Influence of the soil water retention curve type and magnetic water treatment on lettuce irrigation management responses

Lis Tavares Ordones Lemos, Fábio Ponciano de Deus, Michael Silveira Thebaldi, Adriano Valentim Diotto, Valter Carvalho de Andrade Júnior and Rodrigo César de Almeida

ABSTRACT

This study aimed to evaluate the influence of magnetized water use on lettuce irrigation management responses, and based on the generated data, to evaluate by simulation the influence of soil water retention curve type on the lettuce irrigation management responses. This work was divided into three stages: 1 – determination of field and laboratory soil water retention curves; 2 – lettuce crop irrigation management experiment using soil water retention curve with field data, evaluating different soil water tensions to start irrigation and different water types (magnetically treated water, and non-treated water); and 3 – estimation of the irrigation management responses (simulation) using the soil water retention curve performed in the laboratory (using non-treated water), compared with the experimental results (stage 2). The use of magnetically treated water determined the soil moisture maintenance for a longer time and fewer irrigation events, leading to less water being applied and electricity consumption. The use of the soil water retention curve derived from the field data determined less water and electric energy consumption in Lucy Brown lettuce irrigation, in comparison with the simulated use of the soil water retention curve from laboratory data.

Key words | microirrigation, optimization, soil water matric potential, tensiometry

HIGHLIGHTS

- Iceberg lettuce irrigation with magnetically treated water determined lower number of irrigations.
- Soil irrigated with magnetized water maintained its moisture for a longer time.
- Magnetically treated water irrigation may have hindered the capacity of water uptake by lettuce.

INTRODUCTION

Over the years, water availability has been a concern of many economic sectors. In irrigated agriculture, researchers have been currently concerned with the development of techniques and equipment for water use optimization. Irrigation with magnetically treated water has been scientifically evaluated over the years, and has brought positive improvements in water use reduction, and qualitative and productive benefits for some crop production (Maheshwari & Grewal 2009; Surendran et al. 2016; Yusuf & Ogunlela 2017).
According to some authors, magnetic treatment modifies the physical structure of water molecules and their chemical composition, altering the hydrogen bonds, van der Waals forces, and sizes of the water clusters, decreasing the surface tension and increasing the viscosity (Toledo et al. 2008; Mostafazadeh-Fard et al. 2011; Khoshravesh-Miangoleh & Kiani 2014; Surendran et al. 2016). According to Mostafazadeh-Fard et al. (2011), Surendran et al. (2016) and Selim et al. (2019) these modifications in water molecules promote the maintenance of soil moisture for a longer time, which may explain the productive benefits and water savings.

Another factor that has been investigated is the effectiveness of the irrigation management methodology. The use of soil water retention curves for irrigation management, performed in the laboratory, may overestimate the values of water content, especially the field capacity, and consequently the irrigation depths (Morgan et al. 2001; Jabro et al. 2009; Brito et al. 2011). According to the authors, this overestimation may be due to the combination of entrapped air in the soil and the soil sample compaction in the collection, increasing the soil density and microporosity. Additionally, there are studies highlighting the occurrence of errors from laboratory methods, especially in high water potentials, associated with fine and extra-fine texture soil, leading to water content overestimation (Bittelli & Flury 2009; Solone et al. 2012; van Lier et al. 2019). A potentially more reliable alternative is the use of soil water retention curves performed in the field (Morgan et al. 2001; Jabro et al. 2009; Brito et al. 2011). Although there are several studies evaluating the differences between the soil water retention curves carried out in the field and in the laboratory, there are few studies that have assessed the impact on the irrigation management responses on different crops.

Based on the given information, it is expected that the use in irrigation of water subjected to magnetic treatment, associated with the use of the soil water retention curve with data from field testing for irrigation management, will determine reduction in water amount and in electricity consumption. In this sense, this study aimed to evaluate the influence of magnetized water use on lettuce irrigation management responses, and based on the generated data, to evaluate by simulation the influence of soil water retention curve type on the lettuce irrigation management responses.

**METHODS**

**Experimental planning**

Figure 1 shows a flowchart of the development stages of the experiment.

Initially, two forms of soil water retention curve construction were performed (in the field, and in the laboratory) – Stage 1. The objective was to evaluate the influence of the soil water retention curve determination method on the lettuce crop irrigation management responses. Subsequently, a lettuce crop irrigation management experiment was performed using the soil water retention curve made by the field data – Stage 2. It evaluated different combinations of soil water tensions to start irrigation and types of water (magnetically treated water, and non-treated water). Finally, using the data generated in the field experiment, an estimate (simulation) of the irrigation management responses was performed, using the soil water retention curve performed in the laboratory – Stage 3. These results were compared with the Stage 2 results.

