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Effect of electromagnetic treatment of treated wastewater on soil and drainage water

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ABSTRACT

To reduce the negative effects of using treated wastewater (TW) on soil properties, several techniques, methods, and strategies are used. One of these new techniques is electromagnetic (EM) water treatment technology. Using the aqua-4D physical water treatment device, we studied the effect of irrigation with electromagnetically treated TW (ETW) on soil and drainage water characteristics. Replicated pot experiments involving electromagnetically treated and non-ETW applied to cultivated and uncultivated soil were conducted under shelter. Results showed that irrigation with ETW increases soil moisture, soil electrical conductivity (ECe) and soil available K, whereas it decreases soil alkalinity (pH) and soil chemical contents such as Na^+, Cl^-, Ca^{2+}, Mg^{2+}, and SO_4^{2-} compared with non-ETW, for both uncultivated and cultivated soils. It was also observed that irrigation with ETW caused a significant increase in volume, electrical conductivity (EC), and soluble salts of drainage water compared to non-ETW. In this regard, our study has shown promising potentials for EM treatment to use TW in agriculture as well as to improve soil quality.

Keywords: Drainage water; Electromagnetic water treatment; Soil salinity; Treated wastewater; Tunisia; Water salinity

1. Introduction

It is imperative to save water to preserve this vital resource. Water resources are under pressure, particularly in semi-arid and arid regions, where water is scarce. Nevertheless, the demand for water increases while the resources availability decreases because of the groundwater overexploitation, pollution by solid discharges, and waste in rivers, unbalanced distribution, sectoral conflicts of water use, population growth, and management incapacity. In Tunisia, water resources are limited and agriculture is the main water resources consumer, about 76% of total national consumption. The treated wastewater (TW) use as an alternative resource has become essential to cope with water scarcity and to meet the growing demand for water of agricultural irrigation. The TW use in agricultural practices, (i) allows the fertilizing material contained in these waters to be exploited, thus saving fertilizers and (ii) constitutes a measure to protect coastal waters by preventing the TW discharge into the sea. Besides the TW advantages, it presents risks. Its physico-chemical quality can ultimately lead to the irrigated soil degradation and the metallic elements accumulation in soil and plants. To deal with these problems, emerging new techniques to improve the TW quality as well as to reduce water consumption, is of significant importance. One of these new techniques is EM

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water treatment technology. It is an effective treatment and less expensive than other conventional methods of water treatment. Since the late 1970s, research has mainly focused on the magnetic field, so that today, speaking of EM treatment, we only refer to magnetic treatment. The magnetic water treatment attracts a special attention due to its simplicity, safety, ecological purity, and low operating costs [1]. In recent decades, many authors have highlighted the beneficial effect of magnetic treatment on wastewater and have demonstrated the high efficiency of this treatment as a complement or alternative to wastewater treatment [2,3].

Magnetically treated water (MTW) is a water passed through a magnetic field, leading to change on behavior of water molecules and salts ions, causing changes in water physical and chemical properties [4]. The water structure is directly influenced by the magnetic field, due to the dipole polarization of water molecules [5]. Water is composed of hydrogen and oxygen atoms, and its molecules are linked by an intermolecular force which is the hydrogen bonds. Kiselev and Heinzinger [6] reported that changes in water structure under the magnetic field influence were linked with hydrogen bonds. When the magnetic field intensity or the magnetized time increases, this field weakens the hydrogen bonds in water [7]. On the opposite, other research has shown that hydrogen bonds become stronger [8] or more stable [9] under the magnetic field influence causing modifications on the water structure. The literature review indicates that the magnetic field effect on the water depends on the intensity of this field, the magnetization duration, the water temperature, and its flow [10]. The magnetic field effects on the water have been the subject of researcher's interest in different fields despite controversy and lack of a complete understanding of phenomena. The reported results have low reproducibility, are little consistent and are seldom accepted by physicists. Besides, the mechanisms behind these effects and the changes that the magnetic treatment brings to water are not yet clear.

In fact, many researchers presented scientific results showing that magnetic water treatment was an applied simple solution for many agricultural applications such as seedling growth [11]. The MTW can improve the soil physical properties [12]. According to Fanous et al. [13], magnetic devices are not used because they cause chemical changes in the water salts but for the MTW ability to affect directly the physico-chemical soil properties. The authors have shown a decrease in salinity and in pH of the soil irrigated with MTW. Indeed, previous studies have shown several positive effects in soils irrigated with MTW, in particular the increase in its moisture [14,15]. Mostafazadeh-Fard et al. [16] observed, under trickle irrigation, that the average water content of soil irrigated with MTW was significantly higher at the depths of 0–20, 20–40, and 40–60 cm compared to the soil irrigated with untreated water. They confirmed that irrigation with MTW increased significantly the soil moisture up to 7.5% higher than the moisture of the irrigated soil with the same dose of untreated water. They concluded that irrigation with MTW can be used to save irrigation water. These results can be explained by the soil porosity improvement, which is responsible for water retention and infiltration, following irrigation with electromagnetically treated water as has been shown by Moussa et al. [17]. In this previous study, ETW has been shown to provide (i) better water retention and (ii) better leaching effect [17]. The improvement in soil microporosity explains increased water retention and availability in the root zone which allows a reduction in the use of irrigation water while the improvement in soil macroporosity explains increased drainage water that allows irrigation with saline water.

Soil salinity is one of the most serious agricultural problems. Increasing soil salinity, increases the time required for germination and causes a significant decrease in crop yields and plant fertility. Various researchers have reported the MTW ability to decrease soil salinity [18]. Furthermore, Yadollahpour and Rashidi [19] reported that the magnetic treatment of saline irrigation water is reportedly an effective method for soil desalination. Moreover, Hilal et al. [10] conducted an experiment in soil columns to evaluate the MTW effect on soil salinity and the availability of some nutrients in sandy soil. They indicated that soil salinity was significantly decreased after the leaching with different magnetically treated irrigation water compared with untreated water at all soil depths, and that the highest salinity values were recorded for the deeper soil layers (15–30 cm). In addition, they reported that the total salt amount removed from the soil after leaching was significantly higher with MTW compared with untreated water. Mohamed and Ebead [20] studied the effect of irrigation with MTW on faba bean growth and composition in sandy soil and found that soil salinity was significantly decreased. Magnetic water treatment proven to have a favorable effect in enhancing soil quality.

The literature review showed that the EM treatment of irrigation water influences several soil properties such as salinity and moisture content (using different water qualities). These results led us to hypothesize that the EM treatment may be effective as a complementary treatment to TW and that the ETW will have a different effect on soil and drainage water than untreated water. The TW valorization in agriculture requires effective treatment. The EM treatment was used because it is a simple method and less costly (installation and maintenance) than other conventional water treatment methods. There are practically no reported studies, with valid scientific experiments, on the irrigation with ETW effects on soil and drainage water characteristics. The current study objective is to investigate the efficiency of EM water treatment to improve TW quality at the farmers' level and to evaluate the effects of irrigation with ETW compared with a control on some soil characteristics (soil moisture, pH, ECe, and chemical components) under different conditions (with and without plants), and changes in the drainage water characteristics (volume, pH, EC, and soluble salts).

2. Materials and methods

2.1. Electromagnetic device

The EM device Aqua–4D® 60E, provided by the Swiss company Aqua–4D Water Solutions, was used for the irrigation water treatment. It consists of two basic modules:

- An electronic box pre-programmed to generate EM waves.

- Treatment units specially designed to transmit the EM waves into the water. Each treatment unit is composed of two separate coils which diffuse the EM waves in the water.

Aqua-4D is a physical water treatment technology based on quantum physics and electrodynamics. It operates at low EM fields of a few tens of milli-teslas at the generator level (voltage of the order of 10 V and intensity of the order of 1 A) and low frequencies between 0 and 10 kHz; two waves of harmonic frequencies are imposed simultaneously [21].

The experiment was carried out using the settings (frequencies and intensities) recommended by the device's manufacturer [17]. The device's characteristics are not revealed (confidential data protected by European Patent EP2364954A1).

2.2. Experimental design and method

The experiment was implemented in February 2016, in the National Research Institute of Rural Engineering, Water and Forests (INRGREF, Ariana, Tunisia). The experiment was conducted in plastic pots (height: 30 cm, diameter: 32 cm) under shelter in the natural conditions, the holes in the bottom of each pot served to the drainage water recovery.

Each pot was filled as follows:

- a gravel layer 3 cm thick covered with a geotextile filter to stabilize the soil and filter the drainage water.
- a layer of reconstituted topsoil 22 cm thick with a mixture of small aggregates, previously sieved to remove any pebbles or non-soil material.

In the pots, the soil was a sandy clay loam (clay = 26%, silt = 44%, and sand = 30%), according to the classifying United States Department of Agriculture texture triangle, rich in calcium carbonate (25%) due to its limestone parent material and was poor in organic matter (ca. 1%). Soil chemical characteristics before the start of the experiment were the following: pH 8.1; ECe 1.1 dS m^{-1}; and soluble cations and anions (meq L^{-1}) were Ca^{2+} 5.0, Mg^{2+} 3.0, K^+ 0.9, Na^+ 6.1, Cl^- 5.6, HCO_3^- 5.0 CO_3^{2-} 0.0, and SO_4^{2-} 4.2. ECe and ions were measured in the soil saturation extract.

