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Research paper

Development and production of iceberg lettuce irrigated with magnetically treated water

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Irrigated agriculture has become a concern, given the scarcity of freshwater. To reduce its water consumption, new techniques and technologies have been proposed. Based on this, the objective of this work was to evaluate the influence of different soil water tensions at initiation of irrigation with magnetically treated water, on 'iceberg' lettuce Lucy Brown (*Lactuca Sativa* L.) development and production. The experiment was conducted in a greenhouse, using a completely randomized factorial design, to evaluate two water types (magnetically treated water – MW and ordinary water – OW) and four soil water tensions at initiation of irrigation (T1 – 15 kPa, T2 – 25 kPa, T3 – 40 kPa and T4 – 70 kPa), with three replicates. Tensiometers were used to estimate soil water tension. The evaluated parameters were: aerial part fresh and dry total mass; commercial head fresh and dry mass, root fresh and dry mass; stem fresh and dry mass; stem length and diameter; percentage of leaves with tip burn, total and commercial yield; water use efficiency related to total and commercial yield; plant exposed area; and dry matter content. Despite achieving greater water use efficiency, the magnetic treatment may have hindered the removal of water from the soil by the crop, especially at increased soil water tension at initiation of irrigation.

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INTRODUCTION

The increase in water use efficiency in irrigated agriculture has become one of the main objectives of many research investigations (Valnir Júnior et al., 2017). These studies, beyond aiming to positively impact the economy, aim to enable cultivation and food security in water-stressed locations. In this regard, companies in the sector have also invested in the development of techniques and technologies to reduce water consumption, while maintaining or increasing production.

Use of water subjected to magnetic treatment in irrigated agriculture has been investigated, with productive and qualitative benefits in production having been observed, in addition to saving water and increasing the efficiency of water use and fertilizers. Most of these studies took place in developing countries, such as Nigeria, Pakistan, India, and Brazil, among others, and were aimed at enabling irrigated cultivation in environments with problems of water availability (Adeniran et al., 2020; Al-Said et al., 2018; Surendran et al., 2016; Pradela et al., 2018).

As an example of water saving, in some studies it was observed that when using magnetically treated irrigation water, the soil moisture and water tension was maintained for a longer time (Surendran et al., 2016; Lemos et al., 2021). According to Mostafazadeh-Fard et al. (2011), this could possibly be explained by the increase in soil osmotic pressure. Additionally, the authors comment that modification of the structure of the water clusters makes the water more cohesive; therefore, water molecules can easily attach to soil particles and penetrate into micropores, increasing water retention by the medium.

According to some authors, magnetic treatment causes physical and chemical changes to the water (Pang and Deng, 2008; Toledo et al., 2008; Cai et al., 2009; Mostafazadeh-Fard et al., 2011; Pang et al., 2012; Khoshravesh-Miangoleh and Kiani, 2014; Surendran et al., 2016; Wang et al., 2018). The following were observed: decrease in internal hydrogen bonds of water clusters, decrease in size [of what?] and strengthening of bonds between clusters; decreased contact angle between water and surfaces; decreased surface tension; decreased hydrophobicity of different materials; increased viscosity; decreased specific heat; increased dielectric constant; and increased electrical conductivity.

For lettuce cultivation, irrigation is an important technique, and the use of magnetically treated water has the potential to create economic benefits due to the high cultivation water demand of lettuce (Geisenhoff et al., 2016; Baudoin et al., 2017). Lettuce is a crop that offers macro- and micro-nutrients essential to the human diet, being one of the most produced and consumed leafy vegetables in the world (Hotta, 2008; Geisenhoff et al., 2016; Baudoin et al., 2017; Urbano et al., 2017). For example, in 2017, Brazilian lettuce production was 671.5 thousand tons, representing 50% of the area of all vegetable production, with the iceberg variety ranking second in importance among the types of lettuce (Kist et al., 2020).

Some studies have evaluated the use of magnetically treated water in the irrigated cultivation of lettuce. Putti et al. (2015b), using magnetically treated water for lettuce irrigation, found an increase of 63% in the fresh weight of the commercial head of iceberg lettuce, with a reduction in the applied water volume, as well as a reduction in the crop cycle, increasing water use efficiency. Pradela et al. (2018) observed a dry weight increase in total aerial parts (11.02%) and roots (12.09%) of iceberg lettuce seedlings irrigated with magnetically treated water.

Despite several studies pointing to the productive and water-saving benefits of magnetic treatment of water for irrigated agriculture, there is still a need for more scientific evaluation of this treatment's effectiveness under different edaphoclimatic conditions. This is needed to establish the security of investments in this technology, even more so when made by farmers in developing countries and with water availability challenges.

Thus, the objective of this work was to evaluate the influence of different soil water tensions at the initiation of irrigation with magnetically treated water on iceberg lettuce Lucy Brown (*Lactuca sativa* L.) development and production.

METHODS

Study site

The experiment was conducted in a greenhouse (7 x 30 m in size, with transparent 150 µm plastic with anti-UV additive on the top, and anti-aphid screen on the sides), in the south of Minas Gerais, Brazil (21°14'S, 45°00'W and 910 m amsl). According to the Köppen-Geiger classification, the region´s climate is Cwa (subtropical climate with dry winter, temperatures below 18°C, and hot summer, with temperatures above 22°C), with a mean annual air temperature of 20.4°C and mean annual precipitation of 1 460 mm (Alvares et al., 2013).

During the experiment, the air temperature and relative humidity were monitored with a digital thermohygrometer (model HT-600, from Instrutherm), installed in a meteorological shelter inside the greenhouse (2 m above ground level). In addition, water evaporation was monitored inside the greenhouse with a mini-evaporimeter (cylindrical stainless-steel container with 60 cm in diameter and 25 cm high).