**Location of the experiment and water magnetic treatment**

The field essays were conducted in a greenhouse (7 × 30 m in size, with transparent plastic anti-UV additives (150 μm)), in the south of Minas Gerais state, Brazil (21°14’S, 45°00’W and 910 m). According to the Köppen-Geiger climate classification, the region’s climate is Cwa, with an average annual air temperature of 20.4 °C and an average annual precipitation of 1,460 mm (Alvares et al. 2013).
The measured air temperatures inside the greenhouse during the experiment were: maximum of 31.0 ± 2.4 °C, minimum of 19.0 ± 1.8 °C, and average of 25.0 ± 1.5 °C. The relative humidity values were: maximum of 91.2% ± 6.3%, minimum of 41.0% ± 9.2%, and average of 66.1% ± 5.9%.

A Sylocimol Residencial magnetizer from the Timol Indústria e Comércio de Produtos Magnéticos (Uberlândia, MG, Brazil) was used to magnetize the water. This equipment is composed of alternating magnets and covered by stainless-steel protection, and subjects the water to a magnetic field of 5,860 gauss, with the capacity to magnetize 1,000 L in one hour of exposure (TIMOL 2012). The equipment was allocated and kept inside a 500 L water tank throughout the experiment.

**Determination of the soil water retention curve**

The soil of the experimental area was classified as Typic Hapludox (Soil Survey Staff 1999). Table 1 shows the results of the chemical and physical soil analysis, referring to depths of 0–20 cm and 20–40 cm.

<table>
<thead>
<tr>
<th>Parameter (unit)</th>
<th>Depth (cm)</th>
<th>Depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0–20</td>
<td>20–40</td>
</tr>
<tr>
<td>pH</td>
<td>6.60</td>
<td>6.40</td>
</tr>
<tr>
<td>K (mg dm⁻³)</td>
<td>87.00</td>
<td>39.22</td>
</tr>
<tr>
<td>P (mg dm⁻³)</td>
<td>10.03</td>
<td>4.89</td>
</tr>
<tr>
<td>Na (mg dm⁻³)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Ca (cmolc dm⁻³)</td>
<td>4.82</td>
<td>4.16</td>
</tr>
<tr>
<td>Mg (cmolc dm⁻³)</td>
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<td>1.83</td>
</tr>
<tr>
<td>Al (cmolc dm⁻³)</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>H + Al (cmolc dm⁻³)</td>
<td>1.03</td>
<td>1.10</td>
</tr>
<tr>
<td>SB (cmolc dm⁻³)</td>
<td>7.14</td>
<td>6.09</td>
</tr>
<tr>
<td>t (cmolc dm⁻³)</td>
<td>7.18</td>
<td>6.13</td>
</tr>
<tr>
<td>T (cmolc dm⁻³)</td>
<td>8.17</td>
<td>7.19</td>
</tr>
<tr>
<td>V (%)</td>
<td>87.43</td>
<td>84.71</td>
</tr>
<tr>
<td>Mg (%)</td>
<td>0.56</td>
<td>0.65</td>
</tr>
</tbody>
</table>

1 K = potassium; P = phosphorus; Na = sodium; Ca = calcium; Al = aluminium; H + Al = potential acidity with SMP extractor; SB = sum of exchangeable base; t = effective cation exchange capacity; T = cation exchange capacity at pH 7.0; V = base saturation index; Mg = magnesium; MO = organic matter; P-Rem = remaining phosphorus; Zn = zinc; Mn = manganese; Cu = copper; B = boron; S = sulfur; \( \rho_b\) = soil bulk density; pH in water, KCl and CaCl₂ = 12.5 ratio; Ca = Mg + Al – extractor; KCl = 1 mol/L; S = extractor – monocalcium phosphate in acetic acid; P = Na – K – Fe – Zn – Mn – Cu – Mehlich extractor 1; H = Al – extractor: SMP; organic matter (MO) – oxidation: Na₂C₂O₇ 4N + HSO₄ 10N; B – hot water extractor.

To determine the soil water retention curve in the field, two beds in the area (1.2 x 2.4 m) were selected: one for the magnetically treated water evaluation (MW), and one for non-treated water evaluation (OW). The beds were delimited by a PVC sheet 20 cm high above the ground surface to avoid water runoff, and 50 cm below the ground surface to prevent lateral water flow. The objective was to promote only drainage and evaporation of water during the test (Figure 2).