The experiment was laid in randomized complete block design comprising four treatments. For each treatment, there were five replicate pots, leading to a total of 20 pots. The experiment was based on the combination of the following:

- *two cultivation status*: uncultivated bare soil (P_0) or soil cultivated with the Tunisian barley (*Hordeum vulgare* L.), local variety "Manel" (P_1). The barley seeds were planted on the soil surface and covered with 1.5 cm of soil on February 18, 2016 at the rate of nine seeds per pot. This crop was chosen because it tolerates the irrigation water salinity,
- *two types of water irrigation*: TW treated electromagnetically by the Aqua-4D device (T_1) or TW non-electromagnetically treated (T_0).

Irrigation water quality: TW were supplied from the Charguia wastewater treatment plant (brought back from the Choutrana storage basin – Regional Commissariat for Agricultural Development of Ariana, Tunisia). The TW origin is globally urban. The purification treatment is biological and activated sludge type (secondary treatment). Before irrigation and before the EM treatment, the TW were analyzed and their characteristics are given in Table 1.

The TW were rich in NaCl. In Tunisia, the TW quality depends on the drinking water quality which is generally outside the norm and rich in salts (1–2 g L^{-1}). EC and pH are among the main factors indicating the irrigation water quality. Temporal variation of the pH, EC of the TW are given in Fig. 1. As seen in Fig. 1, the TW EC presented significant variation from one period to another, due to the variation of the quality of the water available in the storage basin. The salinity varied widely from 2.6 to 9.0 dS m^{-1} (median 3.5). Maybe we came across a peak period. In fact, the TW were recovered during a period of four months and the quality of the water available in the storage basin varied from one sampling to another and we have not been able to provide the water quantity necessary for all irrigations from the start of the cycle (problems of storage and change of chemical and bacteriological water quality). TW can then be divided into four groups depending on the date of collection and on the EC values (Table 2).

Electromagnetic water treatment protocol: the treatment tube was arranged vertically with a valve at the bottom and a funnel at the top. At each irrigation event, TW was allowed to flow through the EM field in the device's treatment unit for about 5 min [17]. Then, the treated water (T_1) was collected and immediately applied to irrigate the pots. The irrigation water chemical properties did not change after EM treatment (data not shown).

Irrigation water management: irrigation was conducted using a measuring cylinder to provide the necessary water quantity. The pots were irrigated 23 times. At each irrigation event, irrigation doses were provided for T_0 and T_1 and the

Table 1
Chemical characteristics of irrigation treated wastewater

	pH	EC (dS m^{-1})	Anions (meq L^{-1})			Cations (meq L^{-1})			
			HCO_3^-	Cl^-	SO_4^{2-}	Na^+	K^+	Ca^{2+}	Mg^{2+}
Mean	8.3	5.3	4.8	36.9	14.3	34.2	1.4	10.1	7.6
Med.	8.3	3.3	3.7	21.1	16.6	20.0	1.5	7.3	9.0
CV (%)	2	49	35	52	45	55	20	40	58

All values were measured over 23 dates from February 23 to May 17, 2016. Med: median; CV: coefficient of variation.

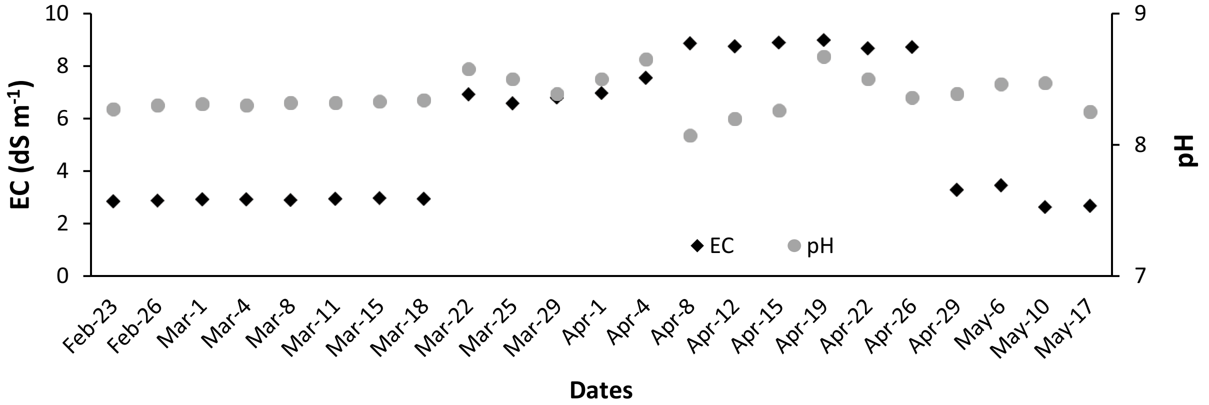

Fig. 1. Temporal variation of the pH and electrical conductivity (EC) of treated wastewater used for irrigation.

Table 2
Classification of the treated wastewater (TWW) used for irrigation according to their electrical conductivities (EC)

	Irrigation water (TWW)			
	Group 1	Group 2	Group 3	Group 4
Dates	23/02–18/03	22/03–04/04	08/04–26/04	29/04–17/05
Number of irrigation	8	5	6	4
EC (dS m^{-1})	2.92 ± 0.03	6.97 ± 0.33	8.82 ± 0.11	3.01 ± 0.36

All EC values are the mean ± standard deviation.

water supplies have been adjusted according to the climatic conditions. During the first period of the irrigation cycle, from February 23 to April 15, the same dose of water was brought in for the different treatments. From April 19 and following the rise in temperature, the irrigation dose for P_1 was increased, so that the drainage water quantity is sufficient for the different analyzes. After application on 23 dates, cumulative irrigation doses (per pot) were approximately: D_1 = 340 mm, for P_0T_0 and P_0T_1; D_2 = 373 mm, for P_1T_0 and P_1T_1 which correspond to a total volume $V_1 = 27 \times 10^{-3}$ m^3 for P_0T_0 and $V_2 = 30 \times 10^{-3}$ m^3 for P_0T_1. In terms of water management, irrigation was stopped on May 17: about 10 d before plant harvesting and soil sampling.

2.3. Sampling and analyses

Soil samples were taken after the plant harvesting, in plastic bags, one mix samples per pot. Soil samples were air-dried, gently crushed with a porcelain mortar, passed through a 2 mm sieve, and then stored in plastic containers at room temperature in the dark.

An aqueous solution was extracted from the soil saturated paste (standard method, USDA 1954) to determine ECe and dissolved elements. ECe was determined directly in the soil saturation extract using a conductivity-meter, water quality meter pen type (model 8361, Cond & TDS). Calcium (Ca^{2+}) and magnesium (Mg^{2+}) were measured by using complexometry in the presence of ethylenediamine tetraacetic acid (EDTA). Sodium (Na^+) and potassium (K^+) were determined with a flame photometer type JENWAY PFP7 (NF-A20-603). Bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) were measured by using titration with sulfuric acid (H_2SO_4) in the presence of methyl orange and phenolphthalein. Chloride (Cl^-) was measured by using precipitation titration in the presence of silver nitrate ($AgNO_3$). Sulfate (SO_4^{2-}) was determined by nephelometry in the presence of 0.1 N hydrochloric acid and the dosage was carried out by the spectrometer, type UV-VIS, at 650 nm. pH was determined from a soil/water mixture (1/2.5). The measurement was made on the filtrate by the electro-metric method using a direct reading pH meter (NF ISO 10390 2005). The soil moisture was measured by the gravimetric method. This method consists of drying (at 105°C) a soil sample to constant weight and measuring the soil sample mass after and before drying, the difference between the two masses is the weight of water contained per soil sample.

At each irrigation, water samples were taken from both irrigation and drainage water (1 sample of the drainage water from each pot = 20 samples), and for 23 dates. Water samples were taken in Pyrex glass bottles, previously sterilized. The pH and EC measurements were made directly on the water samples using the same pH-meter and conductivity-meter described above. The determination of the soluble salts contained in the water samples was carried out according to the same principles mentioned for the saturated soil solutions.

2.4. Statistical analysis

Data were statistically analyzed by using an analysis of variance (ANOVA) and the Tukey test at the 5%

significance level. Data were analyzed using XLStat software v. 2014.5.03 (Addinsoft).

Statistical analyses included calculation of basic descriptive statistics average, minimum, maximum, standard deviation, and coefficient of variation (CV). The interpretation of CV was based on the following limits: CV < 10%: low variability. 10% < CV < 20%: average variability. CV > 20%: high variability.

Data from the P_0 treatment (uncropped soil) and data from the P_1 treatment (cropped soil) were analyzed separately.

