Effects of solarisation on soil thermal-physical properties under different soil treatments: A review

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ABSTRACT

Solarisation technology allows for improving soil quality as well as crop productivity. The influence of the properties and method of use of plastic materials used to cover soils, such as the number and thickness of layers, and colour of the material, significantly alters soil thermal-physical properties. These effects can be managed and modified to increase solarisation efficiency by achieving a decrease in vapour movement between the soil surface and the atmosphere. Also, soil solarisation establishes microclimates that increase the effectiveness of fertilisers, thus modifying the soil thermal-physical properties. However, there is a lack of complete and general overview of this widely used technology. This paper presents a comprehensive review of soil solarisation technology and describes the impacts it has on soil thermal-physical properties when combined with different soil treatments. It is well-known that the efficiency of solarisation technology increases with temperature. However, we describe that the heat

transfer effectivity depends on several different soil thermal-physical properties such as the soil thermal flux, conductivity, diffusivity, soil volumetric heat capacity, and soil temperature. Other soil physical properties such as soil texture, soil bulk density, soil porosity, and soil volumetric moisture content have contributions to make. Moreover, there are several external factors which significantly modify the effectiveness of heat transfer under different solarisation conditions, particularly the weather conditions, the type of tillage management, properties of plastics used and moisture content. We conclude that more research needs to be done: (i) to quantify the degree to which soil thermal-physical properties affect soil solarisation technology, and (ii) to assess the impact of soil technology on crop productivity and quality.

Keywords: Solarisation technology; soil thermal-physical properties; external factors; tillage management; soil mulches; fertiliser.

1. INTRODUCTION

Solar is a cost-effective and eco-friendly energy source in agriculture. Therefore, it is an indispensable source of natural and clean energy for farmers, especially in the underdeveloped and developing regions of the world (Gatea, 2010; Waewsak et al., 2006). Solar energy can also be used to develop other kinds of technologies, such as soil solarisation technology (solar heating). Soil solarisation aims to improve soil properties and controls the soil-borne disease by improving soil water and temperature conservation (Cerdà et al., 2016; da Silva et al., 2018; Kanaan et al., 2018).

By mulching the soil with a polyethene film, which can be transparent or black, solar heating is transferred to the wet soil horizons and strongly alters the solarisation process. This solarisation technology, which can be applied without using chemicals or pesticides, enhances the elimination of soil pathogens. It is one of the best alternatives in terms of environmental sustainability for controlling weeds and pests in high-temperature 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- and arid areas. It is reported to be a key factor for agricultural productivity and soil health (Simmons et al., 2016).

Solarisation of soils is a non-permanent type of soil management as the plastic cover is removed after some weeks. It is used just to enhance: (i) ploughing process; (ii) addition of fertilisers and their mixture into the soil; (iii) maximum irrigation field capacity; and (iv) disinfestation, especially at sites with hot conditions during long summers lasting between 4 and 6 months (Morra et al., 2018; Simmons et al., 2016).

Other benefits of solarisation technology are the modification of the microbial populations, soil functionality, nutrients availability, weed growth and the amount of dissolved organic matter because of its effect on soil temperature (Al-Shammmary et al., 2016; Morra et al., 2018). For example, organic matter, soluble forms of nitrogen (NH_4^+ , NO_3^-) and some macro and meso-nutrients (K, Mg, Ca, Na) can increase after applying a solarisation technique (D'Addabbo et al., 2010). Grünzweig et al. (1999) also found that

nitrogen accumulation can increase during soil solarisation because of the higher decomposition rates of the organic matter and the death of microbial biomass. According to Braida et al. (2008), soil organic matter combined with solarisation application can significantly affect soil elasticity which leads to positive effects on soil health by reducing soil compaction, increasing water-holding capacity and heat transfer (Al-Shammary et al., 2017; Chaudhari et al., 2013).

Solarisation technology is reported to be effective in increasing soil productivity in many geographical areas (Dai et al., 2014). However, in agricultural ecosystems, it has been noted that solarisation technology has some technical limitations due to some inevitable impacts on soil properties and climatic differences (Katan, 2017; Morra et al., 2018). Over the past two decades, soil mulching using plastic films has improved soil solarisation technology due to a reduction in evaporation of soil moisture and improved soil physical properties such as soil bulk density, porosity and soil temperature (Castello et al., 2017). However, the intensity of sunlight, which affects soil heating, has a significant influence on the efficiency of solarisation technology. Furthermore, the soil depth, air temperature (T), and moisture content (μ) are also important variables in the performance of the solarisation process (D'Addabbo et al., 2010).

Soil solarisation technology significantly influences the establishment of microclimates that lead to an increase in the effectiveness of fertilisers in the soil, a reduction in the amount of irrigation (Jiang et al., 2017; Mahdavi et al., 2017), and an improvement of the physical structure of the soil (Figueiredo et al., 2017). Also, it is often presented as improving soil structure in terms of bulk density (ρ_b), porosity (Φ) and volumetric moisture content (Θ). As a result of these positive impacts, solar heating could generally improve soil quality.

The type of tillage system, the addition of fertiliser, and the influence on inherent soil properties of the plastic mulch are all technical, or management factors, that significantly impact on soil solarisation (Al-Shammary et al., 2017) and soil thermal-physical properties (Blanco-Canqui and Ruis, 2018; Ozpinar et al., 2018). However, there is a lack of a complete and general review of this widely used technology. Therefore, this paper presents a comprehensive review of the literature on soil solarisation technology and describes the impacts on soil thermal-physical properties when combined with different soil treatments.

Specifically, we assess and clarify: (i) how soil solarisation technology works; (ii) the main factors that affect solarisation technology; (iii) mulching cover material properties; and (iv) positive and negative impacts on crop production, soil properties, and the environment.

To achieve these goals, an extended literature review was conducted in order to cover the most important key questions related to how soil solarisation works, the main factors that affect solarisation technology, and its effects on soil thermal-physical properties. A total of 210 original research articles, 13 reviews, and 5 books or book chapters were found dating from 1977 to 2019. It is also important to state that the search was performed only for indexed and peer-reviewed manuscripts in English.

2. DEFINITION OF SOIL SOLARISATION TECHNOLOGY AND ITS ADVANTAGES AND DISADVANTAGES

Soil solarisation can be defined as a technology which allows improving the soil thermal-physical properties and is considered as a non-chemical method (Al-Shammary and Al-Sadoon, 2014) which must be applied before planting (Özyilmaz, 2019). Solarisation technology has been studied by many researchers under different soil management systems in more than 60 countries (Gamliel and Katan, 2005), particularly in arid and semi-arid climates such as in Israel (Katan et al., 1976), California (Pullman et al., 1979), China (Shi et al., 2018), Egypt (Satour et al., 1988; Satour et al., 1991), Spain (Basallote-Ureba and Melero-Vara, 1993), Australia (Forster and Merriman, 1985), New Zealand (McLean et al., 2001), Turkey (Benlioglu et al., 2002; Özyilmaz, 2019) and Iraq (Al-Shammary and Al-Sadoon, 2014). On the other hand, solarisation can be broadly categorised into different groups depending on the different applications carried out by farmers such as i) using the transparent polyethene sheets or other plastic material; ii) designing closed glasshouses; and, iii) applying novel technologies as sprayable plastics (Gamliel and Katan, 2005).

The effectiveness of the solarisation process depends on the ability to transfer the heating power through the soil profile with temperatures reaching 55°C during some weeks (Merfield, 2019; Morra et al., 2018). However, each specific area can show different thermal responses because of different antecedent soil conditions, moisture content being a key factor. The presence of water increases the thermal conductivity, transfer and heat penetration into the soil and, subsequently, the solarisation efficiency (Al-Shammary and Al-Sadoon, 2014; Gamliel and Katan, 2005). For instance, Costa et al. (2019) indicated that solarisation technology is able to transfer the solar radiation out of the plastic film (e.g. polyethene film) on a previously watered field surface for a period of time of not less than 30 days. These authors recommend that the soil should be subjected to furrow or drip irrigation at a watering rate of not less than 30 mm/m² for a period of two days prior to the solarisation technology application.