To evaluate the soil water retention characteristics to which plants were subjected, the soil water retention curves were made after incorporating the planting fertilization. In order to promote repetitive assessment, in each bed six tensiometers were installed at 12.5 cm (depth defined to indicate irrigation), six at 25 cm (to check the amount of water at the effective depth of the lettuce roots), and three at 40 cm (evaluation depth to ensure saturation of the soil profile).

The soil was subjected to saturation (zero reading on the tensiometer at all depths) using 30 drip emitters with a flow rate of 4 L h⁻¹. Once the saturation condition was reached, water application was interrupted, and the beds were covered with impermeable material to prevent water evaporation and allow only drainage. The beds were kept covered until the field capacity condition occurred in the soil. This condition was defined considering the first derivative of the soil moisture model as a function of time equal to −0.01 (Oliveira et al. 2001; Casaroli & van Lier 2008). A regression analysis (\( p \leq 0.05\)) was performed to define the most representative soil moisture model as a function of time. Subsequently, the fitted mathematical models were compared by the F-test (\( p \leq 0.05\)).

After reaching equilibrium (field capacity condition), the impermeable material was removed in order for the soil to dry until the recommended reading limit of the tensiometer, i.e. −80 kPa. The maintenance of the water column inside the tensiometers was performed routinely.

Tensiometer readings were performed concomitantly with the soil moisture measurement in the laboratory by the standard method (gravimetric method). The soil water retention curve was determined to a depth of 12.5 cm. Soil volumetric water content was obtained from gravimetric water content multiplying it by the soil bulk density after
bed-making (1.14 ± 0.05 g cm$^{-3}$). Sampling was more frequent on the first day (0, 3, 6, 12 and 24 hours after saturation), and later evaluations were daily.

A digital tensimeter (model TENSIOMETER, from the company Hidrodinâmica Irrigation. URL: http://tensimetro.com.br/) was used to read the tensiometers. Equation (1) was used to determine the soil water tension or the matric potential from the reading of the tensiometer:

$$\Psi_m = L - 0.098 \, h$$

where $\Psi_m$ is the soil water tension or matric potential (kPa), $L$ is the tensiometer reading (kPa), and $h$ is the water column height in the tensiometers (cm).

The $F$-test ($p \leq 0.05$) was performed to evaluate the water type (MW and OW) influence on the behavior of the field soil water retention curves.

A soil water retention curve was also determined in the laboratory, using soil cores made from deformed soil samples, from saturated condition to a tension of −98 kPa, being −0.98, −1.96, −3.92, −5.88, −7.84 and −9.8 kPa in the hanging-water funnel, and −98 kPa in the pressure plate apparatus. For this, we used six soil deformed samples submitted to a 2 mm sieve, from 0 to 0.20 m deep to prepare the soil cores with a bulk density of 1.14 g cm$^{-3}$, the same found in field conditions, in order to compare its hypothetical irrigation management responses with the results from the actual use of the soil water retention curve performed in the field (comparison only with non-treated water).

For the field (magnetically treated water – MW, and non-treated water – OW) and laboratory data (non-treated water – OW), regression analyses ($p \leq 0.05$) were performed to define the most appropriate mathematical model of the relationship between volumetric soil moisture and soil water tension. Linear models, second-degree polynomial, power and logarithmic models were evaluated.

**Lucy Brown lettuce irrigation management**

The irrigation management evaluation was carried out in a Lucy Brown lettuce (*Lactuca sativa* L.) cultivation, transplanted 23 days after sowing, at a spacing of 0.30 × 0.30 m (32 plants per bed). During the experiment, temperature and relative humidity were monitored with a digital thermo-hygrometer (model HT-600, from the company Instrutherm), installed in a weather shelter (2 m in relation to the soil surface) inside of the greenhouse.

The experimental design was completely randomized, in factorial 2 × 4 with three replications (R1, R2 and R3). The treatments were composed by the combination of two water types (MW and OW) and four soil water tensions to start irrigation (T1 = 15 kPa, T2 = 25 kPa, T3 = 40 kPa and T4 = 70 kPa), the irrigation process being performed to raise the soil moisture to field capacity condition. As a limit of −80 kPa is indicated for proper functioning of the tensiometers (Azevedo & Silva 1999), −70 kPa was defined as the treatment with the greatest distance from the field capacity tension. The soil water retention curve used for the crop...
management was the one derived from the field with non-treated water.

In one repetition of each experimental combination (type of water and soil water tension), three tensiometers at 12.5 cm was used to manage the irrigation. The readings of the tensiometers were performed daily at 9 am and 3 pm.