3. Results and discussion

3.1. Effect on soil characteristics

3.1.1. Effect on soil moisture

Average soil moisture values were around 13.3%, 16.4%, 19.6%, and 23.5% for P_0T_0, P_0T_1, P_1T_0, and P_1T_1, respectively. As shown in Fig. 2, the soil moisture was higher when irrigated with ETW compared to untreated water (T_0). This increase was around 3.1 and 3.9 percentage points (arithmetic difference of two percentages which represents the soil moisture) for P_0 and P_1, respectively. The ETW effect on increasing soil moisture was significant for P_0 and P_1. Note that the cultivated soil was wetter because the applicated irrigation dose (D_2) was higher compared to the dose (D_1) applicated to the uncultivated soil. Results confirm that ETW led to an increase in the soil moisture: the water penetrates better into the micropores, meaning soils stay moist for longer, thus reducing irrigation frequency and saving water. This technology is used to improve soil moisture conditions for better plant growth as well as to prevent water stress.

Our results can be explained by the fact that the soil irrigated with untreated water (T_0) reached its permanent wilting point before that irrigated with ETW and that the field capacity was greater in the case where the soil was irrigated with ETW (data not shown), hence a better soil moisture. The following results are consistent with our present study. According to Surendran et al. [22], irrigation with MTW (saline and hard water) caused higher soil moisture compared to the control. Similarly, Zlotopolski [23] showed that the soil columns retained 25% more water after irrigation with MTW, probably due to the decrease in the water surface tension. It was also shown that the soil irrigated with MTW was wetter than the control soil irrigated with the same water amount but not magnetically treated [24]. When water is exposed to an EM field, its solubility increases, and its surface tension decreases [19]. These effects increase soil wettability properties. Magnetic water treatment increases water absorption in soil. Hilal and Hilal [25] observed that irrigation with MTW tripled soil water retention and reduced soil compaction. In addition, they added that the MTW loss by evaporation was lower. Gabrielli et al. [26] also found that aragonite formation, after water magnetization, increases soil osmotic pressure decreasing evaporation. In several studies, this increase in soil moisture may be due to the decrease in surface tension and viscosity of water after exposure to EM fields [27]. The increase in soil moisture after irrigation with ETW may be due to greater movement of soil water, hence the increase in soil saturated hydraulic conductivity and soil water infiltration as mentioned by Al-Mosawi et al. [12], or by improving the soil macroporosity as shown by Moussa et al. [17]. This soil moisture increase has been explained differently: during the magnetization the water molecules which have been influenced by the hydrogen bonds and the Van der Waals forces and were in reaction with the ions are released, making the water more cohesive. Therefore, the water molecules easily attach to the soil particles, penetrate into the soil micropores, and do not move to the lower soil depths [16,28].

3.1.2. Effect on soil pH

ETW effect on soil pH is shown in Table 3. The results indicated that both before and after the irrigation cycle, the soil pH remains basic with a slight decrease (non-significant variation) compared to the initial soil pH (8.1). The slight decrease in soil pH has been observed in some other basic soils irrigated with saline TW and has been reported by

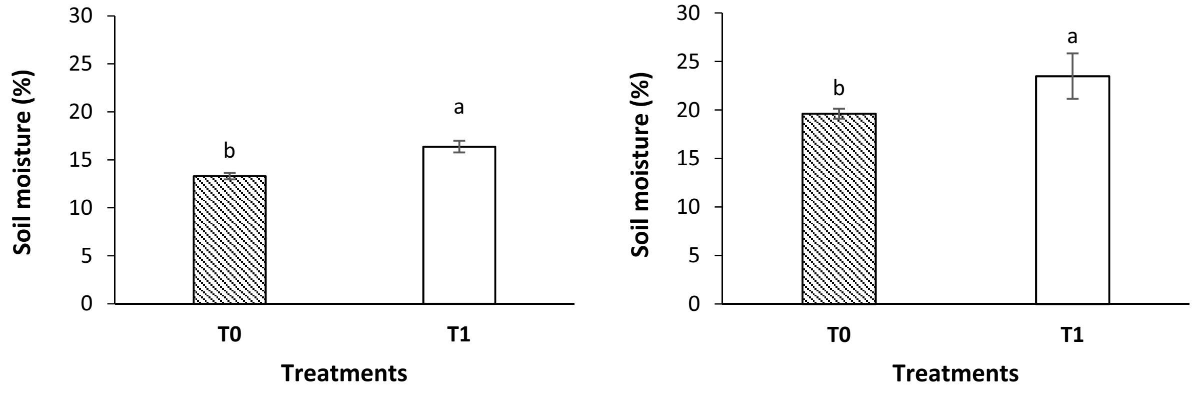

Fig. 2. Variation of the soil moisture (%) according the irrigation water treatment (T_0: untreated irrigation water, T_1: electromagnetically treated irrigation water). All values are the mean of five replications (n = 5). Bars with the same letter do not differ significantly according to the Tukey test (p < 0.05). Error bars are ± standard deviation. (a) uncultivated soil (P_0), (b) cultivated soil (P_1).

several authors [29]. This was explained by leaching with irrigation water of active calcareous which are responsible for the soil alkalinity [30].

At the end of the experiment, the soil pH analysis results showed an alkaline character and the pH values were slightly affected by irrigation with ETW (Table 3). There was a slight significant decrease of 0.3 units in the average soil pH using ETW compared with untreated water, for both uncropped and cropped soils. Zlotopolski [23] reported that the decrease in alkalinity is one of the main observed MTW effects in the soil. These findings concur with those of Fanous et al. [13], Abedinpour and Rohani [31], and Maheshwari and Grewal [32]. The decrease in soil pH has a positive impact on plant growth and productivity [33]. However, Maheshwari and Grewal [32] hypothesized that soil acidification may be relatively greater due to the release of more important organic acids into the rhizosphere by plants irrigated with MTW compared to plants irrigated with untreated water. This hypothesis may be valid in our cultivated soils.

3.1.3. Effect on soil electrical conductivity

A summary of the soil ECe results at the end of the experiment is illustrated in Fig. 3. ECe measurements of saturated soil extracts have shown that irrigation with TW caused an increase in the soil ECe values compared to the initial soil. ECe values raised from 1.1 dS m^{-1} before irrigation to 6.0–10.0 dS m^{-1} after irrigation (Fig. 3). This increase was significant for all treatments. This is related to the high salinity of the TW used for irrigation. The results showed that the soils were affected by the salinization phenomenon and this was explained by the high EC of irrigation TW [34]. In arid irrigated areas, irrigation practices mobilize naturally occurring salt in the soil and concentrate those salts already present in the supply water. The use of saline irrigation water is a main factor in soil salinization.

The results also showed that the ETW use significantly influenced the soil salinity. The salinity of the soil irrigated with ETW was clearly lower than the salinity of the soil irrigated with untreated water. It's noticed that using ETW, the soil ECe value decreased from 8.9 to 6.0 dS m^{-1} for P_0 and from 10.1 to 7.5 dS m^{-1} for P_1. Thanks to the ETW use, we note a significant decrease in soil salinity of around 33% and 26% for P_0 and P_1, respectively. Our results agree with those of Ahmed and Abd El-Kader [35] who stated that the mean ECe values of soil irrigated with MTW were less than those of non-MTW. In this context, Mohamed [33] reported that the ECe of sandy soil decreased after irrigation with magnetic saline water and concluded that the magnetic treatment of irrigation water reduces the risk of soil salinization. According to Zlotopolski [23], MTW changes the distribution of salts between the soil layers by reducing their contents in the upper layers which are more important for agriculture. Amer et al. [36] stated that irrigation with freshwater, saline water, and highly saline water magnetically treated had a positive effect on the decrease in soil ECe after plant harvesting compared to the soil irrigated with untreated water and that the changes were decreased with increasing depth. Moreover, Hamza [37] and Gudigar and Hebbara [38] studies have shown that soil samples leached with MTW had lower salinity compared with those leached with non-MTW. Their results were explained by the elimination of more salts using MTW compared with non-MTW.

The previous results reveal that irrigation with MTW can be considered as one of the most valuable modern technologies that can be able to reduce salt accumulation to improve soil conditions around plant roots [13] and to limit the harmful effects of irrigation with saline water. But there is still no consensus because the literature reveals also very different, even opposite, results. On the one hand, Maheshwari and Grewal [32] reported that irrigation with MTW increased significantly soil salinity. Abedinpour and Rohani [31] showed that the magnetic treatment of all used water types led to no significant difference on the soil ECe values.