It is important to remark that we were not able to find a long list of publications relating to the perception of the residents that live close to plasticised fields, and the opinion and experience of farmers after several years of application of solarisation technologies. Some studies carried out in China and the USA highlighted that farmers are worried about the water consumption, the elevated costs of the materials, the treatment of the residues, and the amount of fertiliser that must be applied (D. Hemphill, 1993; Goldberger et al., 2015; Ingman et al., 2015).

2.1. Advantages

Soil solarisation has demonstrated positive impacts on some soil characteristics such as soil porosity and availability of soil moisture content because of the improvement in water use efficiency and the reduction in evaporation (Zribi et al., 2015). Also, soil aggregation improves (Kader et al., 2017), and some authors have even demonstrated that solarisation can cause a decrease in soil bulk density (Chen et al., 2015a; Mulumba and Lal, 2008; Wang et al., 2016b). As a result, there is some improvement in the conservation of the topsoil temperatures, which is directly related to better seed germination and root growth (Zhang et al., 2009). Moreover, solarisation can lead to a reduction in weed and pest pressure (McKenzie et al., 2001) by controlling soil-borne diseases as well as increasing soil biological activity

(Stapleton, 2000). Greenberger et al. (1987) noted that soil solarisation reduces the number of heat-sensitive SBPs such as *Verticillium dahliae*, *Sclerotium rolfsii* and *Fusarium*. Also, Zhang et al. (2018) confirmed that it can cause a reduction in soil salinity, which is vital for the conservation of agricultural productivity and soil fertility in the medium to long terms (Jordán et al., 2010; Moreno and Moreno, 2008). Another key question is related to the clear reduction of water and soil losses (Steinmetz et al., 2016). From an economic point of view, this technology requires only a one-off payment which is less expensive compared to the periodical chemical soil disinfestation (Gamliel and Katan, 2005). Indirectly, the reduction in the use of chemical products also benefits sustainable land management practice (Kanaan et al., 2018).

2.2. Disadvantages and issues to be solved

Logically, soil solarisation technology also has negative impacts to be resolved in agriculture despite the numerous of advantages mentioned above. Some authors confirmed that certain drawbacks are associated with the use of soil technology. The solarisation technology is useful only in certain climatic regions characterised by warm conditions and long summers (Ham et al., 1993; Liebman and Gallandt, 1997). Furthermore, solarisation can only be used once a year in the field (Özyılmaz, 2019), and avoids the lack of a crop for some several weeks when implemented (Gamliel and Katan, 2005). For crops with deep roots or deep soil layers, its effectivity is also reduced if the porosity of the soil is elevated before planting (Díaz-Hernández and Salmerón, 2012). Another disadvantage is that the continuous application of solarisation may generate negative influences on beneficial soil microbial communities because of the modification of soil temperature and moisture (Buyer et al., 2010; Gamliel and Stapleton, 1993; Muñoz et al., 2015; Tu et al., 2006). Some authors observed that negative communities of *Bacilli* and *Gammaproteobacteria* can increase, and Actinobacteria, Alphaproteobacteria and Acidobacteria may be reduced (Cohen et al., 2018; Kanaan et al., 2018), thus affecting directly the soil quality (Steinmetz et al., 2016). Recently it has been observed that even mycotoxin concentrations in soil could increase (Sabburg et al., 2015; Simmons et al., 2014), and also cause fungal development (Fenoll et al., 2010). Simmons et al.

(2014) observed that a long duration of application of solarisation could show negative effects on fungal epidemics, and on the diversity and richness of the bacteria. Some plastic mulches used for solarisation are found to lead to greenhouse gas emissions, decreasing organic matter contents due to the shifting of the edaphic biocoenosis such as towards mycotoxigenic fungi (Cuello et al., 2015; Steinmetz et al., 2016), However, it has also been recommended not to use organic amendments to solve this issue because it could lead to a decrease in the soil microbial communities (Gamliel et al., 2000; Kipfer et al., 2010). Some studies also demonstrated that soil mulching can cause soil water repellence (Ahmed et al., 2016), thus adversely affecting soil respiration and microbial dynamics (An et al., 2015). Due to the increase in water retention, the risk of high salinity could appear in some cases (Dong et al., 2008), generating a risk of leaching of nutrients, fertilisers and pesticides (Haraguchi et al., 2004; Kim et al., 2014; Leib et al., 2000) which can be transported by both runoff and sediment losses (Zhang et al., 2013). Finally, some technical problems can also be considered as disadvantages. The main ones are related to the elevated costs of the initial investment including the specialised equipment necessary, ongoing monitoring tasks, and the challenges of the removal and disposal processes which result in plastic waste generation with associated high environmental negative impact (Adhikari et al., 2016; Levitan and Barros, 2003; Malinconico et al., 2008; Zhang et al., 2019).

3. SOIL SOLARISATION TECHNOLOGY PRINCIPLES AND PROCEDURES

The procedure for soil solarisation technology combined with different soil treatments can be outlined as depicted in Figure 1 (Abu-Irmaileh, 1991; Barrera Necha and Bautista-Baños, 2016; Gamliel and Katan, 2005; Katan and DeVay, 1991):

- a) The field is cleared of plant waste because the soil field should be disturbed as little as possible after plastic removal to avoid recontamination, and the baseline soil physical and chemical properties are determined. Then, it is necessary to select the best time for starting soil mulching considering the climatic conditions related to air temperature and solar radiation. The use of meteorological data from previous years is highly recommended.
- b) The selection of an appropriate soil management system is made, including the determination of the primary and secondary equipment to be used. The selection of the best soil tillage depth is also a requirement because solarisation employs the heat of the soil surface through repeated daily cycles. Applying a soil management system by tilling the deepest layers can default the maximal thermal transfer and compact the soil, thus closing the soil pores.
- c) Fertilisers are added to the soil by mixing in using disc harrows.
- d) A thermocouple-type (*K*) thermometer is used at different soil depths under the mulch units to measure soil temperature and the temperature in the gap between the mulch cover and the soil surface.
- e) The field is irrigated to its maximum field capacity because the most appropriate soil moisture strongly affects soil thermal conductivity and enables the activation of biological activities.
- f) The soil is covered by mulch (e.g. polyethene film). The polyethene film is properly unrolled so that it is perfectly attached to the soil surface (Figure 1) in order to achieve maximum efficiency of the solarisation.
- g) Solar radiation, soil and ambient temperatures are measured every hour.

- h) Calculations of soil parameters, such as bulk density, porosity, etc., are conducted after removing the covers from the soil.
- i) Finally, the field is ready for seed and seedling sowing.

4. SOIL THERMAL-PHYSICAL PROPERTIES AFFECTED BY SOLARISATION TECHNOLOGY

The effects of solarisation technology are reported in combination with several factors including soil tillage system, soil structure, mulching cover material properties, fertilisers, moisture content, soil temperature and climatic conditions as depicted in Figure 2 (Braunack et al., 2015; Jiang et al., 2017; ÖZ, 2018).

4.1. Soil tillage system

The tillage system employed is one of the key factors on solarisation technology, especially in dryland agricultural fields, because it affects the soil thermal-physical properties due to the strong effects of moisture content, μ , soil temperature, T_s , and structure of the soil (soil bulk density ρ_b , soil porosity Φ) as shown in Table 1. The two types of soil management used with solarisation are differentiated in Figure 3: conservation tillage (no-tillage) and conventional tillage (ploughing). It can be observed that soil solarisation process is affected by tillage systems through the interaction with other biological, physical and chemical properties of the soil. For instance, conventional tillage can show positive influences by enhancing soil thermal efficiency compared with conservation tillage. This is because ploughing leads to changes in the soil structure in the surface layer (Maharjan et al., 2018; Ordóñez et al., 2018) by generating a less dense structure in the surface soil layer, playing an important role in reducing soil ρ_b (Downie et al., 2015; Dunbabin et al., 2013) compared to the deeper soil layers (Bottinelli et al., 2017; Licht and Al-Kaisi, 2005). Soil Φ is also influenced by the tillage system (Figueiredo et al., 2017; Głąb and Kulig, 2008; Pires et al., 2017). On the

other hand, Copec et al. (2015); Kuzucu and Dökmen (2015) have reported that tillage system can increase Φ because tillage leads to an increase in stored water by increasing infiltration and reducing evaporation.