A drip irrigation system (distribution uniformity – DU equal to 95.4%) was used for irrigation, with self-regulating dripper ClickTif NaanDanJain (average flow of 2.14 ± 0.08 L h⁻¹), with a spacing of 30 cm (16 emitters per bed). Additionally, two irrigation lines were used per bed, spaced by 60 cm. Equation (2) was used to estimate the irrigation water depth. The irrigation time was calculated by Equation (3). There was assumed to be 95% application efficiency, and according to Yuri et al. (2002) an effective depth of the root system of 25 cm (250 mm).

\[
LI = \frac{(\theta_{cc} - \theta_t)z}{E_a DU}
\]  

(2)

where \(LI\) is the irrigation depth (mm), \(\theta_{cc}\) is the volumetric soil moisture at field capacity (cm³ cm⁻³), \(\theta_t\) is the volumetric soil moisture at the time of reading (cm³ cm⁻³), \(z\) is the effective depth of the root system (mm), \(E_a\) is the application efficiency (decimal), and \(DU\) is the uniformity of distribution of the irrigation system (decimal).

\[
T = LI \times \frac{A}{n_e q_a} \times 60
\]  

(3)

where \(T\) is the irrigation time (min), \(A\) is the bed area (m²), \(q_a\) is the average flow of the emitters (L h⁻¹), and \(n_e\) is the number of emitters per bed.

Electric energy consumption was estimated for each treatment by Equation (4), proposed by Bilibio et al. (2010) and adapted for this work. Electric energy consumption was estimated per unit area and crop cycles to facilitate later estimation by users.

\[
EC = 2.78 \times 10^{-7} \frac{\Sigma LI Hman}{\eta_{MB}}
\]  

(4)

where \(EC\) is the electric energy consumption (kWh m⁻² cycle⁻¹), \(\Sigma LI\) is the total applied irrigation depth during the crop cycle (mm cycle⁻¹), \(Hman\) is the manometric height of the pumping system (kPa), and \(\eta_{MB}\) is the pump efficiency (decimal).

The irrigations required a manometric height of 176.4 kPa (18 mca) from the pumping system. Based on the pump performance curve, the pump efficiency was 47% (model BC-91S, 1/2 cv, Schneider Motobombas).

Irrigation management responses

Evaluation of field data

The field data were analyzed to evaluate the influence of the irrigation water magnetic treatment on the lettuce irrigation management responses. For the irrigation management, the soil water retention curve constructed in the field was used. We evaluated the following irrigation management responses: soil water tension data during the experiment for each treatment; number of irrigation events (NI); average interval between irrigations (II); total applied irrigation depth during the crop cycle (\(\Sigma LI\)); and electric energy consumption estimate (EC).

For the soil water tension data comparison between each treatment, an analysis of variance on ranks was used, by the Kruskal–Wallis test with 5% of probability, followed by Tukey’s test, also at 5% of significance for pairwise multiple comparison.

Simulation of irrigation management responses

Using the soil water tension data measured during the experiment, simulation of irrigation management responses was estimated using the soil water retention curve made in the laboratory. The objective was to evaluate the influence of the soil water retention curve data source on the lettuce irrigation management responses. Total applied irrigation depth during the crop cycle (\(\Sigma LI\)) and electric energy consumption (EC) were estimated.

RESULTS AND DISCUSSION

Soil water retention curve performed in the field

Table 2 presents the summary of the regression analysis \((p \leq 0.05)\) of the soil moisture data (\(\theta_t\)) as a function of the time (t) for the field test.
All mathematical models presented significant fitting to the data for both types of water (except the linear model for magnetized water use). The third-degree polynomial model was selected for both types of water due to the higher value of the determination coefficient (greater than 85%). Figure 3 shows the behavior of the data fit and the respective model for each treatment.

Comparing the fitted mathematical models using the F-test \((p \leq 0.05)\), significant differences were found between data generated by the models, demonstrating that the type of water significantly influenced the behavior of the soil moisture over time. The soil moisture at field capacity for magnetically treated and non-treated water was 0.356 and 0.340 cm\(^3\) cm\(^{-3}\) respectively, reached in 3.35 and 4.98 days, respectively. The soil moisture at saturation for magnetically treated and non-treated water was 0.359 cm\(^3\) cm\(^{-3}\) (±0.005 cm\(^3\) cm\(^{-3}\)) and 0.456 cm\(^3\) cm\(^{-3}\) (±0.019 cm\(^3\) cm\(^{-3}\)), respectively.

It was possible to observe that the use of magnetically treated water showed greater mobility compared with the non-treated water use, reaching the soil moisture at field capacity 1.63 days before. This result is in agreement with Khoshravesh-Miangoleh & Kiani (2014), where greater accumulated infiltration and water infiltration rate were observed in the use of magnetically treated water.