3.1.4. Effect on soil chemical contents

Concentration of available cations Na^+, K^+, Ca^{2+}, and Mg^{2+}, as well as anions HCO_3^-, Cl^-, and SO_4^{2-} in the soil, at the end of the experiment, are summarized in Table 3. Results showed that the decrease in the soil ECe using ETW was accompanied by a variation in the soil chemical contents. Compared to the control (before irrigation started), the ions concentrations in the soil solution has increased considerably. As seen in Table 3, for the cations, the dominance of sodium was clear: $Na^+ > Ca^{2+} > Mg^{2+} >> K^+$. Regarding anions,

Table 3
Variation of the chemical characteristics of (a) uncultivated soils and (b) cultivated soils according to the treatment of irrigation water (T_0: untreated irrigation water, T_1: electromagnetically treated irrigation water)

	pH	HCO_3^-	Cl^-	SO_4^{2-}	Na^+	K^+	Ca^{2+}	Mg^{2+}
				(a)				
T_0	8.1 ± 0.1*a*	4.5 ± 0.3*a*	56.6 ± 6.6*a*	28.6 ± 7.1*a*	44.0 ± 11.1*a*	1.5 ± 0.2*b*	26.9 ± 2.2*a*	17.8 ± 4.0*a*
T_1	7.8 ± 0.1*b*	4.3 ± 0.5*a*	42.5 ± 8.9*b*	14.0 ± 3.1*b*	32.9 ± 7.7*b*	2.3 ± 0.3*a*	18.5 ± 2.5*b*	11.7 ± 0.5*b*
				(b)				
T_0	8.0 ± 0.2*a*	4.7 ± 0.4*a*	68.2 ± 5.5*a*	29.5 ± 4.0*a*	49.9 ± 2.5*a*	1.5 ± 0.3*b*	32.4 ± 7.1*a*	18.3 ± 1.2*a*
T_1	7.7 ± 0.1*b*	4.6 ± 0.7*a*	54.2 ± 7.5*b*	15.9 ± 4.1*b*	38.5 ± 4.0*b*	2.3 ± 0.2*a*	20.8 ± 1.9*b*	12.7 ± 2.1*b*

Ions in meq L^{-1}. All values are the mean ± standard deviation of five replications ($n = 5$). The different letters are significantly different according to the Tukey test ($p < 0.05$).

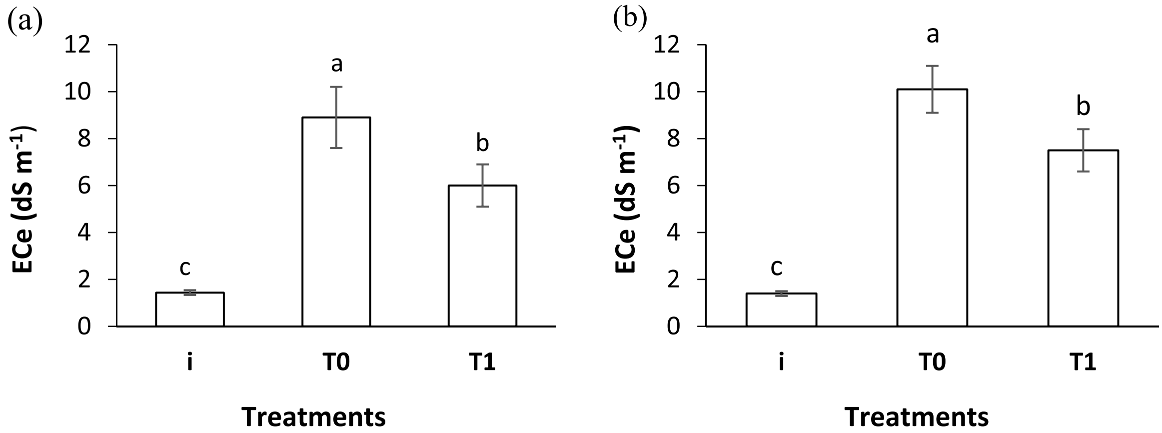

Fig. 3. Variation of the soil electrical conductivity (ECe) according to the irrigation water treatment (T_0: untreated irrigation water, T_1: electromagnetically treated irrigation water). All values are the mean of five replications ($n = 5$). Bars with the same letter do not differ significantly according to the Tukey test ($p < 0.05$). Error bars are ± standard deviation. (a) uncultivated soil (P_0), (b) cultivated soil (P_1), *i*: initial soil EC.

chlorides dominance has been noted: $Cl^- >> SO_4^{2-} >> HCO_3^-$. By comparing T_0 and T_1 treatments, the results showed that the Na^+, Cl^-, Ca^{2+}, Mg^{2+}, and SO_4^{2-} contents accumulation in soil irrigated with ETW has significantly decreased compared to the soil irrigated with untreated water. The Na^+, Cl^-, Ca^{2+}, Mg^{2+}, and SO_4^{2-} concentrations decreased by 25%, 25%, 31%, 34%, and 51%, respectively for P_0 and by 23%, 20%, 36%, 30%, and 46%, respectively for P_1. Hence, the ETW use has improved soil quality by reducing the concentrations of excess undesirable salts in the soil. Moreover, ETW had no significant effect on HCO_3^- soil content, while its concentration decreased (Table 3). In fact, higher soil moisture increases the soil salts leaching, reducing their concentrations in the soil. The results (Table 3) showed also an increase in the soil available K^+ using ETW, increasing its availability to plants. High contents of soluble salts accumulated in the soil can decrease the soil productivity and cause a slowdown and inhibition of several plant species growth. Irrigation with electromagnetically treated water allowed a reduction in the concentration of undesirable salts in the soil which has a positive impact on agriculture.

Excess salts removal or decreasing their activity is necessary for increasing the productivity of salt-affected soils [36]. Amer et al. [36] added that after plant harvesting, Mg^{2+}, Na^+, Cl^-, and SO_4^{2-} contents in soil extraction decreased while Ca^{2+} and K^+ contents in the soil extraction increased due to MTW. In this respect, Hachicha et al. [18] showed that significantly less Na^+ and Cl^- were found in soil irrigated with treated saline water. They also found that the concentrations of SO_4^{2-}, Mg^{2+}, Ca^{2+}, and HCO_3^- contents decreased using electromagnetically treated saline water. Furthermore, it was proven that irrigation with MTW had a significant effect on the Cl^-, Na^+, and SO_4^{2-} contents decrease in the soil, compared to control [23]. Zlotopolski [23] added that these ions are undesirable in the soil since they have very strong negative impacts on plant growth and yield. In the same study, the authors showed that Ca^{2+} and Mg^{2+} contents did not change using MTW. Similarly, a comparison of concentrations of different ions of two soils, one irrigated with MTW and another irrigated with non-MTW, showed that Na^+ concentrations were 12.1% and 22.5% higher after using untreated saline water at soil depths of 0–25 and 25–50 cm, respectively [39]. Mostafazadeh-Fard et al. [40] showed that MTW use, under trickle irrigation, has good potential to reduce soil cations and anions, in order to recover the soils affected by the salt. They observed that the average of sodium, magnesium, bicarbonate, chloride, and sulfate ions in the soil irrigated with MTW decreased significantly up to 33.6%, 33.6%, 32.8%, 32.5%, and 37.3%, respectively, compared with the soil irrigated with non-MTW. Their results were explained by the higher soil water content following irrigation with MTW. According to Mohamed and Ebead [20], using different MTW sources, soil soluble Cl^-, HCO_3^-, Mg^{2+}, and Ca^{2+} were significantly increased. On the contrary, soil soluble Na^+ and SO_4^{2-} were decreased using MTW. Moreover, our results are consistent with those of Mohamed and Ebead [20] and Hilal et al. [10] who observed a significant increase of the K^+ concentration in soil water extract after leaching with different MTW compared with different untreated water at all studied soil depths.

3.2. Effect on drainage water characteristics

3.2.1. Effect on drainage water volume

Temporal variation of drainage water volume, according to the irrigation water treatment (T_0 and T_1) and the cultivation status (P_0 and P_1), are shown in Fig. 4. Results presented in the previous figure showed that the difference between the drainage water volumes from soil irrigated with ETW and those drained from soil irrigated with untreated water, was clear. The cumulative volumes of drainage water, for P_0T_0, P_0T_1, P_1T_0, and P_1T_1 treatments, are presented in Fig. 5. It was observed that the volumes of drainage water from soil irrigated with ETW were higher than those from soil irrigated with untreated water, for P_0 and P_1. The results showed that this increase in the drainage water volume became clearer over time: when the irrigation number was increased.

