, the least significant design (LSD) analyses at 0.05 confidence level were performed to compare the means of the treatments. All statistical analyses were carried out using the SAS 9.4 software and SigmaPlot v.13 (Systat Software Inc.).

Soil sampling and analysis

The soil sampling procedure involved several steps. Firstly, the experimental site was cleared of plant waste, and then, soil samples were collected from the field at three depths (0–10, 10–20, and 20–30 cm). Samples were then smoothed by passing them through a 2-mm-diameter sieve and dried at ambient air conditions. Soil mechanical analysis was performed using a triangular diagram according to the United States Department of Agriculture (USDA) texture classification. Electric conductivity (EC) was measured according to the procedure of (Krishna 2016). Soil pH was analysed following (Vogt et al. 2015), and for the organic matter by the method of (Kroetsch and Wang 2007). Soil ρ_b was measured by the core method as detailed by (Walter et al. 2016).

Results

Soil properties

Table 1 presents the average of the soil's physical and chemical properties at the 3 depths. The soil layer 20–30 cm depth recorded the highest values of bulk density, averaging 1.29 g cm^{-3} . The lowest values were recorded at the surface (0–10 cm) with an average of 1.21 g cm^{-3} , indicating that this soil property increases with depth. Similarly, the deepest layer (20–30 cm) registered the highest average soil moisture of 38%, while the lowest (31%) was recorded at the surface. The highest average soil organic matter (8%) was found at the 0–10 cm depth, and the other soil layers showed less than 5% organic matter content.

Moreover, the average electrical conductivity indicated higher values at the surface (up to 20.06 ds/m^{-1}) compared with the deeper layers. Finally, it is important to highlight that all the soil nutrients showed higher values at the surface layers (0–10 cm) than in the deeper ones (10–20 and 20–30 cm). Only Mg^{+2} registered the highest value at the middle layer of 10–20 cm.

Soil temperature changes

Figure 2 depicts the average diurnal soil temperature variation for the black, clear, and control treatments at each of the 3 soil layers. The Tukey test was applied to check whether there are statistically significant differences in diurnal soil temperature changes for the soil depths and treatments (Table 2).

Fig. 2

Diurnal average soil temperature ($^{\circ}\text{C}$) variations for the gap between mulch and soil surface and at the three soil depths for each soil management system

Table 2

Application of Tukey test to check statistically significant differences in diurnal soil temperature changes

Comparisons		Black vs clear	Black vs control	Clear vs control
Soil depth (cm)	Gaps	$P = 0.017$	–	–
	0–10	$P = 0.046$	$P = 0.001$	$P = 0.061$
	10–20	$P = 0.061$	$P = 0.257$	$P = 0.328$
	20–30	$P = 0.406$	$P = < 0.001$	$P = 0.006$

At 0–10 cm, statistically significant differences at the 5% level were found between the use of black and both the clear plastic mulch ($P = 0.046$) and the control ($P = 0.001$). However, this was not the case between the clear and the control treatment ($P = 0.061$). It is observed that the black and clear plastics reached average diurnal temperatures above 59 °C, and for the control plot, this was above 43 °C. During all times, the black plastic plots registered higher soil temperatures than both the clear one and the control treatments, reaching maximum average values from 65 to 74 °C between 11:00 and 14:00 h. The highest soil temperatures reached by the clear plastic was 66 °C at 11:00 h. At the end of the monitoring time (15:00 h), the clear plastic and the control plots showed similar temperatures (50–51 °C). Conversely, the black plastic displayed average soil temperatures higher than 62 °C.

For the middle soil layer (10–20 cm), the black and clear plastics did not show statistically significant differences ($P = 0.061$) at the 5% level. Between the hours of 9:00 and 10:00 h, soil temperature was similar for the clear and black mulches with average values between 57.7 and 60 °C. For all treatments, the soil temperature peaked at 11:00 h, the black plastic registering a maximum average value of 68 °C. After the peak, the clear plastic clearly demonstrated a faster rate of decline followed by the control treatment. At the end of the monitoring period, the clear plastic showed similar temperatures to the control plot, an average of 48.8 °C. The average soil temperature for the monitoring hours was 60 °C for the black plastic, 48.8 °C for the clear plastic, and 47 °C for the control treatment.