Table 3 shows the summary of the regression analysis \((p \leq 0.05)\) of the volumetric soil moisture data adjustment as a function of the soil water tension, referring to the field test, in the use of non-treated water (OW) and water subjected to magnetic treatment (MW).

Almost all mathematical models represented significantly \((p \leq 0.05)\) the soil moisture data as a function of the soil water tension for both types of water (except the linear model for magnetized water use). The logarithmic model was selected to represent the soil water retention curve for both types of water. Figure 4 shows the behavior of the data fitting for each treatment, as well as the fitted mathematical models.

Comparing the fitted mathematical models by the F-test \((p \leq 0.05)\), there were not found to be any significant differences between the data generated, demonstrating that the type of water did not significantly influence the soil water retention behavior.

Considering the estimated values of soil moisture at field capacity (0.356 cm\(^3\) cm\(^{-3}\) for magnetized water, and 0.340 cm\(^3\) cm\(^{-3}\) for non-treated water) for the fitted mathematical models presented in Figure 3, tensions equivalent to 7.22 kPa for magnetized water and 10.54 kPa for non-treated water were observed. Although there are no significant differences between models, it is interesting to

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Table 2 | Summary of regression analysis \((p \leq 0.05)\) in adjusting the soil moisture data (cm\(^3\) cm\(^{-3}\)) as a function of time (days), using non-treated water (OW) and water with magnetic treatment (MW), referring to the field test

<table>
<thead>
<tr>
<th>Model</th>
<th>Non-treated water (OW)</th>
<th>Magnetized water (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Regression mean square</td>
<td>Residual error</td>
</tr>
<tr>
<td>Linear</td>
<td>3.17*</td>
<td>0.022</td>
</tr>
<tr>
<td>2nd degree</td>
<td>2.12*</td>
<td>0.019</td>
</tr>
<tr>
<td>3rd degree</td>
<td>1.59*</td>
<td>0.019</td>
</tr>
<tr>
<td>Power</td>
<td>3.17*</td>
<td>0.028</td>
</tr>
<tr>
<td>Logarithmic</td>
<td>3.17*</td>
<td>0.025</td>
</tr>
</tbody>
</table>

* - significant at 5% probability, ns - not significant at 5% probability.

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Table 3 | Summary of the regression analysis ($p \leq 0.05$) in adjustment of the volumetric soil moisture data as a function of the soil water tension, using non-treated water (OW) and water with magnetic treatment (MW), referring to the field test

<table>
<thead>
<tr>
<th>Model</th>
<th>Non-treated water (OW)</th>
<th>Magnitized water (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Regression mean square</td>
<td>Residual error</td>
</tr>
<tr>
<td>Linear</td>
<td>3.30*</td>
<td>0.028</td>
</tr>
<tr>
<td>2nd degree</td>
<td>2.20*</td>
<td>0.022</td>
</tr>
<tr>
<td>3rd degree</td>
<td>1.65*</td>
<td>0.019</td>
</tr>
<tr>
<td>Power</td>
<td>3.31*</td>
<td>0.013</td>
</tr>
<tr>
<td>Logarithmic</td>
<td>3.31*</td>
<td>0.013</td>
</tr>
</tbody>
</table>

* – significant at 5% probability, ** – not significant at 5% probability.

Figure 4 | Soil water retention curves performed in the field with magnetically treated water (MW) and non-treated water (OW) with details of the data adjustment model.

Note that the soil moisture at field capacity using water subjected to magnetic treatment was obtained with less retention force (31.5% less). According to some authors, the cause of this effect may be associated with the surface tension decrease and water viscosity increase (Toledo et al. 2008; Mostafazadeh-Fard et al. 2011; Khoshravesh-Miangoleh & Kiani 2014; Surendran et al. 2016). An analogous result was found by Zlotopolski (2017) that observed lower soil water tension values using magnetic water in lettuce irrigation, the soil moisture being maintained for a longer time.

As there was no statistical difference between the curves when changing the type of water, the soil water retention curve performed in field conditions for non-treated water was selected for the irrigation management due its higher value of the determination coefficient for the curve fitting ($R^2 = 94.3\%$). Considering the soil water tension equal to 10 kPa in the module to represent the field capacity in the irrigation management, this resulted in a soil moisture of $0.342 \, \text{cm}^3 \, \text{cm}^{-3}$.

Soil water retention curve performed in the laboratory

Table 4 shows the summary of the regression analysis ($p \leq 0.05$) of the fitting of the volumetric moisture data as a function of the soil water tension, referring to the laboratory analysis.

Almost all mathematical models represented the data significantly ($p \leq 0.05$), the exception being the linear model. The power model was selected (Figure 5) due its highest value of the determination coefficient ($R^2 = 94.1\%$).