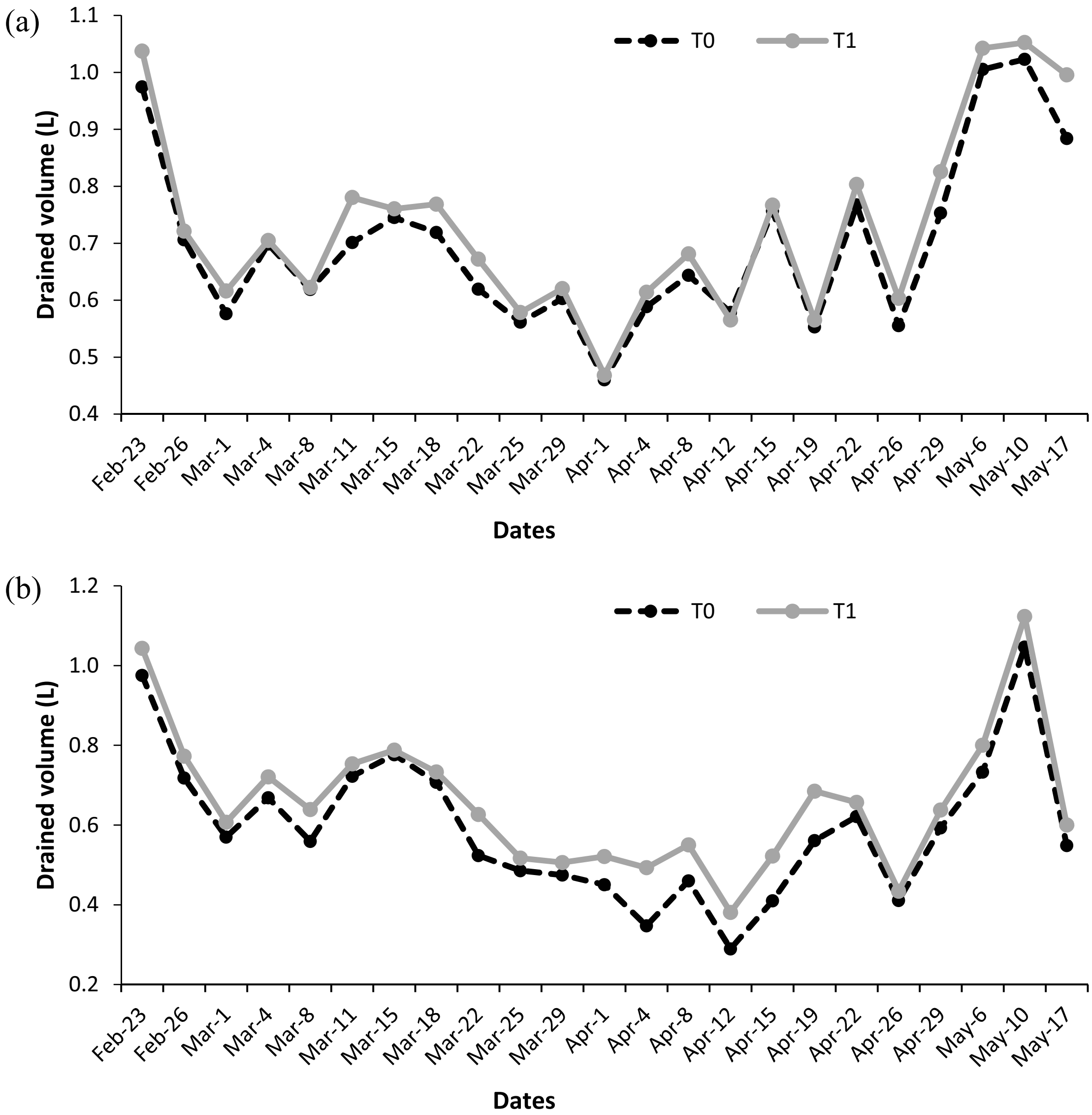

Fig. 4. Temporal variation of drained volume from the soil according to the irrigation water treatment (T_0: untreated irrigation water, T_1: electromagnetically treated irrigation water). All values are the mean of five replications (n = 5). 1 L = 10^{-3} m^3. (a) uncultivated soil (P_0), (b) cultivated soil (P_1).

For example, the difference between drainage water volumes, after irrigation with T_0 and T_1, was visible after 10 irrigations for the cultivated soil (Fig. 5b). This experiment was conducted taking into account the cumulative effect of EM treatment. In other words, the more the irrigation number increases, the more the effect manifests.

Moreover, drainage water volumes from P_1 were lower than those from P_0 although the irrigation dose of P_1 was higher than that of P_0. This was explained by the barley water requirement. For the uncultivated soil, the total irrigation dose per pot was equal to 27.1 × 10^{-3} m^3, the average volumes of drainage water were around 16.1 × 10^{-3} m^3 and 16.9 × 10^{-3} m^3 for the T_0 and T_1 treatments, respectively. For the cultivated soil, the total irrigation dose per pot was equal to 29.8 × 10^{-3} m^3, the average volumes of drainage water were around 13.7 × 10^{-3} m^3 and 15.1 × 10^{-3} m^3 for the T_0 and T_1 treatments, respectively. After 23 irrigations, we noted that 62% and 51% of the irrigation water were drained using ETW and only 59% and 46% for the untreated water for P_0 and P_1, respectively. The increase in the drainage water volume was significant for P_0 and P_1. The improvement in soil macroporosity reported by Moussa et al. [17] can explain the better water drainage in our case. Drainage is particularly important in semi-arid and arid areas to prevent secondary salinization.

3.2.2. *Effect on drainage water electrical conductivity*

Temporal variation of drainage water EC from the soil (P_0 and P_1) according to the irrigation water treatment (T_0 and T_1) are presented in Fig. 6. The results showed that the EC values varied from 2.5 to 9.5 dS m^{-1}, 2.7 and 11.2 dS m^{-1},

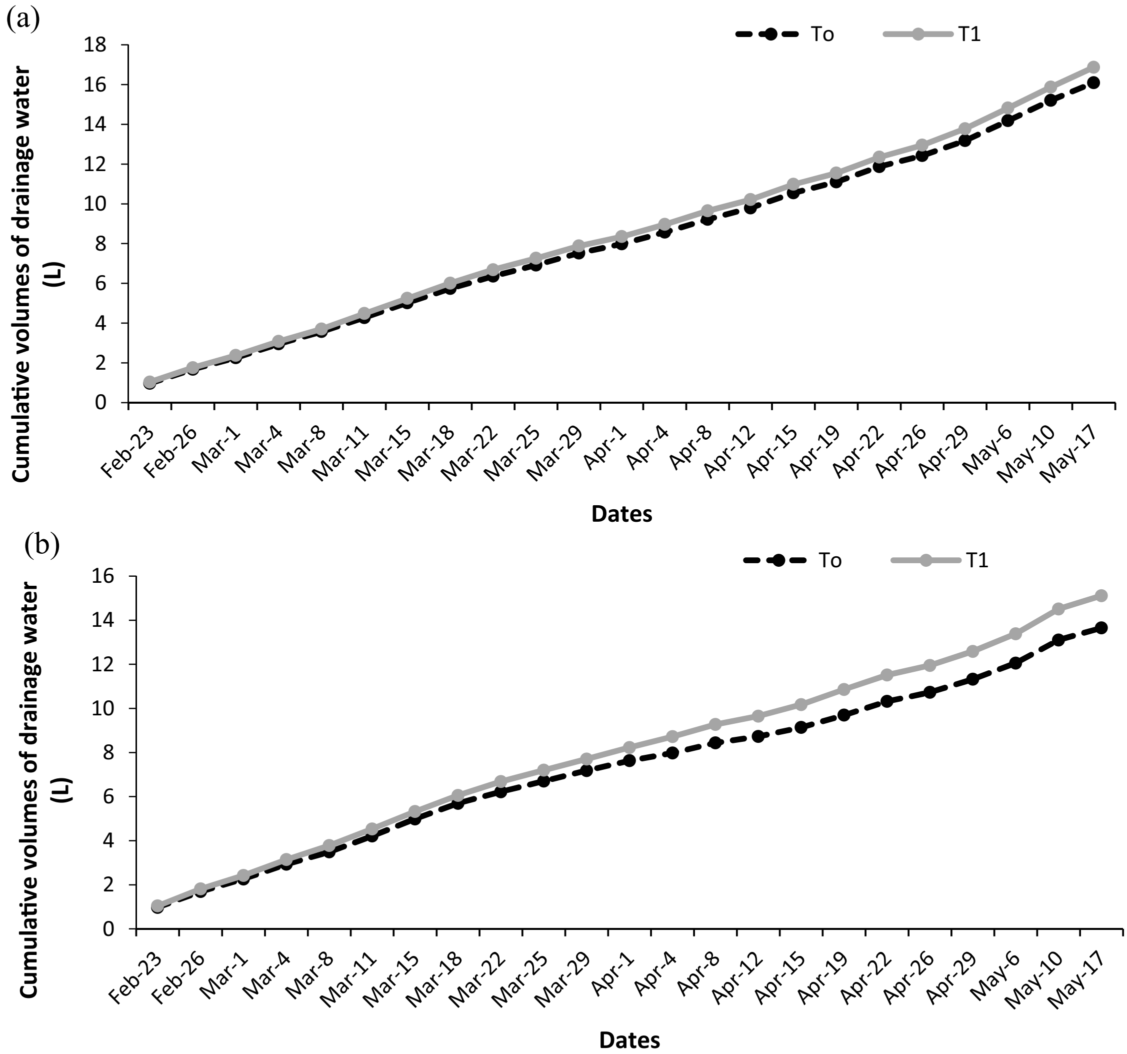

Fig. 5. Cumulative volumes of drainage water from the soil according to the irrigation water treatment (T_0: untreated irrigation water, T_1: electromagnetically treated irrigation water). All values are the mean of five replications (n = 5). 1 L = 10^{-3} m^3. (a) uncultivated soil (P_0), (b) cultivated soil (P_1).

