Effects of magnetized fresh water on seed germination and seeding growth of cotton

Jihong Zhang, Kai Wei, Quanjiu Wang, Yan Sun and Weiyi Mu

ABSTRACT

Magnetized water treatment technology is usually used to improve poor quality water, and there is still a lack of study on fresh water. To understand the biological effects of different strength magnetized fresh water (MFW), seed germination and potted experiments on cotton were carried out to study the effects of MFW with different magnetic intensity (0, 100, 300, 500 mT). Results showed that the surface tension coefficient of MFW reduced by 7.3–10.5%, whilst dissolved oxygen concentrations increased by 8.8–12.7%. Germination strength indexes of cotton cultivated with MFW significantly increased, showing potential and vigor indexes of 16.8–22.4% and 47.4–78.0%, respectively. The emergence rate of cotton irrigated with MFW was faster and higher, with recorded values of 7.7–13.1%. The net photosynthetic rate (P_n) and instantaneous water use efficiency (*iWUE*) of cotton increased significantly, whereas the stomatal limit value (L_s) decreased. In all, results suggest the total biomasses of MFW irrigated cotton have significantly increased. Therefore, it is suggested that MFW may more effectively promote the utilization of water and light in cotton under magnetic field intensities of 300–500 mT. The results can provide guidance for the efficient utilization of magnetized fresh water in arid and semi-arid areas.

Key words | cotton seedling, fresh water, magnetic field intensity, photosynthesis, seed germination

Jihong Zhang
Kai Wei
Quanjiu Wang (corresponding author)
Yan Sun
Weiyi Mu
State Key Laboratory of Eco-Hydraulics in Northwest Arid Region of China,
Xi'an University of Technology,
Xi'an 710048,
China
E-mail: *wquanjiu@163.com*

HIGHLIGHTS

- Magnetized fresh water can improve the activity of water molecules and the amount of dissolved oxygen.
- The biological magnetic effect of magnetized fresh water is closely related to magnetization intensity.
- Magnetization treatment can bring into play the physiological effect of irrigation water and improve water production capacity.

INTRODUCTION

As a new type of green and pollution-free water treatment technology (Esmaeilnezhad *et al.* 2017), magnetization is simple, efficient, and low input (Luo *et al.* 2020). It has been widely used in wastewater treatment (Ji *et al.* 2010), water purification (Yao *et al.* 2019), scale reduction (Sohaili *et al.* 2016), construction (Ghorbani *et al.* 2019), materials (Pour *et al.* 2017), textiles (Lipus *et al.* 2013), and aquaculture (Hassan *et al.* 2019). The basic principle of magnetized water is that after the liquid water passes through a certain intensity magnetic field at a given flow rate, a series of changes have taken place in the physical and chemical properties of water under the influence of Lorentz force (Chibowski

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& Szcześ 2018), which appears to create the possibility of improving the production capacity of fresh water (Ambashta & Sillanpää 2010). The development of magnetized water research has achieved good results in agricultural irrigation (Selim & Selim 2019; Sultan *et al.* 2019), and study on irrigation experiments with magnetized brackish water showed reduced harm of brackish water, promotion of crop growth, and increased crop yields (Hachicha *et al.* 2018; Liu *et al.* 2020). Surendran *et al.* (2016) indicated that under field conditions, the yield of eggplant under magnetized water irrigation increased by 17.0%. Mahmoud *et al.* (2019) showed that the grain yield, straw yield, and biological yield of magnetized brackish water increased by 19.24%, 33.97%, and 26.99%, respectively. Moreover, studies on the early growth of crops found that magnetized water irrigation significantly improved germination rate, germination index, activity index, salt tolerance index, and other physiological factors of corn (*Zea mays* L.) seeds, and promoted the growth of maize seedlings under saline conditions (Aghamir *et al.* 2015). Sayed (2014) indicated that magnetized water treatment had a significant positive effect on plant growth parameters (i.e. height, leaf area, leaf, stem, root fresh weight, and dry weight) of broad bean (*Vicia Faba* L.) seedlings. Studies on the utilization of light energy of crops by magnetic water showed that the net photosynthetic rate, stomatal conductance, intercellular CO_2 concentration and water use efficiency of *Populus* × *euramericana 'Neva'* in magnetized brackish water irrigation were all increased, while transpiration rate and stomatal limit values decreased compared with that of unmagnetized water (Liu *et al.* 2019). Alfaidi *et al.* (2017) found that the contents of chlorophyll a, b, carotenoids, total pigment, soluble protein, and total protein in guinea grass (*panicum maximum*) leaves significantly increased after irrigating with magnetized water. Research indicates that the growth promoting effect of magnetized water appears to be related to the magnetic field strength and irrigation water quality. Massah *et al.* (2019) indicated that the intensity of the magnetic field and the type of treated water had a significant effect on the germination and growth characteristics of wheat seeds. The germination rate of seeds treated with 400 mT of distilled water was the highest (53.3%), the fresh weight of seedlings treated with 600 mT of distilled water was the highest, and the root length of wheat seeds treated with 400 mT of groundwater was the largest (155.3 mm).