Applying the $F$-test ($p \leq 0.05$) between the fitted models of soil water retention curves performed in the field and in the laboratory, both with non-treated water, it was observed that the obtained models were statistically different.

Assuming the same soil water tension value regarding the field capacity found in the field test (10 kPa in the module), this would result in a volumetric soil moisture

Table 4 | Summary of the regression analysis ($p \leq 0.05$) in adjustment of the volumetric soil moisture data as a function of soil water tension, referring to the laboratory analysis

<table>
<thead>
<tr>
<th>Model</th>
<th>Laboratory test</th>
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<tbody>
<tr>
<td></td>
<td>Regression mean square</td>
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<td>Linear</td>
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<td>2nd degree</td>
<td>3.48*</td>
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<tr>
<td>Power</td>
<td>5.22*</td>
</tr>
<tr>
<td>Logarithmic</td>
<td>5.22*</td>
</tr>
</tbody>
</table>

* – significant at 5% probability, ** – not significant at 5% probability.
equivalent to 0.439 cm$^3$ cm$^{-3}$. Pinto et al. (2018) found similar values (around 0.4115 cm$^3$ cm$^{-3}$) considering the same soil water tension (10 kPa) in the same type of soil.

Comparing the values of soil moisture at the field capacity obtained in the field (0.342 cm$^3$ cm$^{-3}$) and in the laboratory (0.439 cm$^3$ cm$^{-3}$) (both using non-treated water), overestimation was observed in the laboratory estimate (28.36% increase). Some authors state that the soil water retention characteristics, as well as the soil moisture at field capacity obtained in field conditions, represent the soil more adequately when compared with laboratory methods (Morgan et al. 2001; Jabro et al. 2009; Brito et al. 2011). According to the authors, soil sampling can modify the original soil bulk density because of sample compaction, which leads to a reduction of the porous space.

Irrigation management responses

Soil water tension data during the experiment, number of irrigations ($N_I$) and average interval between irrigations ($I_i$)

Figure 6 shows the estimated soil water tensions ($\Psi_{eq}$) during the experiment for the different experimental combinations.

It was possible to observe less data variability using magnetized water in almost all treatments. Table 5 shows the Tukey's test significance of pairwise multiple comparison for soil water tension data in different combinations of soil water tensions to start irrigation (T1, T2, T3 and T4) and types of water (MW and OW).

Varying the types of water for each soil water tension to start irrigation, no significant differentiation was observed ($p \leq 0.05$). In the other way, comparing the soil water tensions to start irrigation, considering fixed the type of water, it was observed: MW – T2 treatment being an exception that was statistically equal to T3, all other treatments were statistically different from each other; OW – the soil water tension variation during the experiment for T2 was statistically equal to T3; and T3 was statistically equal to T4, all other treatments being different from each other.

Table 6 shows the number of irrigations ($N_I$) carried out and the average interval between irrigations ($I_i$) for each experimental combination (water type and soil water tension).

It was possible to observe a smaller number of irrigations ($N_I$) in the use of magnetized water (with the exception of the T2 treatment, where the use of magnetized water determined a greater number of events). Analogous behavior was observed in several studies, where, in general, less variability of soil moisture in time was observed in irrigations using magnetized water, determining a lower frequency of irrigation (Mostafazadeh-Fard et al. 2011; Surendran et al. 2016; Al-Ogaidi et al. 2017). Additionally Zlotopolski (2017) observed lower values of soil water tension when using magnetized water.

According to some authors, the magnetization process makes the water more cohesive, defining smaller dimensions of water clusters, determining greater attraction to soil particles and less movement of water in soil pores (Mostafazadeh-Fard et al. 2011; Surendran et al. 2016; Al-Ogaidi et al. 2017). The authors explain that the water cohesion increase was the result of molecules released in reaction with ions by hydrogen bonds and van der Waals forces, leading to greater ease of water penetration in soil micropores, reducing percolation. Additionally, the authors explain that calcium carbonate ions in the water form aragonite crystals after magnetizing the water, which are deposited in the soil. This process determines the elevation of soil osmotic potential, decreasing crop evapotranspiration and maintaining soil moisture for a longer time. Surendran et al. (2016) pointed out that the maintenance of soil moisture for a longer time may also be associated with reduced water evaporation capacity. Kareem & Adeniran (2020) also observed a reduction in Lagos spinach
Figure 6 | Estimated soil water tension (kPa) during the experiment for different combinations of soil water tensions to start irrigation (T1, T2, T3 and T4) and types of water (MW and OW). \( \Psi_{cc} \) – soil water tension referring to field capacity (10 kPa).

