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Exploring the Impact of Magnetic Water on the Physiological and Functional Parameters of Maize as a Vital Industrial Crop

Hamid Bakhtiari[1], **Mohsen Okhovat**[*2]

[1]*Department of Civil and Environmental Engineering, Water, Energy and Environment Center, Imam Hossein University, Tehran, Iran*
[2]*Biosystem Mechanical Engineering Department, Tarbiat Modares University, Tehran, Iran*

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ABSTRACT

Magnetized water as an environmentally friendly method boosts crop yield and quality. In this study, we investigate the effects of magnetized water treatment on vegetation growth responses and physiological parameters and vegetation growth responses of maize plants and physiological parameters. For this purpose, we provided the experimental design for a semi-large scale in the field. We evaluated three irrigation regimes including 2.31 (100%), 1.73 (75%), and 1.15 (50%) inches per foot with magnetized water, and compared to normal irrigation water during the cultivation period. In the context of maize cultivation in the field, it is noteworthy that the use of magnetized water resulted in a higher germination percentage of maize seeds compared to those irrigated with regular water. Furthermore, the length, weight, and number of seeds per ear in magnetized water treatment, especially 100%, were significantly more than control, which increased grain yield (about 30%). Meanwhile, the chlorophyll content of maize was reduced in an irrigation-dependent manner the lowest was in 50% treatment but magnetized water increased photosynthetic pigment content in leaves. The distribution pattern of insoluble sugars mirrored that of soluble sugars under the irrigation regimes in both treatments. However, the application of 100% magnetized water notably enhanced soluble sugars compared to the control. In addition, the production of anthocyanin and carotenoid increased by magnetized water 100% in maize leaves. Proline accumulation was also noted to decrease with reduced irrigation water levels in both magnetized and normal treatment groups, ranging from 100% to 50%. Hence, our findings indicate that the use of magnetic water may enhance crop yield by facilitating the transport of sugars through the increased presence of photosynthetic pigments and enhanced sugar synthesis. This effect is likely influenced by the specific water quantity needed for maize irrigation in conjunction with magnetic water application.

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1. Introduction

In countries such as Iran, where the rainy season is typically unpredictable, crop production relies heavily on sufficient irrigation during the dry season. Agriculture accounts for the majority (over 90%) of water consumption in Iran (Shahraki, 2020). Prioritizing water consumption based on efficiency in agriculture is crucial. As water scarcity becomes more prevalent, reducing water input per unit area becomes essential. This shift not only addresses current water shortages but also mitigates competition among various water-use sectors and alleviates environmental concerns. This approach is paramount for sustainable agricultural practices (Fakhar and Kaviani, 2024). Therefore, the cultivation of crops must adopt efficient water consumption strategies in agriculture, especially in the face of inadequate freshwater resources.

Incorporating magnetic water treatment as an environmentally friendly approach represents a novel technology that enhances crop yield without the use of chemicals, albeit its limited adoption in many countries. The passage of water through a magnetic field lowers water surface tension, facilitating enhanced nutrient absorption for plant growth by improving mineral solubility in water (Zaidi *et al.*, 2014; Teixeira da Silva and Dobránszki, 2014). The

[*] Corresponding author.
E-mail address: mohsen.okhovat@modares.ac.ir

chemical and physical properties of water change in a magnetic field and result in special functions (Liu and Shi, 2013). The induction of a magnetic field for water treatment could range from 1,000 to 6,000 G and affect the efficiency related to the index of the treatment pipe (Kochmarsky, 1996). For example, the strength of 4,000 to 5,000 G for a magnetic field led to the efficiency of 60% to 80% of the heater and low–pressure boilers. Therefore, this technology has a high potential to modify crop yield without a destructive effect on the soil and environment.

The magnetic field can be utilized for seed germination, seedling development, shoot and root growth, and yields of different plant species (Teixeira da Silva and Dobránszki, 2014). For example, magnetized water increased the growth and the yield of eggplant (Kishore *et al.*, 2022), maize (Alattar *et al.*, 2019), sunflower (Matwijczuk *et al.*, 2012), wheat (Hozayn and Qados, 2010), soybean (Radhakrishnan and Kumari, 2012), bean (Kishore *et al.*, 2023), and tomato (Baiyeri *et al.*, 2023). In addition to vegetative growth, Muraji et al. (1992) Also demonstrated that root growth of maize (*Zea mays*) Depends on the magnetic field when seedlings were exposed to fields at alternating frequencies of 40–160 Hz. Meanwhile, the magnetic field affects the physiological and biochemical responses (Podleśna *et al.*, 2019) and chemical composition (Rani *et al.*, 2022) in plants. For example, Mroczek-Zdyrska et al. (2016) indicated that magnetic field pretreatment of *Phaseolus vulgaris* changes physiological factors like the biosynthesis of chlorophyll, carotenoid, phenolic and flavonoid compounds.

Corn, also known as maize, is one of the most significant industrial crops globally. Its versatility and high yield make it an essential component in various industries, ranging from food production to biofuels (Yaheliuk *et al.*, 2024). Corn is a staple food for millions of people and serves as a primary feed source for livestock. Its ability to adapt to different climates and soil types allows it to be cultivated in various regions, making it a crucial crop for food security (Assaf *et al.*, 2024). This plant is a staple food for millions of people and serves as a primary feed source for livestock. Its ability to adapt to different climates and soil types allows it to be cultivated in various regions, making it a crucial crop for food security (Gali *et al.*, 2024).