Finally, at 20–30 cm, no significant statistical differences between the black and

clear plastics were obtained ($P = 0.406$). On the other hand, both soil management systems showed significant differences when compared with the control treatment. It is important to remark that the average of the clear plastic soil temperature is similar at the 0–10 and 10–20 cm depths, but higher than at 20–30 cm. These results confirmed that, when using the clear plastic, the soil temperature becomes lower than the black one, but it can conserve temperature along the soil profile depth. However, the black plastic showed a decrease by 5 °C from the surface to the deepest layer, although the hourly temperature was always higher than for the clear plastic and the control plots.

Variation of soil thermal characteristics with soil depths and management systems

Figure 3 depicts box plots of the effect of the soil management system and depth on the soil thermal characteristics (thermal flux q_h , thermal conductivity k , and the volumetric heat capacity C_v). It is observed

that q_h decreases with increasing soil depth for all treatments (Fig. 3a–c). The average q_h at 10 cm soil depth with the clear mulch was 55 W m⁻², which was much

higher than at the 10–20 (6.8 W m⁻²) and 20–30 cm (6 W m⁻²) depths. At the 10 cm soil depth, the black mulch recorded a higher average q_h (63 W m⁻²) than the clear mulch. Also, a lower average value of q_h was obtained at the 10–20 cm (8 W m⁻²) and 20–30 cm (6 W m⁻²) depths.

For the clear and black mulch plots, the values were drastically different at the 0–10 cm soil depth. However, the differences decreased significantly for the two deeper soil layers.

Figure 3 shows box plots of the effect of the soil management system and depth on the soil thermal characteristics (thermal flux, soil thermal conductivity, and soil volumetric heat capacity) with soil management system and soil depth.

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Fig. 3

Variation of thermal soil characteristics (thermal flux, soil thermal conductivity, and soil volumetric heat capacity) with soil management system and soil depth

AQ4

The results indicated that the soil management systems also influenced soil thermal conductivity at different soil depths (Fig. 3d–f). Both the clear and black plastics recorded mean values of k around $0.9 \text{ W m}^{-1} \text{ K}^{-1}$ at the two deeper depths, while the surface layer recorded around $0.65 \text{ W m}^{-1} \text{ K}^{-1}$. For the control plot, the variability of the results was higher than for the soils with plastic mulches, although all the values were in general lower than the mulch plots.

In general, C_v increased with soil depth for all the soil management systems (Fig. 3g–i). The highest mean value of C_v was $25 \times 10^5 \text{ J m}^{-3} \text{ K}^{-1}$ for the soils

with clear mulch and $3 \times 10^6 \text{ J m}^{-3} \text{ K}^{-1}$ for the black mulch at the 20–30 cm depth. For 10–20 and 0–10 cm soil depths, the clear mulch registered 2.3×10^6 and $1.6 \times 10^6 \text{ J m}^{-3} \text{ K}^{-1}$, respectively, while the values for the black mulch were slightly higher at 2.7×10^6 and $1.9 \times 10^6 \text{ J m}^{-3} \text{ K}^{-1}$, respectively.

Table 3 shows an analysis of the variance (ANOVA) for the individual effect of the soil management systems and soil depths on soil thermal characteristics and their interaction. These results are presented according to the coefficient of determination, mean square error, least significant difference, and standard errors of differences of means. Significant differences ($P < 0.05$) were observed in the plastics used per soil depth for all the soil thermal characteristics. Soil qh , k , and C_v showed a significant positive correlation with both clear and black plastic mulches used as well as with soil depths.

Table 3

Results of analysis of variance (ANOVA) for the interaction of the mulching systems and soil depths

Treatment	Df	R^2			$M.S_{Error}$			Soil L_{sd} (W/m ² K)
		Soil qh (W/m ²)	Soil k (W/m K)	Soil C_v (J/m ³ K)	Soil qh (W/m ²)	Soil k (W/m K)	Soil C_v (J/m ³ K)	
Mulching	2	-	-	-	10.166	0.002	4.645E8	3.158
Soil depth	2	-	-	-	10.166	0.002	4.645E8	3.158
Mulching vs soil depth	4	0.985	0.944	0.998	10.166	0.002	4.645E8	5.469

Df, degrees of freedom; R^2 , coefficient of determination; $M.S_{Error}$, mean square error; L_{sd} , least significant difference of the differences of means; qh , thermal flux; k , thermal conductivity; C_v , volumetric heat capacity.