In contrast, no-tillage has some positive impacts on soil moisture capacity as it reduces evaporation (Lampurlanés et al., 2016; Zhao et al., 2018), and soil aeration, and subsequently improves soil thermal properties (Blanco-Canqui and Ruis, 2018). The tillage system has a significant impact on soil thermal properties in the short term (Al-Shammary et al., 2017; Allmaras et al., 1977) as tillage leads to decreased soil thermal conductivity (k) (Blanco-Canqui and Ruis, 2018), soil thermal flux density ($q\dot{h}$) (Azooz et al., 1997), soil volumetric heat capacity (C_v) and soil thermal diffusivity (D) (Blanco-Canqui and Ruis, 2018). No-tillage has a significant effect on soil temperature (T_s) in the upper 20 cm of soil during spring, which could be reduced compared to conventional tillage (Blanco-Canqui and Ruis, 2018). Other authors have reported a higher soil temperature during solarisation in rotary ploughing compared to mouldboard ploughing due to the higher bulk density resulting from the former (ρ_b) (Al-Shammary and Al-Sadoon, 2014). According to Dec et al. (2009), tillage systems could improve soil structure stability because it reduces soil compaction, and water movement in the soil, consequently improving the heat flow.

Soil solarisation has been shown to improve soil structure because it reduces soil compaction by decreasing soil moisture evaporation (D'Addabbo et al., 2010; Melero-Vara et al., 2007). Other studies report that the depth of the tillage does not make any significant difference to the soil bulk density (Jabro et al., 2016; Karuma et al., 2014), and possibly does not have any influence on the effectivity of solarisation. However, no detailed studies of this assertion have been published to our knowledge. Therefore, more research needs to be carried out in order to clarify the impact of bulk density and depth of tillage on heat transmission into the soil.

4.2. Mulching properties

Using an appropriate mulching system, soil temperature can be elevated to levels at which microorganisms cannot survive, thus reducing diseases in agricultural production (Adekiya et al., 2017; Qi

et al., 2018; Steinmetz et al., 2016). Figure 4 shows the types of mulching material commonly used to cover the soil (Adhikari et al., 2016; Guo et al., 2016; Kader et al., 2017), namely: (i) inorganic materials such as polyethylene plastic films; (ii) organic materials such as plant products and animal waste; (iii) special inert materials such as gravel and concrete, and (iv) mixed materials including plastic, straw, concrete and gravel.

One of the most important elements in the mulches used in solarisation technology is the inorganic material (polyethene) because of its high heating power transmission (Gill, 2014). In the past, materials such as paraffin have also been used because they are more effective at soil heating and faster at the killing of pathogenic soil fungi (Al-Kayssi and Al-Karaghoul, 2002). Nowadays, it is not used because it has been found to increase the biological degradation of litter and soil organic matter (Sinkevičienė et al., 2009).

There is a general consensus that the optimal materials to be used are plastic covers (Kitiş, 2011). They could be considered as a major factor to help soil quality, improve weed management and control the yield response. Also, some kinds of plastics show some mechanical and spectroradiometric properties that can affect heat flow raised in the soil and during weed control. However, they have a drawback of not being biodegradable, recoverable and reusable (Adhikari et al., 2016). Some authors observed that plastic residues reduce nutrient availability (Ibarra-Jiménez et al., 2011), decrease sowing quality (Chang-Rong et al., 2014), and harm soil structure through reducing some soil physical properties (Gao et al., 2019). Thus, from an ecological point of view, they are not the most sustainable solution. Recent soil heating studies used biodegradable plastic covers such as sprayable porous polymer depending on its natural rubber, EVA-doped cover and polyamide-based cover material (Adhikari et al., 2016; Candido et al., 2011; J. Ruhoff et al., 2014; Yang et al., 2015). They are considered easy to apply, providing a good mechanical range of properties, although they were not so effective at transferring soil heat through the soil in several cases. Logically, materials of plant origin, for example, wood shavings, hull, and straw, that are environmentally friendlier are being used (Flores et al., 2007; Mahrer et al., 1984). Moreover, other authors have confirmed that they have other extra benefits apart from being biodegradable such as minimal water and soil losses, maintaining soil temperature in order to raise harvest production, and conserving soil microbial activity (Prosdocimi et al., 2016). Although organic mulching materials are highly recommended, farmers perceive

291 them as not the best. A high number of farmers do not accept the application of organic mulches due to the
 292 lack of subsidies, and also consider that the mulch portrays the appearance of the fields as dirty and
 293 abandoned areas (Cerdà et al., 2018a; Cerdà et al., 2018b). Furthermore, properties of the mulching cover
 294 such as the number of layers, thickness and colour of material strongly affect the efficiency of the
 295 solarisation technology due to the increase in humus formation and resultant water holding capacity
 296 (Castello et al., 2017; da Silva et al., 2018; Ito et al., 2011; ÖZ, 2018). The covering material requires a
 297 specific set of properties, which must be conveniently based on the environmental factors of the location
 298 and also be cost-effective (Wang et al., 2015). Applying mixed materials (combinations of organic and
 299 inorganic materials) could be considered as one of the best strategies for soil management through the
 300 application of solarisation technology (Abouziena, 2015; Dong et al., 2009; Luo et al., 2015). Special inert
 301 materials such as gravel mulch also be used to decrease soil surface evaporation, and preserve soil moisture
 302 contents to meet the demands of plants, resulting in an increase in crop yield in several reported cases (R.
 303 Lemon, 1956; Xie et al., 2006; Yamanaka et al., 2004). However, Yuan et al. (2009) showed that the sizes
 304 of the gravel mulches had a significant negative correlation with the evaporation processes.

305 It has been reported that the mulch type significantly influences soil thermal-physical properties
 306 (Table 2) such as soil bulk density ρ_b and mechanical perturbations (Al-Shammary and Al-Sadoon, 2014;
 307 Nishigaki et al., 2017; Nzeyimana et al., 2017), as a consequence of reducing soil compaction (Kader et al.,
 308 2017; Nishigaki et al., 2017). Furthermore, mulching system properties can increase the soil volumetric
 309 moisture content Θ as a result of reduction in soil water evaporation which helps to retain soil water content
 310 (μ) (Al-Shammary et al., 2016), and subsequently reduce the amount of irrigation consumption by an
 311 increase in soil hydraulic conductivity (Adekiya et al., 2017).

312 Regardless, a strong relationship between solarisation technology and soil thermal-physical
 313 properties has been demonstrated in a study that investigated the positive influence of residual plastic film
 314 fragments on soil bulk density ρ_b , porosity (Φ) and volumetric moisture content (Θ) under two treatments
 315 with and without residual plastic film (Mahdavi et al., 2017). Also, Al-Shammary and Al-Sadoon (2014)
 316 proposed that covering the soil surface with plastic mulch improves the soil quality because it prevents

mechanical perturbations in the topsoil. Moreover, other authors found that plastic mulching significantly reduces the organic content of the soil because it negatively affects microbial dynamics (Cuello et al., 2015). Also, Ham et al. (1993); (Tong et al., 2017) argued that these biological properties are due to the changes in soil thermal conductivity (k), soil thermal flux density (qh), soil volumetric heat capacity (C_v), and soil temperature (T_s), which drastically increase when mulching is applied.

