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The Performance of the DES Sensor for Estimating Soil Bulk Density under the Effect of Different Agronomic Practices

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Received: 28 February 2020; Accepted: 21 March 2020; Published: 26 March 2020

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Abstract: The estimation of soil wet bulk density (ρ_n) and dry bulk density (ρ_b) using the novel digital electromechanical system (DES) has provided information about important parameters for the assessment of soil quality and health with a direct application for agronomists. The evaluation of the DES performance is particularly appropriate for different tillage methods, mulching systems, and fertilizers used to increase soil fertility and productivity, but currently, there is a lack of information, particularly in the arid areas in underdeveloped countries. Therefore, the main aim of this study was the application of a novel digital electromechanical system (DES) to evaluate bulk density, wet (ρ_n) and dry (ρ_b), under different soil treatments according to the variations in thermal efficiencies (η_{th}), microwave penetration depths (M_{DP}), and specific energy consumption (Q_{con}) in an experimental area close to Baghdad (Iraq). The experimental design consisted of 72 plots, each 4 m^2. The agronomic practices included two different tillage systems (disc plough followed by a spring disk and mouldboard plough followed by a spring disk) and twelve treatments involving mulching plastic sheeting combined with fertilizers, to determine their effect on the measured soil ρ_n and ρ_b and the DES performance in different soils. The results indicated that soil ρ_n and ρ_b varied significantly with both the tillage systems and the mulching systems. As expected, the soil ρn and ρb, M_{DP}, and Q_{con} increased with an increase in the soil depth. Moreover, the tillage, soil mulching, and soil depth value significantly affected η_{th} and Q_{con}. A strong relationship was identified between the soil tillage and M_{DP} for different soil treatments, leading to the changes in soil ρ_b and the soil dielectric constant (ε').

Keywords: digital electromechanical system; bulk density; agricultural system; mulching system

1. Introduction

Computers and mechatronic techniques (CMT) used in production agriculture bring substantial benefit to both researchers and enterprises operating in developing countries [1,2]. Agro-environmental studies have paid considerable attention to the use of CMT for measuring and controlling soil properties and processes [3–5]. There has been increasing interest in research on the application of CMT for soil bulk density measurements because of their direct effects on soil quality and health, which are related to soil functions and ecosystem services such as biodiversity conservation, productivity, and hydraulic conductivity [6], which have direct consequences for agronomical research.

The measurement of bulk density (ρ) in agronomical research is of considerable importance, as it greatly expands soil compaction [7,8]. Soil dry bulk density (ρ_b) is defined as the ratio between soil dry mass and its total volume, whereas wet bulk density (ρ_n) is defined as the mass of wet soil divided by its volume [6], which is determined by the following two groups of methods: Direct methods such as core, clod, and excavation sampling [9] and indirect methods such as radiation and regression approaches using pedotransfer functions [10]. However, despite several studies using these methods to measure soil ρ_b, in a recent review, Al-Shammary et al. [6] noted that soil ρ_b measurement methods continue to be difficult to use, being time-consuming and leading to mistakes, particularly when the sampling is carried out at different soil depths, as well as different moisture conditions and rock fragment contents. Another major limitation is the difficulty of controlling the quality of soil ρ_b measurements and the loss or gain of moisture by the samples [11,12].

Recently, an innovative system has been developed to minimize errors during the remote measurement of soil bulk density at different soil depths in cultivated fields, i.e., the digital electromechanical system (DES) [13,14]. The DES for measurements is summarized in Al Shammary et al. (2019) [14]. In brief, it involves several stages as follows: Inserting the DES into the soil to collect the soil samples; weighing and drying the collected soil samples with different drying times; estimating the soil ρ_b by data processing with an electric control unit; and finally, sending the results to a PC. The main advantages of the DES technology are that it saves time and increases the precision of in situ measurements. Furthermore, it estimates the volumetric moisture content and porosity. However, at the moment, this device has some limitations which need further improved such as the maximum soil depth for analysis is 30 cm and the extreme difficulties of using it in soils with high gravel content or steep slopes.

In arid and semiarid areas of underdeveloped countries, where agricultural productivity is low because of the extreme climate conditions and the lack of financial support, solarization techniques have become indispensable in sustainably improving productivity [15,16]. Solarization techniques are promising methods to improve the physical properties of soil, such as soil temperature, ρ_b, and moisture content (μ) which are directly related to soil quality and soil health [17,18]. However, human factors such as soil management practices can considerably affect the efficiency of soil solarization technology, such as mulching, tillage, or fertilizers [19–23].

Different tillage practices directly affect soil ρ_b and μ, depending on the type of equipment used [24,25], tillage time [26], or the direction of the tractor and machinery passes [27,28]. Several advantages of tillage practices are related to the suppression of weeds and the aeration of the soil profile [29]; furthermore, they can increase the generation of rills, soil compaction, and soil and nutrient losses [30–32].

Some researchers have confirmed that soil mulching can lead to an increase in the soil organic matter content [33], which improves soil physical quality (soil ρ_b and μ) because mulching reduces soil compaction through a decrease in soil moisture evaporation [34–36] because the humus formation, as well as the resultant water holding capacity, is increased [25,35]. Wu et al. [37] and Wang et al. [38] stated that mulching applications are significantly influenced by an increase in the soil temperature through a thermal transfer between the ambient surroundings and the soil. For example, the soil temperature is considerably influenced by the color and number of layers of mulch [39,40]. Moreover, as other authors have recently demonstrated, the application of catch crops, straw mulches, or plastics reduces the soil erosion rate by several orders of magnitude [41,42].

Finally, the combination of fertilizer with solarization techniques has been confirmed to be beneficial because of its effectiveness by improving soil fertility [43,44]. Although these practices are often discussed today by the supporters of ecological farm management [45,46], the addition of fertilizer leads to an increase in the organic and nutrient contents of the soil, which indirectly and positively influences soil ρ_b and water holding capacity through more active root growth [43,47]; however, a clear risk of water and soil pollution is present [48].

Thermal efficiency (η_{th}), microwave penetration depth (M_{DP}), and energy consumption (Q_{con}) are significant indicators used to describe the electromechanical performance in the soil under different management practices [13]. However, no previous study has described the influence on other soil properties such as ηth, M_{DP}, and Q_{con} and their direct influence on the soil bulk density changes under different soil treatments such as mulching, tillage, or fertilizers. The soil property, η_{th}, is defined as the percentage of the energy used for drying soil samples to the incident microwave source energy, which depends on the mass of soil moisture evaporated, product temperature, incident microwave power, time [49], and soil texture [13]. Thus, the estimation of η_{th} is an important component of the electromechanical performance measurement in agriculture experiments and plays a key role in its Q_{con} which is defined as the power supplied from the microwave drying unit for the evaporation of soil moisture.

Therefore, the main aim of this research was to evaluate the use of a novel digital electromechanical system DES developed by Al-Shammary et al. [13] in a cultivated field with a representative arid climate in central Iraq, where solarization technology is commonly used to increase food production. We estimated the thermal efficiency (η_{th}), microwave penetration depth (M_{DP}), and energy consumption (Q_{con}) for the DES technology under different soil management systems (mulching, tillage, and fertilizers) at different soil depths during the driest season of the year in an experimental plot close to the city of Baghdad.

2. Materials and Methods

2.1. Experimental Area Description

This research took place in an experimental farm at Zafaraniah (south of Baghdad), Iraq (44°27′52.6"E, 33°13′59.8"N, 34 m a.s.l.) from 10 July to 21 August 2018. The experimental site is representative of the intensively farmed soils in south Baghdad which have an average temperature of approximately 34.6 °C in summer and 9.9 °C in winter [50]. Furthermore, annual precipitation is approximately 160 mm [51]. Before the experiments, some soil properties were measured and are presented in Table 1. Soil ρ_b and μ were measured under controlled conditions (no treatment) at three different soil depths with five replicates [14]. The particle size distribution was prepared according to the hydrometer procedure used by [52]. Soil texture was silty clay (14% sand, 41.6% silt, and 44.4% clay). The loss-on-ignition method was used at 400 °C for 16 h to estimate the soil organic matter (SOM) [52], showing values close to 8.0 g kg^{-1} at the surface and less than 5 g kg^{-1} at a soil depth of 20 cm.