In summary, remarkable achievements have been made in irrigated wheat, corn, broad bean, and eggplant with magnetized water; nevertheless, research on irrigating cotton with magnetized water is scarce. At the same time, most of the studies on magnetized water irrigation focus on the application of brackish water, while there are few studies on magnetization of fresh water. Therefore, it is of interest to explore the effects of MFW with different magnetic fields on the growth of cotton, especially on the fragile and sensitive seedling stage of cotton growth. Thus, this paper target the analysis of cotton seed germination, seedling emergence, seedling growth, photosynthetic characteristics parameters, and biomass distribution pattern, along with studying physical and chemical properties of MFW, and the effects of MFW with different magnetization intensities (0, 100, 300, 500 mT). Cotton seedling growth and photosynthetic characteristics were discussed, and suitable magnetization intensities for cotton seed germination and seedling growth determined. The results can provide theoretical basis and technical support for the efficient utilization of fresh water resources in arid and semi-arid areas.

MATERIALS AND METHODS

Overview of test area

The experimental area is in the Kunqi River alluvial plain (41 °35′N, 86 °10′E, and 901 m a.s.l.), the Bazhou irrigation experimental station of Xinjiang, on the edge of Tarim Basin at the southern foot of Tianshan Mountain. Lying in the middle of the Eurasian continent, it belongs to the typical dry continental climate in the warm zone, with scarce rainfall, intense positive and negative rainfall, large temperature difference between day and night, sufficient sunshine in the test area, averaging 3,036.2 h of annual sunshine (Chen *et al.* 2018). Average temperatures oscillate at 11.5 °C, with minimum and maximum temperatures of −30.9 °C and 42.2 °C, respectively (Yang *et al.* 2016). Annual precipitation falls between 53.3–62.7 mm, whilst annual evaporation, annual wind and maximum wind speed are recorded amomg 2,273–2,788 mm (Liang *et al.* 2019), 2.4 m s^{-1} and

22 m s^{-1} (Li *et al.* 2019), in that order. The fresh water used for the test came from Kongke River with an average salinity of 0.72 g L^{-1} and pH of 7.80.

Magnetizers and magnetized water devices

Three external sintered Rufe-B CHQ permanent magnet magnetizers (Shanghai Juncai Magnetic Materials Co., LTD., China) were used with magnetic field strengths of 100, 300, and 500 mT. The effective magnetic field area was 8 cm × 10 cm and magnetic field intensities was calibrated with a 5180-Gaussian Meter (F.W. BELL Co., USA). The magnetized water device is composed of a water box, peristaltic pump, magnetizer, water pipeline, and valves (Figure 1). Water pipelines are of PVC with a 2.5 cm diameter (cross-sectional area of 4.91 cm^2), and 10 cm of effective magnetic distance (i.e. effective pipiline length through which the magentic field was applied). As shown in Figure 1, 100 L of fresh water placed in the water box and pipelines opened, one at a time, through manually controlled valves. A peristaltic pump (0.74–12 L h^{-1}) was used to circulate the water. A section of the circulating pipeline was placed between the two poles of the magnetizer, and the magnetic induction line was cut perpendicular to the magnetic field. The flow rate was adjusted to 0.5 m s^{-1} by the peristaltic pump, and the flow was cyclically magnetized by the magnetic field. The magnetization time was 30 min, and the retention time of the magnetized water was 8 days (Coey & Cass 2000).

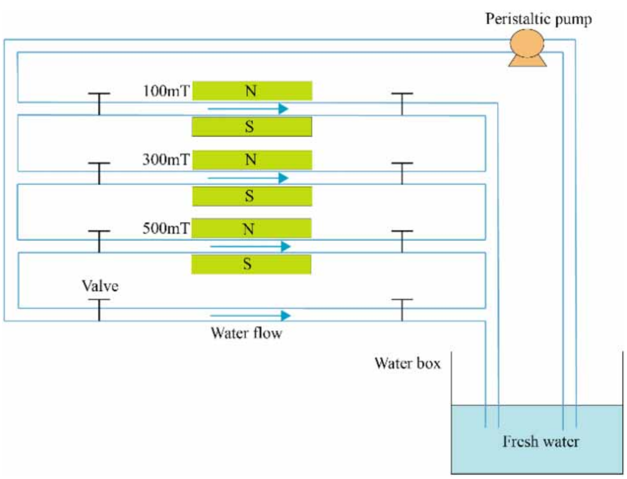

Figure 1 | Schematic diagram of magnetized water device.

Experimental design and process

The magnetized water device mentioned above was used to magnetize fresh water, whilst unmagnetized fresh water was used as a control. A total of four water clusters were formed, including unmagnetized fresh water (FM0), 100 mT magnetized fresh water (FM1), 300 mT magnetized fresh water (FM3) and 500 mT magnetized fresh water (FM5). A series of experiments including cotton seed germination, potted experiments in a cotton field, and physicochemical properties test were carried out for each cluster. The objective was to analyze the influence and mechanics of MFW under diversified magnetic field intensities on cotton seed germination and seedling growth.