Therefore, we recommend further investigation into the following two vital aspects. Firstly, the effectivity of the different types (materials, colours, and thickness) to improve soil quality in agriculture areas, and, secondly, the perception of farmers. It is clear that the application of any soil remediation technique, nature-based solution or improvement action, would be impossible without understanding the opinion of the stakeholders (Keesstra et al., 2018; Wallace and Jago, 2017). Therefore, each new study should combine consideration of the economic incentives (prices and the ability to be subsidised) and biophysical aspects (soil quality) of plastic mulches.

4.3. Fertiliser types and additions

The type of fertiliser applied with solarisation technology can improve soil thermal-physical properties. Table 3 summarises the main results collected from the literature. Currently, there are many types of fertilisers, but organic manure (such as farmyard manure and chicken manure) are mostly used with solarisation technology. This is largely due to the fact that organic manure improves soil properties due to containing nitrogen and phosphate, essential ingredients for soil quality (Haynes and Naidu, 1998).

Soil solarisation technology significantly influences the establishment of microclimates that result in increased fertiliser productivity in the soil (Jiang et al., 2017; Zhou et al., 2017). The influence of organic and chemical fertilisers during the application of soil solarisation technology on soil physical properties has also been investigated. Some authors observed that organic fertiliser significantly decreases the bulk density ρ_b by increasing porosity Φ due to the decrease in soil structural stability (Al-Shammmary et al., 2017; Chaudhari et al., 2013; Merante et al., 2017). Fertilisers are also able to increase soil Φ because they can

enhance the organic content (Haynes and Naidu, 1998). Moreover, the types of fertilisers used with solarisation technology modify the soil temperature (T_s) and soil thermal-physical properties. For example, research on chemical fertilisers with black plastic mulching indicated the highest soil temperature of 78.3°C (time 11 am) at a soil depth of 10 cm while the mean ambient temperature and solar radiation were 47°C and 1125 w/m², respectively (Al-Shammary et al., 2016). Jia et al. (2019); (Liu et al., 2018) concluded that the soil k , q_h , C_v , and D can also increase when fertilisers are applied, possibly because of their positive correlation with organic matter content, the water-holding capacity of the soil and heat transfer. However, no significant differences between fertilisers on soil thermal-physical properties have been demonstrated (Al-Shammary and Al-Sadoon, 2014).

Another area that has not received much attention is the utilisation of solarisation technology in organic farming fields. It would be interesting to contrast the influence of the covers used in fields with and without fertilisers, by considering parameters such as soil quality, productivity and changes in soil properties over medium to long-term periods.

4.4. Soil moisture content (μ)

Soil moisture content (μ) is one of the most significant factors influencing solarisation efficiency, and, therefore, affecting soil thermal-physical properties. The main impacts of soil moisture content are summarised in Table 4. As indicated by some researchers, soil solarisation technology is able to reduce irrigation water consumption (Cerdà et al., 2016; Saglam et al., 2017; Zhou et al., 2017), which is a significant cost saving in semi-arid and arid environments. Moreover, it has been highlighted that the reduction in irrigation water generally results in an improvement of the soil quality (Hayes et al., 2012; Taparauskienė and Miseckaitė, 2014). Furthermore, soil moisture content has a strong relationship with other soil physical properties including bulk density and porosity (Mei-Xian et al., 2013; Teng et al., 2016), and volumetric moisture content (Zhang et al., 2018), which could enhance or degrade the effectiveness of soil infiltration and permeability (Di Prima et al., 2018). Soil moisture content plays a significant role in the soil microbial biomass carbon levels (Smith, 1993) because plastic mulch helps to accelerate

Carbon/Nitrogen metabolism, which affects both soil organic matter stocks, soil-water repellence and greenhouse gases control (Kader et al., 2017). Soil microbial communities are able to interact among themselves when plastic mulches reach a correct balance of soil moisture content; however, this effectivity will vary depending on the bulk density, porosity and structural stability due to its denser mineral fraction (Guo et al., 2015; Schoenholtz et al., 2000).

Thus, we highlight the necessity to conduct studies related to the hydrological response of the soil aggregates, comparing scenarios with and without solarisation technology. This will give insights into the type of material that could be used, and thus save economic resources and minimise water use for irrigation.

Moreover, it is interesting to note how other authors demonstrated that the modification of soil moisture content as a result of solarisation technology could also affect the thermal flux density (q/h), thermal conductivity (k), volumetric heat capacity (C_v), diffusivity (D), and soil temperature (T_s) because the heat flow increases when soil μ improves (Al-Shammary et al., 2017; Badía et al., 2017; Mengistu et al., 2017). Regardless, there is a lack of information about the possible hygrometrical changes below the cover that would modify the microbiological activity. Thus, urgent research must be carried out to clarify the consequences of solarisation technology on microbiological activity, one of the most important elements in soil health (Rinot et al., 2019).

4.5. Soil temperature (T_s)

Soil temperature (T_s) is a fundamental factor in the solarisation process due to its effect on soil thermal-physical changes, as indicated in Table 5. T_s is a clear indicator of thermal flux density (q/h) in soils, being directly proportional to thermal conductivity (k). The modification of soil moisture movement results in an increase in thermal flow and k . In addition, soil ρ_b decreases as T_s increases, thus affecting heat transfer and q/h (van Lier and Durigon, 2013). Many studies have confirmed that high T_s ($>40^\circ\text{C}$) during soil solarisation technology results in an increase in efficiency of solarisation and, consequently, thermal-physical changes can be observed. However, this situation can be harmful to live organisms and their activities (Al-Shammary et al., 2016).

Normally the highest soil temperature with solarisation technology is observed around midday. When the temperature decreases, usually during the night, the effectivity of the solarisation technology at deeper soil depths is drastically decreased (Cohen et al., 2018; Vela et al., 2017; Yao et al., 2016). Several studies have demonstrated a linear increase in all thermal properties with an increase in soil temperature (Lamond and Pielert, 2006; Mengistu et al., 2017; Sun et al., 2016).

Abu-Hamdeh (2003); (Mengistu et al., 2017) found that soil volumetric heat capacity (C_v) is also affected when T_s increases because soil management significantly impacts on soil C_v , thus reducing ρ_b and increasing Φ (Al-Shammmary et al., 2017); Sun et al. (2016) argued that soil diffusivity (D) also experience an increase with T_s .

From a holistic point of view, if soil temperature significantly changes, the soil volumetric heat capacity and diffusivity also change, leading to a reduction in bulk density and an increase in porosity (Barry-Macaulay et al., 2015; Sun et al., 2016). We propose this assumption be tested to support, or otherwise, the possible risks of aggregate stability and soil structure in cultivated soils.

Nowadays, there is an open debate about the colour of the cover materials in relation to their temperature effects. Some authors have reported that transparent plastics, in comparison to the black ones, have shown a higher effectivity for solarisation technology because of a higher absorption rate of solar radiation to increase soil temperature (Ito et al., 2011; ÖZ, 2018; Tesfaye et al., 2016). However, other groups of researchers contradict this assumption (Al-Shammmary et al., 2016; Ibarra-Jiménez et al., 2012). Therefore, if this key question can finally be answered, the definition of the use of a specific colour could help to increase soil biological activity and metabolism (Li et al., 2004; Subrahmaniyan et al., 2006), speeding up the decomposition of organic matter in the soil, which would strongly affect soil thermal-physical properties because of increases in the water-holding capacity (Al-Shammmary et al., 2017; Jia et al., 2019; Wang et al., 2016a).

Regardless, a key question could be more related to the colour that is more effective considering the type of crop, weather conditions, soil types, and tillage. Possibly, the debate is more related to the identification of the appropriate cover to use depending on external factors other than colour.