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 analyses of the soil, referring to the depths of 0 to 20 cm and 20 to 40 cm.

Table 1. Chemical and physical soil analysis results from the experimental area soil, referring to the depths of 0 to 20 cm and 20 to 40 cm[1]

Parameter (unit)	Depth (cm)	
	0–20	20–40
pH	6.60	6.40
K ($mg{\cdot}dm^{-3}$)	87.00	39.22
P ($mg{\cdot}dm^{-3}$)	10.03	4.89
Ca ($cmolc{\cdot}dm^{-3}$)	4.82	4.16
Mg ($cmolc{\cdot}dm^{-3}$)	2.10	1.83
Al ($cmolc{\cdot}dm^{-3}$)	0.04	0.04
H+Al ($cmolc{\cdot}dm^{-3}$)	1.03	1.10
SB ($cmolc{\cdot}dm^{-3}$)	7.14	6.09
t ($cmolc{\cdot}dm^{-3}$)	7.18	6.13
T ($cmolc{\cdot}dm^{-3}$)	8.17	7.19
V (%)	87.43	84.71
m (%)	0.56	0.65
M.O. ($dag{\cdot}kg^{-1}$)	2.96	2.39
P-Rem ($mg{\cdot}L^{-1}$)	67.10	67.70
Zn ($mg{\cdot}dm^{-3}$)	2.98	1.79
Fe ($mg{\cdot}dm^{-3}$)	63.13	57.76
Mn ($mg{\cdot}dm^{-3}$)	85.78	68.12
Cu ($mg{\cdot}dm^{-3}$)	5.46	5.27
B ($mg{\cdot}dm^{-3}$)	0.28	0.27
S ($mg{\cdot}dm^{-3}$)	64.37	61.33
Sand (%)	10	
Silt (%)	29	
Clay (%)	61	
ρ_s ($g{\cdot}cm^{-3}$)	1.14	

[1]*K – potassium; P – phosphorus; Ca – calcium; Mg – magnesium; 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;* m *– aluminium saturation index; M.O. – organic matter; P-Rem – remaining phosphorus; Zn – zinc; Mn – manganese; Cu – copper; B – boron; S – sulfur;* ρ_s *– soil bulk density*

Crop implantation

Lettuce cultivar Lucy Brown (*Lactuca sativa* L.) seedlings were transplanted into 24 manually constructed beds (bed area (A) of 2.88 m^2, equivalent to 1.2 x 2.4 m), 23 days after sowing, at a spacing of 0.30 x 0.30 m (32 plants per bed).

The crop planting and cover fertilizations were the same for all beds, and carried out based on the results of the chemical analysis of the soil, following recommendations of Ribeiro et al. (1999).

For planting, 30 $t{\cdot}ha^{-1}$ of manure (8.64 $kg{\cdot}bed^{-1}$) and 1 $t{\cdot}ha^{-1}$ of NPK fertilizer (4-30-10 ratio, 0.288 kg per bed) were used. The cover fertilization was carried out 10 and 20 days after transplanting, applying 30 $g{\cdot}m^{-2}$ of ammonium sulfate (86.4 $g{\cdot}bed^{-1}$) and 5 $g{\cdot}m^{-2}$ of potassium chloride (14.4 g per bed).

In order to guarantee the survival of the seedlings after transplanting, as well as to standardize the size of the plants, daily irrigation was carried out for 8 days after transplanting, in order to maintain the soil moisture at the field capacity. The total irrigation depth at this phase was 15.85 mm (average 1.98 $mm{\cdot}d^{-1}$).

Experimental design and treatments

The experimental design was completely randomized, in a factorial 2 x 4, with 3 replications (R1, R2 and R3). The treatments consisted of the two types of water (magnetically treated water – MW; and ordinary water – OW) and four soil water tensions to start irrigation (T1 – 15 kPa, T2 – 25 kPa, T3 – 40 kPa and T4 – 70 kPa) combinations.

Figure 1A shows the treatment distribution in the experimental area, as well as the location of tensiometers used in irrigation management. Figure 1B presents the details of the equipment distribution in the beds, and the designation of the useful plot (8 plants) and the border plants. Each bed had 32 plants (n_p).

The Sylocimol Residential Magnetizer was used for the water treatment. This equipment is composed of alternating magnets that subject the water to a 3860 G magnetic field, with the capacity to magnetize 1 000 L in 1 h of exposure. The equipment was located and kept inside a 500 L water tank throughout the experiment. The soil water tension treatments were related to values for initiation of irrigation, with sufficient water depth to raise the soil moisture to field capacity. The water was collected from an earth dam reservoir close to the experimental area.