2.5 and 13.5 dS m^{-1}, and 2.6 and 15.1 dS m^{-1} for P_0T_0, P_0T_1, P_1T_0, and P_1T_1, respectively. It was noted that during the first eight irrigations the two curves were almost superimposed (Fig. 6) which means that there was no difference between the drainage water EC after irrigation with T_0 and T_1 for P_0 and P_1. From the ninth irrigation (March 22), the EC values increased for all treatments. At the 20th irrigation (April 26), the EC values of P_0T_1 and P_1T_1 reached a constant level, but those of P_0T_0 and P_1T_0 decreased. After 23 irrigations, the mean EC values of the drainage water were of the order of 5.7, 6.8, 6.9, and 7.9 dS m^{-1} for P_0T_0, P_0T_1, P_1T_0, and P_1T_1, respectively. The corresponding CVs were 44%, 46%, 54%, and 59% for P_0T_0, P_0T_1, P_1T_0, and P_1T_1, respectively. The variability of the drainage water EC coefficients of variation was high since the TW quality used for irrigation varies from one irrigation to another. So, we thought it unnecessary to calculate the averages and conclude over the entire period at once. Therefore, we proceeded to make a descriptive analysis of the results obtained for each parameter, each time that the irrigation water quality changed. Drainage water were then classified into four groups according to the variation of the irrigation water EC presented below. The obtained results (Table 4) showed that regardless of the TW EC value, the drainage water EC varied by the same trend: CE increased for P_0T_1 and P_1T_1 compared to P_0T_0 and P_1T_0. Drainage water EC was significantly influenced by ETW, especially by increasing the irrigation number. Irrigation with ETW caused a significant increase in drainage water EC values compared to untreated water, indicating more salts removal from the saline soil. In fact, the soil irrigated with ETW had improved its salinity, in which the salts were leached by the drainage water. Similar results were reported in literature. Zlotopolski [23] showed that the salt content at a depth of 90 cm in a soil column irrigated with MTW was 1.2 times higher than that of the control. That is, the salts have accumulated in the soil lowest depths. This can explain the high drainage water EC in our case. In our study, the soil layer in the pots did not

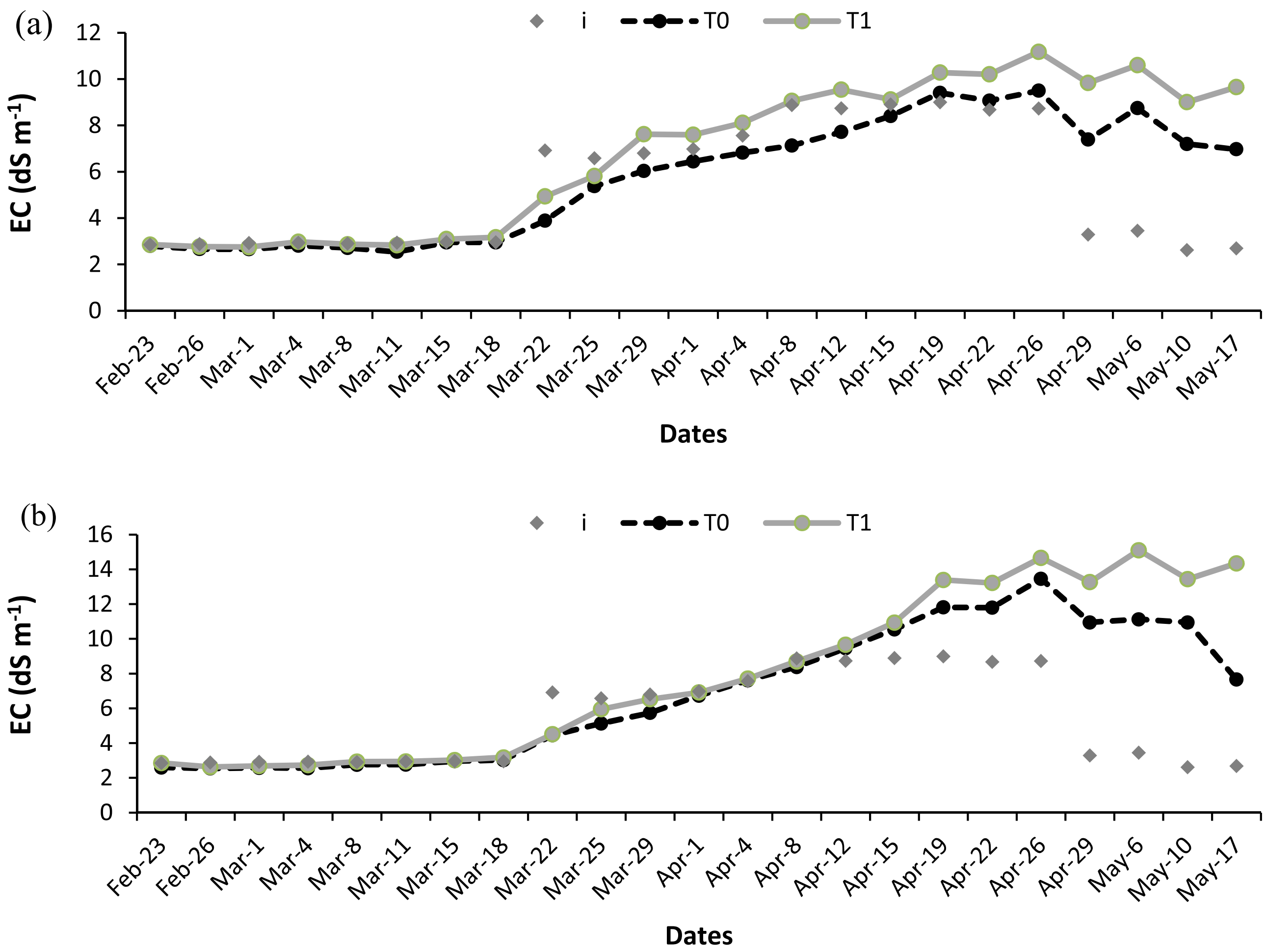

Fig. 6. Temporal variation of drainage water EC according to the irrigation water treatment (T_0: untreated irrigation water, T_1: electromagnetically treated irrigation water). (a) uncultivated soil (P_0), (b) cultivated soil (P_1), *i*: irrigation water EC.

exceed 22 cm; therefore, the salts were evacuated by the drainage water. According to Gudigar and Hebbara [38], the MTW use increase the leachates salinity compared to untreated water. Same findings were reported by Hilal et al. [10], who found that the soil leaching has been improved using MTW and that the total salt removal from the soil after six leachates was significantly increased with MTW compared with non-MTW. Raheem and Azzubaidi [41] reported that EC is a general indicator for all anions and cations being leached and that EC values of the drainage water were increased by increasing the magnetic intensity.

3.2.3. Effect on drainage water pH

The results presented in Table 4 showed that the drainage water pH, from both uncultivated and cultivated soils, slightly varied following the ETW use. pH values slightly decreased under T_1 treatment. In fact, ETW had no significant effect on the drainage water pH from both uncultivated and cultivated soils. The ETW effect on the drainage water pH variation was negligible for P_0 and P_1. Similarly, Raheem and Azzubaidi [41] found that the drainage water pH were slightly affected by MTW and that the maximum increase in pH values was 8.7%.

3.2.4. Effect on drainage water soluble salts

Data concerning the effect of irrigation with ETW and untreated water on the dissolved concentration of each chemical component in the drainage water are summarized in Table 4. During the experiment, the drainage water quality was very variable due to the variability in the irrigation water quality and the different studied treatments. Therefore, similarly the obtained results were analyzed according to the irrigation water quality. The soluble salts chemical analysis showed that the drainage waters were dominated by sodium and chloride. These are common non-toxic elements that only become problematic when concentrated in the soil. Results showed that the drainage water soluble salts (Table 4) were higher than that of the irrigation water (Table 1). According to FAO [42], subsurface drainage water from arid areas always has a higher salinity than the supply water, a higher proportion of Na^+ and Cl^-, an increased hardness, and a higher sodium adsorption ratio. The concentrations of Cl^-, SO_4^{2-}, K^+, Na^+, Mg^{2+}, and Ca^{2+}

Table 4
Variation of the chemical characteristics of drainage water according to the irrigation water quality which varies depending on the date. EC in dS m^{-1} and ions in meq L^{-1}

