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Effect of Magnetic Water Treatment on the Growth, Nutritional Status, and Yield of Lettuce Plants with Irrigation Rate

Fernando Ferrari Putti [1,*], Eduardo Festozo Vicente [1], Prínscilla Pâmela Nunes Chaves [2], Luís Paulo Benetti Mantoan [2], Camila Pires Cremasco [1], Bruna Arruda [1], Juliane Cristina Forti [1], Josué Ferreira Silva Junior [3], Marcelo Campos [1], André Rodrigues dos Reis [1] and Luís Roberto Almeida Gabriel Filho [1]

1 School of Sciences and Engineering, São Paulo State University (UNESP), Tupã 17602-496, SP, Brazil
2 School of Agriculture, São Paulo State University (UNESP), Rua José Barbosa de Barros, Botucatu 18610-034, SP, Brazil
3 Department of Agronomy, Federal University of Triângulo Mineiro/Iturama, Uberabe 38280-000, MG, Brazil
* Correspondence: fernando.putti@unesp.br; Tel.: +55-(14)-3404-4200

Abstract: Climate change is causing an increase in dry spells, altering rainfall patterns and soil moisture, and affecting water and nutrient plant uptake, which inevitably affects vegetable production. To mitigate this issue, some technologies that allow the maintenance of the ideal soil moisture for the uptake process are being investigated. Considering this, we hypothesize that the use of water treated with a magnetic field can increase water use efficiency in lettuce crop production. Thus, the present study aimed to evaluate the effect of the irrigation rate of magnetically treated water on biomass accumulation and nutrient uptake by lettuce plants. An experiment was conducted in a randomized block design with a 2×5 factorial arrangement of two water sources (conventional water and magnetically treated water) and five irrigation application rates to replace crop evaporation: 25, 50, 75, 100, and 125%, with five replicates. The use of magnetically treated water increased the concentrations of nitrogen and phosphorus in leaves, meaning that it induced higher nitrogen assimilation, leading to increases in agronomical characteristics (leaf number, fresh and dry shoot weight, fresh and dry root weight). The conclusions of this study showcase that magnetically treated water has beneficial effects on lettuce plants, improving their nutritional status and yield. Moreover, the results presented can lead to an increase in water use efficiency, thus optimizing irrigation management.

Keywords: *Lactuca sativa*; magnetic field; nutrients; water depth

Citation: Putti, F.F.; Vicente, E.F.; Chaves, P.P.N.; Mantoan, L.P.B.; Cremasco, C.P.; Arruda, B.; Forti, J.C.; Junior, J.F.S.; Campos, M.; Reis, A.R.d.; et al. Effect of Magnetic Water Treatment on the Growth, Nutritional Status, and Yield of Lettuce Plants with Irrigation Rate. *Horticulturae* **2023**, *9*, 504. https://doi.org/10.3390/horticulturae9040504

Academic Editor: Daniel Drost

Received: 3 March 2023
Revised: 11 April 2023
Accepted: 14 April 2023
Published: 19 April 2023

1. Introduction

Lettuce (*Lactuca sativa*) is one of the most produced, commercialized, and consumed vegetables in Brazil, as it can be produced all year round and has desired culinary characteristics and consumer acceptance [1].

A common feature of leafy vegetables, such as lettuce, is the large transpiration area. Thus, the cultivation of these vegetables, in general, requires irrigation technology for water supply to guarantee the crop needs [2]. In addition to water availability, nutritional balance is another critical factor for lettuce development. Plant growth and development depend on a balanced supply of macro- and micronutrients, and the amount varies depending on the developmental stage and environmental and stress conditions, where excesses and deficiencies of macro- and micronutrients can be harmful to the plant metabolism [3]. These two factors (water and nutritional balance) are intrinsically linked since nutrient uptake, transport, and translocation are water-dependent during all phases of plant growth and development [4–6]. Nutrient uptake by plants is directly influenced by soil tension, which affects plant development through low nutrient uptake values [7].

Irrigation in agriculture may increase crop productivity because the water supply can be regulated to each crop species according to the specific demand, avoiding the deficit or excess of water. Brazil has an extensive irrigated area, counting approximately seven million hectares, being among the ten largest irrigated areas in the world [5]. However, the quantity of available irrigation water has decreased over the years, driving the development of strategies to reduce water consumption without impacting the productivity of crops that are dependent on irrigation systems.

The effects of a severe deficit of water, depending on the phenological stage of the plant, may be irreversible, preventing the plant from completing its cycle [8]. This process occurs because the plant suffers a reduction in leaf area, as well as in the number of stomata, which consequently leads to a decrease in the absorption of water and nutrients, thus reducing photosynthesis activity [9,10], due to photo-oxidation and degradation of chlorophyll [11].

To mitigate this issue, some technologies that allow the maintenance of the ideal soil moisture for the uptake process are being investigated [12]. In this context, studies using magnetically water treatment in irrigation systems demonstrate positive effects such as an increment in the soil moisture and a reduction in the volume of water applied [13–15], resulting in increased nutrient uptake by the plants. In addition, gains in the yield were observed. Beneficial effects of irrigation with magnetically treated water were reported for tomatoes [16,17], wheat [18], and eggplant [19]. The authors related these results to the fact that the magnetic field is able to cause alternations in the osmotic pressure, resulting in the improvement of cellular capacity to absorb water [20]. The desired effect of magnetically treated water on nutrient uptake may be attributed to an increase in membrane permeability by reorientation of membrane phospholipids, which subsequently affect sodium and calcium channels in the membrane, leading to the entry of ions into the cell [21,22].

Several studies characterized the magnetically treated water and pointed out alterations in pH, electrical conductivity, tension, and adsorption [23–25]. The magnetically treated water, once applied in the soil, was reported to lead to changes, such as the reduction of water retention in the ground, thus providing a decrease in water tension, which was related to the alterations in the water structure [26,27].

The achievement of water and nutrient balance in plants may influence the enzymatic and photosynthetic activity (chlorophyll and reactive oxygen species), as well as primary metabolisms [28–34]. Therefore, the objective of this study was to evaluate the effect of magnetically treated water on the nutrient concentration and yield of lettuce plants, a leafy vegetable, in two cultivation cycles, under rain-protected conditions, and in different irrigation rates of water supply.

2. Materials and Methods

2.1. Experimental Area

The experiment was conducted from January to May 2013 in a greenhouse located in the experimental area of the Department of Rural Engineering of the São Paulo State University (UNESP), Botucatu City, São Paulo state, Brazil, at geographical coordinates 22°51′ S, 48°26′ W and altitude of 786 m [35]. According to the Köppen classification [36], the region has a Cfa-type climate (humid subtropical).

The experiment was conducted under a rain-protected environment in a tunnel greenhouse measuring 27 m in length and 7 m in width, with a side height of 1.7 m and a center height of 3.0 m. The cover consisted of 150-µm-thick clear additive polyethylene film, and the sides were covered with 30% shade cloth to intercept insects and animals. The length of the greenhouse was oriented from north to south.

The soil in the ground of the greenhouse, where the experiment was conducted, is classified as Dystric Ferralic Nitisol (Rhodic) (according to the World Reference Base for soil resources—WRB) with a moderate medium/clayey structure. The soil chemical characteristics were determined according to Raij [37] and presented as follows: $CaCl_2$ pH 5.9, organic matter 24 g dm^{-3}, P (resin) 191 mg dm^{-3}, H + Al 17 mmol dm^{-3}, K 4.8 mmol dm^{-3}, Ca

68 mmol dm^{-3}, Mg 25 mmol dm^{-3}, sum of bases (SB) 97 mmol dm^{-3}, cation exchange capacity (CEC) 114 mmol dm^{-3}, bases saturation index (V%) 85 mmol dm^{-3}, B 0.51 mg dm^{-3}, Cu 4.8 mg dm^{-3}, Fe 14 mg dm^{-3}, and Zn 8 mg dm^{-3}.

The greenhouse soil was prepared using a micro tractor with a rotating hoe that churned up a surface soil layer of approximately 30 cm. Subsequently, the plots were marked, where each plot had a total area of 5 m^2, and the rows were made with a standard hoe. Weed control was performed manually when necessary.

Soil matric potentials (Ψ) were calculated from disturbed soil samples, according to Richards [38]. The soil moisture values as a function of the matric potentials were: 26.62, 20.96, 19.93, 18.41, 15.8, 15.59, and 14.8 kg kg^{-1} for potentials of 10, 30, 50, 100, 300, 500, and 1500 kPa, respectively.

2.2. Planting and Plant Management

To produce lettuce seedlings (*Lactuca sativa*), pelleted seeds of the Verônica variety were used. One seed per cell was sown in 128-cell expanded polystyrene trays using the commercial Tropstrato substrate (HA-Hortaliças) (pine bark, peat, expanded, and vermiculite). After the seeds had been sown, the trays were kept in a nursery for three days, and to assist the germination, an automatic misting system was used, triggered every 2 h.

Before transplantation, all plots in the greenhouse were irrigated with an automatic misting system to reach the field capacity, calculated using the retention curves (−10 kPa) [39,40].

The germinated seedlings were transplanted to the greenhouse soil, where the experiment was conducted. The spacing between plants was 0.25 m × 0.30 m, and a total of 50 plants were used per plot.

In the first 7 days after transplanting (DAT), no difference in the irrigation water was applied, and during this period, the irrigation rate was equal for all the plots.

After this initial period, the irrigation was applied according to the treatments twice a day: once in the morning and once in the afternoon.

Two cycles of the culture were performed, with 35 days each. The establishment of the second cycle follows the same management and plot locations, with 7 days interval between the cycles.

2.3. Experimental Design and Treatments

The experimental design comprised a factorial 5 × 2, with randomized blocks and five replications. Repetition comprised five lettuce plants. Treatments consisted of five irrigation water application rates based on the percentage of the replacing water lost to crop evaporation: 25, 50, 75, 100, and 125% and two water sources: conventional water (CW) and magnetically treated water (MW).

2.4. Conventional Water and Magnetic Treatment of Water

In this study, a magnetizer (Sylocimol Rural) was used to obtain the MW. The equipment used is capable of magnetizing 1000 L of water in 20 min and was developed with permanently oriented magnets and stainless steel that exposes the water to a magnetic field of 3860 Gauss or 0.386 T. The magnetic water was stored in tanks of 500 L capacity, and magnetization was kept constant.

For the chemical monitoring purpose of the CW and MW, macro- (P, K, S), micronutrients (Cu, Mo, Zn, Fe, Mn, Ni), Na, Ba, Cd, Cr, pH, and electrical conductivity (EC) were determined. Magnetic water samples were taken right after magnetic treatment, before application, and carried out for 96 h at 0; 1; 2; 3; 4; 5; 6; 12; 24; 48; 72; and 96 h after the sample. The analytical determinations for both CW and MW were carried out by atomic emission spectrometry NexION 300D (PerkinElmer) with inductive plasma. The results for CW chemical characterization are presented as follows: P 147 µg kg^{-1}, K 575 µg kg^{-1}, S 254 µg kg^{-1}, Cu 1.94 µg kg^{-1}, Mo 0.30 µg kg^{-1}, Zn 19.7 µg kg^{-1}, Fe 8.92 µg kg^{-1}, Mn 0.78 µg kg^{-1}, Ni 0.33 µg kg^{-1}, Na 3464 µg kg^{-1}, Ba 21.9 µg kg^{-1}, Cd 0.31 µg kg^{-1}, Cr

0.45 μg kg^{-1}, pH 7.33, and EC 68.1 μS cm. The results for MW chemical characterization are presented in Figure 1.

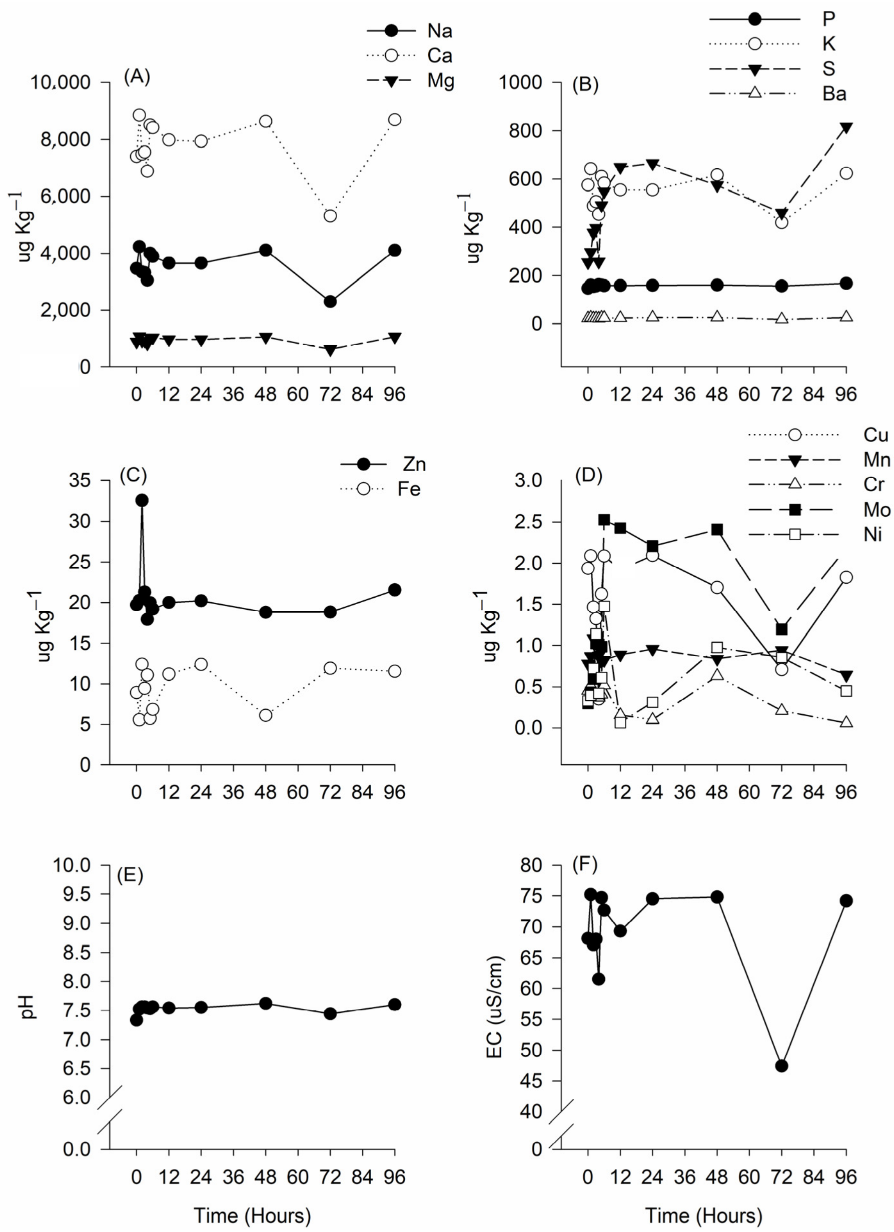

Figure 1. Chemical characterization of water treated magnetically. The monitoring was performed for 96 h (0; 1; 2; 3; 4; 5; 6; 12; 24; 48; 72; and 96 h after treatment). (**A**) (Na, K, Mg); (**B**) (P, K, S, Ba); (**C**) (Zn, Fe); (**D**) (Cu, Mn, Cr, Mo, Ni); (**E**) pH; (**F**) (pH); electrical conductivity (EC).

2.5. Irrigation Management

A drip-type irrigation method was used with two independent systems: one for CW and another for MW. Each system was counted with an independent water tank with 500 L of capacity, and pressure gauges were set to regulate the operation, which was kept at 10-m water column (mWc) pressure. For the MW system, piping was built to allow the MW to return to the tank, and the water was constantly magnetized.

The main irrigation line consisted of a 1-inch-diameter hose, and all lateral lines were directly inserted into this main line. For the application of the different treatments, a pipe record was installed for each drip line.

Each plot was irrigated with three lines, with 0.30 m of space between drippers, at a mean flow rate of 1.472 L h^{-1} and pressure of 10 m.c.a.

The reference evapotranspiration of the crop (ETo) (mm day^{-1}) was determined by the following equation:

$$ETo = kc.Kp.Eca \quad (1)$$

where kc is the crop coefficient (dimensionless), Kp is the coefficient of the class A tank (dimensionless), and Eca is the evaporation of the class A tank (mm day^{-1}).

The crop coefficient (kc) adopted was the one recommended by Allen et al. [41], which at the beginning (up to 7 DAT) was 0.7 (CW for all the treatments), for the half-season 8–21 DAT) was 1.0 (CW and MW, according to the treatments), and at the end (22–35 DAT) was 0.95 (CW and MW, according to the treatments).

The correction coefficient (Kp) of the class A tank was calculated using the equation proposed by Snyder [42]:

$$Kp = 0.482 + 0.024 \ln (b) - 0.00376{*}W + 0.0045{*}RH \quad (2)$$

where b is the border of the vegetation area around the class A tank (m^2), W is the wind speed at 2 m in height (km day^{-1}), and RH (maximum and minimum) is the mean relative humidity (%).

For the Kp calculation, propose b and W were disregarded, as no vegetation around the class A tank and no wind incidence were presented. A meteorological shelter (inside the greenhouse) containing a digital thermohygrometer was used to monitor the temperature (maximum and minimum) (T) and relative humidity (maximum and minimum) (RH) of the environment. The readings were performed daily at 9:00 a.m. (Figure 2).

The evaporation (Eca) was monitored daily with a class A tank.

To adjust the irrigation water, a distribution uniformity test was performed for the irrigation system, following the procedure proposed by Merriam and Keller [43]. Four lateral irrigation lines were selected, located at the beginning (0 m), at 1/3 (1 m), at 2/3 (2 m), and at the end (3 m) of the derivation line. Four emitters were selected in each lateral line at the same points. Water flow measurements were taken to calculate the coefficient of uniformity (CU) by the following equation:

$$CU = q_{25}/q_a \quad (3)$$

where q_{25} is the average of the 25% lowest flow rate values collected (L h^{-1}), and q_a is the average flow rate measured (L h^{-1}).

To calculate the water sheet to be applied, the application intensity (I) of the system was determined by the equation:

$$I = q/Sd{*}Sl' \quad (4)$$

where q is the flow rate (L.h^{-1}), Sd is the spacing between drippers (m), and Sl' is the spacing between lines (m).

The irrigation was realized daily, and the irrigation time (Ti) (min) was determined by the following equation:

$$Ti = Eto/Ea{*}I \quad (5)$$

where ETo is the evapotranspiration of the reference crop (mm day^{-1}), Ea is the water application efficiency of the system (dimensionless), and I is the intensity of application.

2.6. Soil Moisture, Plant Harvest, and Determination of Plant Nutrients

During the two cycles, soil water tension was measured daily using a set of three tensiometers (Hidrodinâmica) per plot.

The plant harvest was performed 35 DAT for the 1st and 2nd crop cycles, where the border plants were disregarded, and only central plants were evaluated. On these occasions, the leaves were cut from the stalk, the number of leaves was counted, and the fresh mass was obtained. Roots were removed from the soil, washed, and the fresh mass was obtained.

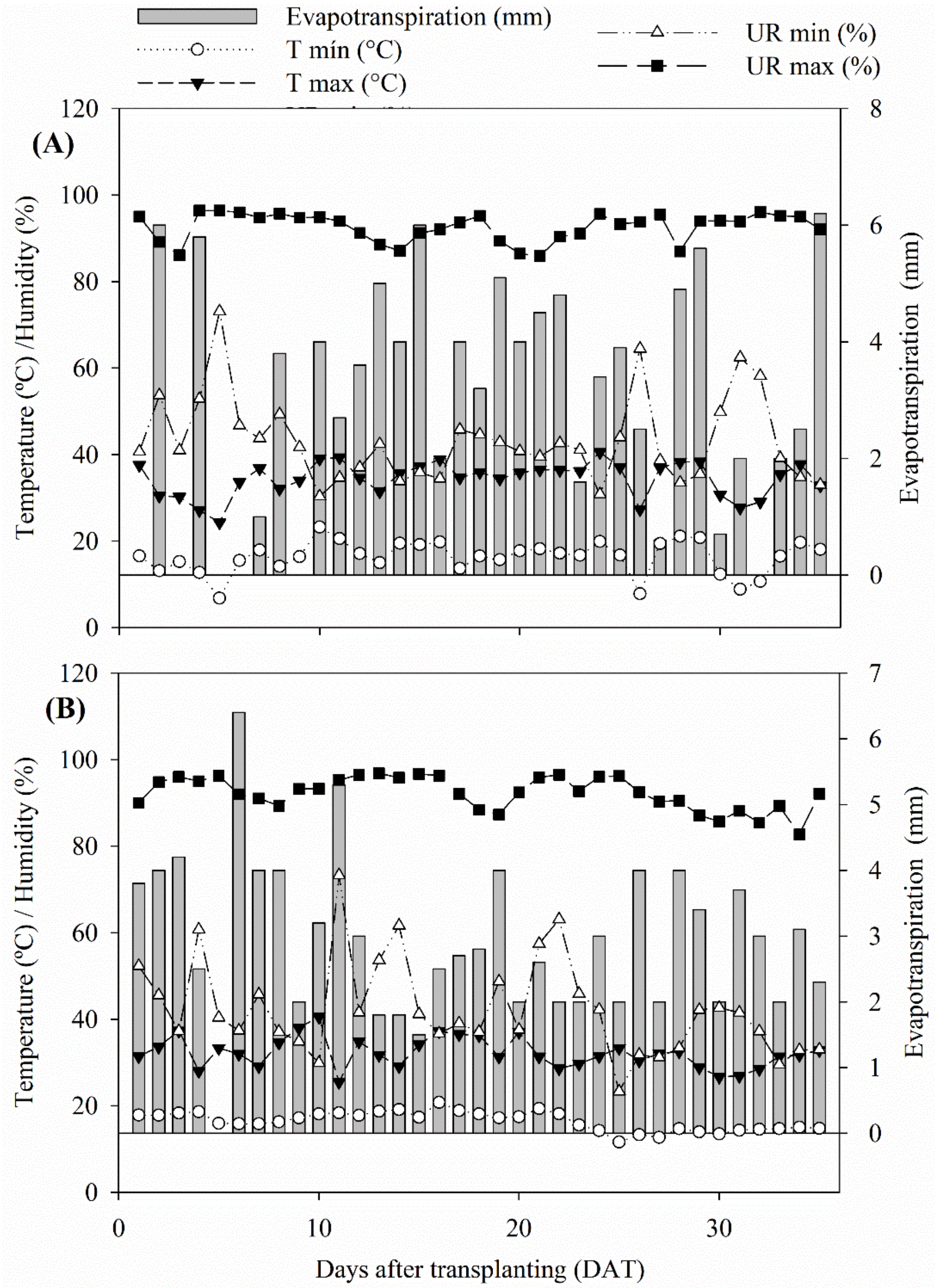

Figure 2. Temperature (Tminimum and Tmaximum), relative humidity (RHminimum and RHmaximum), and evapotranspiration from January to May 2013. Botucatu, São Paulo, Brazil. (**A**) 1st cycle; (**B**) 2nd cycle of the experiment.