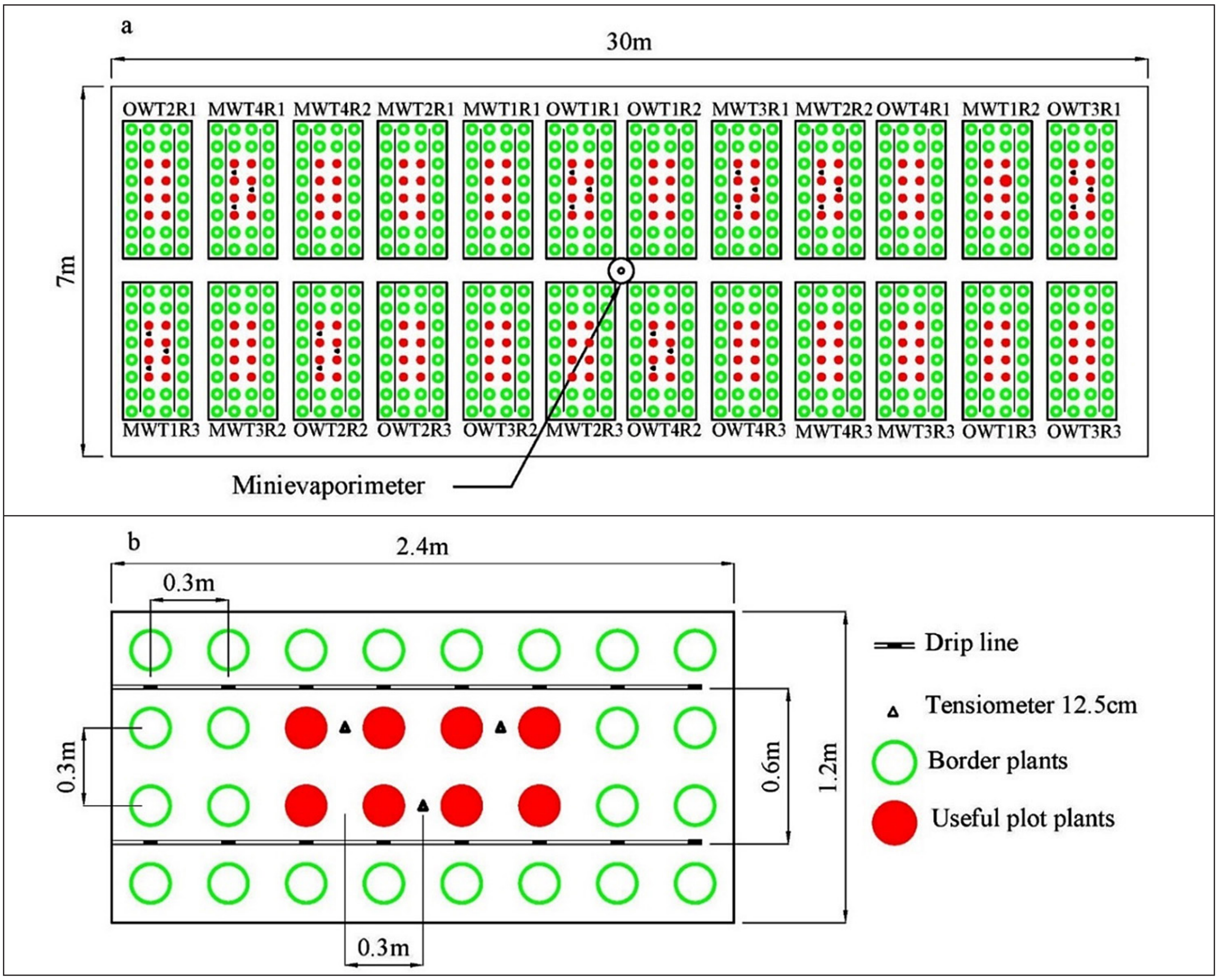

Figure 1. (a) Treatment distribution in the experimental area and location of tensiometers. (b) Details of the equipment distribution in the beds, and designation of the useful plot (8 plants) and the border plants

Irrigation management and experimental conduction

The soil water retention curve used was generated from data from in-situ evaluation, following recommendations by Jabro et. (2009), carried out in the experimental area (Eq. 1).

$$\theta_l = 0.44554 - 0.04528\ \ln(|\Psi_m|) \tag{1}$$

where θ_l is the volumetric soil moisture ($cm^3 \cdot cm^{-3}$), and Ψ_m is the soil water tension or matric potential (kPa).

The soil water tension (retention of water by solid soil surfaces) was estimated by Eq. 2 using the average readings (L) of 3 tensiometers for each treatment. Tensiometers were installed at 0.125 m depth. This depth corresponds to half of the 'iceberg' lettuce crop effective root depth (z = 25 cm) (Murakami et al., 2002; Yuri et al., 2002). The water column height inside the tensiometers (h) was 22.5 cm.

$$\Psi_m = L - 0.098 \cdot h \tag{2}$$

where L is the average tensiometer reading (kPa), and h is the water column height inside the tensiometers (cm).

Tensiometer readings were performed twice a day (9:00 and 15:00), with a digital tensimeter (Hidrodinâmica Irrigation). Estimation of net irrigation depth (LL) was made using Eq. 3:

$$\text{LL} = (\theta_{cc} - \theta_l) \cdot z \tag{3}$$

where LL is the net irrigation depth (mm), θ_{cc} is the volumetric soil moisture at field capacity ($cm^3 \cdot cm^{-3}$), and z is the lettuce effective root depth (mm).

The soil of the experimental area had volumetric moisture and soil water tension at field capacity equal to 0.341 $cm^3 \cdot cm^{-3}$ and 10 kPa, respectively. This information was used to carry out irrigation management for the experiment, where a drip system was used (95.4% irrigation system uniformity of distribution – UD), composed of ClickTif NaanDanJain pressure-compensating emitters (average flow – qa, of 2.14±0.08 $L \cdot h^{-1}$), at 0.3 m spacing (16 emitters per bed – n_e).

Equation 4 was used to estimate the gross irrigation depth (LB). A system application efficiency value (E_a) of 95% was adopted according to Pizarro Cabello's (1996) recommendations. The irrigation time (T) was estimated by Eq. 5.

$$\text{LB} = \frac{\text{LL}}{E_a \text{UD}} \tag{4}$$

where LB is the gross irrigation depth (mm), E_a is the application efficiency (decimal), and UD is the irrigation system uniformity of distribution (decimal).

$$T = \text{LB} \cdot \frac{A}{n_e q_a} \cdot 60 \tag{5}$$

where T is the irrigation time (min), A is the bed area (m^2); q_a is the average flow of the emitters ($L \cdot h^{-1}$), and n_e is the number of emitters per bed.

Evaluated parameters

Crop development

During the experiment 3 plants of each treatment replicate were photographed weekly, until the 49th day after transplanting. Figure 2 shows the scheme used to photograph the plants, as well as an example picture taken during the experiment.