4.6. Pedoclimatic factor

It has been confirmed that there exists a clear relationship between climate and soil type in relation to its formation, evolution, and conservation practices (Rodrigo-Comino et al., 2018; Smith et al., 2015). Climatic conditions affect the level of solar radiation which in turn influences soil temperature, thus, influencing the biological processes (Oberholzer et al., 2017), which can be observed in the short- and medium-terms. Logically, there exists an extremely strong dependence between soil solarisation technology and high levels of solar energy. Therefore, it is important to identify areas where solarisation technologies will be installed given the new trends of temperatures over the world due to climate change. Climate change is resulting in increased duration of the drying periods and elevated temperatures during the non-common seasons (Davidson and Janssens, 2006; Odó Camps and Concepción Ramos, 2011).

Ben-Yephet et al. (1988) demonstrated in a pioneer study that the success of soil solarisation technology is significantly influenced by the intensity and length of sunlight exposure. Other authors have also insisted upon the influence of the location of soil solarisation technology use (Sosnowski et al., 2009). Some studies have demonstrated that the average ambient temperature in glasshouse conditions gradually increases when disinfection starts, but the solarisation efficiency decreases during precipitation and cloudy weather (Dai et al., 2014; Morra et al., 2018). Therefore, soil solarisation technology is widely used in the Mediterranean, deserts and tropical climates that record greater solar radiation levels and higher temperatures, thus increasing solarisation efficiency (Al-Shammary et al., 2016). Dai et al. (2014); Katan and DeVay (1991); (Morra et al., 2018) found that solarisation requires a duration lasting between 40 and 60 days for its influence to reach up to 30 cm soil depth, a time sufficient to sanitise it. This is because the use of soil solarisation can cause a significant reduction in microbial biomass, enzymatic activities, and weed population including *Cyperus rotundus* in the short-term (S. F. Ricci et al., 1999).

The absorption of solar radiation is also conditioned by the inherent properties of the soil, colour and texture playing key roles (Adekiya et al., 2017; Dong et al., 2018; Pituello et al., 2016). For example,

dark coloured soils absorb more solar energy compared to lighter coloured soils, thus increasing their soil temperature (T_s) (Stapleton et al., 2000). We emphasise the importance of pedoclimatic surveys (Dagois et al., 2017; Oberholzer et al., 2017), considering soil formation and evolution under different climatic conditions, or stationary situations, in order to shed light on when the stakeholders should use solarisation technology.

5. IMPACT OF SOLARISATION ON SOIL THERMAL-PHYSICAL PROPERTIES

Soil solarisation technology practices in experimental agriculture have several advantages, including conservation and improvement of soil properties. There have been several longitudinal studies investigating the effects of soil solarisation under different soil treatments. Two types of soil properties, which are significantly affected by soil solarisation technology, are the physical and thermal properties.

5.1. Soil physical properties

The improvement of soil physical properties using solarisation technology combined with different soil treatments is one of the major challenges today (Tables 1-5). In this section, we present specific impacts of solarisation technology on some physical properties as indicated in the literature.

5.1.1. Soil bulk density (ρ_b)

Soil ρ_b influences solarisation technology through the solarisation management process, such as tillage system, plastic cover type, and fertiliser or additive type, as well as moisture content and soil temperature (Mondal et al., 2016). It has been demonstrated that the no-tillage system results in an increase in soil ρ_b due to the increase in soil compaction (Downie et al., 2015; Muñoz-Romero et al., 2010). A

relationship between soil tillage management and hydrothermal properties has been reported to influence soil ρ_b (Williams et al., 2016).

Huo et al. (2017) studied the combined plastic mulching with buried straw layer on soil organic carbon fractions in a saline arid soil in Northwest China. They used the following treatments: (i) deep ploughing with no plastic film mulching; (ii) deep ploughing with plastic film mulching; (iii) buried maize straw layer with no mulching; and (iv) buried maize straw layer plus plastic film mulching. Their results showed that plastic film mulching increased soil moisture and temperature but reduced soil compaction. This is large because, by reducing evaporation of soil moisture, plastic covering prevents mechanical perturbations in the topsoil which reduces compaction.

Another study conducted in Iraq investigating the impact of different mulches on soil ρ_b found that soil mulching systems have a significant effect on ρ_b due to a decrease in soil moisture evaporation (Al-Shammary and Al-Sadoon, 2014). On the other hand, no-covering resulted in an increase in soil ρ_b under conventional tillage such as mouldboard, disc, and rotary ploughing. Other studies performed in Turkey, the United States, and China suggested that organic fertiliser with solarisation technology can improve the physical properties of soils, having a positive effect on ρ_b by improving soil biological fertility (Celik et al., 2010; Mitchell et al., 2017; Zhang et al., 2017).

5.1.2. Soil porosity (Φ)

It is well-known that soil Φ is influenced by the tillage system employed, and decreases with soil depth (Figueiredo et al., 2017; Głab and Kulig, 2008; Pires et al., 2017). Investigations into the differential impacts of mulch type on soil physical properties concluded that the soil mulch system has a significant effect on Φ (Sinkevičienė et al., 2009). Furthermore, the results revealed that the improvement of soil physical properties varied across the studied locations and mulch type due to the increase in organic matter which can also improve soil aggregation, thus positively influencing Φ (Nzeyimana et al., 2017).

5.1.3. Volumetric moisture content (θ)

The influence of solarisation technology on θ is also dependent on the soil tillage method, covering properties (i.e., type of mulching cover material and thickness), fertiliser type, moisture content, and pedoclimatic factors (Kader et al., 2017). Covering the soil affects soil moisture content by reducing the evaporation rate (Mutetwa and Mtaita, 2014).

On the other hand, some studies have proposed that soil solarisation technology is useful for reducing soil moisture losses by conserving water and increasing water use efficiency (Anikwe et al., 2007; Jiang et al., 2017; Lal Bhardwaj, 2013). Particularly, the use of plastic film decreases the amount of water loss caused by evaporation (Al-Shammary et al., 2017; Jiang et al., 2017; Ogundare et al., 2015). Moreover, the number of layers covering the soil has been surveyed and its effect on θ compared to soil without covering has been reported. The double plastic covering had a higher θ for soil compared to soils without mulching because of reduction in evaporation (Al-Shammary et al., 2017). Ogundare et al. (2015) compared plastic and organic treatments with control plots and solarisation technology and observed the effects on soil θ . They indicated that plastic covered soil obtained the highest value of soil θ compared to other soil treatments. Also, the colour of the cover material has been a determinant factor. The transparent plastic covering is reported to retain the greatest amount of moisture compared to black or blue plastic covering at 10 cm soil depth (Ashrafuzzaman et al., 2011).

5.2. Soil thermal characteristics

Soil thermal characteristics are dynamic as they are dependent on the effects of external factors and soil physical characteristics such as tillage depth, bulk density, and moisture content, as well as the current soil field conditions (Wilhelm and Bockheim, 2016; Xiukang et al., 2015; Zhang et al., 2018). However, reports in the literature on soil thermal characteristics are limited (Blanco-Canqui and Ruis, 2018). Mengistu et al. (2017) stated that the soil thermal characteristics are determined by the soil structure, particle size distribution, bulk density (ρ_b), moisture content (μ), and soil temperature (T_s). It is observed that factors

affecting solarisation technology can play an important role in the management practices of soil thermal properties. Therefore, it is important to determine how the soil tillage system, structure, mulching properties, fertiliser, moisture content, soil temperature, and climatic conditions affect and control the transfer of heat in field conditions (Pramanik et al., 2015). Regardless, there has been an increasing amount of literature describing soil thermal characteristics under different conditions, because the investigation into soil thermal characteristics is needed to accurately predict soil temperature (Hu et al., 2016). Furthermore, solar heating integrates soft plants and animal material into the soil, which is mulched under a clear plastic cover. However, some reports propose that there are no significant differences in soil temperature (T_s) paralleled with the solarisation technology process, with black plastic showing the highest temperature due to good light absorption compared to other colours (Oz et al., 2017).