Experiment 1—seed germination test

Seed germination tests were performed as described in a previous study with three repetitions (Fu *et al.* 2010). Fifty cotton seeds of the same size and full grain were selected and arranged evenly in a petri dish with tweezers. The petri dish was then marked and covered with a layer (1.7 mm) of fine filter paper (qualitative filter with 3 μm of mesh size). 20 mL of cluster water was added to the corresponding culture dish and the seeds were covered with a layer (the same as the filter paper layer described previously). After having absorbed enough water (24 h), the excess water was drained, and the seeds were placed in the culture dish in the incubator at 28 ± 1 °C, with a light intensity of 800 Lx. The numbers of germinations were recorded every day, and the corresponding cluster water (5 mL) was added every day to maintain the moisture content of the filter paper. The radicle length of cotton seeds was measured on the eighth day. The germination condition was evaluated by calculating germination potential (*GP*), germination rate (*GR*), germination index (*GI*), and vigor index (*VI*) as follows (Mosse *et al.* 2013):

$$GP = \frac{N_4}{N_T} \times 100\% \tag{1}$$

$$GR = \frac{N_8}{N_T} \times 100\% \tag{2}$$

$$GI = \sum \frac{G_t}{D_t} \tag{3}$$

$$VI = GI \times L \tag{4}$$

Table 1 | Soil physical properties in experimental cotton field

Soil texture	Depth/cm	γ_d/(g cm^{-3})	θ_s/(cm^3 cm^{-3})	FC/(cm^3 cm^{-3})	PWP/(% cm^3 cm^{-3})	ECe /(ds m^{-1})
Sandy loam	0–5	1.60	0.396	0.197	0.05	5.52
	5–10	1.62	0.394	0.195	0.05	5.49
	10–15	1.63	0.396	0.196	0.04	5.45
	15–20	1.67	0.395	0.194	0.06	5.43
	average	1.63	0.395	0.196	0.05	5.47

γ_d, θ_s, FC, PWP, and K_s represent soil bulk density, saturated volume water content, field capacity, wilting coefficient, and extract conductivity, in that order.

where, N_4 and N_8 are the numbers of seeds germinated in 4 and 8 days, respectively; N_T is the total number of seeds; G_t is the number of seeds germinated at day t (D_t); L is the average radicle length of seed on the eighth day.

Experimental 2—potted experiments in a cotton field

To simulate a cotton field growth environment, all potted plants were buried, randomly divided, and repeated three times for each cluster. Saline alkali soil from 0–20 cm depth (Table 1) from the surface of the cotton field was used in the experiment. The inner diameter and height of the plastic basin used in the test were 30 and 20 cm respectively, and eight air holes with a diameter of 10 mm were set at the bottom of the basin. Each barrel was uniformly loaded with 20 kg of soil sample and fertilizer with the following composition: carbamide (N 45.4%) 6.8 g, compound fertilizer (N 12%, P 18%, K 15%) 6.4 g, organic fertilizer (organic matter >35%) 24 g. After, the fertilizer and soil were evenly mixed, 7.065 L of cluster water was irrigated to the corresponding plastic basin. Each pot was seeded with 20 cotton seeds, with a sowing depth of 2–3 cm. As in the field, the soil surface was covered with plastic film mulch after sowing.

Fourteen days after sowing, the rate of emergence was measured and only 4 cotton plants were kept in each pot, with the remaining seedlings being removed. The length of cotton seedlings was then measured, the dust on the surface removed, and fresh weight of the seedling measured after washing and drying. For that purpose, seedlings were placed in an oven at 105 °C for 1 h and dried at 75 °C. The dry weight of the seedling was measured after cooling down. Plant height, stem diameter at cotyledon node, number of leaves per plant, and area of single leaf of potted cotton were measured. The stem diameter was measured with an electronic vernier caliper with an accuracy of 0.01 mm. The number of leaves was counted manually. Plant height, leaf width, and vein length were measured with measuring tape with an accuracy of 1 mm. The area of a single leaf was calculated with the formula length × width × 0.84 (Tan *et al.* 2017). The growth indexes of potted cotton seedlings were measured every 10 days. Thirty days after final singling, the net photosynthetic rate (P_n), stomatal conductance (G_s), intercellular CO_2 concentration (C_i), and transpiration rate (T_r) of the main functional leaves (from the top to the bottom of the fourth leaf) of cotton seedlings were measured using LC Pro SD full-automatic portable photosynthetic instrument (UK ADC) equipped with an LED artificial light source. Then, the stomatal limit $L_s = 1 - C_i/C_a$ (C_a is atmospheric CO_2 concentration) and instantaneous water use efficiency $WUE = P_n/T_r$ were calculated (Liu *et al.* 2017). When determining the photosynthesis parameters of cotton seedlings, according to the meteorological environment conditions during 10:00–12:00 am in a cotton field, the light intensity was set as 1,100 μ mol m^{-2} s^{-1}, the concentration of CO_2 was 36 μ mol mol^{-1}, and the temperature was 30 °C. The SPAD value of chlorophyll in cotton seedling leaves was measured using the SPAD-502 Plus Chlorophyll Meter (Konica Minolta, China). Forty days after final singling, the cotton seedlings were removed slowly. The cotton branches were then cut with fruit scissors, the dust was removed from the surface, the cotton branches were washed and dried, and the dry weight of each part was weighed.