Table 1. Characteristics of the soil of the studied field.

Soil Depth (cm)	Moisture Content (%)	Soil Organic Matter (g kg^{-1})	Soil Dry Bulk Density (g cm^{-3})	Particle Size Distribution (%)		
				Clay	Silt	Sand
0–10	27.7	8.0	1.31	47	41	12
10–20	38.2	4.8	1.35	45	41	14
20–30	41.6	4.0	1.39	41	43	16

2.2. Procedures and Agronomic Practices Assessed

First, we decided to perform a split-plot design with a systematic plot arrangement for the experiment (Table 2). The DES performance was tested for the following two different tillage systems: (i) disc plough followed by a spring disk and(ii) mouldboard plough followed by a spring disk. Both systems were tested using the same Explorer 85 DT tractor. Each tillage system was divided by 12 treatments using soil mulching and fertilizers, as shown in Table 2. Furthermore, 0.40 kg m^{-2} of cattle waste as the organic fertilizer and 0.06 kg m^{-2} of diammonium phosphate (DAP) as a source of phosphorus were applied.

Table 2. Interactions between experimental factors testing the digital electromechanical system (DES) performance, tillage systems, mulching treatments, and soil depths.

Tillage systems	1) Mouldboard ploughing and spring disk harrowing (MP + SD) 2) Disc ploughing and spring disk harrowing (DP + SD)
Mulching with fertilizer treatments	1) Transparent plastic (single sheet) and chemical fertilizer (TSC) 2) Transparent plastic (single sheet) without fertilizer (TSW) 3) Transparent plastic (single sheet) and organic fertilizer (TSO) 4) Transparent plastic (double sheet) without fertilizer (TDW) 5) Transparent plastic (double sheet) and organic fertilizer (TDO) 6) Transparent plastic (double sheet) and chemical fertilizer (TDC) 7) Black plastic and organic fertilizer (BO) 8) Black plastic without fertilizer (BW) 9) Black plastic and chemical fertilizer (BC) 10) Without mulch and chemical fertilizer (WC) 11) Without mulch and organic fertilizer (WO) 12) Without mulch and fertilizer (WW)
Soil depths (cm)	1) 0–10 2) 10–20 3) 20–30

Soil samples were collected and dried at 60 °C to estimate some physical and chemical characteristics such as: organic matter (49.4%), pH (7.07), and EC (5 2.4 dSm^{-1}). In all, each treatment was characterized by three replicates for a total of 72 plots, with an area of 2 × 2 m. Finally, the last factor considered for this study was the soil depth, considering 0 to 10, 10 to 20, and 20 to 30 cm. The field was prepared according to the procedure used in [17,53], wherein the following procedure for the use of soil solarization was outlined (Figure 1): (i) starting the preparation of the experimental area; (ii) selecting the soil management systems that will be used; (iii) designing and dividing the experimental area, and then adding the fertilizers; (iv) irrigating until reaching the water holding capacity; (v) covering the soil; and (vi) removing the mulch to estimate the soil parameters.

2.3. Description of the DES, Soil ρb, and μ Measurements

After removing the mulch from the experimental area, we measured the soil ρb and μ in each plot by using the DES technology. The design of the novel DES technology is illustrated in Figure 2A,B and Figure 3.

2.3.1. Electric Control Unit (ECU)

The electric control unit (ECU) was designed and built experimentally for control operation of the DES, which included electronic circuits of load cells unit, a gearbox motor, a microwave unit, and power source, as shown Figures 2B and 3 [13].

2.3.2. Microwave Drying Unit (MDU)

The microwave drying unit (MDU) consisted of a slotted waveguide, three volumetric cylinders (VCs), three load cells (LCs), a power transmission device, and a cutting scraper, as shown Figure 2B [14].

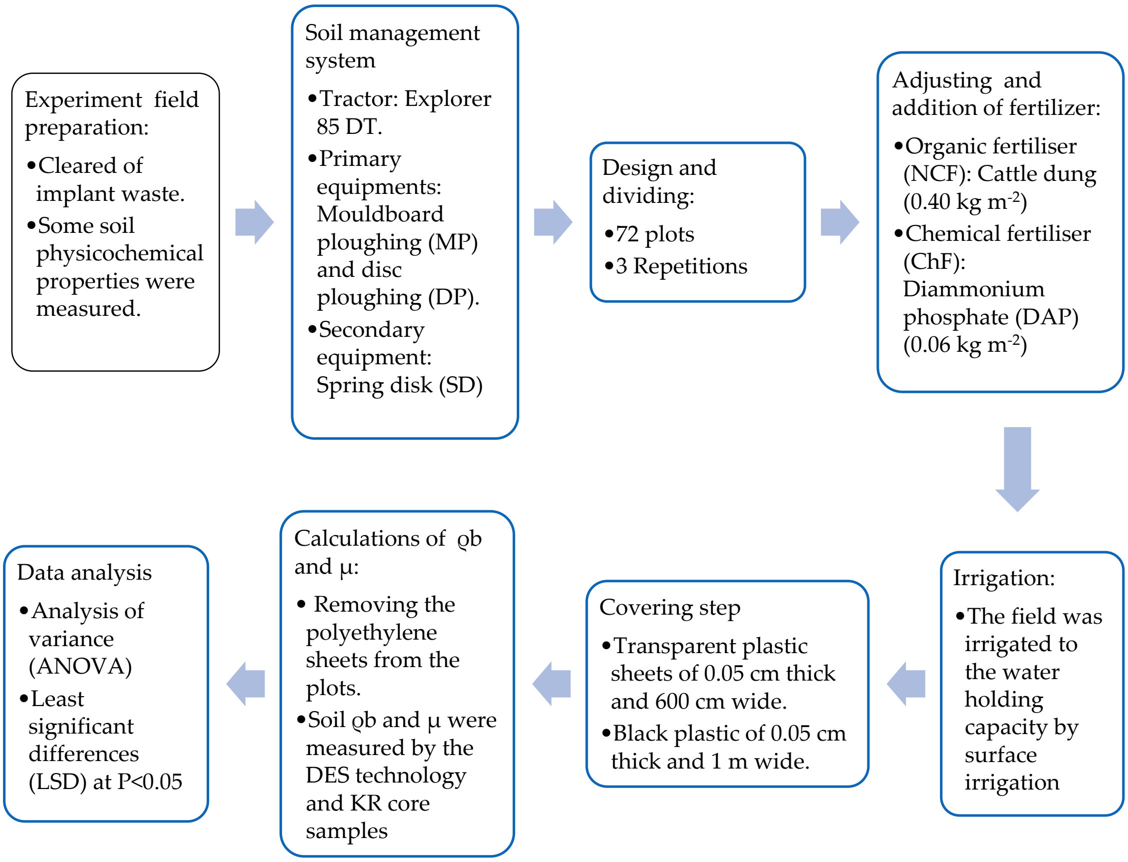
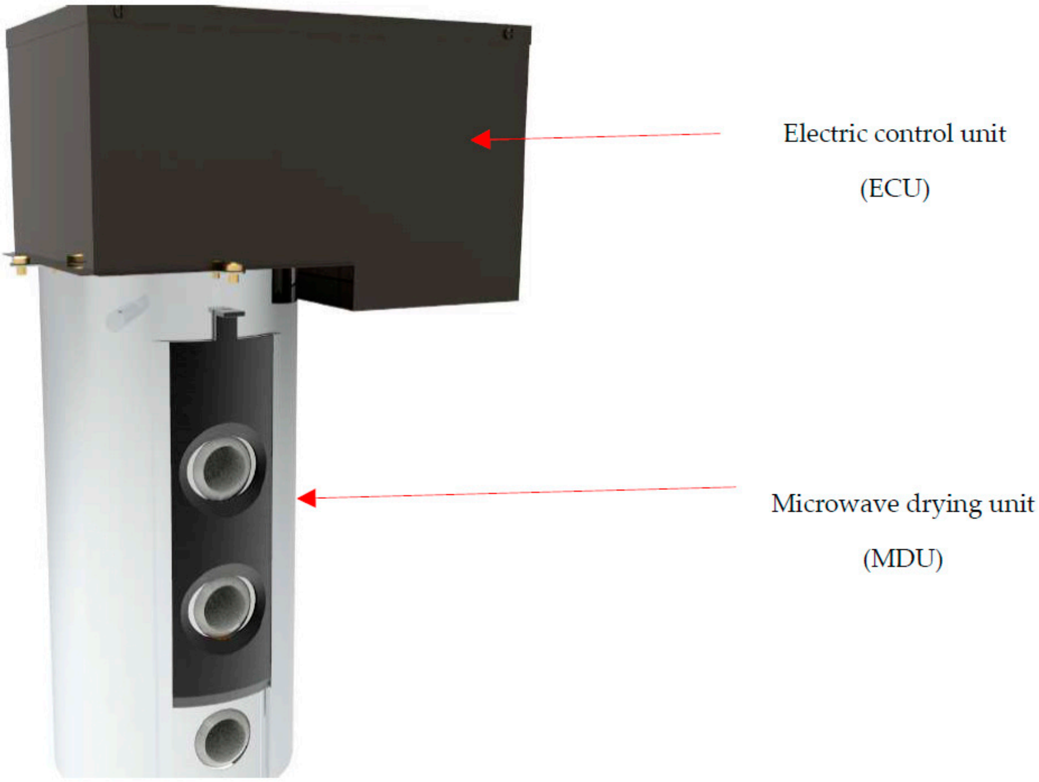