Using the ImageJ software (1.52a version), the average exposed area of the photographed plants (Ap) was estimated over time for each treatment. The ruler readings were used to validate the information processed in the software. The time when the maximum exposed area (Apmax) occurred was determined.

After harvesting (57 days after transplanting) the stem length and diameter (L_s and D_s) of the plants were measured with a digital pachymeter (accuracy of 0.01 mm).

The percentage of leaves with tip-burn (PFtb) was also assessed (Eq. 6). Tip-burn is characterized as a physiological disorder due to calcium deficiency, burning the edges of young leaf growth points, favouring the entry of microorganisms (Yuri et al., 2006; Turini et al., 2011).

$$\text{PLtb} = \frac{\text{NLtb}}{\text{NLt}} \text{ x } 100 \qquad (6)$$

where PLtb is the percentage of leaves with tip-burn (%), NLtb is the number of plant leaves with tip-burn, and NLt is the total number of plants leaves.

Crop productive parameters

The productive parameters evaluated were: total fresh and dry weight of the plants aerial shoot (FW_t and DW_t); commercial head fresh and dry weight (FW_c and DW_c); fresh and dry root weight (FW_r and DW_r); fresh and dry stem weight (FW_s and DW_s); total and commercial yield (Y_t and Y_c); water use efficiency related to total and commercial yield (WUE_t and WUE_c); and dry matter content (C).

Fresh weights were measured immediately after harvest with a digital scale (0.01 g accuracy). Following the guidelines of Yuri et al. (2004), the commercial fresh weight (FW_c) was determined after the removal of the darker external leaves that were in contact with the soil, leaving the lighter and more compact leaves. The dry weights were measured after drying the constituents in a forced circulation oven at 65°C.

The total and commercial yield (Y_t and Y_c, respectively) were estimated using Eqs 7 and 8:

$$Y_t = 0.01\frac{n_p FW_t}{A} \qquad (7)$$

where Y_t is the total yield (t·ha^{-1}), n_p is the number of plants in a bed, FW_t is the total fresh weight of the plant aerial parts, and A is the bed area (m^2).

$$Y_c = 0.01\frac{n_p FW_c}{A} \qquad (8)$$

where Y_c is the commercial yield (t·ha^{-1}), FW_c is the commercial head fresh weight of the plants.

Water use efficiency related to total and commercial yield (WUE_t and WUE_c, respectively) were estimated using Eqs 9 and 10:

$$\text{WUE}_t = \frac{Y_t}{\Sigma \text{LB}} \qquad (9)$$

where WUE_t is the water use efficiency related to total yield (t·ha^{-1}·mm^{-1}), Y_t is the total yield (t·ha^{-1}), and ΣLB is the gross irrigation depth applied to each treatment (mm).

$$\text{WUE}_c = \frac{Y_c}{\Sigma \text{LB}} \qquad (10)$$

where WUE_c is the water use efficiency related to commercial yield (t·ha^{-1}·mm^{-1}), Y_c is the commercial yield (t·ha^{-1}).

The dry matter content (C) is the ratio between the total dry (DW_t) and fresh (FW_t) weight of the plants' aerial parts (Eq. 11). According to Di Gioia et al. (2017), this index quantifies the conversion percentage from fresh to dry matter.

$$C = \frac{\text{DW}_t}{\text{FW}_t}100 \qquad (11)$$

where C is the dry matter content (%), DW_t is the average total dry weight of the plants aerial shoot (g·plant^{-1}), and FW_t is the average total fresh weight of the plants aerial part (g·plant^{-1}).

Data analysis

The data were subjected to analysis of variance by the F Test at 5% probability, and the factors that showed significant differences were analysed using the Tukey test, also at 5% of probability, using the software SISVAR 5.7 (Ferreira, 2011).

RESULTS AND DISCUSSION

Experimental weather conditions

The air temperature recorded inside the greenhouse during the experiment were as follows: maximum temperature of 31.0 ± 2.4°C, minimum temperature of 19.0 ± 1.8°C, and average temperature of 25.0 ± 1.5°C. For air relative humidity, maximum value was 91.2 ± 6.3%, minimum 41.0 ± 9.2%, and average 66.1 ± 5.9%. For daily evaporated depth in the mini-evaporimeter, the maximum, minimum and average values were 8.91, 0.42 and 3.58 mm·d^{-1}, respectively.

Figure 3 shows the temporal variability of the average, maximum and minimum air temperature, and relative humidity during the experiment, as well as the daily values of the evaporated water depth in the mini-evaporimeter.

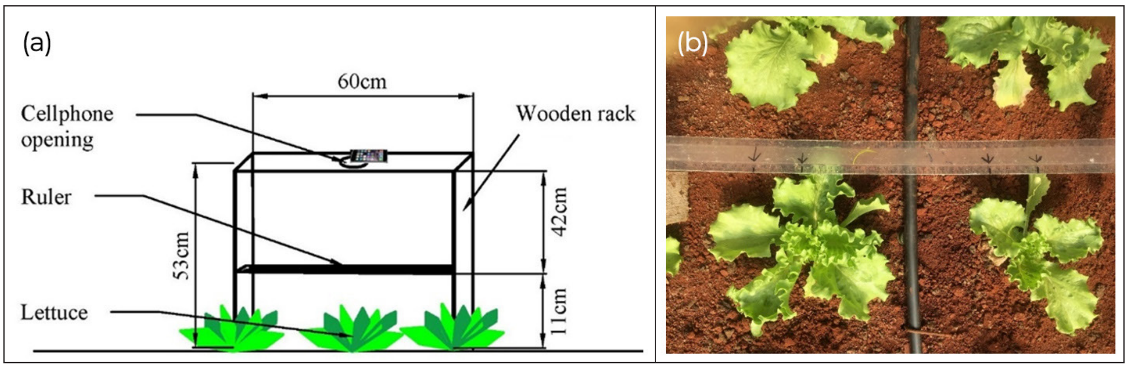

Figure 2. (a) Scheme of the structure used to take photographs of the plants in the experiment., (b) Example of a photo taken with details of the graduated ruler and the plants (b).