Determination of physicochemical properties of magnetized water

In order to clarify the mechanism, the physicochemical properties of magnetized water, including surface tension, dissolved oxygen content, electrical conductivity (EC), and pH were measured. The surface tension was determined by a SCZL202 automatic tension tester (Zibo Shengkang Electric Co., Ltd, China), and the dissolved oxygen content was measured by HQ40 portable dissolved oxygen meter (HACH, USA). EC and pH were determined by DDS-307 electrical conductivity meter and PHSJ-4A pH meter, respectively (Shanghai INESA Scientific Instrument Co., Ltd, China).

Data processing and analysis

Data were recorded in Excel 2016 and analyzed using SPSS 22.0 software (IBM Corp. USA). The least significant difference (LSD) method ($P < 0.05$) was used for comparison of multiple values.

RESULTS AND DISCUSSION

Germination characteristics of cotton seeds

GP, *GR*, *GI*, and *VI* are important indicators to reflect seed germination strength (Kumar *et al.* 2011). *GP* and *GR* directly reflect the initiation of the metabolic process, while *GI* and *VI* reflect the seed's potential for rapid and uniform emergence. Compared with FM0, the *GP*, *GR*, *GI*, and *VI* of cotton irrigated with MFW were significantly increased ($P < 0.05$), in the ranges of 22.2–26.3%, 16.8–22.4%, 22.2–27.0%, and 47.4–78.0%, respectively (Table 2). The increased range of *GP* was greater than that of *GR*, while the amplitude of *VI* was greater than that of *GI*, indicating that fresh water magnetization could significantly improve seed strength and enhance the germination potential of cotton. This is consistent with the results of studies on the application of magnetized water to promote the germination of wheat seeds (Massah *et al.* 2019). As reported, smaller water cluster structure and higher dissolved oxygen after magnetization of fresh water were found, which provide good water and gas environments for seed germination and are conducive to improved seed germination (Surendran *et al.* 2016). Comparing cotton seeds cultivated with fresh water against those under different magnetized intensities, the results suggested that *GI*'s cotton seeds cultivated by FM3 improved the most, whereas *GP*, *GR*, and *GI* of cotton seeds treated with FM1 were slightly larger than FM5. At the same time *VI* was slightly smaller than FM5, but none of them was significant ($P > 0.05$).

Table 2 | Germination indexes of cotton seeds under different strengths of magnetized fresh water

Treatment	*GP* (%)	*GR* (%)	*GI*	*VI*
FM0	53.3 ± 1.2b	71.3 ± 1.2c	17.6 ± 0.7b	26.4 ± 0.8c
FM1	66.0 ± 2.0a	86.0 ± 2.0ab	21.6 ± 0.5a	38.9 ± 1.3b
FM3	67.3 ± 3.1a	87.3 ± 1.2a	22.4 ± 0.8a	47.0 ± 2.5a
FM5	65.3 ± 1.2a	83.3 ± 2.3b	21.5 ± 0.5a	41.6 ± 1.4b

GP, *GR*, *GI*, and *VI* represent germination potential, germination rate, germination index, and vigor index, in that order. Different letters within a column indicate significant differences among all treatments at $P < 0.05$.

Effect of MFW on the emergence rate of cotton

High seedling emergence rate and seedling uniformity are the guarantees for high and stable yield (Mo *et al.* 2017). The emergence of cotton seeds started 3 days after sowing (Figure 2). With the increase of emergence time, the emergence rate of cotton gradually increased and tended to stabilize. As shown in Figure 2, the emergence rate of cotton under MFW irrigation was faster and higher when compared to freshwater irrigated seeds. The emergence rate and full seedling formation of cotton irrigated with FM0 was 77.3% and 8 d, respectively, while the emergence

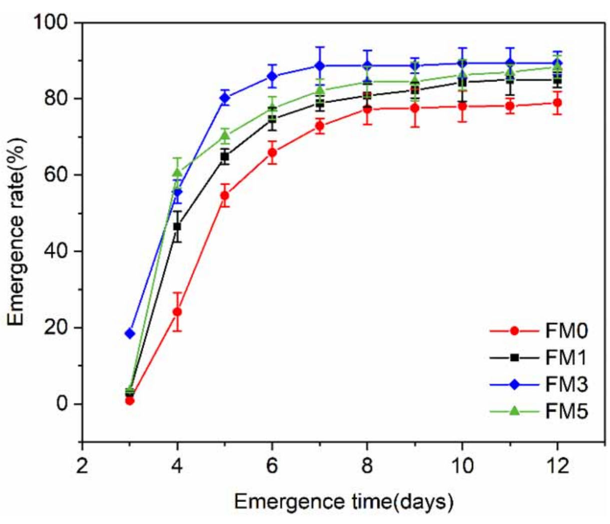

Figure 2 | The effect of different strengths of magnetized fresh water irrigation on the emergence rate of cotton.