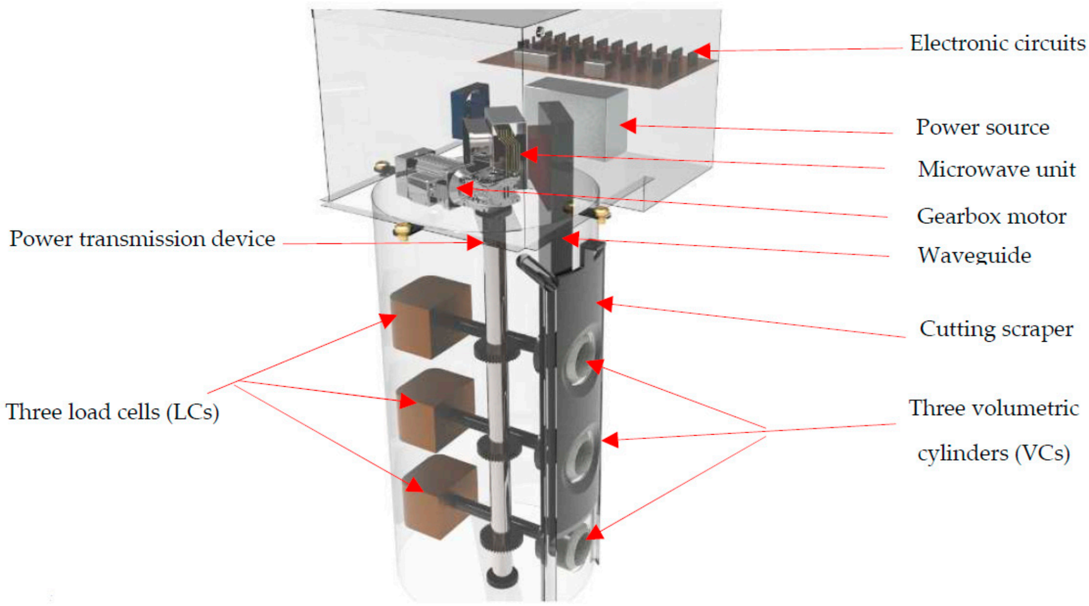
Figure 1. Experimental workflow chart [17,53].

2.4. *Working Mechanism of the DES Technology to Measure Soil ρb and μ*

Figure 4 illustrates the working mechanism of the DES. The DES is vertically inserted into the soil via the penetration cylinder which removes a cylindrical tube of the soil. Then, the DES works by collecting the soil samples and weighing them. Soil samples are collected from the different soil layers by three volumetric cylinders controlled by an Arduino UNO board with HC-05 Bluetooth, a motor, and transmission tools [13]. The cutting scraper tries to eliminate the possible excess of soil and plants from outside the VCs in a vertical direction. Then, the soil samples are weighed using the Arduino board, three proportional amplifiers (HX711), three load cell sensors YZC-131, and a 433-MHz RF transmitter/receiver module. The MDU is responsible for drying and weighing the soil samples. All the data are received in a connected PC by a receiver module and the Arduino board. Finally, the NetBeans software (Java) was used to estimate soil *ρb* and μ.



(**A**)



(**B**)

Figure 2. (**A**) Two main subunits of the digital electromechanical system (DES); (**B**) Description of the DES.

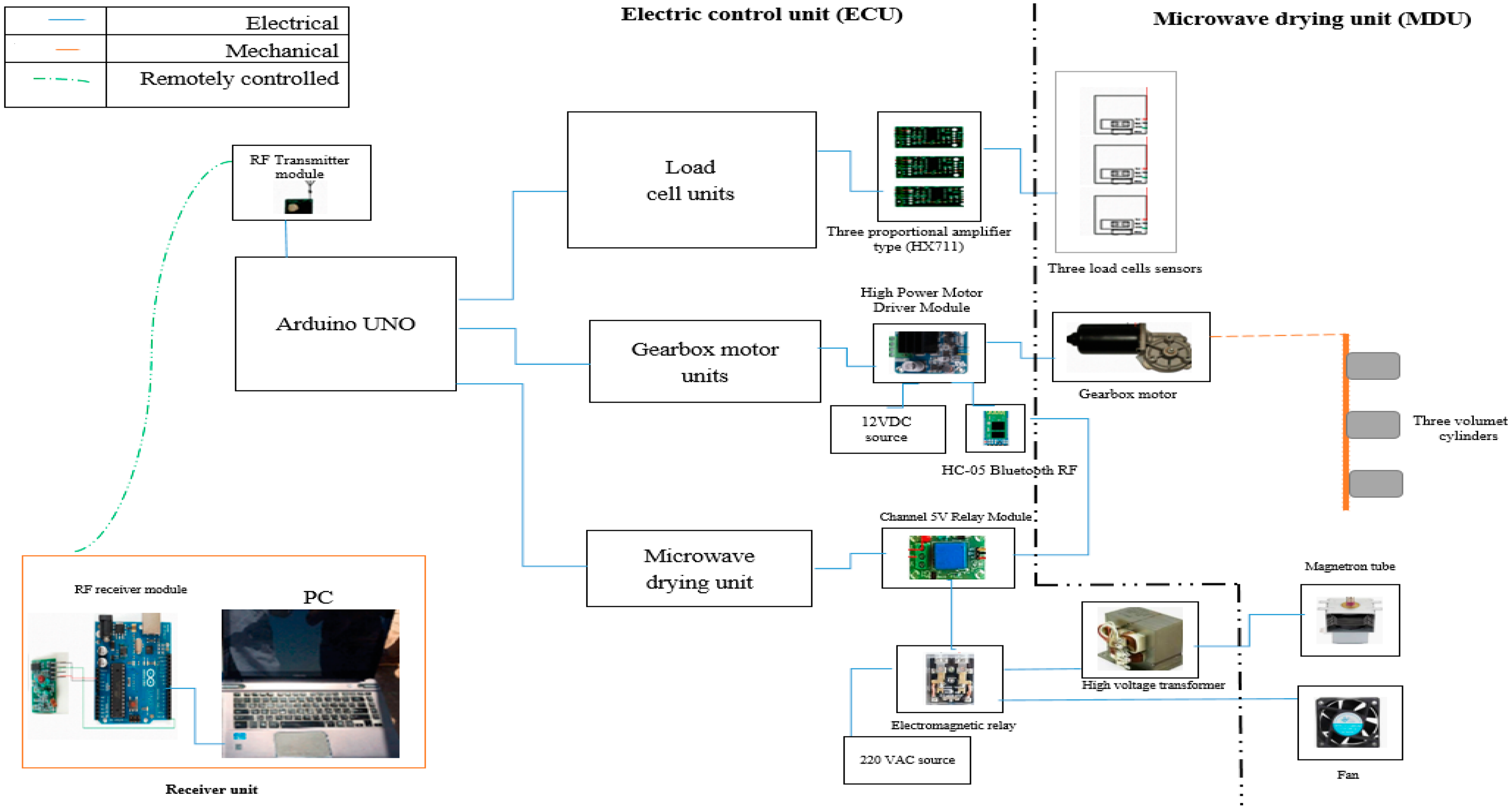


Figure 3. Block diagram displays the components of the digital electromechanical system (DES).