5.2.1. Soil thermal conductivity (k ; $W/m\ K$)

Soil k plays a significant role in calculating heat transfer at the soil surface under ambient conditions and is influenced by geotechnical properties such as mineralogical composition, temperature, dry density, moisture content (Bi et al., 2018; Chen et al., 2015b; Yun and Santamarina, 2008).

No-tillage management can increase soil k by increasing soil moisture content μ and has a better exchange of energy compared to the soil under conventional tillage due to an increase in heat transfer (Blanco-Canqui and Ruis, 2018). Furthermore, a significant difference between tillage depth with solarisation on soil k has been reported (Al-Shammary and Al-Sadoon, 2014). In this case, k increases with increasing soil depth due to the loosened soil as a result of the tillage process, thus increasing the gas exchange between ambient and soil pores. Soil k depends on bulk density (ρ_b), porosity (Φ), and volumetric moisture content (θ) due to the heat transfer in the soil being dependent on the solid phase and mineral composition of the soil (Łydźba et al., 2017; Tokoro et al., 2016). Soil k is strongly impacted by μ due to their logarithmic relationship, improving the heat flow and enhancing the soil k . Furthermore, k increases with soil depth due to the increase in soil ρ_b (Abu-Hamdeh, 2000; Merante et al., 2017). The differential

impact of soil Φ and θ on soil k has been investigated and a relationship found between k , Φ and θ (Alrtimi et al., 2016). Soil ρ_b has an increasing relationship with k . The plastic covering influences k by decreasing evaporation (Al-Shammary et al., 2017). Soil k has a direct relationship with θ under mulching conditions by reducing moisture lost (Al-Shammary and Al-Sadoon, 2014; Azooz et al., 1997; Usowicz et al., 2017). Also, organic matter content has a positive significant influence on soil k , both increasing with one another (Jia et al., 2019; Liu et al., 2018; Usowicz et al., 2016). Soil k is influenced by soil temperature in most soil types due to the changes in heat flow in the soil which can influence the movement of moisture, increasing soil temperature (T_s) with solarisation technology, resulting in a change in water state (Al-Shammary and Al-Sadoon, 2014; Lamond and Pielert, 2006; Usowicz et al., 2017).

5.2.2. Soil volumetric heat capacity (C_v ; J/m^3K)

Soil C_v 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 it depends on θ and ρ_b (Evelt et al., 2012). Soil tillage systems, soil structure, mulching material properties, fertiliser, μ , and T_s are all related to θ and ρ_b and have significant effects on the C_v of a soil. There are several reports in the literature that determine soil C_v under different soil treatments (Al-Shammary and Al-Sadoon, 2014; Levy and Schmidt, 2016; Usowicz et al., 2017). Also, soil C_v is strongly influenced by μ and soil depth (O'Kelly and Sivakumar, 2014). For example, the soil thermal properties of the Antarctic regions have been studied, and it was found that soil C_v is dependent on μ and ρ_b , and increases with soil depth. Furthermore, C_v increases with increasing ρ_b and μ (Levy and Schmidt, 2016). There is very little knowledge about soil C_v within tillage systems and the addition of fertiliser. However, the tillage system has greater impacts on soil C_v as it is directly related to ρ_b (Al-Shammary and Al-Sadoon, 2014; Evelt et al., 2012).

The effect of the cover properties on soil C_v has been investigated and the results suggest significant differences between the number of plastic covering layers of the soil. A double layer covering has the highest value C_v when compared to single or none due to increased storage of heat in the soil (Al-Shammary

and Al-Sadoon, 2014). Numerous studies have proposed that soil C_v increases linearly with μ due to the absorption of solar radiation that increases the moisture content μ (Al-Kayssi et al., 1990; Liu et al., 2008; Łydźba et al., 2017). The application of organic fertiliser can significantly alter the organic content of a soil within a short period, and, when combined with solarisation technology, can result in significant changes in the soil's thermal properties due to the soil ρ_b decreasing and Θ increasing, consequently impacting on C_v (Dec et al., 2009).

5.2.3. Soil thermal diffusivity (D ; m^2/sec)

Soil D is defined as the ratio of thermal conductivity (k) to the volumetric heat capacity (C_v) of soil (Arkhangelskaya and Lukyashchenko, 2018). Soil tillage systems, soil structure, mulching material properties, the addition of fertiliser, μ , and T_c of soil are related to k and C_v with significant impacts on the soil D (Al-Shammary and Al-Sadoon, 2014; Blanco-Canqui and Ruis, 2018). The effect of soil heating under tillage and addition of fertiliser on soil D has been previously reported. When the number of fertiliser increases, there is a decrease in the structural stability by increasing organic content with a denser mineral fraction of the soil, which can decrease soil D (Al-Shammary et al., 2017; Blanco-Canqui and Ruis, 2018; Gnatowski, 2009; Hu et al., 2016). Tillage can indirectly decrease soil D by increasing the moisture content of the soil. Soil D is dependent on ρ_b and Θ , which have a significant effect on k and C_v (Blanco-Canqui and Ruis, 2018).

However, other studies report that soil D is a fundamental property for investigating the thermal process of a soil which depends on μ and Θ (Arkhangelskaya and Lukyashchenko, 2018; Gnatowski, 2009; Usowicz et al., 2017). Soil D is amplified by increasing ρ_b and μ through improving heat transfer (Miyajima et al., 2015; O'Kelly and Sivakumar, 2014; Usowicz et al., 2016). However, soil D is decreased by increasing soil μ (Makarychev and Bolotov, 2017) and increases with soil depth (Levy and Schmidt, 2016). Therefore, it can be deduced that solarisation technology can provide a positive influence on soil D and soil evaporation (Jabran et al., 2016; Liang et al., 2017). As a result, soil mulching could be useful in reducing

soil moisture loss, and thus reducing the temperature of the soil (Pramanik et al., 2015; Usowicz et al., 2013). The pioneering study conducted by Allmaras et al. (1977) reported that fertiliser containing organic matter could increase soil D by increasing k and C_v through changes in soil ρ_b and Θ . However, it is not clear whether it is the case for all the soil types and crops.

5.2.4. Soil heat flux density (qh ; w/m^2)

Soil qh is a single-valued function of k and is related to temperature and soil depth. The qh in a soil is dependent on the amount of energy reaching the surface of the soil and is influenced by climatic conditions, topography, time of day, soil texture, tillage management, mulch system, and application of fertiliser (Al-Shammary and Al-Sadoon, 2014; Usowicz et al., 2017; van Lier and Durigon, 2013). The influence of the depth of a tillage system was reported as significant on soil qh due to the increase in soil temperature near the soil surface by solar radiation (Al-Shammary and Al-Sadoon, 2014). Furthermore, the tillage system decreases soil k by reducing ρ_b and increasing Φ (Azooz et al., 1997; Dec et al., 2009). In this way, plastic mulch could reduce soil temperature and qh due to the plastic covering absorbing solar radiation and reducing heat loss (Abzalov, 2016; Colaizzi et al., 2016). (Nishigaki et al., 2017) demonstrated that, for cultivated soils, covering reduces by more than 49% of evaporation losses and solar radiation on the soil surface, which is important in estimating the qh between the soil surface and the atmosphere. This is strongly related to the number of plastic layers on the soil (single or double). Layers on the surface produce a relatively large net radiation at the soil surface when using transparent mulches. Water condenses under the transparent plastic covering at night, and the reflected radiation can be absorbed from the soil which protects it from extreme soil temperature increases (Al-Shammary and Al-Sadoon, 2014).