rates of cotton irrigated with FM1, FM3 and FM5 were 80.8%, 88.6%, and 84.4% respectively, with full seedling formations of 8 d, 7 d, and 8 d, in that order. Compared with FM0, the emergence rate of cotton irrigated with MFW increased by 7.7–13.1%, and the full seedling formation of cotton irrigated with FM3 was advanced by 1 d. Similarly, Moussa (2011) applied magnetized water irrigation to improve the emergence rate of snow peas and chickpeas. In general, the most remarkable seeding emergence was by FM3, followed by FM5 and FM1.

The seedling strength was analyzed by seedling length, young root length, seedling fresh weight, seedling dry weight, and seedling water content. The cotton seeds were removed 14 days after sowing and seedling activity indexes were measured and analyzed (Table 3). Compared to FM0, the activity of cotton seedlings under MFW irrigation was significantly increased ($P < 0.05$), and the seedling length, root length, fresh weight, dry weight, and water content increased by 4.0–8.0%, 20.3–35.5%, 40.1–73.1%, 18.7–34.4%, and 2.7–4.3%, respectively. Among them, the seedling root length and seedling fresh weight increased condiderably while the water content of the seedling showed moderate intensification, indicating that MFW mainly improves seedling vitality and ensures the seedling health by promoting root growth and boosting fresh weight. The effects of MFW on the activity of cotton seedlings were significantly different ($P < 0.05$). By and large FM5 had a greater promoting effect on root length, fresh weight, and dry weight, while FM3 had the greatest promotion effect on length and water content.

Effect of MFW on cotton morphological development

The growth indexes of cotton enlarged with time, and a small difference between growth indexes of cotton irrigated with magnetized and unmagnetized fresh water was observed, 10 d after final singling. The longer the time of growth, growth indexes for both cotton irrigated with magnetized and unmagnetized fresh water gradually increased (Figure 3). In the same growth period, plant height, stem diameter, leaf number, and single leaf area of cotton irrigated with MFW were larger than those of FM0. After 10–40 d of final singling an average growth rate (slope of plant height growth curve) of 0.46 cm d^{-1} was recorded for FM0, with a peak growth rate on plant height between 10–20 d after final singling. At the same time the average growth rates of cotton plant height under FM1, FM3, and FM5 were 0.56, 0.70, and 0.63 cm d^{-1}, respectively. All peaks of plant height growth rate occurred between 30–40 d after final singling. 40 d after seedling, plant height of cotton irrigated with FM1, FM3, and FM5 increased by 21.5%, 51.1%, and 33.0%, respectively, compared to FM0 (Figure 3(a). After 10–40 d of final singling, an average growth rate (slope of stem diameter growth curve) of 0.11 mm d^{-1} was recorded for FM0, with a peak growth rate on stem diameter between 20–30 d after final singling. Meanwhile the average growth rates of cotton stem diameter under FM1, FM3 and FM5 were 0.15, 0.17, and 0.14 cm d^{-1}, respectively. All the peaks of stem diameter growth rate occurred between 30–40 d after final singling. 40 d after final singling, stem diameter of cotton irrigated with FM1, FM3, and FM5 increased by 27.8%, 47.3%, and 28.0%, respectively, compared to FM0 (Figure 3(b)). In addition, 40 d after final singling, the number of cotton leaves irrigated with FM1, FM3, and FM5 increased by 20.0%, 46.7%, and 26.7% (Figure 3(c)), respectively, while the single leaf area increased by 20.1%, 47.0%, and 33.8% (Figure 3(d)), respectively, compared to FM0. Generally speaking, FM3 had the greatest promoting effect on cotton growth, followed by FM5 and FM1.

Table 3 | Characteristics of seedling activity of cotton under magnetized and unmagnetized fresh water

Treatment	Seedling height (cm)	Seedling root length (cm)	Fresh weight (g)	Dry weight (g)	Seedling water content (%)
FM0	7.5 ± 0.1c	4.6 ± 0.2c	5.89 ± 0.11d	0.87 ± 0.02d	85.17 ± 0.04d
FM1	7.8 ± 0.1b	5.5 ± 0.3b	8.25 ± 0.15c	1.04 ± 0.02c	87.43 ± 0.04c
FM3	8.1 ± 0.1a	5.9 ± 0.2ab	9.57 ± 0.28b	1.07 ± 0.03b	88.81 ± 0.06a
FM5	7.9 ± 0.2b	6.2 ± 0.4a	10.19 ± 0.12a	1.17 ± 0.01a	88.49 ± 0.09b

Different letters within a column indicate significant differences among all treatments at $P < 0.05$.