Table 5 | Tukey’s test significance of pairwise multiple comparison soil water tension data in different combinations of soil water tensions to start irrigation (T1, T2, T3 and T4) and types of water (MW and OW)

<table>
<thead>
<tr>
<th>Treatments</th>
<th>MWT1</th>
<th>MWT2</th>
<th>MWT3</th>
<th>MWT4</th>
<th>OWT1</th>
<th>OWT2</th>
<th>OWT3</th>
<th>OWT4</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWT1</td>
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<td>–</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MWT2</td>
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</tbody>
</table>

* – significant at 5% probability, ** – not significant at 5% probability.
Table 6 | Number of irrigations performed and average interval between irrigations (days) for different combinations of soil water tension to start irrigation (T1, T2, T3 and T4) and types of water (OW and MW)

<table>
<thead>
<tr>
<th>Soil water tension</th>
<th>&amp;</th>
<th>Non-treated water (OW) &amp;</th>
<th>Magnetized water (MW) &amp;</th>
<th>Non-treated water (OW) &amp;</th>
<th>Magnetized water (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>18</td>
<td>13</td>
<td>2.7</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td>9</td>
<td>10</td>
<td>5.4</td>
<td>4.9</td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>9</td>
<td>7</td>
<td>5.4</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>T4</td>
<td>4</td>
<td>3</td>
<td>12.3</td>
<td>16.3</td>
<td></td>
</tr>
</tbody>
</table>

(Celosia argentea) evapotranspiration with the use of magnetized water.

**Total applied irrigation depth during the crop cycle ($\sum LI$)**

Table 7 shows the Tukey’s test result ($p \leq 0.05$) to evaluate the total applied irrigation depth for different combinations of soil water tension to start irrigation and types of water, considering the soil water retention curve built in the field (actual applied values).

A significant reduction was observed in the total applied irrigation depth using magnetized water for irrigation (with T2 treatment as exception). The reduction was 34.62%, 18.62% and 26.34% for T1, T3 and T4, respectively. Selim et al. (2019) also observed reduction in the amount of water applied (25% reduction) for wheat crops irrigated with magnetically treated water compared with non-treated water.

Regarding the influence of soil water tension to start irrigation on total irrigation water depth, it was observed that T3 > T1 > T2 > T4 for non-treated water, and T2 > T3 > T1 > T4 for magnetized water. In both types of water, T4 treatment obtained the lowest irrigation depths. Koetz et al. (2006) points out that generally, longer intervals between irrigations determine lower total applied irrigation depth.

**Electric energy consumption (EC)**

Table 8 shows the Tukey’s test result ($p \leq 0.05$) to evaluate the electric energy consumption estimate for different combinations of soil water tensions to start irrigation and the types of water, considering the soil water retention curve from the field (actual applied values).

The use of water subjected to magnetic treatment determined lower electric energy consumption in all soil water tensions (with the exception of T2 treatment). Reductions were of 54.7%, 18.6% and 26.5% for T1, T3 and T4 respectively. For T2, the use of magnetized water increased 10% the electric energy consumption in relation to the use of non-treated water. The lowest EC value was reached using magnetically treated water with 70 kPa tension ($0.0075 \text{ kWh m}^{-2} \text{ cycle}^{-1}$), due to the lower total applied irrigation depth and longer interval between irrigations. The highest consumption was reached using non-treated water with 40 kPa for soil water tension to start irrigation ($0.0177 \text{ kWh m}^{-2} \text{ cycle}^{-1}$), this being the treatment that demanded a larger total applied irrigation depth.

**Simulation of irrigation management responses**

**Comparison between applied and simulated irrigation depth during the crop cycle**

Table 9 shows the Tukey’s test result ($p \leq 0.05$) to evaluate the soil water retention curve data source (field – applied
irrigation depths, and laboratory – simulated irrigation depths) considering the total applied irrigation depth for different soil water tensions to start irrigation. The total applied irrigation depths using the laboratory soil water retention curve were simulated.

It was observed in all soil water tensions that the hypothetical use of the soil water retention curve performed in the laboratory in the lettuce irrigation management provided significantly the highest total applied irrigation depth. Increases were observed of 52.72%, 46.45%, 42.71% and 37.80% for T1, T2, T3 and T4 respectively using non-treated water, and 53.95%, 46.42%, 41.79% and 38.20% for T1, T2, T3 and T4 respectively using magnetized water. This result highlights the importance of the representativeness of the soil water retention curve for effective irrigation management.