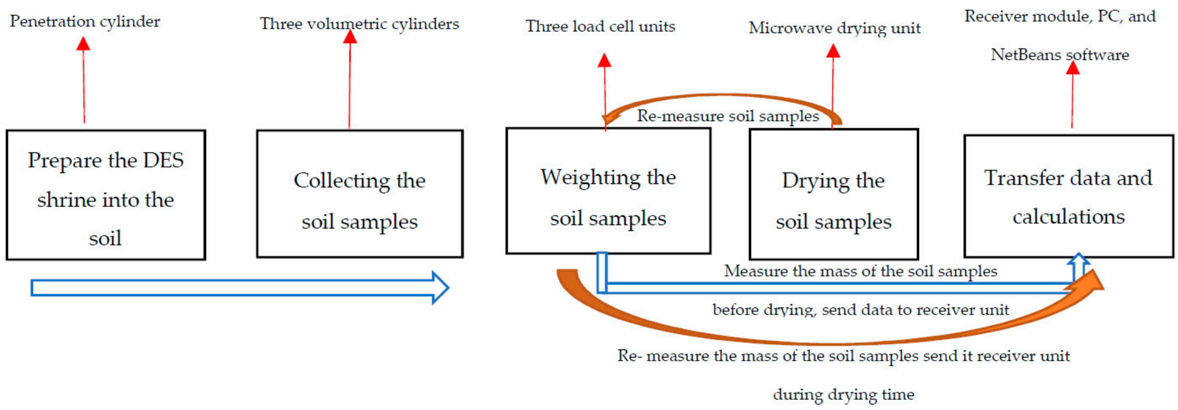


Figure 4. Schematic diagram of the working mechanism of the DES.

2.5. Mathematical Calculations

Thermal efficiency (η_{th}), microwave penetration depth (M_{DP}), and energy consumption (Q_{con}) were calculated using the DES and analyzed in this study. Firstly, η_{th} was calculated as follows [49]:

$$\eta th = \frac{cp\ m_w\ \Delta T + m_w \lambda w}{Pmac * \varphi * t} \quad (1)$$

cp: Specific heat of water (J.g °C^{-1})
m_w: Mass of soil moisture evaporated (g)
ΔT: Product temperature in (°C)
λw: Latent heat of vaporisation of water (J.g^{-1})
P_{mac}: Incident microwave power (W)
φ: Conversion coefficient of the magnetron
t: Microwave time (s)
Then, M_{DP} was estimated as follows [54]:

$$Dp = \frac{\lambda o}{2\pi(2\varepsilon')^{1/2}}\left\{\left[1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2\right]^{1/2} - 1\right\}^{-1/2} \quad (2)$$

Dp: Microwave penetration depth (m)
λo: Free space wavelength (m) can be calculated using ($\lambda 0 = c/f$)
c: Velocity of light (m.s^{-1})
f: Frequency (GHz)
ε': Soil dielectric constant (without unit) can be calculated using $\varepsilon' = (1 + 0.44\ p_b)^2$
p_b: Soil bulk density (Mg.m^{-3}) [55]
ε'': Soil loss factor
Finally, Q_{con} was calculated as follows [13]:

$$Q_{com} = \frac{E_{total}}{\mu} \quad (3)$$

E_{total}: Total energy supplied from microwave drying unit (kJ)
μ: Mass of soil moisture evaporated (kg).

2.6. Data Analysis

To assess the results obtained using the DES technology under different treatments, the repeated-measures analysis of variance (ANOVA) was carried out. SAS 9.4v [56] was used to compare the averages of soil ρ_n, ρ_b, η_{th}, M_{DP}, Q_{con}, and soil ε' of a total of 72 agronomic practices for the three different soil depths by running a global ANOVA F-test and a Fisher's least significant difference (LSD) considering a significance level of 0.05.

3. Results and Discussions

3.1. Microwave Penetration Depth (M_{DP})

The microwave penetration depth (M_{DP}) of soil uses a frequency of 2450 MHz, with different soil treatments for both soil tillage systems, as shown in Table 3. In general, the M_{DP} in a soil sample accounts for the varying performance and efficiency of microwave technologies [57]. The microwave drying unit (MDU) for the DES is more suitable for dry soil samples because of the larger M_{DP} values [58,59]. It was necessary for the electromagnetic radiation to be efficiently transferred through the soil samples to dry them. The samples kept the radiation, and transformed it into thermal energy, possibly due to the effect of the soil ε' and the electromagnetic field applied. Water absorbs electromagnetic radiation more effectively than soil. Therefore, wetter soil heats the entire soil more effectively and increases the rate of drying [60]. At the same time, the values of thermal energy were noted to be dependent on the agronomic practices and soil depth, which demonstrated a significant impact on the M_{DP} values. The M_{DP} values for all the considered soil treatments ranged from 1.83 to 2.32 m. Again, in the majority of soil treatments, the M_{DP} value increased in the DP + SD system as compared with in the MP + SD system, with the DP + SD system showing 2.04 m and the MP + SD system showing 2.02 m, with the soil ε' increasing in the DP + SD system because of the increases in the soil ρ_b (Table 3). We confirmed the effect of the tillage, mulching, and fertilizers at three different soil depths on the soil ε'. The DP + SD system showed the highest average soil ε' reaching 2.49; meanwhile, the MP + SD system obtained the lowest value of 2.44. This could be attributed to the increased smoothing of soil clods in the case of the DP + SD system as compared to the MP + SD system. This fact resulted in the generation of fewer voids between soil aggregates, increasing the soil ρ_b, particularly after irrigation [24,61]. This finding is in agreement with [55] that reported that the soil ρ_b affects the soil ε' in different tillage systems.

The soil mulching system significantly affected the M_{DP} value. The highest values were found using the BC, reaching 2.09 m, and the lowest values were found with TDO at 1.98 m. We hypothesized that this is due to the M_{DP} being affected by the soil ρ_b and μ. This could also be caused by the BC treatments which allowed for a reduction in the evaporation of water and resulted in an increase in the soil ρ_b [62]. The M_{DP} value was also affected by the soil depth (Table 4). The soil depth of 20 to 30 cm yielded the highest M_{DP} value (2.26 m), and the lowest value of 1.89 m was obtained at a soil depth of 0 to 10 cm. This could be attributed to the increase in soil ρ_b at a depth of 20 to 30 cm as compared to that at a depth of 10 to 20 and 0 to 10 cm. There was also a significant difference between the interaction factors and the M_{DP} value. The interaction between tillage and mulching systems indicated a significant difference in the M_{DP} value; the M_{DP} value was the highest in the case of the DP + SD system with BC (2.10 m) and the lowest (1.95 m) in the case of the MP + SD system with TSC. A positive correlation was found between the tillage system and the soil depth for the M_{DP} value. The highest M_{DP} value was obtained for the DP + SD system at a soil depth of 20 to 30 cm and the lowest M_{DP} value was obtained for the MP + SD system at a soil depth of 0 to 10 cm. The ANOVA results for the effects of the tillage systems, mulching systems, and soil depths on soil ε' and M_{DP} are provided in Table 5; we observed that the most significant factor that influenced both soil ε' and M_{DP} was the soil depth, followed by the interaction between the tillage system and the soil depth.

3.2. The Thermal Efficiency of the DES (η_{th})

The thermal efficiency of the DES (η_{th}) is a better indicator of the DES for measuring soil ρ_b, as it largely compensates the energy implicated for increasing the soil moisture content to the incident power by the heat source in the microwave unit [13]. The effects of the tillage system, mulching system, and soil depth on the η_{th} are presented in Table 6. A clear difference in the η_{th} was found between the tillage systems by using the DES. The MP + SD system recorded the higher average values of η_{th} (17.9%). Meanwhile, the DP + SD system recorded the lowest η_{th} value (15.8%). These results reflected the proportional decrease in the evaporated soil moisture and the drying time in the case of the MP + SD treatment, resulting in an increase in the η_{th} as compared with the DP + SD system [63]. The η_{th} value for the DES with different soil treatments (mulch + fertilizer) was statistically significant. The DES results showed that among the soil treatments, the η_{th} reached higher values in TDO and TSO (20.7 and 20.2%, respectively) than other soil treatments, as soil with BC and WC showed the lowest η_{th} value (14% and 13.1%, respectively), which could be attributed to the increase in the soil moisture content with TDO and TSO or to the addition of organic fertilizers that allowed the mulch to increase the water holding capacity [47,64], which indirectly affected the evaporated soil moisture.