Discussion

After investigating changes in soil thermal characteristics (TCs) under different soil solarisation systems (black and clear plastics and control) at 3 different soil depths, significant differences among treatments are confirmed. This analysis will clearly help enterprises and farmers in choosing the most efficient plastic mulch. The heat transfer along the soil depth is a complex process influenced by environmental factors (temperature) and soil management techniques (tillage,

fertilisers, etc.) (Pramanik et al. 2015; Alrtimi et al. 2016). In this paper, only one type of soil was tested under specific conditions. Therefore, we recommend that studies be undertaken on the different representative soil types close to Baghdad and also that these be monitored for more concrete results. It is confirmed that the TCs are mostly controlled by soil bulk density, moisture content, and soil texture (Łydźba et al. 2016; Al-Shammary et al. 2019), which are also linked to thermal flux, soil thermal conductivity, and soil volumetric heat capacity (Levy and Schmidt 2016; Alrtimi et al. 2016).

It is shown in Table 1 that the soils of the study area are characterised by a heavy texture (silty clay; (USA 1975)) in the soil profile. The soils have high values of bulk density and moisture content (Al-Shammary et al. 2018). We observed that the highest average bulk density values were measured at the deepest layer (20–30 cm depth) and the lowest values at the surface layer (0–10 cm depth). This could be the first clear key factor that is controlling soil temperature. These differences may be attributed to the different agricultural management practices throughout the cropping season using machinery to plough the soil, which is more intense for soils with high contents of clays and silts (Ramos et al. 2000; Wang et al. 2014). Furthermore, deeper soils are generally denser because of the overburden of the upper horizons (Chaudhari et al. 2013). Therefore, our results can be put in a context highlighted only under the special conditions of soil texture and management system. The differences in bulk density also affect the water content of the soil layers (Castillo et al. 2003; He et al. 2017). It was observed that the soil moisture content was also higher at the deepest soil layer, which may be attributed to the low soil μ (drier soil) of the top layer, compared with the middle and bottom layers, the lower evapotranspiration rates, and the consumption of water by the crops (Francone et al. 2010; Ruiz-Sinoga et al. 2011). Therefore, considering all of these key soil characteristics, the differences among soil horizons could be clearly justified. The size and distribution of the solid soil particles clearly affected the thermal conductivity (k) of the soil, which was also confirmed by other previous studies conducted in Iraq (Al-Temmami 2015).

Furthermore, considering the differences in bulk density, the porosity will also be different. Soil porosity is considered a key factor in soil temperature changes because how easily gas and liquid fluxes can go through the soil depends on the pore sizes and interconnections. It is well-known that air shows very low values

of k compared with water and solid material (Buczko et al. 2006). Therefore, a higher air content would reduce the contact between soil particles, thus reducing k (Al-Shammary and Al-Sadoon 2014b). Confirming this situation in our studied soils, it would be important to assess if the current soil management system carried out by heavy machinery that increases soil compaction is affecting the thermal conductivity through the soil profile. One example can be noted in the research carried out in the Croatian vineyards by Bogunovic et al. (2017a). They observed in soils tilled by tractors that soil functions such as soil respiration or CO_2 was highly affected after each tractor pass. Therefore, another research line for the future should be related to monitoring soil under a no-tillage management system and its influence on TCs. Several authors have highlighted that tillage highly affects some soil responses such as soil and water losses, soil compaction, soil respiration, carbon sequestration, and liberation and the loss of fertility in some extreme cases due to the deterioration of soil aggregates (Adimassu et al. 2019; Buczko et al. 2006; Cerdà et al. 2009).

AQ5

Another key factor that shows strong differences among soil treatments at different soil depths is the high soil organic matter of the top layer (0–10 cm) compared with the 10–20, and 20–30 cm soil depths. Soil nutrient contents demonstrated that the surface layer is very rich and has the potential to be very fertile. The high content of organic matter due to human additions also correlates with a higher water retention capacity (Behera and Shukla 2015; Camilli et al. 2016) as was confirmed with our soil analysis. Therefore, the conservation of high organic matter content could enhance soil heat transmission through the soil profile. On the other hand, it would also be important to investigate whether fertilisers are kept in the soil all year round with the same high rates and that no losses occur after extreme rainfall events or tractor passes as other authors have demonstrated in agricultural fields (Borrelli et al. 2016; Szalai et al. 2016).