Some authors point out that the determination of the soil water retention curve in the laboratory can be subject to errors due to inadequate procedures such as: inadequate contact between soil and porous plate; decrease in hydraulic conductivity of soil due to sample compaction; soil dispersion as a result of the sample moistening process, changing the natural flow characteristics in the soil; and reduced soil sample height determining less soil profile representativeness (Bittelli & Flury 2009; Solone et al. 2012; van Lier et al. 2019).

Electric energy consumption (EC)

Table 10 shows the Tukey’s test result (p ≤ 0.05) to evaluate soil water retention curve type (field – applied irrigation depths, and laboratory – simulated irrigation depths) considering the electric energy consumption estimate for different soil water tensions to start irrigation. The electric energy consumption estimates using the laboratory soil water retention curve were simulated.

In all soil water tensions to start the irrigation, a significant increase in the electric energy consumption was observed in the hypothetical use of the soil water retention curve from the laboratory in the lettuce irrigation management. The increase in consumption was of 52.7%, 46.5%, 42.7% and 37.8% for T1, T2, T3 and T4 respectively using magnetized water.

### Table 9

<table>
<thead>
<tr>
<th>Soil water tensions</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-treated water</td>
<td>138.72 b</td>
<td>132.87 b</td>
<td>169.71 b</td>
<td>97.45 b</td>
</tr>
<tr>
<td>Laboratory (simulated)</td>
<td>211.86 a</td>
<td>194.59 a</td>
<td>242.19 a</td>
<td>134.29 a</td>
</tr>
<tr>
<td>Magnetized water</td>
<td>90.69 b</td>
<td>146.11 b</td>
<td>138.11 b</td>
<td>71.48 b</td>
</tr>
<tr>
<td>Laboratory (simulated)</td>
<td>139.62 a</td>
<td>213.93 a</td>
<td>195.82 a</td>
<td>99.20 a</td>
</tr>
</tbody>
</table>

Different lowercase letters in the vertical differ significantly (p ≤ 0.05) with changing water type.

### Table 10

<table>
<thead>
<tr>
<th>Soil water tensions</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-treated water</td>
<td>0.0145 bB</td>
<td>0.0139 bC</td>
<td>0.0177 bA</td>
<td>0.0102 bD</td>
</tr>
<tr>
<td>Laboratory (simulated)</td>
<td>0.0221 aB</td>
<td>0.0203 aC</td>
<td>0.0253 aA</td>
<td>0.0140 aD</td>
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<tr>
<td>Magnetized water</td>
<td>0.0095 bC</td>
<td>0.0153 bA</td>
<td>0.0144 bB</td>
<td>0.0075 bD</td>
</tr>
<tr>
<td>Laboratory (simulated)</td>
<td>0.0146 aA</td>
<td>0.0223 aA</td>
<td>0.0204 aB</td>
<td>0.0104 aD</td>
</tr>
</tbody>
</table>

Different lowercase letters in the vertical differ significantly (p ≤ 0.05) with changing water type, and different uppercase letters in the horizontal differ significantly (p ≤ 0.05) with changing soil water tension.
Practical observations

The result of this research presents, to the scientific and growers’ community, a discussion that should be the focus of today’s research on irrigated agriculture, which is the rational and sustainable use of water. In terms of water subjected to magnetic treatment use on different crops’ irrigation, despite this experiment showing water and energy savings, this study should be extended to the productive and economic evaluation of the use of water magnetization technology.

In addition, this research demonstrated the need for further studies on the rational assessment of irrigation management methods. The use of soil water retention curves developed in the laboratory has long been preferred for irrigation management of various crops: although there is a lot of knowledge of the negative impacts of the soil sampling process, as well as the process of making the curve in the laboratory compared with the field reality, there are practically no studies that assess the practical impact, i.e., evaluations in irrigated crops. Even with this study having demonstrated this impact, it is still necessary to continue evaluations, to strengthen the debate with the scientific community and irrigating farmers regarding the improvement of irrigation management methods.

CONCLUSIONS

The use of the water subjected to magnetic treatment in the irrigation of iceberg lettuce cv. Lucy Brown determined the maintenance of soil moisture for a longer time, defining a smaller number of irrigation events, less volume of water applied, and less electric energy consumption. Despite the need to continue evaluating the impact of this technology on other combinations of crops, soils and climates, it has potential in saving water and electricity, improving the management of water resources.

The use of the soil water retention curve derived from the field data determined less water and electric energy consumption in Lucy Brown lettuce irrigation, in comparison with the simulated use of the soil water retention curve derived from laboratory data. This finding presents itself as an opportunity for the growers themselves to make their retention curves in the irrigation area, with the potential to achieve high irrigation efficiencies, providing savings in water and electricity.

ACKNOWLEDGEMENT

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES