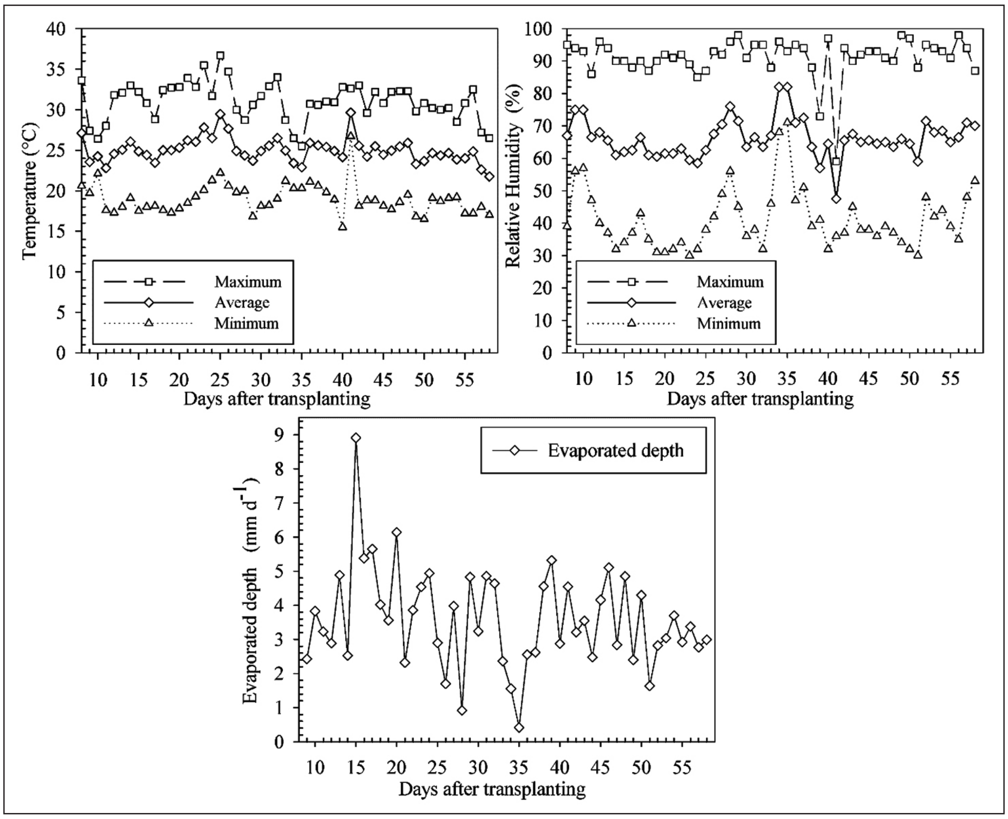

Figure 3. Maximum, average, and minimum temporal variability of air temperature, relative humidity, and evaporated water depth in the mini-evaporimeter, as a function of days after transplanting

According to FAO Plant Production and Protection Paper No. 230 (Baudoin et al., 2017), lettuce crop performance is greatly influenced by weather conditions, with better development occurring in the air temperature range of 7 to 23°C, and relative humidity range 75 to 85%. Despite these guidelines, Valeriano et al. (2016) obtained satisfactory development in lettuce subjected to an average temperature of 32.5°C and an average relative humidity of 62%.

Crop development

Figure 4 presents average exposed area (Ap) of the lettuce plant as a function of the days after transplanting for the different experimental combinations.

Application of magnetically treated water resulted in a lower value of maximum exposed area (Apmax) – approximately 528 cm^2 for magnetically treated water, and 658 cm^2 for ordinary water. Additionally, it was observed that the timing of Apmax occurred around 42 days after transplanting for both types of water. Conversely, Putti et al. (2015a) observed a shorter development time for iceberg lettuce using magnetically treated water compared to ordinary water. Additionally, Adeniran et al. (2020) observed an increase in leaf area and height of Lagos spinach plants when using water subjected to magnetic treatment.

According to some authors, the magnetic treatment process results in water becoming more cohesive, with water clusters having smaller dimensions, causing greater attraction to soil particles and less movement of water in soil pores (Al-Ogaidi et al., 2017; Mostafazadeh-Fard et al., 2011; Surendran et al., 2016). The authors explain that the increase in cohesion is the result of the molecules being released from reaction with ions via hydrogen bonds and van der Waals forces, leading to greater ease of water penetration into soil micropores, reducing percolation. Additionally, the authors explain that calcium carbonate ions in the water form aragonite crystals after magnetic treatment, which are deposited in the soil. This elevates the soil osmotic potential, decreasing crop evapotranspiration and maintaining soil moisture content for a longer period. Surendran et al. (2016) pointed out that the maintenance of soil moisture for a longer time may also be associated with reduced evaporative capacity. Kareem and Adeniran (2020) also observed a reduction in Lagos spinach (*Celosia argentea*) evapotranspiration with the use of magnetically treated water.

As presented, the magnetic treatment of water resulted in lower soil water tension, maintaining soil moisture for a longer time, which would facilitate water and nutrient uptake by crops. However, based on the lower values recorded for average plant exposed area with magnetically treated water, it is hypothesized that, although soil moisture is retained for longer, the increase in water retention by the soil may have decreased water evaporation from the soil and, additionally, increased resistance for uptake of water by plant roots.

Regarding lettuce stem length (L_s) and diameter (D_s) for the different experimental combinations, there were no significant differences ($p \leq 0.05$) for any of the factors evaluated. Average lettuce stem length and diameter were 93.3 and 16.1 mm, respectively.

Maboko et al. (2007) recorded higher values for Lucy Brown lettuce in hydroponic cultivation, being 122.8 and 28.4 mm in length and stem diameter, respectively. According to Yuri et al. (2002), 'iceberg' lettuce stem length is important in the processing of the product, where values below 60 mm are the most appropriate, being acceptable up to 90 mm. According to Neves et al. (2016), smaller stems decrease losses in processing, determine greater compactness to the heads of lettuce, and have greater bolting resistance (number of days between sowing and initial stem elongation, with the formation of floral structures). The average values achieved here (L_s = 93.3 mm and D_s = 16.1 mm) are thus not within the recommended limits.

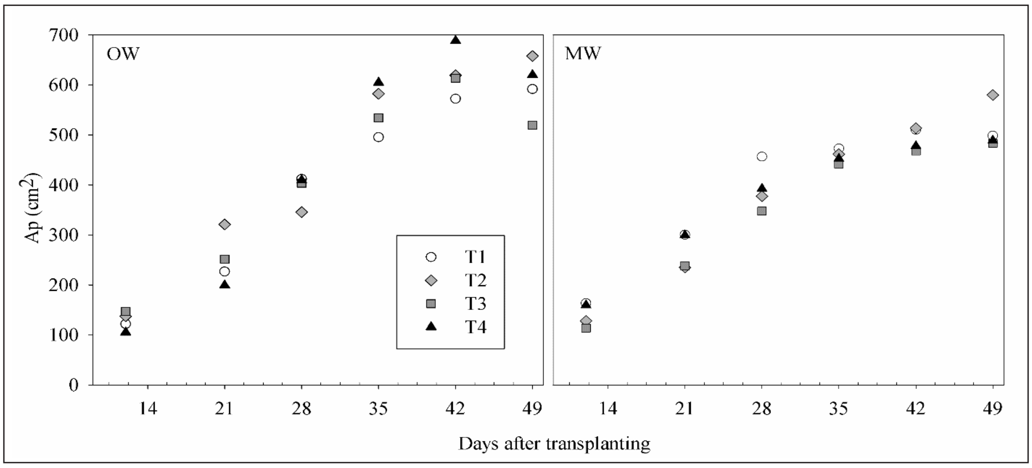

Figure 4. Average exposed area of the lettuce plant (cm²) as a function of days after transplanting, for the different combinations of soil water tension at initiation of irrigation (T1, T2, T3 and T4) and water type (OW and MW)

A possible cause of the longer stem length achieved in the experiment may be the air temperature (Al-Said et al., 2018; Neves et al., 2016; Baudoin et al., 2017). These authors recommend an ideal air temperature range of 7 to 23°C for lettuce, whereas the present experiment recorded an average value of 25°C and occurrences of even higher temperatures (Fig. 3).

Table 2 shows the results of the Tukey test ($p \leq 0.05$) conducted for the percentage of leaves with tip-burn (PLtb) vs the different experimental combinations.

Significant differences ($p \leq 0.05$) were observed in PLtb only for type of water in the soil moisture condition closest to the field capacity (T1 treatment), with an increase of 75.62% with use of magnetically treated water. As the use of magnetically treated water was able to maintain soil moisture for a longer time (Fig. 4), this may have increased the occurrence of lettuce tip-burn. Plamondon et al. (2011) demonstrated a significant influence of soil water tension at initiation of irrigation with ordinary water on PLtb, where higher soil moisture determined higher values of PLtb.

Crop production parameters

Table 3 shows the results of a Tukey test ($p \leq 0.05$) on total and commercial fresh weight (FW_t and FW_c), total and commercial dry weight (DW_t and DW_c), fresh and dry root weight (FW_r and DW_r), and fresh and dry stem weight (FW_s and DW_s).

None of the parameters showed significant differences due to the type of water used. The opposite was observed by Putti et al. (2015b), who recorded a significant increase in the fresh weight of iceberg lettuce using water subjected to magnetic treatment. Pradela et al. (2018) observed an increase in the dry weight of lettuce seedling aerial shoots using magnetically treated water. Most authors who have observed a significant effect using magnetically treated water in irrigation, impute this to the water's physical and chemical changes, resulting in improvements in the plant's ability to absorb water and nutrients, in addition to increasing the plant's rate of metabolic activities (Maheshwari and Grewal, 2009; Putti et al., 2015b; Ul Haq et al., 2016; Pradela et al., 2018).

With ordinary water use, it was observed that there were no significant differences ($p \leq 0.05$) for any dependent variable due to the soil water tension at initiation of irrigation. The average values of the parameters were: FW_t = 516.75 g·plant^{-1}, FW_c = 447.21 g·plant^{-1}, DW_t = 15.00 g·plant^{-1}, DW_c = 10.89 g·plant^{-1}, FW_r = 7.38 g·plant^{-1}, DW_r = 0.565 g·plant^{-1}, FW_s = 32.13 g plant^{-1}, and DW_s = 1.26 g plant^{-1}. The average values of FW_t, FW_c and DW_c were close to the values obtained by De Souza et al. (2013), being 574.8 g·plant^{-1}, 412.3 g·plant^{-1} and 14.1 g·plant^{-1}, respectively. Some authors have observed decreases in FW_c values with increasing soil water tension at the initiation of irrigation (Santos and Pereira, 2004; Coelho et al., 2005). In the results presented by Silva et al. (2018) there was no significant difference in FW_t by irrigation depth, however there was an increase in DW_t and a reduction in DW_r with irrigation depth increase. The same trend was found by Putti et al. (2015b) for DW_r.

For the use of magnetically treated water, a significant reduction ($p \leq 0.05$) of the parameters FWt, FW_c, DW_t, FW_r, FW_s and DW_s was observed with an increase soil water tension at initiation of irrigation, being: T1 > T2 = T3 > T4 for FW_t, T1 = T2 = T3 > T4 for FW_c, T1 = T2 > T3 = T4 for DW_t, T1> T2 = T3 = T4 for FW_r, T1 = T2 = T3 > T4 for FWs, and T1 > T2 = T3 = T4 for DW_s. Analogous to these results, Putti et al. (2015b) obtained an increase in iceberg lettuce FW_t, DW_t and FW_r with increase in magnetically treated water depth. Zlotopolski (2017) also obtained benefits from an increase in depth increase, resulting in an increase in lettuce FW_t.

The parameters of DW_c and DW_r did not show a significant influence ($p \leq 0.05$) of modifying soil water tension at initiation of irrigation using magnetically treated water. Average values for DW_c and DW_r were 11.67 and 0.633 g·plant^{-1}, respectively.

Considering the hypothesis that irrigation with magnetically treated water resulted in an increase in the resistance to water uptake by the plants, the increase in soil water tension at the initiation of irrigation intensified this resistance, resulting in a decrease in most of the production parameters. This contradicts what has been reported observed by some authors, who recorded better performance in the productive parameters of several crops using magnetically treated water. An increase in total and commercial fresh weight, as well as fresh root weight, and amount of nutrients absorbed by plants was observed with magnetically treated water, even for the lowest water depths (Putti et al., 2015b; Yusuf and Ogunlela, 2017; Zlotopolski, 2017; Selim et al., 2019; Adeniran et al., 2020).

Table 4 shows the results for Tukey tests ($p \leq 0.05$) on total and commercial yield (Y_t and Y_c, respectively), water use efficiency referring to total and commercial yield (WUE_t and WUE_c), and dry matter content (C), for different experimental combinations.

The type of water significantly influenced ($p \leq 0.05$) the WUE_t (average of 0.69 t·ha^{-1}·mm^{-1} for MW, and 0.48 t·ha^{-1}·mm^{-1} for OW) and WUE_c (average of 0.62 t·ha^{-1}·mm^{-1} for MW, and 0.42 t·ha^{-1}·mm^{-1} for OW), when using tension T1 for irrigation management. An increase of 43.8 and 47.6% for WUE_t and WUE_c, respectively, was observed using magnetically treated water compared to ordinary water. Conversely, Putti et al. (2015b) found an increase in lettuce yield and dry weight using magnetically treated water.

In the use of magnetically treated water, a significant reduction ($p \leq 0.05$) of Y_t, Y_c, WUE_t, and WUE_c was observed with increasing soil water tension at initiation of irrigation: T1 > T2 = T3 > T4 for Y_t, T1 = T2 = T3 > T4 for Y_c, T1 > T2 = T3 = T4 for WUE_t, and T1 > T2 = T3 = T4 for WUE_c. For parameter C, an increase was observed with increasing soil water tension at initiation of irrigation (T4 > T2 > T1 = T3).

Table 2. Percentage of lettuce leaves with tip-burn (%), for different combinations between soil water tensions at initiation of irrigation (T1, T2, T3 and T4) and water type (OW and MW)[1]

Type of water	Soil water tension at initiation of irrigation			
	T1	T2	T3	T4
Ordinary water	16.01 bA	17.00 aA	17.41 aA	18.94 aA
Magnetically treated water	28.09 aA	14.72 aA	14.84 aA	19.29 aA

[1]*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 at initiation of irrigation (Tukey test)*

Table 3. 'Iceberg' lettuce total and commercial fresh weight (FW_t and FW_c), total and commercial dry weight (DWt and DWc), fresh and dry root weight (FW_r and DW_r), and fresh and dry stem weight (FW_s and DW_s), for the different experimental combinations[1]

Parameter	Type of water	Soil water tension to start irrigation			
		T1	T2	T3	T4
FW_t (g·plant^{-1})	Ordinary water	604.77 aA	513.45 aA	544.29 aA	404.50 aA
	Magnetically treated water	563.42 aA	493.23 aB	490.38 aB	315.17 aC
FW_c (g·plant^{-1})	Ordinary water	529.85 aA	414.78 aA	480.29 aA	363.90 aA
	Magnetically treated water	505.63 aA	439.12 aA	435.46 aA	252.53 aB
DW_t (g·plant^{-1})	Ordinary water	15.22 aA	13.92 aA	15.92 aA	14.93 aA
	Magnetically treated water	16.50 aA	16.57 aA	14.00 aB	13.19 aB
DW_c (g·plant^{-1})	Ordinary water	11.23 aA	10.45 aA	10.67 aA	11.40 aA
	Magnetically treated water	13.37 aA	12.39 aA	10.98 aA	9.94 aA
FW_r (g·plant^{-1})	Ordinary water	7.99 aA	7.34 aA	7.05 aA	7.13 aA
	Magnetically treated water	9.68 aA	7.63 aB	7.60 aB	6.91 aB
DW_r (g·plant^{-1})	Ordinary water	0.62 aA	0.54 aA	0.51 aA	0.59 aA
	Magnetically treated water	0.91 aA	0.55 aA	0.58 aA	0.59 aA
FW_s (g·plant^{-1})	Ordinary water	45.14 aA	25.97 aA	35.02 aA	22.37 aA
	Magnetically treated water	32.41 aA	30.67 aA	30.39 aA	13.05 aB
DW_s (g·plant^{-1})	Ordinary water	1.63 aA	1.16 aA	1.25 aA	0.99 aA
	Magnetically treated water	1.45 aA	1.14 aB	1.16 aB	0.7 aB

[1]*Different lowercase letters in the vertical differ significantly* (p ≤ 0.05) *with changing water type for the same parameter, and different uppercase letters in the horizontal differ significantly* (p ≤ 0.05) *with changing soil water tension at initiation of irrigation (Tukey test)*

Table 4. Total and commercial yield (Y_t and Y_c), water use efficiency referring to total and commercial yield (WUE_t and WUE_c), and dry matter content (C) of lettuce for the different experimental combinations[1]

Parameter	Type of water	Soil water tension at initiation of irrigation			
		T1	T2	T3	T4
Y_t (t·ha^{-1})	Ordinary water	67.19 aA	57.05 aA	60.48 aA	44.94 aA
	Magnetically treated water	62.60 aA	54.80 aB	54.49 aB	35.02 aC
Y_c (t·ha^{-1})	Ordinary water	58.87 aA	46.09 aA	53.37 aA	40.43 aA
	Magnetically treated water	56.17 aA	48.79 aA	48.38 aA	28.06 aB
WUE_t (t·ha^{-1}·mm^{-1})	Ordinary water	0.48 bA	0.43 aA	0.36 aA	0.46 aA
	Magnetically treated water	0.69 aA	0.38 aB	0.39 aB	0.49 aB
WUE_c (t·ha^{-1}·mm^{-1})	Ordinary water	0.42 bA	0.35 aA	0.31 aA	0.41 aA
	Magnetically treated water	0.62 aA	0.33 aB	0.35 aB	0.39 aB
C (%)	Ordinary water	2.54 aC	2.77 aB	3.04 aB	3.75 aA
	Magnetically treated water	2.95 aC	3.39 aB	2.86 aC	4.19 aA

[1]*Different lowercase letters in the vertical differ significantly* (p ≤ 0.05) *with changing water type for the same parameter, and different uppercase letters in the horizontal differ significantly* (p ≤ 0.05) *with changing soil water tension at initiation of irrigation (Tukey Test)*

With the use of ordinary water, changing the soil water tension at initiation of irrigation only had a significant effect on *C* ($p \leq 0.05$); increasing soil water tension resulted in an increase in *C* (T4 > T3 = T2 >T1). This corroborates the finding of Dos Santos and Pereira (2004), who point out that reduced values of *C* for lettuce crop are desirable, providing more flavour despite obtaining shorter post-harvest storage time/shelf-life.

The average values of Y_t, Y_c, WUE_t, and WUE_c for the tensions using ordinary water were, respectively: 57.42 $t \cdot ha^{-1}$, 49.69 $t \cdot ha^{-1}$, 0.42 $t \cdot ha^{-1} \cdot mm^{-1}$ and 0.37 $t \cdot ha^{-1} \cdot mm^{-1}$. Dos Santos and Pereira (2004) observed a reduction in WUE_t values with increasing soil water tension at initiation of irrigation, ranging from 0.469 $t \cdot ha^{-1} \cdot mm^{-1}$ (−15 kPa) to 0.380 $t \cdot ha^{-1} \cdot mm^{-1}$ (−51.95 kPa). Maggi et al. (2006) recorded the highest value of WUE_t (0.3685 $t \cdot ha^{-1} \cdot mm^{-1}$) for lettuce in irrigation management using −35kPa soil water tension to initiate irrigation. On the other hand, Kirnak et al. (2016) obtained an increase in lettuce yield by increasing irrigation depth. Coelho et al. (2005) observed an increase in Lucy Brown lettuce total and commercial yields with a reduction in soil water tension at initiation of irrigation. These authors observed the highest values of Y_t (69.85 $t \cdot ha^{-1}$) and Y_c (59.40 $t \cdot ha^{-1}$) for the treatment closest to field capacity (−27.92 kPa).

Neves et al. (2016) obtained an average total yield of 24.13 $t \cdot ha^{-1}$ for lettuce Lucy Brown grown on open field and protected environment. According to the authors, this low value was attributed to the occurrence of high temperatures during the experiment.

Lima Junior et al. (2010) observed a quadratic relationship for total and commercial yield for Raider-Plus lettuce vs water depth; total and commercial productivity increased as irrigation depths increased. The maximum total yield was estimated with a water depth of 203.9 mm, equivalent to 65.58 $t \cdot ha^{-1}$, while for commercial lettuce head the maximum point was reached with an irrigation water application of 204.3 mm, resulting in a 35.31 $t \cdot ha^{-1}$ yield. For *Laureau* lettuce, Lima Junior et al. (2012) also found a relationship for total and commercial yield vs water depth that can be explained by a quadratic regression. The maximum point for total yield was estimated with a 159.1 mm irrigation water depth, equivalent to a yield of 66.9 $t \cdot ha^{-1}$; and for commercial head, an irrigation depth of 164.8 mm resulted in a yield of 36.5 $t \cdot ha^{-1}$.

The non-significant effect on total (average of 57.42 $t \cdot ha^{-1}$) and commercial (average of 49.69 $t \cdot ha^{-1}$) yield of lettuce from modifying soil water tension at initiation of irrigation with ordinary water may be explained by the possibility that the error of the soil water retention curve performed in the field (1.3%) may have reduced the necessary differences between irrigation depths, and consequently reduced the possibility of significant differences in the evaluated parameters at the 5% level of probability.

CONCLUSION

Although the use of magnetically treated water increased the water use efficiency of lettuce production (only for the T1 soil water tension), damage to plants was evident as the lowest maximum exposure area and the highest percentage occurrence of tip-burn. In addition, irrigation with magnetically treated resulted in a reduction in crop production parameters with increasing soil water tension at initiation of irrigation, potentially due to a higher resistance to water uptake by the plants. In this context, despite the observed water savings, the use of this technology in crops where water availability is restricted cannot yet be considered, without deeper investigations of technical and economic feasibility, for different crop types and edaphoclimatic conditions.

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