To obtain the dry mass of the root and shoot and to quantify the concentration of elements in the shoot, the shoot was washed with deionized water, and the shoot and root were dried in a convection oven for 72 h at 65 °C. After, the dried material was weighed to obtain the dry mass. The shoot was crushed in a Wiley mill (Tecnal Equipamentos, Piracicaba-SP, Brazil) and sieved through 1 mm mesh. Macro- (N, P, K, Ca, Mg, and S) and micronutrients (Fe, B, Cu, Mn, Zn, Si, and Na) in the shoot were determined according to the method proposed by Malavolta et al. [44].

2.7. Statistical Analysis

Analysis of variance ($p \leq 0.01$) with the F test was used to determine the effect of the different irrigation application rates and water types on the lettuce plants and was performed separately for each cycle. When the F test was significant for the interaction between the factors, the unfolding of the interaction was carried out. When the F test was significant for application rates (quantitative), adjust of regression analysis ($p \leq 0.01$) was performed, and the model with the lowest p-value or highest coefficient of determination (R^2) was used. In the soil water tension analysis, the paired t-test was used for each treatment, in which the presence of a significant difference was compared point-to-point [45,46]. Principal component analysis was also performed using the Past 4.10 software.

3. Results

We observed that irrigation with magnetically treated water resulted in greater nutritional increments and greater accumulation of shoots.

3.1. Influence of Magnetic Treatment on Soil Moisture

The replacement rates of 25% and 50% ET_0 in both cycles increased the tension in comparison to the other ET_0, reaching −80 kPa at the end of the cycles, which demonstrates low water availability in the soil (Figure 3A–D). MW showed a reduction in soil water tension, at the end of the cycle, under 50% ET_0, compared to the CW. The replacement rate of 75% ET_0 showed intermediate values, reaching maximum values of −20 kPa at the end of the cycles (Figure 3E–F), and the replacement rate of 100 and 125% showed the lowest values, reaching maximum values of −10 to −14 kPa, constantly maintained along the cycles (Figure 3G–J).

3.2. Influence of Magnetic Treatment on Shoot Concentrations of Macronutrients

The application of magnetic and conventional irrigation water sheets promoted changes in the concentrations of macronutrients in lettuce leaves (Figures 4 and 5). However, for K and S, no significant differences were observed.

Data analysis showed that, for the N concentration ($p < 0.01$), there was an interaction between water type and irrigation depth. The magnetic treatment of water positively influenced the nutrient uptake by lettuce plants. In both cycles, N levels showed a similar trend, where plants irrigated with conventional water and plants irrigated with magnetically treated water showed a second-order effect as a function of the different replacement rates, with maximum levels when an ET_0 of 80% was approached (Figure 4A,B). The P content did not show any effect on the cycle for the type of water and irrigation depth ($p < 0.05$) (Figure 4C,D). However, an increasing linear effect was observed for P in both CW and MW treatments as the ET_0 increased. At the 75 and 100% replacement rates, there was greater accumulation when plants were irrigated with MW ($p < 0.05$).

For the macronutrient Ca (Figure 5A,B), a reduction in the contraction was verified as a function of the irrigation depths ($p < 0.01$). However, higher contents were verified for irrigation with MW under 100% ET_0 in both cycles. Regarding Mg, a decreasing linear effect was observed for the treatments irrigated with CW and MW as the ET_0 increased ($p < 0.01$) (Figure 5C,D), and the same trend as Ca was observed, where higher contents were verified for irrigation with MW under 100% ET_0 in both cycles.

3.3. Influence of Magnetic Treatment on Shoot Concentrations of Micronutrients

For the micronutrients Fe, B, Zn, Si, and Na, no differences were observed. Regarding Cu (Figure 6A), in the 1st cycle, higher contents were observed in plants that were subjected to MW as the ET_0 increased ($p < 0.05$). Nevertheless, a decreasing linear response occurred with CW. In the 2nd cycle, in general, MW showed a higher Cu concentration compared to CW (Figure 6B). For Mn (Figure 6C,D), a decreasing linear response was observed in the treatments irrigated with CW and MW ($p < 0.01$), where MW showed higher Mn concentration in comparison to CW for 25, 50, and 100% ET_0 for the 1st cycle (Figure 6C) and for 50, 75, and 100% ET_0 for the 2nd cycle (Figure 6D).

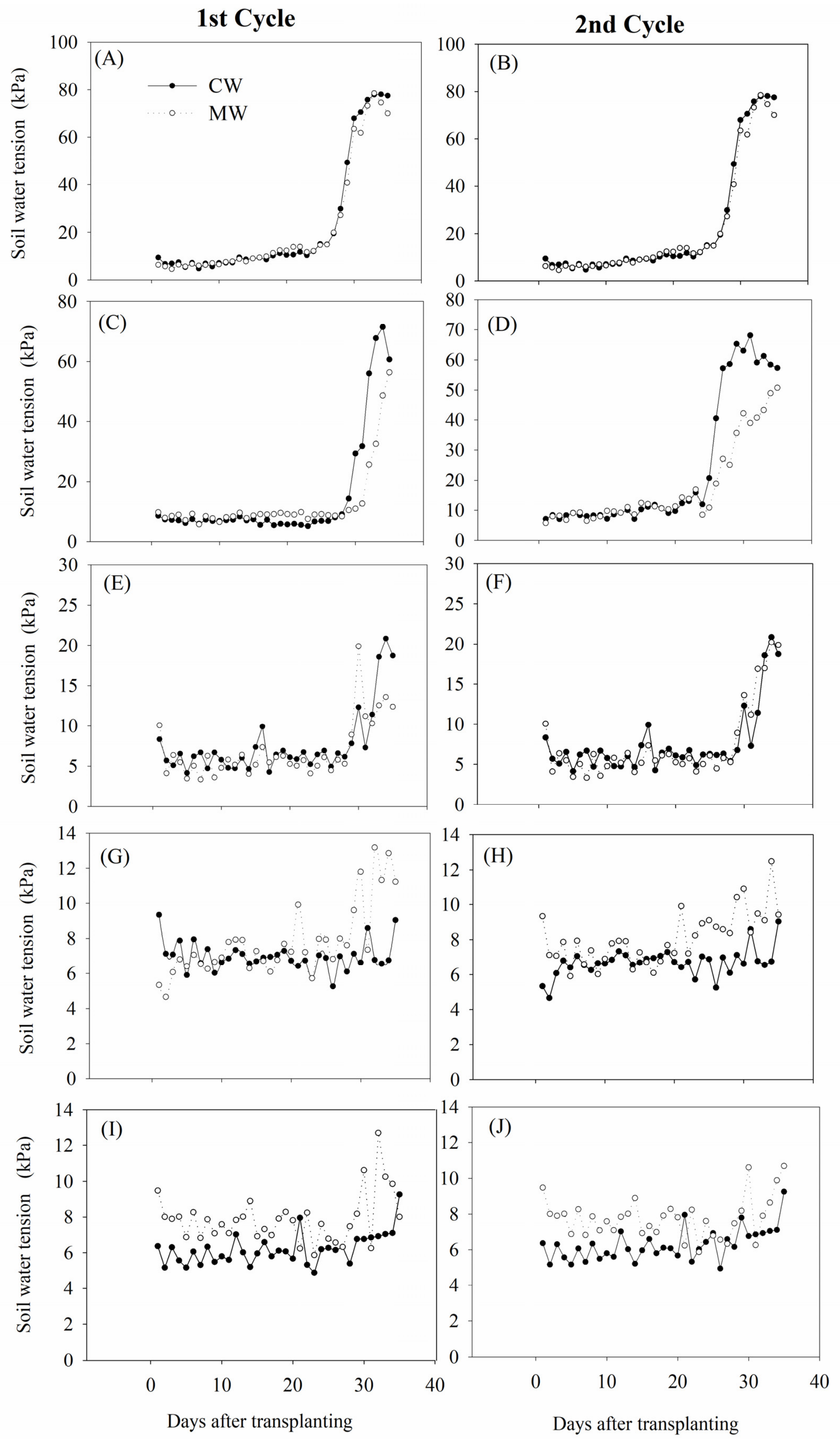

Figure 3. Soil water tension as a function of days after transplantation. (**A**) 1st cycle of the 25% ET_0 irrigation rate; (**B**) 2nd cycle of the 25% ET_0 irrigation rate; (**C**) 1st cycle of the 50% ET_0 irrigation rate; (**D**) 2nd cycle of the 50% ET_0 irrigation rate; (**E**) 1st cycle of the 75% ET_0 irrigation rate; (**F**) 2nd cycle of the 75% ET_0 irrigation rate; (**G**) 1st cycle of the 100% ET_0 irrigation rate; (**H**) 2nd cycle of the 100% ET_0 irrigation rate; (**I**) 1st cycle of the 125% ET_0 irrigation rate; (**J**) 2nd cycle of the 125% ET_0 irrigation rate. CW = conventional water; MW = magnetic water.