6. IMPACT OF SOLARISATION ON PLANT GROWTH AND YIELD

Previous studies have reported the benefits and limitations of solarisation technologies on plant growth as well as crop yield as shown Fig 5 (Ekebafé et al., 2011; Kasirajan and Ngouajio, 2013; Lobell and Field, 2007). The growth response is increased for plants when solarisation is used, especially in nursery seedlings and deciduous tree crops. Liu et al. (2014a); (Liu et al., 2014b) indicated that solarisation could raise the crop yield by approximately 20-50% as a result of a decrease in nitrogen leaching, improving soil physical properties such as soil porosity and temperature, and decreasing soil bulk density and water evaporation (Luo et al., 2010; Qin et al., 2013). Furthermore, some authors have demonstrated that the soluble mineral nutrients and mineralised organic matter, which are considered key growth regulation factors, enhance soil biological activities after the application of solarisation, directly affecting crop yield (Chen et al., 1991); Chen and Katan (1980); (Stapleton and E. DeVay, 1984). However, other authors have also stated that soil solarisation shows several limitations on crop production (Bai et al., 2015; Chang-Rong et al., 2014; Gong et al., 2015; Ibarra-Jiménez et al., 2011; Kim et al., 2014; Liu et al., 2014a) as follow:

- The accumulation of plastic residue in the soil leads to reduced nutrient availability and microbiological activity, which significantly adversely affects crop growth;
- The plastic residue leads to a decrease in sowing quality;
- Plastic mulch wastes lead to reduced soil porosity, thus constraining air circulation, which reduces the activity of the microbial communities, along with water and nutrient penetration speed through the soil profile;
- The root development can be subsequently reduced; and

- Greenhouse gas emissions can be elevated because changing the strength of the carbon source production sometimes results in lower soil fertility and crop growth.

7. CONCLUSIONS AND FUTURE RESEARCH

Solarisation technology can be an interesting land use management tool that can improve soil quality, and consequently increase crop productivity. We observed that there exist several properties of the plastic material used to cover the soil, such as the number and thickness of layers and colour of the material that significantly affect soil thermal-physical properties and can increase solarisation efficiency. Other studies have highlighted the combination of the use of fertilisers and solarisation technology and their influence on soil thermal-physical properties due to the establishment of microclimates that increase the effectiveness of fertiliser. In this comprehensive review, we have summarised the literature on soil solarisation technology and described the impacts of the solarisation process on soil thermal-physical properties when combined with different soil treatments.

After performing an exhaustive literature review, we also observed several areas that lack information that must be provided in future research. Some studies have investigated soil physical properties under the application of solarisation technology, particularly the influence of tillage systems, mulching cover material properties, fertiliser type, soil moisture content and soil temperature on soil bulk density, soil porosity, and soil volumetric moisture content under different conditions. It would be interesting to assess the effects of the different soil tillage systems (tillage depths, different ploughs), mulching material properties (thickness, colour, number of layers, etc.), and fertiliser types (cattle waste, sheep waste, poultry waste, etc.) in combination with solarisation technology to improve soil physical properties. Detailed studies of the influence of solarisation technology on soil thermal properties (soil thermal flux, soil thermal conductivity, volumetric heat capacity, thermal diffusivity and soil temperature) are not reported to date. Therefore, further research is required to determine the impact of solarisation on

soil thermal properties. This research has uncovered several clear gaps in knowledge and indicates the need for further investigation as follows:

- a) Determination of the impact of bulk density and depth of tillage on heat transmission under soil solarisation technology;
- b) Assessment of the economic incentives (prices and the ability to be subsidised) and biophysical aspects (soil quality) of plastic mulches;
- c) Estimation of soil thermal-physical properties under the influence of different soil solarisation management scenarios (mulch type, tillage system, and fertiliser type);
- d) Exploration of the effects of soil solarisation technology on soil thermal diffusivity, flux density, thermal conductivity, and volumetric heat capacity.

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Table 1. The impact of tillage systems combined with soil solarisation technology on soil thermal-physical properties

Soil thermal-physical properties		Main effect	Reasons	References
Physical	Soil bulk density (ρ_b)	Tillage systems decrease soil ρ_b .	Ploughing process followed by harrowing reduces soil compaction and plays an important role in reducing soil ρ_b .	(Downie et al., 2015; Dunbabin et al., 2013; Muñoz-Romero et al., 2010)
	Soil porosity (Φ)	Tillage systems increase soil Φ .	Tillage reduces soil ρ_b resulting in an increase in Φ .	(Figueiredo et al., 2017; Głab and Kulig, 2008)
	Soil volumetric moisture content (Θ)	Tillage systems increase Θ .	Soil Θ is directly proportional to moisture content. Tillage increases stored water by increasing infiltration and reducing evaporation.	(Copeck et al., 2015; Kuzucu and Dökmen, 2015)
Thermal	Soil thermal conductivity (k)	Soil k decreases with tillage.	Soil k is directly proportional to soil ρ_b , tillage reduces ρ_b and the disturbance of soil by tillage can change the air to soil particle volume by creating additional air pockets that may be responsible for reducing the heat capacity of the tilled zone, decreasing soil k .	(Allmar et al., 2000; Blanco-Canqui and Ruis 2018; Dec et al., 2009; Usowicz et al., 2017)
	Soil thermal flux density (qh)	Soil qh decreases with tillage.	Soil qh is directly proportional to soil k , tillage decreases soil k by reducing ρ_b and increasing Φ , resulting in a decrease in soil qh .	(Al-Shammary et al., 2017; Azooz et al., 1997; Dec et al., 2009)
	Soil volumetric heat capacity (C_v)	Soil C_v decreases with soil tillage.	Soil C_v is directly proportional to soil ρ_b , tillage reduces soil ρ_b .	(Blanco-Canqui and Ruis, 2018; Evett, et al., 2012; Usowicz et al., 2017)
	Soil thermal diffusivity (D)	Soil D decreases with tillage.	Soil D is dependent on soil ρ_b , Θ and Φ , a decrease in ρ_b and increase in Θ result in a significant decrease in soil k and C_v , decreasing D .	(Blanco-Canqui & Ruis, 2018)
	Soil temperature (T_s)	The T_s increases with tillage.	Tillage helps to loosen soil and increase gas exchange between the soil pores and the environment, increasing T_s .	

Table 2. Modelled impacts of soil mulching systems with solarisation application on soil thermal-physical properties.

Soil properties		Main effect	Reasons	References
Physical	Soil bulk density (ρ_b)	Soil mulching improves/decreases soil ρ_b .	Soil mulching reduces soil compaction by decreasing soil moisture evaporation, thereby helping to improve soil quality and reducing soil ρ_b compared to uncovered soil. Also, surface covering by plastic mulch prevents mechanical perturbations in the topsoil which can affect soil ρ_b . Soil organic matter with solarisation application increases soil elasticity which leads to reduction in soil compaction, resulting in reduced soil ρ_b .	(Al-Shammmary and Al-Sadoon, 2014; Subrahmaniyan et al. 2006)
	Soil porosity (Φ)	Increasing mulch application and mulch properties increase soil Φ .	Soil ρ_b is decreased by reducing soil compaction with soil mulching, compared to no mulch, thus increasing soil Φ with soil mulching.	(Kader et al., 2017; Nishigaki et al., 2017; Nzeyimana et al., 2017)
	Soil volumetric moisture content (Θ)	Mulching system properties increase soil Θ .	Soil mulching reduces soil water evaporation and helps retain soil moisture content (μ), which is an effective way to reduce soil irrigation consumption. Also, increased soil Φ in mulch treated soil increases soil hydraulic conductivity and, and thus increases in soil Θ .	(Adekiya et al., 2017; Al-Shammmary et al., 2016; Liu et al., 2018)
Thermal	Soil thermal conductivity (k)	k of the soil increases when mulch application is increased.	Soil k is directly proportional to soil Θ . Soil mulching increases soil Θ by decreasing water lost through evaporation, consequently increasing soil k when compared to soil without mulch.	(Al-Shammmary and Al-Sadoon, 2014; Anikwe et al., 2007; Azooz et al., 1997; Usowicz et al., 2017)
	Soil thermal flux density (qh)	Soil qh increases with mulching.	Soil qh is directly proportional to soil k and heat $\ast(\frac{dt}{dx})$. Soil k increases with mulching, and with the increase in temperature by mulching, a relatively large net radiation occur at the soil surface. Water condenses under the mulch during the night, and reflected radiation is absorbed from the soil which maintains T_s , thus increasing soil qh .	(Al-Shammmary and Al-Sadoon, 2014; Ham et al. 1993)
	Soil volumetric heat capacity (C_v)	Soil C_v increases with mulching.	Soil C_v increases as Θ increases. The soil mulching helps the soil's water-holding capacity compared to soil without mulching. The increase in soil μ increases the heat storage capacity of the soil.	(Al-Shammmary and Al-Sadoon, 2014)
	Soil thermal diffusivity (D)	Soil D decreases with mulching.	Soil covering reduces soil compaction which results in a decrease in ρ_b which directly affects soil k and C_v , and indirectly affects soil D , consequently reducing soil D compared to soil without covering.	(Tong et al., 2017)
	Soil temperature (T_s)	T_s increases with mulching.	Solar radiation passes through the mulch and heats the air and soil beneath the mulch and the heat is trapped by the solarisation system, reducing the soil thermal loss which increases T_s	