Surprisingly, a linear relationship was observed between η_{th} and the soil depths. The highest η_{th} value (17.8%) at the soil depth of 0 to 10 cm was recorded, possibly because of the increase in the evaporated soil moisture as compared with the values of 16.9% and 15.8% at the soil depths of 10 to 20 and 20 to 30 cm, respectively. These results disagree with the findings reported in [13], which showed that the η_{th} value increased with an increase in the soil depth because of the influence of μ under different soil textures; here, the increase in the η_{th} value was followed by an increase in the soil depth and the moisture content. These findings indicated that a significant positive correlation existed between the interaction factors and the η_{th} by using the DES. The highest η_{th} value for the MP + SD system with TSC was 23.6%, and the lowest η_{th} value was obtained with the interaction of the DP + SD system with TSW at 12.4%. Furthermore, Table 5 shows the ANOVA results and the effect of each experimental factor on the η_{th} value and the"F" values for η_{th}. The results showed that the tillage system was one of the main factors impacting η_{th} because of the effects of soil μ.

3.3. Specific Energy Consumption for DES (Q_{con})

The estimation of the Q_{con} using the DES is a very important indicator for soil bulk density measurements because it allows the assessment and comparison of different energies supplied during the microwave drying process, as well as the amount of soil moisture evaporated [65]. The Q_{con} dependence on tillage, mulching, and soil depth is shown in Table 7. We observed that the Q_{con} was significantly affected ($P < 0.05$) by the tillage, mulching, and soil depth and their interactions. The DP + SD system obtained the highest Q_{con} value, reaching 23.64 kJ kg^{-1}. Meanwhile, the MP + SD system had the lowest Q_{con} value with 21.31 kJ kg^{-1}. This fact could be related to the increase in the mass of the evaporated water. The treatment carried out with the DP + SD system obtained the highest evaporation because of increased soil moisture content as compared with the MP + SD system. Therefore, the relationship between the Q_{con} and tillage system was demonstrated to be dependent on the evaporation of soil moisture. The mulching system (mulch + fertilizer) was significant for Q_{con}. The maximum average Q_{con} values were 28.13, 26.42, 26.10, 24.19, 23.90, 22.38, 21.17, and 20.82 kJ kg^{-1} for the WC, BC, TSW, TDW, BW, WW, TSC, and TDC treatments, respectively, and the minimum averages were 17.51 and 17.91 kJ kg^{-1} for the TSO and TDO treatments, respectively. This could be attributed to the increased evaporation of soil moisture during the microwave drying process. Therefore, Q_{con} and the evaporation of soil moisture were inversely proportional. No significant difference was found between the soil depth and Q_{con}. However, the highest Q_{con} value was 23.29 kJkg^{-1} at 20 to 30 cm and the lowest value was 21.69 kJ kg^{-1} at 0 to 10 cm. At the soil depth of 0 to 10 cm, the highest evaporation occurred as compared with the soil depths of 10 to 20 and 20 to 30 cm, because of the initial dryer soil conditions. Table 7 also shows the significant difference between the interaction factors in Q_{con}. We observed that the highest value was obtained using DP + SD and TSW 29.54 kJ kg^{-1}, and the lowest Q_{con} value was obtained using MP + SD and TSC with 15.57 kJ kg^{-1}. A summary of the statistics on the factors influencing Q_{con} is presented in Table 5.

Table 3. Mean of the microwave penetration depths (M_{DP}) at various soil depths for the different soil treatments.

Mulching Systems ID (B)	Mulching System-Soil Depth			Tillage Systems-Mulching System		Mean of Mulching System
	Soil Depth (cm) (C)			Tillage System (A)		
	10	20	30	Disc Plough (DP) + Spring Disk	Mouldboard Plough (MP) + Spring Disk	
TSC	1.83^{h}	1.91$^{e–h}$	2.24^{bc}	2.03^{a}	1.95^{a}	1.99^{a}
TSW	1.91$^{d–g}$	1.95^{de}	2.27^{abc}	2.05^{a}	2.03^{a}	2.04^{a}
TSO	1.85^{ghf}	1.91$^{d–g}$	2.24^{bc}	2.01^{b}	1.99^{a}	2.00^{a}
TDW	1.93^{def}	1.95^{de}	2.26^{abc}	2.06^{a}	2.03^{a}	2.04^{a}
TDO	1.84^{gh}	1.90$^{e–f}$	2.20^{c}	2.01^{a}	1.99^{a}	1.98^{a}
TDC	1.86^{fgh}	1.91$^{f–e}$	2.23^{bc}	1.97^{a}	2.00^{a}	2.00^{a}
BO	1.91$^{d–g}$	1.95^{de}	2.27^{abc}	2.03^{a}	2.06^{a}	2.04^{a}
BC	1.96^{de}	1.99^{d}	2.32^{a}	2.10^{a}	2.08^{a}	2.09^{a}
BW	1.91$^{e–g}$	1.95^{de}	2.27^{abc}	2.03^{a}	2.06^{a}	2.04^{a}
WC	1.92$^{e–g}$	1.98^{de}	2.31^{ab}	2.09^{a}	2.04^{a}	2.07^{a}
WO	1.85^{fgh}	1.93^{def}	2.27^{abc}	2.06^{a}	1.97^{a}	2.01^{a}
WW	1.91$^{d–g}$	1.95^{de}	2.27^{abc}	2.09^{a}	2.00^{a}	2.04^{a}
Least significant difference (LSD $_{0.05}$)		B-C 0.08		A-B N.S		B N.S.
Tillage system		Tillage system-soil depth		Mean tillage system		
Disc plough (DP) followed by a spring disk	1.91^{c}	1.95^{b}	2.27^{a}	2.04^{a}		
Mouldboard plough (MP) followed by a spring disk	1.87^{d}	1.93^{bc}	2.25^{a}	2.02^{b}		
$LSD_{0.05}$		A-C 0.03		A 0.04		
Mean of soil depth	1.89^{c}	1.94^{b}				
$LSD_{0.05}$		C 0.02				

* TSC, transparent plastic (single sheet) and chemical fertilizer; TSW+, transparent plastic (single sheet) without fertilizer; TSO, transparent plastic (single sheet) and organic fertilizer; TDW, transparent plastic (double sheet) without fertilizer; TDO, transparent plastic (double sheet) and organic fertilizer; TDC, transparent plastic (double sheet) and chemical fertilizer; BO, black plastic and organic fertilizer; BW, black plastic without fertilizer; BC, black plastic and chemical fertilizer; WC, without mulch and chemical fertilizer; WO, without mulch and organic fertilizer; and WW, without mulch and fertilizer. Alphabet notation (AN) has been used as style for the proper presentation of mean comparison using the LSD test, the AN has some rules. For example, whenever four or more letters are required by more than two treatments, use the dash notation to shorten the string of letters. For example, the string (abcd) is written as a–d, the string (bcdefg) is written as b–g, and so on.

Table 4. Mean of soil dielectric constants (ε′) at various soil depths for the different soil treatments.