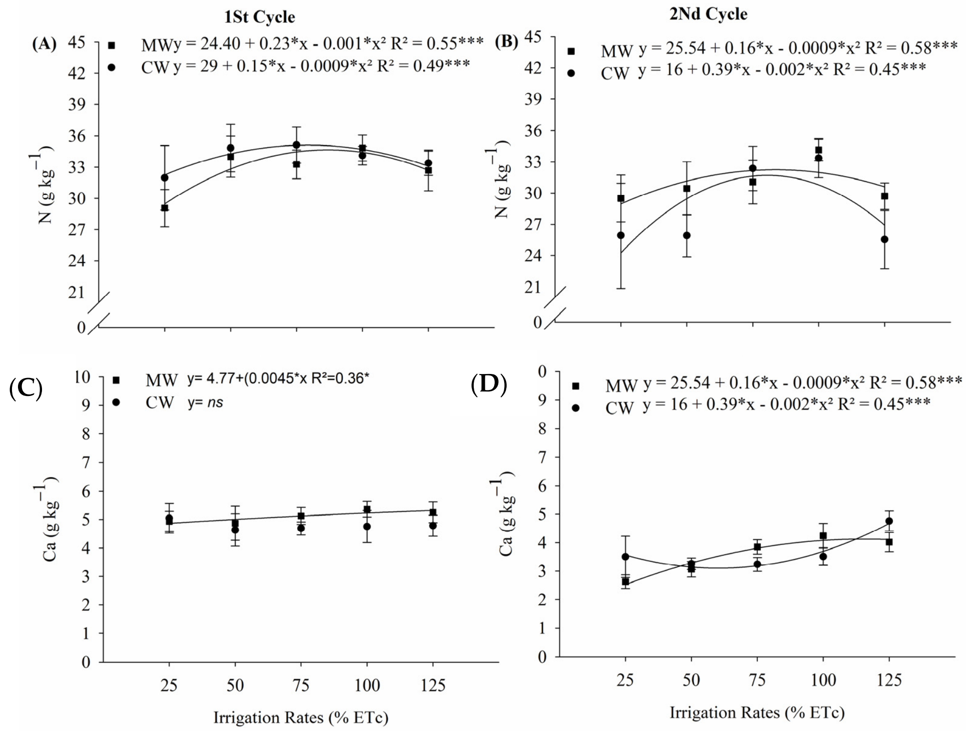

Figure 4. Lettuce as a function of replacement rates and two types of water in two cycles. The concentration of (**A**) N content in the 1st Cycle; (**B**) N content in the 2nd Cycle; (**C**) P content in the 1st Cycle; and (**D**) P content in the 2nd Cycle. Error bars indicate the standard error of the mean (n = 4). Significant regression models with*indicate * $p < 0.10$, ** $p < 0.05$, *** $p < 0.001$ and R^2 as the correlation coefficient. CW: Conventional water; MW: Magnetic Water; *ns*: No significance.

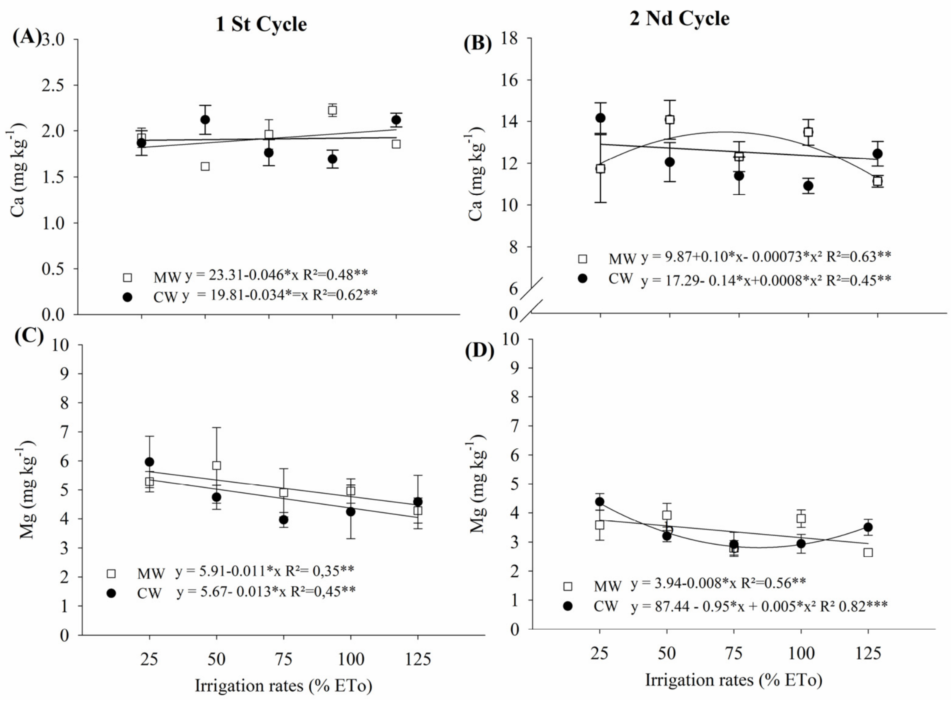

Figure 5. Lettuce as a function of replacement rates and two types of water in two cycles. The concentration of: (**A**) Ca content in the 1st Cycle; (**B**) Ca content in the 2nd Cycle; (**C**) Mg content in the 1st Cycle; and (**D**) Mg content in the 2nd Cycle. Error bars indicate the standard error of the mean (n = 4). Significant regression models with * $p < 0.10$, ** $p < 0.05$, *** $p < 0.001$ and R^2 as the correlation coefficient. CW: Convention water, MW: Magnetic Water, *ns*: No significance.