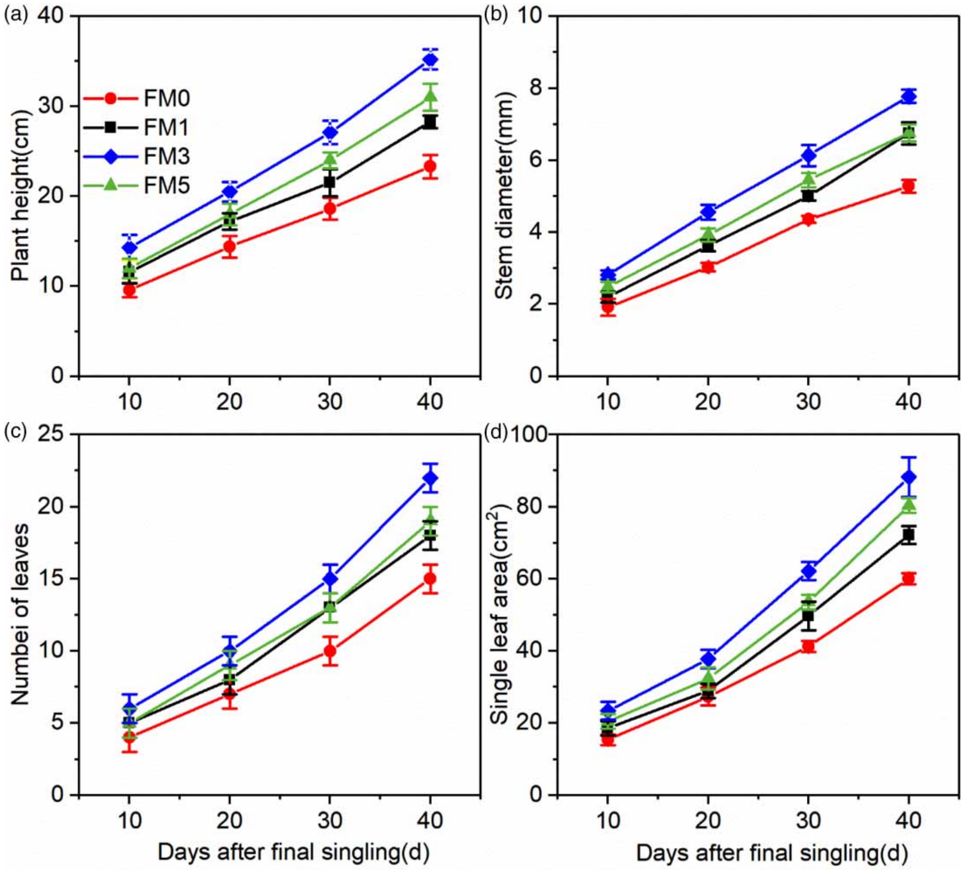

Figure 3 | Effect of magnetized and unmagnetized fresh water irrigation on cotton morphological indexes. FM0 represents unmagnetized fresh water, while FM1, FM3 and FM5 represent fresh water treated with magnetic field intensity of 100, 300 and 500 mT, respectively.

Effect of magnetized fresh water irrigation on photosynthetic parameters of cotton

The P_n of cotton irrigated with FM3 and FM5 increased by 33.9% and 32.8%, respectively, nevertheless there was no significant difference between FM1 and FM0 (Figure 4(a)). The T_r of cotton irrigated with FM1 was slightly smaller than FM0, and the T_r of cotton irrigated with FM3 and FM5 was slightly increased, but not significant (Figure 4(b)). The G_s of cotton irrigated with FM3 and FM5 increased by 69.6% and 40.2%, respectively; however, there was no significant difference between FM1 and FM0 (Figure 4(c)). The C_i of cotton irrigated with FM3 and FM5 increased by 51.3% and 37.9%, respectively, yet there was no significant difference between FM1 and FM0 (Figure 4(d)). Compared with FM0, the *iWUE* of cotton irrigated with FM3 and FM5 increased by 24.4% and 22.3% (Figure 4(e)), while L_s decreased by 21.5% and 25.9% (Figure 4(f)). In general, the most remarkable photosynthetic characteristic parameters were by FM3, followed by FM5 and FM1. The results indicated that MFW could effectively improve stomatal conductance of cotton, reduce stomatal limitation and increase the supply of CO_2, thus improving the photosynthetic carbon assimilation capacity and enhancing the utilization efficiency of light energy and water (Qiu *et al.* 2011). This is consistent with the results of Hasan *et al.* (2017). As reported, magnetization can improve the activity of related enzymes in plants and increase the metabolism rate of crops (ul Haq *et al.* 2016). Free water increased in magnetized crop cells, the photochemical activity of chlorophyll increased, the rate of photophosphorylation accelerated, and the net photosynthetic rate increased (Huuskonen *et al.* 1998).