Mulching Systems ID (B)	**Mulching System-Soil Depth**			**Tillage Systems-Mulching System**		**Mean of Mulching System**
	Soil Depth (cm) (C)			**Tillage Systems (A)**		
	10	**20**	**30**	**Disc plough (DP) + Spring Disk**	**Mouldboard plough (MP) + Spring Disk**	
TSC	2.22^{l}	2.39^{hij}	$2.51^{b–g}$	$2.47^{c–g}$	2.27^{i}	2.37^{d}
TSW	$2.41^{e–i}$	$2.50^{b–h}$	2.59^{ab}	$2.52^{a–e}$	$2.48^{b–g}$	2.50^{abc}
TSO	2.26^{kl}	$2.39^{g–j}$	$2.52^{b–e}$	$2.41^{e–h}$	2.37^{ghi}	2.39^{d}
TDW	$2.44^{d–i}$	$2.51^{b–f}$	$2.55^{a–d}$	$2.52^{a–e}$	$2.48^{b–g}$	2.50^{abc}
TDO	2.23^{l}	2.37^{ijk}	$2.44^{c–i}$	2.32^{hi}	2.38^{ghi}	2.35^{d}
TDC	2.29^{jkl}	$2.39^{g–j}$	$2.52^{b–e}$	$2.41^{e–h}$	$2.39^{f–i}$	2.40^{d}
BO	2.39^{hij}	$2.51^{b–f}$	2.59^{ab}	$2.47^{d–g}$	$2.53^{a–d}$	2.50^{bc}
BC	$2.51^{b–f}$	2.58^{ab}	2.67^{a}	2.59^{abc}	2.59^{abc}	2.59^{a}
BW	2.39^{hij}	$2.51^{b–f}$	2.59^{ab}	$2.46^{d–g}$	$2.54^{a–d}$	2.50^{bc}
WC	$2.41^{e–i}$	2.56^{abc}	2.67^{a}	2.59^{ab}	$2.50^{a–f}$	2.55^{ab}
WO	2.24^{l}	$2.45^{c–i}$	2.59^{ab}	$2.54^{a–d}$	2.31^{hi}	2.43^{cd}
WW	$2.40^{f–j}$	$2.50^{b–h}$	2.59^{ab}	2.60^{a}	2.39^{fgh}	2.50^{bc}
Least significant difference ($LSD_{0.05}$)		B-C 0.11		A-B 0.11		B 0.08
Tillage system	Tillage system x soil depth			Mean tillage system		
Disc plough (DP) followed by a spring disk	2.39^{c}	2.50^{b}	2.58^{a}	2.49^{a}		
Mouldboard plough (MP) followed by a spring disk	2.30^{d}	2.45^{b}	2.55^{a}	2.44^{b}		
$LSD_{0.05}$		A-C 0.05		A 0.03		
Mean of soil depth	2.35^{c}	2.47^{b}				
$LSD_{0.05}$		C 0.03				

* TSC, transparent plastic (single sheet) and chemical fertilizer; TSW+, transparent plastic (single sheet) without fertilizer; TSO, transparent plastic (single sheet) and organic fertilizer; TDW, transparent plastic (double sheet) without fertilizer; TDO, transparent plastic (double sheet) and organic fertilizer; TDC, transparent plastic (double sheet) and chemical fertilizer; BO, black plastic and organic fertilizer; BW, black plastic without fertilizer; BC, black plastic and chemical fertilizer; WC, without mulch and chemical fertilizer; WO, without mulch and organic fertilizer; and WW, without mulch and fertilizer. Alphabet notation (AN) has been used as style for the proper presentation of mean comparison using the LSD test, the AN has some rules. For example, whenever four or more letters are required by more than two treatments, use the dash notation to shorten the string of letters. For example, the string (abcd) is written as a–d, the string (bcdefg) is written as b–g, and so on.

Table 5. Descriptive statistics of parameters studied under influences of experimental factors.

SOV[1]	**Df**	**SS**[2]						**M.S**[3]						**F Value**					
		Soil ρ_n (Mg_{wet} cm^{-3})	**Soil ρ_b (Mg_{dry} cm^{-3})**	**Soil ε'**	**M_{DP} (m)**	**η_{th} of DES (%)**	**Q_{con} for DES (kJ kg^{-1})**	**Soil ρ_n (Mg_{wet} cm^{-3})**	**Soil ρ_b (Mg_{dry} cm^{-3})**	**Soil ε'**	**M_{DP} (m)**	**η_{th} of DES (%)**	**Q_{con} for DES (kJ kg^{-1})**	**Soil ρ_n (Mg_{wet} cm^{-3})**	**Soil ρ_b (Mg_{dry} cm^{-3})**	**Soil ε'**	**M_{DP} (m)**	**η_{th} of DES (%)**	**Q_{con} for DES (kJ kg^{-1})**
Main-plot analysis:																			
Rep	2																		
Tillage system (A)	1	0.68	0.06	0.16	0.04	231.5	294.7	0.68	0.06	0.16	0.04	231.5	294.7	69.1**	6**	7.4**	1.1**	13.1**	7.9**
Error A	2							0.01	0.01	0.02	0.03	17.6	37.39						
Sub-plot analysis																			
Mulching system (B)	11	0.1	0.53	1.08	0.21	1228	2209.7	0.01	0.05	0.09	0.02	111.7	200.9	0.7 $^{n.s}$	5.5**	5.3**	0.6 $^{n.s}$	8.2**	6.7**
A-B	11	1.08	0.85	1.79	0.34	2056.9	3470.6	0.05	0.04	0.08	0.01	89.4	150.9	5.3**	4.9**	4.9**	0.4 $^{n.s}$	8.8**	6**
Error B	44							0.01	0.01	0.02	0.03	13.6	29.8						
Sub-sub plot analysis																			
Depth (C)	2	0.38	0.88	1.75	5.89	146.4	92.1	0.19	0.44	0.87	2.94	73.2	46.1	16.7**	65.4**	60.2**	543.4**	4.0**	1.2$^{n.s}$
A-C	2	1.13	0.96	1.94	5.93	478.7	594.6	0.23	0.19	0.39	1.19	95.7	118.9	28.6**	29.6**	28.1**	223.7**	5.7**	3.2**
B-C	22	0.66	1.47	2.97	6.12	1518.7	2537.3	0.02	0.04	0.08	0.17	43.3	72.5	1.6**	8.8**	8.2**	34.3**	3.1**	2.3**
A-B-C	22	1.95	1.85	3.81	6.28	2614.0	4326.9	0.03	0.03	0.05	0.09	36.8	60.9	4.7**	7.9**	7.6**	16.8**	3.81**	2.2**
Error C	96							0.01	0.01	0.01	0.01	18.1	38.5						
Total	215	2.80	2.32	4.84	7.03	4004.9	8296.8												

1, Source of variance; 2, sum of squares mean square; 3, mean square; ρ_n, soil wet bulk density; ρ_b, soil dry bulk density; ε', soil dielectric constant, M_{DP}, microwave penetration depth, η_{th}, thermal efficiency of the DES technology; Q_{con}, specific energy consumption for DES; **, significant difference at 0.05 level; n.s, no significant main effect.

Table 6. Mean of the thermal efficiency (η_{th}) of the DES at various soil depths for the different soil treatments.

Mulching Systems (B)	**Mulching System-Soil Depth**			**Tillage Systems-Mulching System**		**Mean of Mulching System**
	Soil Depth (cm) (C)			**Tillage System (A)**		
	10	**20**	**30**	**Disc plough (DP) + Spring Disk**	**Mouldboard plough (MP) + Spring Disk**	
TSC	$19.85^{a–e}$	$18.31^{b–j}$	$17.82^{c–k}$	13.75^{ghi}	23.56^{a}	18.66^{abc}
TSW	13.36^{lm}	$14.15^{j–m}$	$14.86^{h–m}$	12.38^{i}	$15.86^{e–h}$	14.12^{ef}
TSO	22.35^{ab}	21.20^{abc}	$16.91^{d–l}$	19.00^{bcd}	21.3^{ab}	20.15^{ab}
TDW	$15.21^{f–m}$	$15.28^{f–m}$	$15.01^{g–m}$	13.81^{ghi}	$16.53^{d–g}$	15.17^{ef}
TDO	22.66^{a}	$19.98^{a–e}$	$19.43^{a–f}$	20.61^{abc}	20.77^{abc}	20.69^{a}
TDC	$20.35^{a–d}$	$18.40^{b–i}$	$16.56^{d–l}$	$14.76^{f–i}$	22.11^{a}	18.43^{abc}
BO	$19.23^{a–g}$	$17.70^{c–k}$	$16.16^{d–m}$	17.32^{def}	18.11^{cde}	17.71^{cd}
BC	13.48^{lm}	$14.63^{h–m}$	13.83^{klm}	$14.51^{f–i}$	13.45^{hi}	13.98^{f}
BW	$15.86^{e–m}$	$15.45^{f–m}$	$14.90^{h–m}$	$16.40^{d–h}$	$14.41^{f–i}$	15.40^{def}
WC	$14.38^{i–m}$	12.83^{lm}	12.06^{m}	12.66^{i}	13.52^{hi}	13.09^{f}
WO	$18.75^{a–h}$	$18.28^{b–j}$	$16.86^{d–l}$	17.30^{def}	$18.63^{b–e}$	17.96^{bc}
WW	$18.08^{c–j}$	$16.43^{d–l}$	$14.98^{h–m}$	16.95^{def}	$16.04^{d–h}$	16.50^{cde}
Least significant difference ($LSD_{0.05}$)		B-C 4.23		A-B 2.96		B 2.42
Tillage system		Tillage system-soil depth		Mean tillage system		
Disc plough (DP) followed by a spring disk	16.00^{b}	15.71^{b}	15.64^{b}	15.79^{b}		
Mouldboard plough (MP) followed by a spring disk	19.59^{a}	18.06^{a}	15.92^{b}	17.86^{a}		
$LSD_{0.05}$		A-C 1.90		A 1.12		
Mean of soil depth	17.80^{a}	16.89^{ab}	15.78^{b}			
$LSD_{0.05}$		C 1.39				