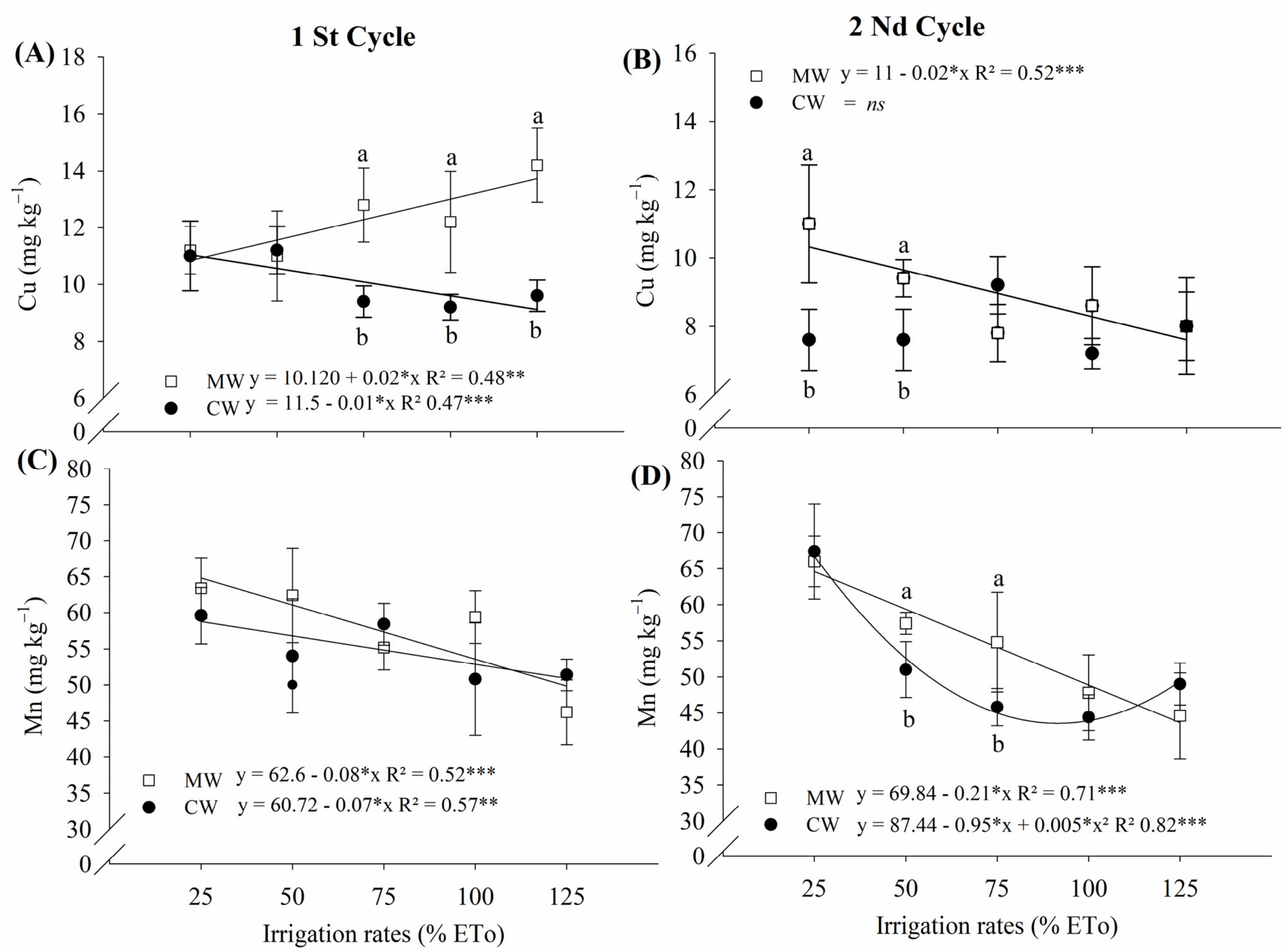

Figure 6. Lettuce as a function of replacement rates and two types of water in two cycles. Concentration of (**A**) Cu in the 1st Cycle; (**B**) Cu content in the 2nd Cycle; (**C**) Mn content in the 1st Cycle; and (**D**) Mn in the 2nd Cycle. Error bars indicate the standard error of the mean (n = 4). Significant regression models with * $p < 0.10$, ** $p < 0.05$, *** $p < 0.001$ and R^2 as the correlation coefficient. CW: Conventional water, MW: Magnetic Water, *ns*: No significance.

3.4. Biometric Components

The fresh root mass of the plants showed a similar trend in both cycles, in which the plants irrigated with CW showed a linear response, and those irrigated with MW showed a second-order reaction, with a maximum accumulation of approximately 80% of the replacement rate, reaching 12 g plant^{-1} (Figure 7A,B). For the 1st cycle, MW showed higher fresh root mass for all ET_0 in comparison to CW (Figure 7A). In the 2nd cycle, MW overcame CWs higher ET_0.

For dry root mass, no adjustment was obtained in the 1st cycle for the data; however, MW showed higher values, in comparison to CW, for 25, 50, and 100% ET_0 (Figure 7C). For the 2nd cycle, magnetic water did not show curve adjustment; however, it presented higher values in comparison to CW for all ET_0, except for 75% (Figure 7D).

The use of magnetically treated water positively affected the biometric components of the lettuce plant, as well as the effect of the water replacer rates. Regarding the number of leaves (Figure 8A,B), when the plants were irrigated with magnetically treated water, the effect for both cycles was of the second-order, close to an ET_0 of 80% when a higher number of leaves was estimated.

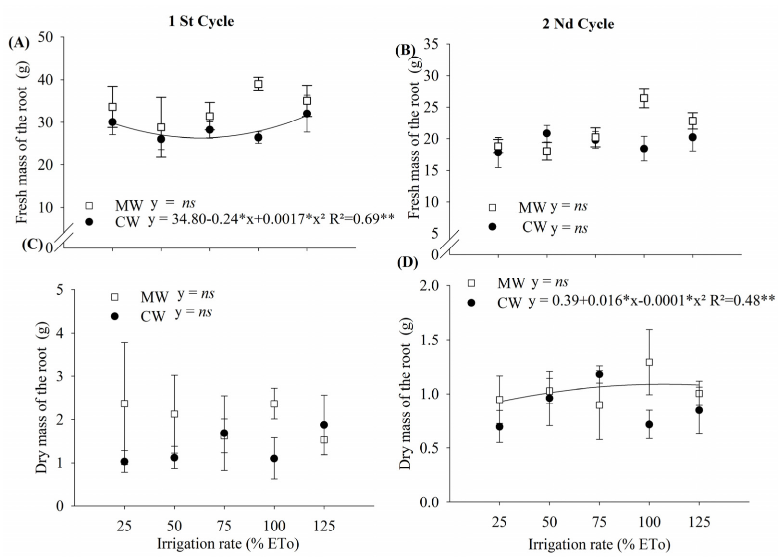

Figure 7. Fresh mass of the root for first cycle (**A**); fresh mass of the root for two cycle (**B**); dry mass of the root for first cycle (**C**) and dry mass of the root for second cycledr (**D**) of lettuce as a function of replacement rates and two types of water. Error bars indicate the standard error of the mean (n = 4). Significant regression models with * $p < 0.10$, ** $p < 0.05$ and R^2 as the correlation coefficient. Cycle, CW: Conventional water, MW: Magnetic Water, *ns*: No significance.

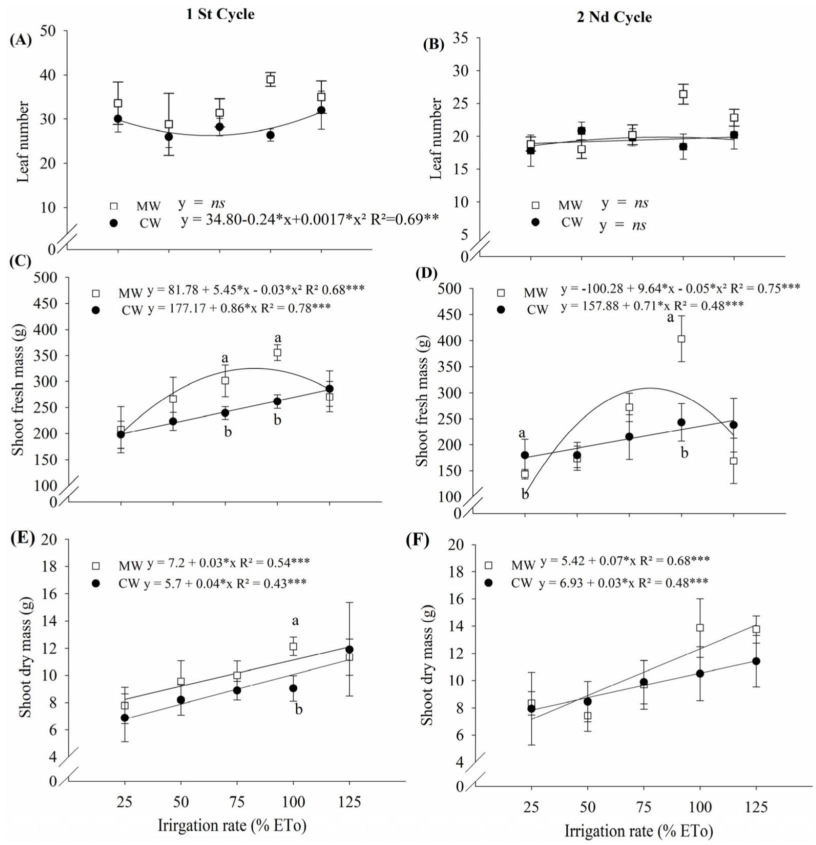

Figure 8. Biometric component of lettuce as a function of replacement rates and two types. Leave number: (**A**) 1st Cycle (**B**) 2nd Cycle; Accumulation of fresh shoot mass: (**C**) 1st Cycle (**D**) 2nd Cycle; shoot dry mass: (**E**) 1st Cycle and (**F**) 2nd Cycle. Error bars indicate the standard error of the mean (n = 4). Significant regression models with * $p < 0.10$, ** $p < 0.05$, *** $p < 0.001$ and R^2 as the correlation coefficient. Cycle, CW: Convention water, MW: Magnetic Water, *ns*: No significance.