		pH	EC	Cl^-	HCO_3^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+	Na^+
					(a)					
23/02–18/03	T_0	8.2 ± 0.08*a*	2.8 ± 0.1*b*	19.0 ± 0.8*b*	4.2 ± 1.5*a*	7.8 ± 0.7*b*	6.1 ± 0.6*b*	5.0 ± 0.5*b*	1.3 ± 0.02*b*	15.8 ± 0.7*b*
(*n* = 8)	T_1	8.2 ± 0.23*a*	2.9 ± 0.1*a*	21.4 ± 0.9*a*	5.0 ± 1.7*a*	9.9 ± 0.8*a*	7.5 ± 0.5*a*	6.1 ± 0.4*a*	1.4 ± 0.05*a*	17.3 ± 0.6*a*
22/03–04/04	T_0	8.2 ± 0.10*a*	5.7 ± 0.5*b*	37.6 ± 2.5*b*	4.4 ± 0.4*a*	13.5 ± 1.7*b*	16.6 ± 1.2*b*	10.8 ± 2.7*b*	1.6 ± 0.03*b*	24.6 ± 2.1*b*
(*n* = 5)	T_1	7.9 ± 0.05*b*	6.8 ± 0.3*a*	47.7 ± 3.5*a*	5.6 ± 0.6*a*	16.3 ± 1.3*a*	21.8 ± 2.0*a*	17.7 ± 2.4*a*	1.8 ± 0.04*a*	30.1 ± 1.6*a*
08/04–26/04	T_0	8.3 ± 0.11*a*	8.5 ± 0.3*b*	64.6 ± 2.7*b*	1.9 ± 1.1*a*	19.7 ± 1.0*b*	27.1 ± 2.1*b*	10.3 ± 0.4*b*	1.8 ± 0.1*b*	49.5 ± 2.9*b*
(*n* = 6)	T_1	8.2 ± 0.06*b*	9.9 ± 0.3*a*	74.0 ± 3.0*a*	3.5 ± 1.1*a*	25.4 ± 2.3*a*	32.7 ± 1.6*a*	12.6 ± 0.7*a*	2.2 ± 0.1*a*	57.0 ± 3.2*a*
29/04–17/05	T_0	8.3 ± 0.14*a*	7.6 ± 0.7*b*	55.5 ± 2.9*b*	1.9 ± 0.2*a*	19.1 ± 3.6*b*	26.8 ± 1.3*b*	9.8 ± 1.0*b*	2.0 ± 0.2*b*	40.0 ± 2.0*b*
(*n* = 4)	T_1	8.3 ± 0.07*a*	9.8 ± 0.6*a*	71.7 ± 3.7*a*	2.5 ± 0.2*a*	30.0 ± 4.4*a*	33.3 ± 2.0*a*	12.3 ± 0.8*a*	2.4 ± 0.1*a*	55.5 ± 3.8*a*
					(b)					
23/02–18/03	T_0	8.3 ± 0.16*a*	2.7 ± 0.1*b*	18.8 ± 0.7*b*	4.1 ± 0.9*a*	7.9 ± 0.6*b*	6.3 ± 0.3*b*	5.3 ± 0.4*b*	1.1 ± 0.1*a*	16.1 ± 0.6*b*
(*n* = 8)	T_1	8.2 ± 0.29*a*	2.9 ± 0.1*a*	21.0 ± 0.9 *a*	5.2 ± 1.0*a*	9.4 ± 0.7*a*	7.3 ± 0.5*a*	6.4 ± 0.5*a*	1.2 ± 0.1*a*	17.5 ± 0.6*a*
22/03–04/04	T_0	8.0 ± 0.10*a*	5.9 ± 0.2*a*	43.6 ± 1.3*b*	4.6 ± 0.4*a*	12.3 ± 0.8*b*	20.6 ± 0.9*b*	10.2 ± 0.5*b*	1.6 ± 0.1*b*	26.6 ± 1.5*b*
(*n* = 5)	T_1	7.9 ± 0.04*a*	6.3 ± 0.4*a*	47.8 ± 1.8*a*	5.6 ± 0.6*a*	15.3 ± 1.0*a*	23.7 ± 1.8*a*	11.8 ± 0.6*a*	1.9 ± 0.1*a*	30.4 ± 1.1*a*
08/04–26/04	T_0	8.3 ± 0.15*a*	10.9 ± 0.3*b*	82.5 ± 2.5*b*	3.4 ± 1.2*a*	24.1 ± 1.5*b*	33.3 ± 1.5*b*	10.6 ± 1.2*b*	1.9 ± 0.1*b*	66.2 ± 1.9*b*
(*n* = 6)	T_1	8.3 ± 0.09*a*	11.8 ± 0.5*a*	91.4 ± 3.9*a*	3.9 ± 1.3*a*	29.2 ± 1.4*a*	37.1 ± 1.9*a*	13.3 ± 0.9*a*	2.3 ± 0.2*a*	72.0 ± 1.2*a*
29/04–17/05	T_0	8.3 ± 0.09*a*	10.2 ± 1.1*b*	76.3 ± 3.9*b*	2.3 ± 0.9*a*	25.5 ± 2.9*b*	35.6 ± 3.3*b*	9.6 ± 1.7*b*	1.9 ± 0.2*b*	57.0 ± 2.8*b*
(*n* = 4)	T_1	8.2 ± 0.07*b*	14.0 ± 0.7*a*	110.1 ± 5.1*a*	3.1 ± 0.2*a*	34.1 ± 1.3*a*	46.6 ± 2.8*a*	15.4 ± 1.2*a*	2.3 ± 0.1*a*	82.1 ± 3.3*a*

All values are the mean ± standard deviation. The different letters are significantly different according to the Tukey test ($p < 0.05$). Statistical analysis was done according to T_0 and T_1 water on each group independently of the others. T_0: untreated irrigation water, T_1: electromagnetically treated irrigation water, (a) uncultivated soil (P_0), (b) cultivated soil (P_1), EC: electrical conductivity.

were significantly higher for P_0T_1 and P_1T_1 compared to P_0T_0 and P_1T_0. In the other hand, the HCO_3^- concentrations were higher but not significantly for P_0T_1 and P_1T_1 compared to P_0T_0 and P_1T_0. It was found that salts were more evacuated by the waters drained from the irrigated soils with ETW which explains the decrease in the ECe mentioned above. Our results showed that the ETW efficiency in removing salts from the soil was more than the untreated water. In this study, using ETW, harmful ions were deeply leached and discharged below the root zone. This difference between the soluble salt contents using ETW was clearest at the end of the irrigation cycle. The soil chemical contents removal by drainage with ETW plays an important role in projects of improvement and reclamation of salt-affected soils. Under Aqua-4D physical water treatment effect, the excess soluble salts are more entrained in dissolved form under the rhizosphere showing (i) a better salts leaching, (ii) improved soil structure, and (iii) higher decrease of soil salinity and toxicity. These observations were confirmed by other studies. For example, El-Fakhrani et al. [43] reported an increase in the drainage water soluble salts concentrations following irrigation with MTW. Hilal et al. [10] indicated that irrigation with MTW resulted in significant increase in soluble K and P concentrations in water leachates as compared with untreated water. Also, Hilal and Hilal [44] reported that MTW not only increased the leaching of excess soluble salts but also dissolved slightly soluble salts such as carbonates, phosphates, and sulfates in the soil. Increased leaching of excess soluble salts such as calcium, sodium, and bicarbonate has been reported by other researchers [40].

4. Conclusions

Agricultural use of unconventional water like treated wastewater with advanced physical treatment methods such as EM treatment can overcome water scarcity problems.

In order to study the physico-chemical characteristics variation of the soil and drainage water under the effect of irrigation with ETW and non-ETW, a set of measurements and analysis were carried out on samples taken from experimental pots subjected at different treatments. Data were studied as a function of cultivation status (cultivated vs. bare soil) and irrigation water treatment (electromagnetically treated or not).

Results showed that several positive effects occur in both of uncultivated and cultivated soils irrigated with ETW such as a decrease of its pH, ECe and Na^+, Cl^-, Ca^{2+}, Mg^{+2}, and SO_4^{2-} contents. The soil was less affected by salinity after irrigation with ETW. It was found that the ETW use caused a significant increase in drainage water EC and ions contents compared to those observed after irrigation with untreated TW. It is a salts redistribution rather than desalination. The results also showed that using ETW, the drainage water volumes were greater than those measured using non-ETW. A high soil drainage is recommended to prevent soil waterlogging and salinization induced by irrigation in arid and semi-arid regions.

This experiment suggests that irrigation with ETW can be recommended for agricultural practices. It can be used to reduce the soil salinization problem and to allow irrigation with slightly saline water. This work proposes a new method for a healthy use of TW in the agricultural sector. To deal with water scarcity problems and the limited supplies of high-quality irrigation water around the world, especially in arid areas, the EM water treatment of Aqua-4D technology can allow to irrigate with a poor-quality water. Therefore, higher quality water can be preserved for essential human consumption. Finally, farmers should be made aware of the magnetic water treatment technique use, which can help to save irrigation water and reduce salts accumulation in the soil.

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Abbreviations

ETW	—	Electromagnetically treated treated wastewater
FAO	—	Food and Agriculture Organization
MTW	—	Magnetically treated water
T_0	—	Untreated irrigation water
T_1	—	Electromagnetically treated irrigation water
TW	—	Treated wastewater
P_0	—	Uncultivated soil
P_1	—	Cultivated soil

References

[1] J. Bogatin, N.P. Bondarenko, E.Z. Gak, E.E. Rokhinson, I.P. Ananyev, Magnetic treatment of irrigation water: experimental results and application conditions, Environ. Sci. Technol., 33 (1999) 1280–1285.

[2] A. Yadollahpour, S. Rashidi, Z. Ghotbeddin, M. Jalilifar, Z. Rezaee, Electromagnetic fields for the treatments of wastewater: a review of applications and future opportunities, J. Pure Appl. Microbiol., 8 (2014) 3711–3719.

[3] N.S. Zaidi, J. Sohaili, K. Muda, M. Sillanpää, Magnetic field application and its potential in water and wastewater treatment systems, Sep. Purif. Rev., 43 (2014) 206–240.

[4] R. Cai, H. Yang, J. He, W. Zhu, The effects of magnetic fields on water molecular hydrogen bonds, J. Mol. Struct., 938 (2009) 15–19.

[5] O. Mosin, I. Ignatov, Basic concepts of magnetic water treatment, Nanotechnol. Res. Pract., 4 (2014) 187–200.

[6] M. Kiselev, K. Heinzinger, Molecular dynamics simulation of a chloride ion in water under the influence of an external electric field, J. Chem. Phys., 105 (1996) 650–657.

[7] Y. Wang, B. Zhang, Z. Gong, K. Gao, Y. Ou, J. Zhang, The effect of a static magnetic field on the hydrogen bonding in water using frictional experiments, J. Mol. Struct., 1052 (2013) 102–104.