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

Table 3. Modelled impacts of fertiliser with solarisation application on soil thermal-physical properties.

Soil properties		Main effect	Reasons	References
Physical	Soil bulk density (ρ_b)	Fertiliser decreases soil ρ_b .	Fertiliser decreases structural stability by increasing organic content with a denser mineral fraction of the soil, which can decrease soil ρ_b .	(Chaudhari et al., 2013; Guo et al., 2016; Haynes and Naidu, 1998)
	Soil porosity (Φ)	Fertiliser increases soil Φ .	Decreasing soil ρ_b increases total pore space by increasing organic content.	(Al-Shammary et al., 2017; Haynes and Naidu, 1998; Li et al., 2017)
	Soil volumetric moisture content (Θ)	Fertiliser increases soil Θ .	Addition of fertiliser increases the water-holding capacity of the soil by increasing the organic matter content and Θ .	(Gao et al., 2018; Haynes and Naidu, 1998;)
Thermal	Soil thermal conductivity (k)	Soil k increases with fertiliser use	Soil k is dependent on soil Φ , fertiliser increases Φ by increasing the organic matter content of the soil, increasing soil k .	(Jia et al., 2019; Liu et al., 2018; Usowicz et al., 2017)
	Soil thermal flux density (q/h)	Soil q/h increases with fertiliser use	Fertiliser increases the organic matter in the soil, influencing soil k and heat production by increasing the water-holding capacity of the soil and increasing heat transfer, influencing soil q/h .	(Al-Shammary et al., 2017)
	Soil volumetric heat capacity (C_v)	Soil C_v is influenced by fertiliser use	Soil C_v is dependent on soil ρ_b and Θ . Fertilisers decrease soil ρ_b , increase Θ by increasing the organic matter content in the soil, impacting soil C_v .	
	Soil thermal diffusivity (D)	Soil D increases with fertiliser use	Increasing the organic matter significantly affects both K and C_v through soil ρ_b and Θ changes, which increase D .	(Al-Shammary and Al-Sadoon, 2014; Dec et al., 2009)

Table 4. Modelled impacts of moisture content (μ) with solarisation application on soil thermal-physical properties.

Soil properties		Main effect	Reasons	References
Physical	Soil bulk density (ρ_b)	Soil ρ_b decreases with μ increase.	Soil ρ_b affects soil compression behaviour changes, which affects soil ρ_b .	(Al-Shammary et al., 2017)
	Soil porosity (Φ)	Soil Φ increases with moisture content increase.	The soil Φ has an inverse relationship with ρ_b which decreases with increasing soil μ , and with more pore space in the soil, soil ρ_b decreases and soil Φ increases.	
	Soil volumetric moisture content (θ)	Soil θ increases with moisture content.	Soil θ is directly proportional to soil μ .	(Al-Shammary et al., 2017)
Thermal	Soil thermal conductivity (k)	Soil k increases with increasing soil μ .	The k of soil has an increasing logarithmic relationship with soil μ , consequently improving the heat flow and enhancing soil k .	(Abu-Hamdeh and Reeder, 2000; Łydźba et al., 2016; Usowicz et al., 2017)
	Soil thermal flux density (qh)	Soil qh has a positive correlation with soil μ .	The qh is directly proportional to soil k and depth. When the soil μ increases, k also increases. Also, soil qh has a relationship to soil depth which influences μ .	(Nishigaki et al., 2017)
	Soil volumetric heat capacity (C_v)	Soil C_v increases with soil μ .	Soil C_v increases linearly with μ , solar radiation absorption by soil increases with increased soil μ , increasing soil C_v .	(Al-Kayssi et al., 1990; Liu et al., 2008)
	Soil thermal diffusivity (D)	Soil D increases with μ .	Soil μ improves the thermal transfer between soil particles and air. Furthermore, D is directly proportional to soil k . Therefore, D increases linearly with increasing μ .	(Miyajima et al., 2015; Usowicz et al., 2016)

Table 5. Impacts of solarisation induced temperature (T_s) on soil thermal-physical properties.

Soil properties		Main effect	Reasons	References
Physical	Soil bulk density (ρ_b)	Soil ρ_b decreases with increasing soil temperature (T_s).	T_s changes the internal microstructure, increases decomposition of organic matter, agrochemicals and biology of the soil, decreasing ρ_b significantly.	(Al-Shammary and Al-Sadoon, 2014; van Lier and Durigon, 2013)
	Soil porosity (Φ)	Soil Φ increases with increasing soil temperature.	Decreasing soil ρ_b increases air quantity in the pores and cracks, increasing soil Φ .	(Sun et al., 2016)
	Soil volumetric moisture content (Θ)	The T_s with mulch is influenced by soil Θ .	Covering of soil affects μ through T_s and conserves water by reducing the rate of evaporation, improving Θ .	(Al-Shammary et al., 2016; Mutetwa and Mtaita, 2014)
Thermal	Soil thermal conductivity (k)	Soil k increases with increasing T_s in most soils.	Soil k and T_s are linearly related under different saturation conditions. Other reasons include that thermal flow in the soil causes the movement of moisture, an increase in T_s results in a change in water state, increasing k . An increase in soil particle vibration results in the soil temperature and k also increasing.	(Al-Shammary and Al-Sadoon, 2014; Lamond and Pielert, 2006; Usowicz et al., 2017)
	Soil thermal flux density (qh)	Soil qh increases with increasing T_s .	The qh is directly proportional to k , which increases as T_s increases, and an increase in moisture movement results in an increase in thermal flow and k . In addition, soil ρ_b decreases as T_s increases, which increases heat transfer and qh .	(van Lier and Durigon, 2013)
	Soil volumetric heat capacity (C_v)	Soil C_v increases with increasing T_s	The T_s resulting from soil management significantly affects soil C_v , reduces ρ_b and increases Φ and C_v .	(Abu-Hamdeh, 2003; Mengistu et al., 2017)
	Soil thermal diffusivity (D)	Soil D increases with increasing T_s	Soil k and C_v increase as T_s increases, which is dependent on ρ_b and μ , and increases D .	(Mengistu et al., 2017; Sun et al., 2016)

Figure 1. A: Tilled bare soil ready for solarisation; B: Soil after tillage; C: Soil preparation with fertilisers and irrigation; D: Soil covered with a polyethylene film; E and F: Placing the polyethylene film on the soil (sources: Barrera Necha and Bautista-Baños, 2016)

Figure 2. Basic framework of the specific factors that affect soil solarisation and soil thermal-physical properties.

Figure 3. Schematic representation of the potential impacts of tillage system on soil physical, chemical and biological characteristics.

Figure 4. Mulching materials used for solarisation technology.

Figure 5. Solarisation effects on plant growth and crop yield