The fresh shoot mass (Figure 8C,D) showed a trend similar to that of the leaf number. Nonetheless, the maximum accumulation occurred when the plants were irrigated with 75% of ET_0 and MW, reaching 310 g plant^{-1}, while irrigation with 75% of ET_0 and CW reached calculated values of 243 g plant^{-1}. Even when irrigated with a higher replacement rate when CW was used, the plants did not get the same fresh mass accumulation compared to MW. A similar trend was observed for the dry shoot mass (Figure 8E,F), which showed a linear accumulation in both cycles.

3.5. Multivariate Analysis

Figures 9 and 10 show the results of the multivariate analysis for the 1st and 2nd cycles, respectively, where clearly the irrigation with MW separated from CW. In the 1st cycle, the principal component analysis applied to all the selected significant variables explained 62.3% of the total data variability ($p < 0.1$) (PC1 41.0% and PC2 21.3%) (Figure 9). In PC1, there was a separation of water type, where Zn and N explained the grouping of CW, and all the other variables explained the grouping for MW.

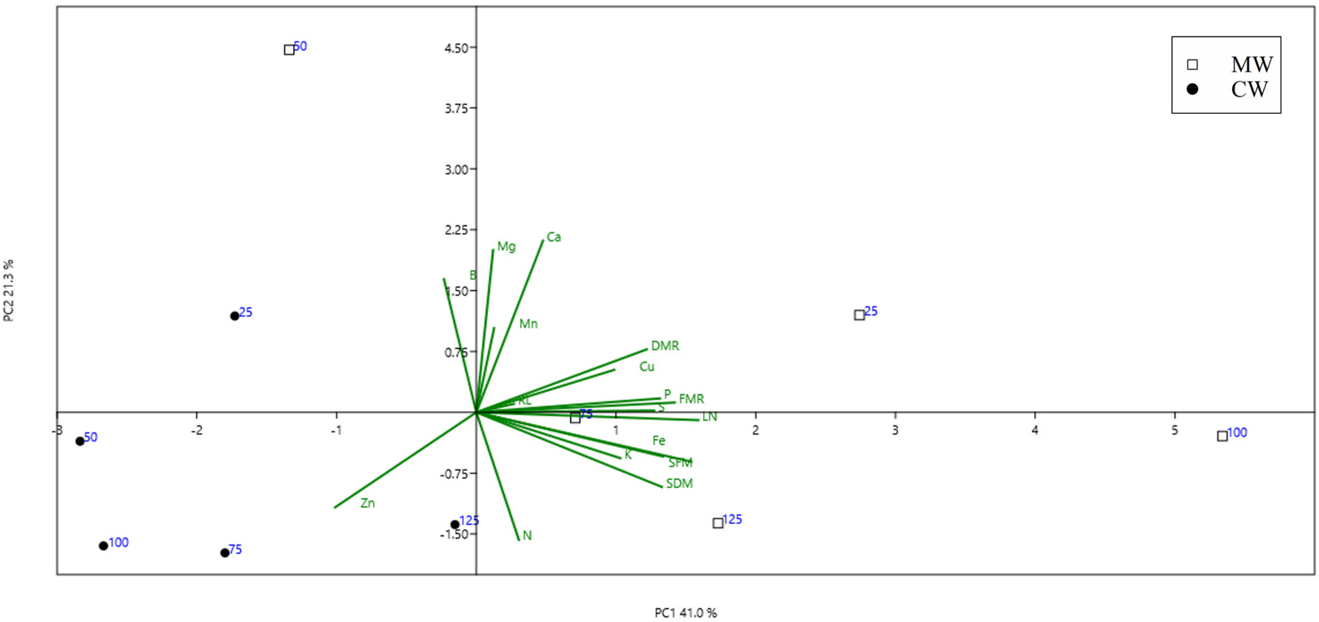

Figure 9. Principal component analyses (PCA) for the 1st cycle of lettuce cultivation as a function of replacement rates (25; 50; 75; 100; and 125%—mean presented in the plot with n = 5) and two types of water (CW: Convention water; MW: Magnetic Water). Biplot: ChoA (Chlorophyll A—determined by Soil Plant Analysis Development (SPAD) index); ChoB (Chlorophyll B—determined by SPAD index); Chototal (ChoA + ChoB); LN (leaf number); RL (root length—obtained with WinRhizo); FMR (fresh mass of root); DMR (dry mass of root); SFM (shoot fresh mass); SDM (shoot fresh mass); macro- N; P; K; Ca; Mg; S, and micronutrients B; Cu; Fe; Mn; Zn.

In the 2nd cycle, the principal component analysis applied to all the selected significant variables explained 63.6% of the total data variability ($p < 0.1$) (PC1 45.5% and PC2 18.1%) (Figure 10). Following the same trend of the 1st cycle, for the 2nd cycle, there was a separation between CW and MW, where most of the variables explained the grouping for MW.