Improving TCs is a matter of great concern in soil science, as thermal TCs are of importance for the determination of rates and directions of soil physical, chemical, and biological processes, as well as for energy and mass exchange with the atmosphere (Pramanik et al. 2015). After monitoring of the mean daily soil temperature, significant differences of TCs between black and clear plastics were confirmed. Our findings showed that the use of plastics increases soil temperature, but black mulch treatment was the most effective at reaching the

highest peak temperatures at the different soil depths. However, we observed smaller variations during the day, and at different soil depths, using the clear plastic. The black mulch was more effective in heating the air and soil beneath it because the heat was trapped by the solarisation system, reducing the soil thermal loss which increases soil temperature (Tesfaye et al. 2016; Ito et al. 2011). Therefore, when farmers intend to use a specific kind of plastic, several factors related to the daily temperature variations, crop thermal necessities, and root development have to be taken into account (Anikwe et al. 2007; Vela et al. 2017; Cohen et al. 2018). The highest soil θ_v

it is q_h please format

θ_v was also obtained using the black mulch treatments, which can be attributed to their higher efficiency in controlling evaporation from the soil as demonstrated on the growth and yield of tomatoes with the influence of three types of mulch in Ibadan in the south of Nigeria (Awoodoyin et al. 2007).

Soil k with mulch treatments (clear or black) was also higher compared with soils without mulch at the 0–10 cm soil depths. This is the case because soil k is directly proportional to soil volumetric moisture content. Soil mulching increases soil moisture content by decreasing water loss through evaporation, consequently increasing soil k compared with the control treatment, which corroborates the studies carried out in Iraq and Poland by Al-Shammmary and Al-Sadoon (2014b) and Usowicz et al. (2016), respectively. Also, soil C_v increases when mulching is used. Soils with black mulch treatment obtained the highest soil C_v compared with soil with clear mulch or without treatment. Soil C_v increases as soil moisture increases, and, as a consequence, the heat storage capacity of the soil also increases (Alnefaie and Abu-Hamdeh 2013).

The influence of the depth of the soil tillage system was also reported as significant on soil θ_v it is q_h please format

θ_v due to the increase in soil temperature near the soil surface by solar radiation (Al-Shammmary and Al-Sadoon 2014b). The current study demonstrated that, when soil depth increases, soil θ_v it is q_h please format

θ_v decreases (Fig. 3). This can be attributed to soil θ_v it is q_h please format

θ_v being directly proportional to soil k , but tillage decreases soil k values by reducing the bulk density (Abu-Hamdeh 2000; Merante et al. 2017; Ingman et al. 2015), resulting in a decrease in soil θ_v it is q_h please format

h. These results also corroborate the findings of other studies reported in Canada and Northern Germany by (Azooz et al. 1997; Dec et al. 2009), respectively.

It is recommended that future research should be directed to the following:

- i) To find the relationship between the use of plastic mulch, organic carbon, and soil nutrients during the year;
- ii) To examine the possible correlation between the use of plastic mulch on TCs and crop production depending on the type of plant;
- iii) To assess the economic costs and farmers' perceptions of the use of plastic mulch and the impacts on soil properties and crop production;
- iv) To assess the environmental impact of the use of plastic mulch when an organic farming system is developed without fertiliser and no-tillage practices.

Conclusions

The use of plastic mulches greatly benefits the TCs at different soil depths. However, we observed several significant differences in soil management systems. The black plastic mulch reached higher diurnal soil temperatures than both the clear mulch and the control treatments. However, the clear plastic mulch showed more regular conservation of the temperature within the soil profile and during the day. Therefore, we underline that, depending on the type of crop and soil physical properties such as bulk density, soil water content, particle size distribution, and organic matter, the effects of the intended type of plastic mulch must be thoroughly checked as mentioned in the above discussions. It is considered necessary to investigate the relationship between the type of plastic mulch, crop production, economic costs, farmers' perceptions, and their possible environmental impacts.

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