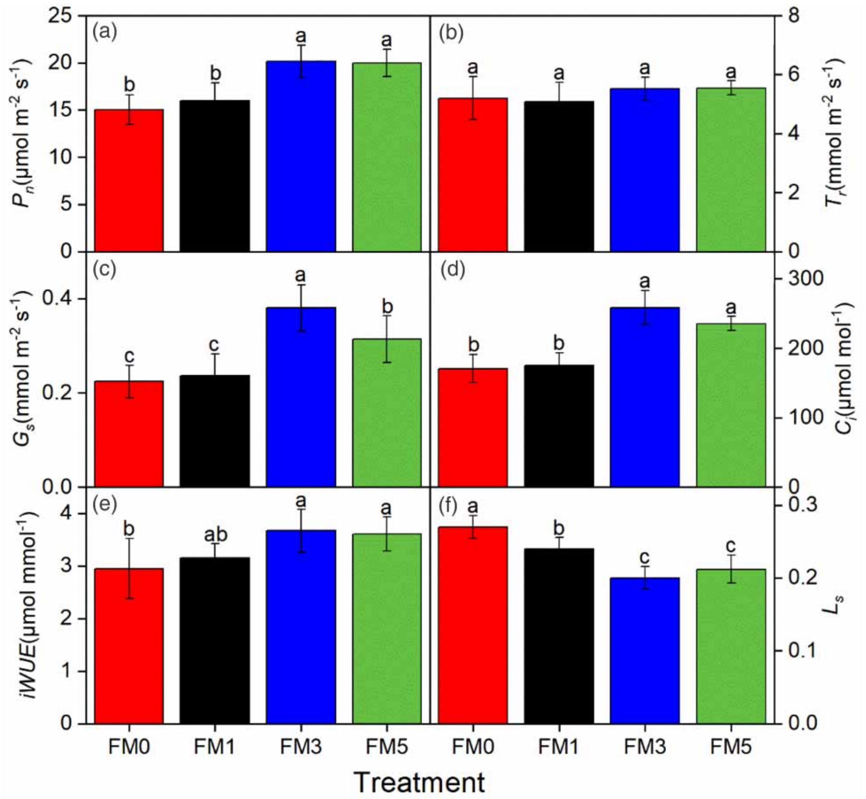

Figure 4 | Characteristic photosynthetic parameters of cotton irrigated with magnetized and unmagnetized fresh water. FM0 represents unmagnetized fresh water, while FM1, FM3 and FM5 represent fresh water treated with magnetic field intensity of 100, 300, and 500 mT, respectively. P_n, G_s, C_i, T_r, *iWUE* and L_s represent the net photosynthetic rate, stomatal conductance, intercellular CO_2 concentration, transpiration rate, instantaneous water use efficiency and stomatal limit, respectively. Different letters within a column indicate significant differences among all treatments at $P < 0.05$.

Effects of magnetized fresh water irrigation on cotton biomass and its distribution

The cotton biomass showed a significant difference between magnetized and unmagnetized fresh water, but not a significant difference among different magnetization intensities (Table 4). Compared with unmagnetized fresh water, leaves, root dry weight and total dry matter of cotton irrigated with MFW increased by 10.7–12.5%, 22.9–33.3%, and 10.3–15.1%, respectively, which conformed to the results of Yusuf & Ogunlela (2015). The stem weight of cotton irrigated with FM5 increased by 18.8% compared with FM0; however, FM1 and FM3 had no significant difference from FM0. In addition, the stem weight ratio of cotton irrigated with FM5 increased by 3.1% compared to FM0, yet FM1 and FM3 decreased slightly. The leaf weight ratio of

Table 4 | Biomass and its distribution of cotton irrigated with magnetized and unmagnetized fresh water

Treatment	Stem (g)	Leaf (g)	Root (g)	Total dry weight (g)	Stem weight ratio (%)	Leaf weight ratio (%)	Root shoot ratio (%)
FM0	5.76 ± 0.12b	11.49 ± 0.20b	1.57 ± 0.12b	18.82 ± 0.42b	30.61 ± 0.21ab	61.06 ± 0.33a	9.10 ± 0.57a
FM1	5.90 ± 0.18b	12.93 ± 1.12a	1.94 ± 0.13a	20.76 ± 1.25a	28.44 ± 0.91bc	62.21 ± 1.76a	10.33 ± 1.10a
FM3	6.11 ± 0.12b	12.83 ± 0.15a	1.93 ± 0.09a	20.87 ± 0.18a	29.28 ± 0.33b	61.47 ± 0.18a	10.2 ± 0.62a
FM5	6.84 ± 0.58a	12.72 ± 0.48a	2.09 ± 0.12a	21.66 ± 0.98a	31.55 ± 1.4a	58.76 ± 0.54b	10.73 ± 1.06a

Different letters within a column indicate significant differences among all treatments at $P < 0.05$.