[8] S.A. Ghauri, M.S. Ansari, Increase of water viscosity under the influence of magnetic field, J. Appl. Phys., 100 (2006) 066101, 1–2, https://doi.org/10.1063/1.2347702.

[9] H. Hosoda, H. Mori, N. Sogoshi, A. Nagasawa, S. Nakabayashi, Refractive indices of water and aqueous electrolyte solutions under high magnetic fields, J. Phys. Chem., 108 (2004) 1461–1464.

[10] M.H. Hilal, Y.M. El-Fakhrani, S.S. Mabrouk, A.I. Mohamed, B.M. Ebead, Effect of magnetic treated irrigation water on salt removal from a sandy soil and on the availability of certain nutrients, J. Eng. Appl. Sci., 2 (2013) 36–44.

[11] X. Liu, H. Zhu, S. Meng, S. Bi, Y. Zhang, H. Wang, C. Song, F. Ma, The effects of magnetic treatment of irrigation water on seedling growth, photosynthetic capacity and nutrient contents of *Populus* × *euramericana* 'Neva' under NaCl stress, Acta Physiol. Plant, 41 (2019) 1–13, https://doi.org/10.1007/s11738–018–2798–1.

[12] K.A. Al-Mosawi, A.H. Mohammed, S.S. Al-Hadi, Effect of magnified and equality of irrigation water in the soil saturated hydraulic conductivity and the soil water infiltration in clay loam soil during the growth stages of barley crop (*Hordium Vulgare* L.), J. Eng. Appl. Sci., 17 (2019) 10114–10121.

[13] N.E. Fanous, A.A. Mohamed, K.A. Shaban, Effect of magnetic treatment for irrigation ground water on soil salinity, nutrients, water productivity and yield fruit trees at sandy soil, Egypt. J. Soil Sci., 57 (2017) 113–123.

[14] M. Khoshravesh, B. Mostafazadeh-Fard, S.F. Mousavi, A.R. Kiani, Effects of magnetized water on the distribution pattern of soil water with respect to time in trickle irrigation, Soil Use Manage., 27 (2011) 515–522.

[15] A.A.M. Al-Ogaidi, A. Wayayok, M.K. Rowshon, A.F. Abdullah, The influence of magnetized water on soil water dynamics under drip irrigation systems, Agric. Water Manage., 180 (2017) 70–77.

[16] B. Mostafazadeh-Fard, M. Khoshravesh, S.F. Mousavi, A.R. Kiani, Effects of magnetized water and irrigation water salinity on soil moisture distribution in trickle irrigation, J. Irrig. Drain. Eng., 137 (2011) 398–402.

[17] M. Moussa, V. Hallaire, D. Michot, M. Hachicha, Micro- and macrostructure changes of soil under irrigation with electromagnetically treated water, Soil Tillage Res., 203 (2020) 104690, 1–11, https://doi.org/10.1016/j.still.2020.104690.

[18] M. Hachicha, B. Kahlaoui, N. Khamassi, E. Misle, O. Jouzdan, Effect of electromagnetic treatment of saline water on soil and crops, J. Saudi Soc. Agric. Sci., 17 (2018) 154–162.

[19] A. Yadollahpour, S. Rashidi, Effects of magnetic treatment of irrigation water on the quality of soil: a comprehensive review, Indo Am. J. Pharm. Res., 4 (2017) 1125–1129.

[20] A.I. Mohamed, B.M. Ebead, Effect of irrigation with magnetically treated water on faba bean growth and composition, Int. J. Agric. Policy Res., 1 (2013) 24–40.

[21] G. Merlin, N. Omri, E. Gonze, E. Valette, G. Cauffet, M. Henry, Hydraulic continuity and biological effects of low strength very low frequency electromagnetic waves: case of microbial biofilm growth in water treatment, Water Res., 83 (2015) 184–194.

[22] U. Surendran, O. Sandeep, E.J. Joseph, The impacts of magnetic treatment of irrigation water on plant, water and soil characteristics, Agric. Water Manage., 178 (2016) 21–29.

[23] V. Zlotopolski, The impact of magnetic water treatment on salt distribution in a large unsaturated soil column, Int. Soil Water Conserv. Res., 5 (2017) 253–2573.

[24] V. Zlotopolski, Magnetic treatment reduces water usage in irrigation without negatively impacting yield, photosynthesis and nutrient uptake in lettuce, Int. J. Appl. Agric. Sci., 3 (2017) 117–122.

[25] M.H. Hilal, M.M. Hilal, Application of magnetic technologies in desert agriculture. I-Seed germination and seedling emergence

of some crops in a saline calcareous soil, Egypt. J. Soil Sci., 40 (2000) 413–421.

[26] C. Gabrielli, R. Jaouhari, G. Maurin, M. Keddam, Magnetic water treatment for scale prevention, Water Res., 35 (2001) 3249–3259.

[27] G.M. Moosa, M.S.J.H. Khulaef, A.C. Khraibt, N.R. Shandi, M.S.K. Al-Braich, Effect of magnetic water on physical properties of different kind of water, and studying its ability to dissolving kidney stone, J. Nat. Sci. Res., 5 (2015) 85–94.

[28] K. Kronenberg, Experimental evidence for effects of magnetic fields on moving water, IEEE Trans. Magn., 21 (1985) 2059–2061.

[29] R.K. Rattan, S.P. Datta, P.K. Chhonkar, K. Suribabu, A.K. Singh, Long–term impact of irrigation with sewage effluents on heavy metal content in soils, crops and groundwater – a case study, Agric. Ecosyst. Environ., 109 (2005) 310–322.

[30] C. Solis, E. Andrade, A. Mireles, I.E. Reyes-Solis, N. Garcia-Calderon, M.C. Lagunas-Solar, C.U. Pina, R.G. Flocchini, Distribution of heavy metals in plants cultivated with wastewater irrigated soils during different periods of time, Nucl. Instrum. Methods Phys. Res., Sect. B, 241 (2005) 351–355.

[31] M. Abedinpour, E. Rohani, Effects of magnetized water application on soil and maize growth indices under different amounts of salt in the water, J. Water Reuse Desal., 7 (2017) 319–325.

[32] B.L. Maheshwari, H.S. Grewal, Magnetic treatment of irrigation water: its effects on vegetable crop yield and water productivity, Agric. Water Manage., 96 (2009) 1229–1236.

[33] A.I. Mohamed, Effects of magnetized low-quality water on some soil properties and plant growth, Int. J. Res. Chem. Environ., 3 (2013) 140–147.

[34] S. Bedbabis, B. Ben Rouin, M. Boukhris, G. Ferrara, Effect of irrigation with treated wastewater on soil chemical properties and infiltration rate, J. Environ. Manage., 133 (2014) 45–50.

[35] M.E.M. Ahmed, N.I. Abd El-Kader, The influence of magnetic water and water regimes on soil salinity, growth, yield and tubers quality of potato plants, Middle East J. Agric. Res., 5 (2016) 132–143.

[36] M.M. Amer, A.G. El Sanat, S.H. Rashed, Effects of magnetized low-quality irrigation water on some soil properties and soybean yield (*Glycine max* L.) under salt affected soils conditions, J. Soil Sci. Agric. Eng., 5 (2014) 1377–1388.

[37] J.N. Hamza, Investigation on using magnetic water technology for leaching high saline-sodic soils, Environ. Monit. Assess., 191 (2019) 519, 1–11. doi: 10.1007/s10661–019–7596–8.

[38] A.H. Gudigar, M. Hebbara, Effect of magnetic treatment on leaching efficiency of salts, Int. J. Curr. Microbiol. Appl. Sci., 7 (2018) 3363–3367.

[39] G.W. Ageeb, A.S. Talaab, M.A. El-Hady, E.I. Eldardiry, M.A.M. Wahab, The impact of magnetized saline irrigation water treatment on soil, water and plant, Biosci. Res., 15 (2018) 4106–4112.

[40] B. Mostafazadeh-Fard, M. Khoshravesh, S.F. Mousavi, A.R. Kiani, Effects of magnetized water on soil chemical components underneath trickle irrigation, J. Irrig. Drain Eng., 138 (2012) 1075–1081.

[41] L.H.A. Raheem, R.Z. Azzubaidi, Leaching of salt affected silty loam soil by using magnetized water, Innovative Syst. Des. Eng., 9 (2018) 1–5.

[42] FAO, Management of Agricultural Drainage Water Quality, C.A. Madramootoo, W.R. Johnston, L.S. Willardson, Eds., Water Reports, International Commission on Irrigation and Drainage, Food and Agriculture Organization of the United Nations, Rome, 1997.

[43] Y.M. El-Fakhrani, S.S. Mabrouk, M.H. Hilal, A.I. Mohamed, B.M. Ebead, Soil cationic and anionic composition and removal under leaching with magnetized irrigation water, Egypt. J. Appl. Sci., 27 (2012) 348–371.

[44] M.H. Hilal, M.M. Hilal, Application of magnetic technologies in desert agriculture. II – Effect of magnetic treatments of irrigation water on salt distribution in olive and citrus fields and induced changes of ionic balance in soil and plant, Egypt. J. Soil Sci., 40 (2000) 423–435.