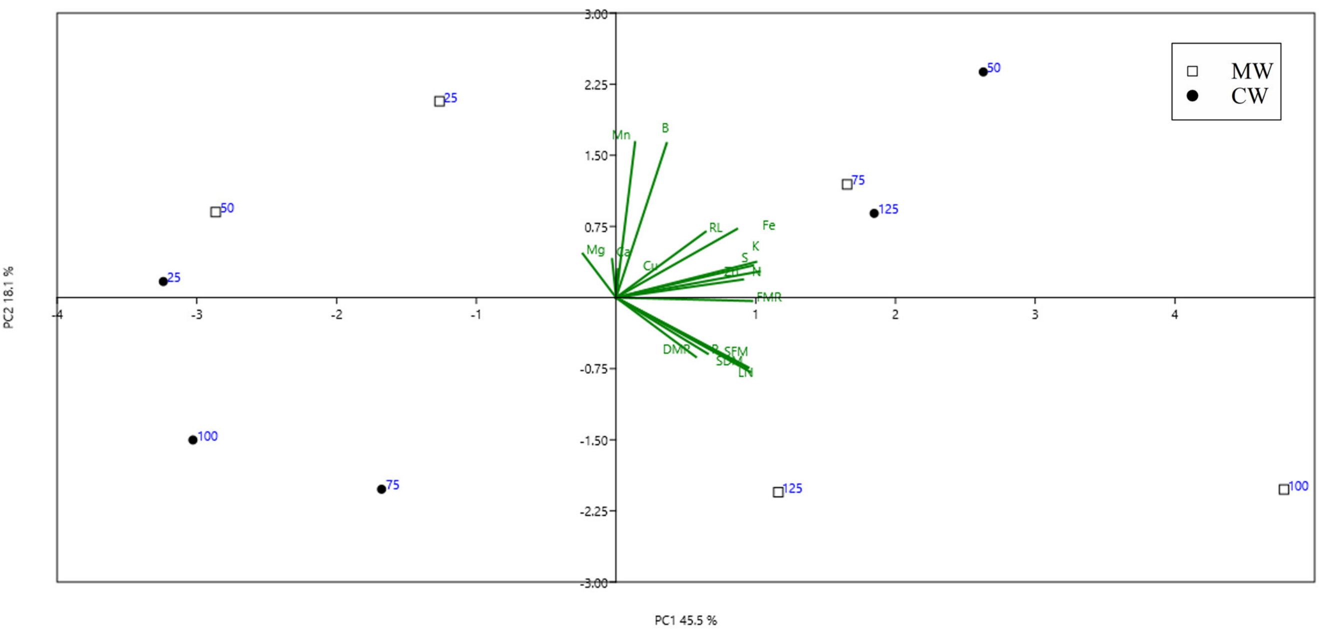

Figure 10. Principal component analyses (PCA) for the 2nd cycle of lettuce cultivation as a function of replacement rates (25; 50; 75; 100; and 125%—mean presented in the plot with n = 5) and two types of water (CW: Convention water; MW: Magnetic Water). Biplot: ChoA (Chlorophyll A—determined by Soil Plant Analysis Development (SPAD) index); ChoB (Chlorophyll B—determined by SPAD index); Chototal (ChoA + ChoB); LN (leaf number); RL (root length—obtained with WinRhizo); FMR (fresh mass of root); DMR (dry mass of root); SFM (shoot fresh mass); SDM (shoot fresh mass); macro-N; P; K; Ca; Mg; S, and micronutrients B; Cu; Fe; Mn; Zn.

4. Discussion

As checked in the water chemical characterization, during the magnetic treatment, when water passes through the magnetic field, its structure and some physical characteristics are altered. According to Pang and Deng [47], these changes include optical properties, electromagnetism, thermodynamics, and mechanics. When the water is subjected to magnetization, changes in the dielectric constant, viscosity, force of surface tension, solidification point, boiling point, and electrical conductivity occur in comparison to these characteristics in pure, non-magnetic water [47]. Besides, the clustering structure of hydrogen-bonded chains and the polarization effects of water molecules is enhanced after magnetization. Other studies report that, in a magnetic field, an increase in the cluster size of liquid water may occur [48].

Studies have shown that high-intensity magnetic fields (>0.2 T) cause an increase in the number of monomeric water molecules. However, at the same time, it increases the assembly of these molecules into tetramers (four molecules of water interacting with each other via hydrogen bonds) [49].

Furthermore, the water coefficient of friction in thin films is reduced in a magnetic field, indicating a possible decrease in the strength of the hydrogen bonds. Salt mobility is reinforced in strong magnetic fields (1–10 T), causing some interruption of the hydrogen bonds [50].

Based on the molecular changes in the structure of water during magnetization, Pang and Deng [47] described the theory of water magnetization according to the views of proton conductivity in the hydrogen bond systems of ice. When water is exposed to a magnetic field, the hydrogen bonds of the molecules approach each other, forming closed chains of hydrogen bonds. Therefore, the application of magnetism facilitates the conduction of the 'molecular electric current' due to the proton conductivity under the action of the Lorentz force of the magnetic field. Thus, the magnetic interactions of these 'molecular electric current' elements with each other or with the external magnetic field result in changes in the distribution and characteristics of the water molecules and, consequently, in their magnetization. Furthermore, the application of a magnetic field to water reduces its surface tension, causing an increase in the dissolution of water in minerals and providing adequate amounts of nutrients for plant growth [51].

The effects of magnetically treated water in the irrigation of lettuce were evaluated in terms of water availability in the soil and nutrient uptake. Irrigation of lettuce with magnetically treated water showed a higher water tension in the soil when compared to conventional water. This result can be related to the action of the magnetic field, which causes a weakening in the matric tension, thus increasing the availability of water in the soil [14,25,26]. This is explained by the magnetization process, which influences the hydrogen bonds and Van der Waals forces, releasing ions and making the water structure more cohesive.

This occurs when calcium (Ca^{+2}) and carbonate (${CO_3}^{-2}$) ions enter in the zone influenced by the magnets since they are pushed in opposite directions due to their charges. As a result, water molecules can be easily aggregated to the soil particles and, therefore, will not be leached. Water molecules will also be able to penetrate easily the micropores of the soil particles, which prevents the water molecules from moving to greater depths [25,26]. Hilal and Hilal [52] also noticed that the magnetic treatment could act in the soil/water ratio and destabilize the gas bubbles present in the soil, causing a change in ionic balance and improving nutrient availability.

As a result of the crop development, from an enzymatic point of view, Surendran et al. and Maheshwari and Grewal [26,53] report that plants irrigated with magnetically treated water showed faster activation of enzymes and hormones during the growth process, which could have resulted in improved nutrient transport and mobilization. Therefore, magnetic treatment probably leads to the aforementioned changes, which may cause shifts in the plant system and phytohormone production, which leads to increased plant growth and activity [54]. Moon and Chung [55] reported that the magnetic field could influence both the activation of ions and the polarization of dipoles in living cells, being also able to alter the structure and function of the plasma membrane [56,57].

From a plant nutritional perspective, according to Maheshwari [52], irrigation with magnetically treated water on horticultural crops appeared to, in some circumstances, when compared to irrigation with no magnetically treated water, alter the soil pH, electrical conductivity, available phosphorus (P) and potassium (K) that are extractable by the crop. The results of the application of MW in the present study suggested a greater availability of macro- (N, P, Ca, and Mg) and micronutrients (Cu and Mn) in the soil due to the higher concentration in the lettuce shoot, which promoted improvement in the yield and quality of the products compared to irrigation with conventional water.

Studies with the soybean crop also indicated an increase in the N and C content when submitted to different electrical conductivity in the solution [58]. When irrigated with magnetically treated water under conditions of water deficit, the soybean crop presented morphological and physiological responses to water stress. The authors concluded that the pretreatment of seeds by magnetic field results in increased photosynthetic pigments, the efficiency of PSII, and performance index based on the absorption of light energy, and promotes the efficiency of photosynthesis as well as mitigates the adverse effects of water stress [59]. When exposed to irrigation with treated water, the corn crop showed the alleviation of adverse effects of water stress by the fact that the magnetic field reduced free radical production and antioxidant enzyme activity [60].

For the culture of peas (*Pisum sativum* L.) and celery (*Apium graveolens* L.), there was an increase in concentrations of Ca and P, as well as effects of MW in the reduction of the pH in the soil, which resulted in higher nutrient uptake [61].

In summary, the literature has reported beneficial results related to the application of magnetically treated water with changes at the biochemical/molecular level as well as at the cellular level, which could reflect in the beneficial effects reported in the present study, related to greater growth of lettuce irrigated with magnetic water in two cycles. Matulovic [62] observes a similar behavior for the lettuce crop.

5. Conclusions

Magnetic water treatment favored increased N and P shoot concentration, promoting higher lettuce plant growth. The application of 75% ETo promoted higher lettuce plant growth.

Technology can be an alternative to increasing water use efficiency. As it has been observed, the treatment with 75% of the ETo (MW) showed a similar trend to that of 100% of the ETo when irrigated with conventional water. Hence, it is possible to reduce around 25% of the water requirement of a culture.

Irrigation with magnetically treated water influenced water tension in the soil, meaning that there was less tension for these treatments than for conventional water.

Nutrient absorption (leaf diagnosis) was affected by water deficit and irrigation with magnetically treated water.

This study presents a technological alternative water treatment with which high yields can be obtained with lower fertilizer costs.

Author Contributions: Conceptualization: F.F.P. and L.R.A.G.F.; Water analysis and writing: E.F.V. and J.C.F.; Formal analyses: C.P.C.; Validation: J.F.S.J.; Writing-review and editing: P.P.N.C., L.P.B.M., A.R.d.R., and B.A.; Editing photo: M.C.; Writing-original draft preparation: F.F.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Council for Scientific and Technological Development (CNPq), grant number 153415/2012-6. The F. F. Putti was funded by grant number #303923/2018-0, and the L. R. A. Gabriel Filho was funded by grant number #315228/2020-2.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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