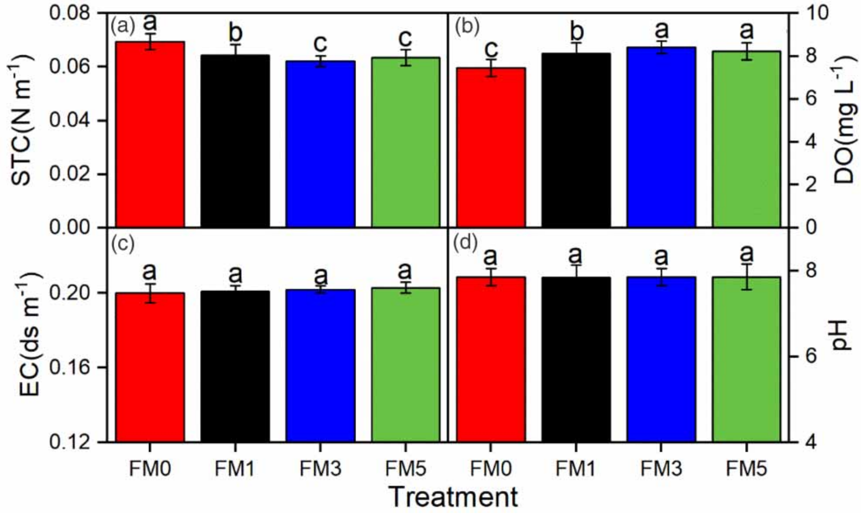

Figure 5 | Changes of physicochemical properties magnetized fresh water. FM0 represents unmagnetized fresh water, while FM1, FM3 and FM5 represent fresh water treated with magnetic field intensity of 100, 300, and 500 mT, respectively. STC, DO, and EC represent the surface tension coefficient, dissolved oxygen content, and electrical conductivity, respectively. Different letters within a column indicate significant differences among all treatments at $P < 0.05$.

cotton irrigated with FM5 reduce by 3.8% compared to FM0. For root shoot ratio, there was no significant difference between magnetized and unmagnetized irrigated cotton. Results indicated that magnetization could promote the overall development of cotton plants by promoting the growth and development of seedling roots.

Changes of physicochemical properties of magnetized fresh water

The surface tension is a macroscopic expression of liquid micro molecular structure, and its change can reflect the change of internal molecular structure (Wang *et al.* 2013; Amor *et al.* 2017), which can be described by the surface tension coefficient (STC). The STC of FM0 was 0.069 N m^{-1}, while the STCs of MFW were 0.062–0.064 N m^{-1}, which reduced by 7.3–10.5% compared to FM0 (Figure 5(a)). The reduced surface tension of MFW was similar to the results of Pang & Deng (2008), which seemed that the internal structure changed (Toledo *et al.* 2008), the average distance between water molecules increased (Wang *et al.* 2013), the hydrogen bonds weakened (Cai *et al.* 2009), the number of free monomer water molecules and dimer water molecules increased (Kney & Parsons 2006), and the chemical bond angle and the radius of water ion gel decreased (Moosavi & Gholizadeh 2014). The dissolved oxygen content (DO) of FM0 was 7.46 mg L^{-1}, while the DOs of MFW were 8.12–8.41 mg L^{-1}, which increased by 8.8–12.7% compared to FM0 (Figure 5(b)), which also verified the results of Lee *et al.* (2019). The electrical conductivity (EC) of FM0 was 0.200 ds m^{-1}, and the ECs of MFW increased slightly but not significantly (Figure 5(c)). The pH of FM0 was 7.86, while the pH of MFW decreased slightly but not significantly (Figure 5(d)). In all, MFW had a great influence on the STC and DO, and FM3 had the best magnetization effect on STC and DO, followed by FM5 and FM1.

CONCLUSIONS

The surface tension coefficient of magnetized fresh water (MFW) decreased by 7.3–10.5%, the dissolved oxygen content increased by 8.8–12.7%, and the water molecular activity was significantly improved. The emergence rate of cotton irrigated with MFW was 7.7–13.1%, and the seedling vigor indexes were significantly increased ($P < 0.05$). MFW could improve the emergence and seedling vigor of cotton by increasing *GP* and *VI* of seeds. The P_n and *iWUE* of cotton irrigated with MFW were increased by 32.8–33.9% and 22.3–24.4%, respectively, and MFW promoted morphological development and biomass by improved cotton photosynthesis and water use efficiency. The water molecular activity of MFW with 300–500 mT magnetic field intensity was best, which was beneficial to the growth of cotton seedlings. The results can provide guidance for the efficient utilization of MFW in arid and semi-arid areas. However, this study only focused on the magnetization of fresh water quality and its effect on the growth of early cotton seedlings, while the effects of magnetized water with different water quality on the physiological growth characteristics, yield, and quality of cotton at the later growth stage need to be further studied.

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DECLARATION OF COMPETING INTEREST

The authors declared that they have no conflicts of interest to this work.

DATA AVAILABILITY STATEMENT

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

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