* TSC, transparent plastic (single sheet) and chemical fertilizer; TSW+, transparent plastic (single sheet) without fertilizer; TSO, transparent plastic (single sheet) and organic fertilizer; TDW, transparent plastic (double sheet) without fertilizer; TDO, transparent plastic (double sheet) and organic fertilizer; TDC, transparent plastic (double sheet) and chemical fertilizer; BO, black plastic and organic fertilizer; BW, black plastic without fertilizer; BC, black plastic and chemical fertilizer; WC, without mulch and chemical fertilizer; WO, without mulch and organic fertilizer; and WW, without mulch and fertilizer. Alphabet notation (AN) has been used as style for the proper presentation of mean comparison using the LSD test, the AN has some rules. For example, whenever four or more letters are required by more than two treatments, use the dash notation to shorten the string of letters. For example, the string (abcd) is written as a–d, the string (bcdefg) is written as b–g, and so on.

Table 7. Mean of the specific energy consumption (Q_{con}; kJ kg^{-1}) of the DES at different soil depths for the different soil treatments.

Mulching Systems (B)	Mulching System-Soil Depth			Tillage Systems-Mulching System		Mean of Mulching System
	Soil Depth (cm) (C)			Tillage Systems (A)		
	10	20	30	Disc plough (DP) + Spring Disk	Mouldboard plough (MP) + Spring Disk	
TSC	20.95$^{c–j}$	22.06$^{b–j}$	30.08$^{d–j}$	26.77^{ab}	15.57^{i}	21.17^{cde}
TSW	28.23^{ab}	25.71$^{a–e}$	24.35$^{a–h}$	29.54^{a}	22.65$^{b–e}$	26.10^{ab}
TSO	16.48^{j}	17.23^{ij}	18.83$^{f–j}$	17.71$^{f–i}$	17.32^{ghi}	17.51^{f}
TDW	24.22$^{a–h}$	24.25$^{a–h}$	24.10$^{e–f}$	26.30^{abc}	22.07$^{c–f}$	24.19^{bc}
TDO	16.40^{j}	18.40$^{g–j}$	18.93$^{f–j}$	17.96$^{f–i}$	17.85$^{f–i}$	17.91^{ef}
TDC	18.28^{hij}	21.61$^{c–j}$	22.58$^{b–j}$	24.98$^{a–d}$	16.66$^{f–i}$	20.82$^{c–f}$
BO	19.08$^{f–j}$	20.40$^{d–j}$	22.71$^{b–j}$	21.23$^{d–h}$	20.23^{hi}	20.73$^{c–f}$
BC	27.30^{abc}	25.18$^{a–f}$	26.80$^{a–d}$	25.34$^{a–d}$	27.51^{a}	26.42^{ab}
BW	23.38$^{b–i}$	23.50$^{b–i}$	24.81$^{a–g}$	22.24$^{b–f}$	25.55$^{a–d}$	23.90^{bcd}
WC	25.95$^{a–e}$	28.38^{ab}	30.08^{a}	28.55^{a}	27.72^{a}	28.13^{a}
WO	19.75$^{e–j}$	20.11$^{e–j}$	21.50$^{c–j}$	21.16$^{d–h}$	19.74$^{e–i}$	20.45^{def}
WW	20.33$^{e–j}$	22.46$^{b–j}$	24.35$^{a–h}$	21.94$^{c–g}$	22.82$^{b–e}$	22.38^{cd}
Least significant difference ($LSD_{0.05}$)		B-C 6.44		A-B 4.66		B 3.59
Tillage system		Tillage system x soil depth		Mean tillage system		
Disc plough (DP) followed by a spring disk	23.86^{a}	23.95^{a}	23.13^{ab}	23.64^{a}		
Mouldboard plough (MP) followed by a spring disk	19.53^{c}	20.93^{ab}	23.46^{ab}	21.31^{b}		
$LSD_{0.05}$		A-C 2.81		A 1.64		
Mean of soil depth	21.69^{a}	22.44^{a}	23.29^{a}			
$LSD_{0.05}$		C N.S				

* TSC, transparent plastic (single sheet) and chemical fertilizer; TSW+, transparent plastic (single sheet) without fertilizer; TSO, transparent plastic (single sheet) and organic fertilizer; TDW, transparent plastic (double sheet) without fertilizer; TDO, transparent plastic (double sheet) and organic fertilizer; TDC, transparent plastic (double sheet) and chemical fertilizer; BO, black plastic and organic fertilizer; BW, black plastic without fertilizer; BC, black plastic and chemical fertilizer; WC, without mulch and chemical fertilizer; WO, without mulch and organic fertilizer; and WW, without mulch and fertilizer. Alphabet notation (AN) has been used as style for the proper presentation of mean comparison using the LSD test, the AN has some rules. For example, whenever four or more letters are required by more than two treatments, use the dash notation to shorten the string of letters. For example, the string (abcd) is written as a–d, the string (bcdefg) is written as b–g, and so on.

3.4. Soil Bulk Density Measurement

The wet (ρ_n) and dry (ρ_b) bulk densities for each soil treatment were determined using the DES. Figure 5 shows two groups with different tillage systems (disc ploughing followed by a spring disk (DP + SD) and mouldboard ploughing followed by a spring disk (MP + SD) under different soil treatments. The findings revealed that the tillage systems with different soil treatments had significant differences ($P \leq 0.05$) in ρ_n (Figure 5a), and the highest average ρ_n value was obtained for the DP + SD tillage system with transparent (single sheet) and chemical fertilizers (TSC) at the soil depth of 20 to 30 cm. In contrast, the lowest average ρ_n value was obtained in the case of the MP + SD system with BO treatments at the soil depth of 10 to 20 cm, which could be attributed to the increased moisture content, as well as water-holding capacity in the DP + SD tillage system with the TSC soil treatment as compared with the MP + SD system with the BO soil treatment. Additionally, the majority of soil ρ_n values showed an increase depending on the soil depths. Moreover, the DES results showed a significant difference ($p < 0.05$) in soil ρ_b for the different tillage systems with different soil treatments (Figure 5b). In this case, soil ρ_b was lower in the case of the TSC soil treatment for the soil depth of 0 to 10 cm in the MP + SD tillage system than in the case of any other soil treatment studied. In contrast, the soil ρ_b was higher using BC for the soil depth of 20 to 30 cm in the DP + SD tillage systems. This could be explained by the less aggressive soil disturbance and crumbling by the MP + SD treatment than that by the DP + SD treatments. The ANOVA results for the influence of each experimental factor on soil ρn and ρ_b are presented in Table 5. The findings showed that soil ρ_n varied significantly ($p \leq 0.05$) with tillage, mulching, and soil depth. Soil ρ_b recorded no significant change with the mulching systems. Soil ρ_n and ρ_b recorded significant ($p \leq 0.05$) effects with the interaction between the experimental factors.

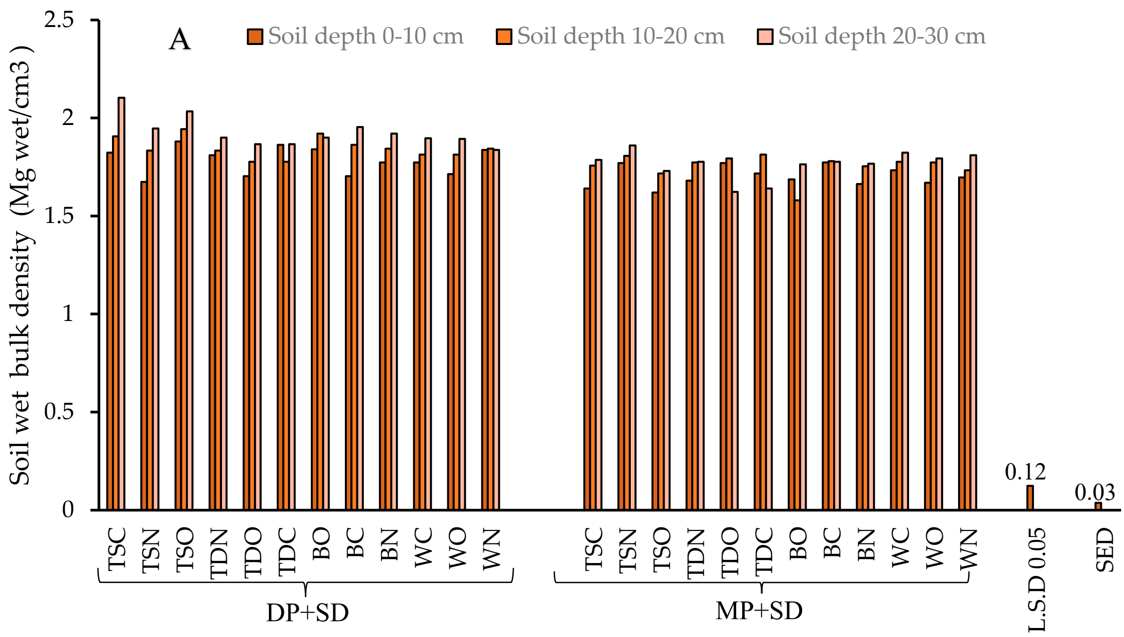


Figure 5. *Cont.*

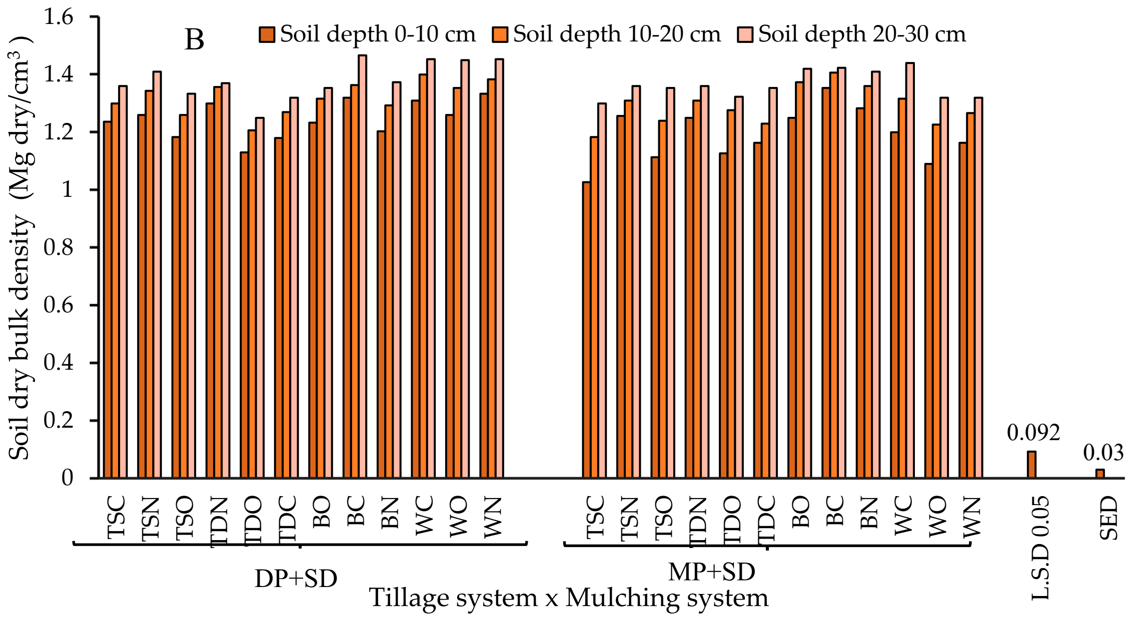


Figure 5. Interaction between the tillage system and mulching system, with three soil depths in soil wet (**A**) and dry bulk density (**B**), using the digital electromechanical system (DES). MP + SD, mouldboard ploughing and spring disk harrowing; DP + SD, disc ploughing (DP) and SD harrowing; TSC, transparent plastic (single sheet) and chemical fertilizer; TSW+, transparent plastic (single sheet) without fertilizer; TSO, transparent plastic (single sheet) and organic fertilizer; TDW, transparent plastic (double sheet) without fertilizer; TDO, transparent plastic (double sheet) and organic fertilizer; TDC, transparent plastic (double sheet) and chemical fertilizer; BO, black plastic and organic fertilizer; BW, black plastic without fertilizer; BC, black plastic and chemical fertilizer; WC, without mulch and chemical fertilizer; WO, without mulch and organic fertilizer; and WW, without mulch and fertilizer.

4. Conclusions and Recommendations

The DES system was tested in a soil solarization technology experiment using different tillage, soil mulching, and fertilizer types at three different soil depths. The effects of treatment on the wet bulk density (ρ_n) and the dry bulk density (ρ_b), which were measured using the DES, were explored. Furthermore, the soil dielectric constant (ε'), microwave penetration depth (M_{DP}), thermal efficiency (η_{th}), and specific energy consumption (Q_{con}) using the DES were determined. The DES results demonstrated that the tillage, mulching, and soil depth had significant effects on soil ρ_b and ρ_n, as well as soil ε', M_{DP}, η_{th}, and Q_{con}. This refers to the applicability of the DES technology to the soil bulk density measurement for soil solarization practices. Furthermore, the use of mouldboard ploughing followed by a spring disk and transparent plastic (single sheet) in solarization practices could help to improve soil properties, increasing the available moisture content and soil aggregation, and decreasing the soil bulk density, evaporated soil moisture, and drying time.

In future research, it would be necessary to investigate the practical challenges associated with the use of the DES for measuring soil bulk density as follow:

- Develop a new design for the DES to measure soil bulk density at depths greater than 30 cm and not compacting the soil too much during the measurement, which would allow its use for geological research or deeper soils;
- Study and measure the systematic error of the bulk density measuring during preparation into the soil using a penetration cylinder and inserting the DES sensor into the soil downwards;
- Determine if it is comparable to a system based on using a microwave for drying the soil (heat from inside) and with a system based on using an oven (heat from outside);

- Design new implementations and solutions to measure soil bulk density while encountering stones or roots during the sampling.

More broadly, research is also needed to determine the economic costs of the DES as compared with traditional measurements of soil bulk density using different agronomic techniques.

The results of this study represent the data of a specific area, which is silty clay, and it is necessary to ascertain the extent to which the results apply to other areas and the use of different soil solarization practices. Nevertheless, the work stresses the need for new approaches in the field of soil survey based on the application of modern surveying and geophysical methods for soil and rocks, and this is undoubtedly the future. However, we should not forget the basic approach to other agronomical applications, which always provides a detailed description of the soils that are sampled for our researches.

Author Contributions: A.A.G.A. designed formal analysis, investigation, and writing—original draft preparation and performed the experiments; A.Z.K. supervision, designed, formal analysis, review and editing; A.K. supervision, writing—review and editing; S.Y.K. supervision, review and editing; M.N. supervision, review and editing; W.P.G. supervision, review and editing; J.R.-C. review and editing; M.A.-M. drawing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: We would like to express sincere thanks to the Government and Ministry of Higher Education and Scientific Research, Iraq for providing funding for this study (as a scholarship for PhD student Ahmed Abed Gatea Al-Shammary).

Conflicts of Interest: The authors declare no conflict of interest.

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