Corn is processed into a wide range of food products, including cornmeal, corn syrup, and popcorn. Its derivatives are used in snacks, beverages, and even as sweeteners in many processed foods (Kaushal *et al.*, 2023). This crop is a key ingredient in the production of ethanol, a renewable biofuel. This has become increasingly important as the world seeks sustainable energy sources to reduce carbon emissions (Rial, 2024). Corn starch is utilized in the pharmaceutical industry as a binding agent in tablets. Additionally, innovations in bioplastics derived from corn are paving the way for more sustainable packaging solutions (Khandeparkar *et al*., 2024).

In this study, to sense the applied aspect of activated water treatment on maize, we investigate the effect of magnetized water on the seed germination of maize plants in agricultural fields. We developed the experimental design from lab to farm and evaluated the different characteristics of maize on a semi-large scale. The vegetative growth and physiological responses of maize plants were determined in different levels of irrigation with magnetized water and compared to normal irrigation water. The yield of maize was evaluated to determine the effect of deficit irrigation on irrigated by normal and magnetized water. Therefore, our results indicate that magnetic field can be used as a positive effect on the growth, development, and yield of maize besides genotype-dependent, although before going on a larger scale, it requires to be tested individually.

2. Materials and methods

2.1. Cultivation condition

This study was performed according to a one-year field-based experiment at the Agriculture Research Station, East of Tehran, Iran. The climate is continental, with an annual average temperature of 28°C. At this station, long-term average annual precipitation amounts to about 141.5 mm/year (National Center of Climate and Drought Crisis Management, 2022). The soil at the research station has been assessed before cultivation, although the station has been in use for research trials for several years. In this study, the *Zea mays* L. (Single Cross 704). was sown on 24 May 2022 Based on randomized complete block design with three replications (RCBD), with a total of 6 treatments. Each experimental treatment plot was 3m × 6m in dimension. In the field, distance between seeds and between rows was 18 and 75 cm, respectively (Fig. 1). This issue is due to the long growth period of the plant, also to prevent the increase of fungal diseases, and also to have better conditions of the farm. Samples were collected in September 2022 for the next analysis.

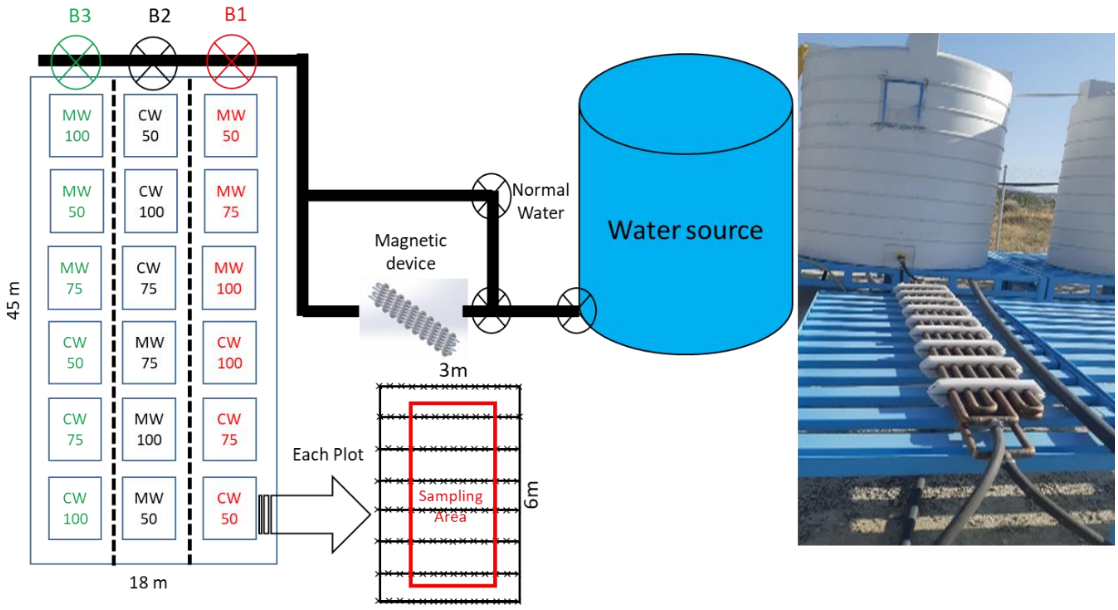

Figure 1. Magnetic in-line water treatment for irrigation of maize field. The experimental design was performed according to replications randomized complete block design (RCBD) with a total of 6 treatments consisting of three replications per treatment. Each plot was 3m × 6m in dimension, and possess 8 rows for maize planting. Sampling was performed from the middle of each plot from 6 rows.

2.2. Soil status evaluation

To quantify the effects of magnetized water on plant growth during irrigation, soil samples were collected from the different parts of the field to measure the macro- and micro-elements using the ICP method, along with soil pH was used as indicators of the soil status in this study. The soil's chemical properties during the growing season are given in Table 1. For harvesting, we uprooted the plants gently and the roots were shaken gently to measure the length of the root and shoot for further analysis.

This study was conducted as a one-year field-based experiment at the Agriculture Research Station in East Tehran, Iran. The climate in this region is continental, characterized by an average annual temperature of 28°C. The station typically receives an average annual precipitation of about 141.5 mm/year. The soil at the research station was evaluated before cultivation, although the station has been utilized for research trials over several years. Zea mays L (Single Cross 704) was planted on May 24, 2022, following a randomized complete block design with three replications (RCBD) and a total of six treatments. Each experimental treatment plot measured 3m × 6m. In the field, the distance between seeds and rows was 18 cm and 75 cm, respectively, to address the long growth period of the plant, prevent fungal diseases, and create optimal farm conditions. Soil samples were collected from various parts of the field to assess macro- and micro-elements using the ICP method, with soil pH serving as an indicator of soil status. The chemical properties of the soil during the growing season are outlined in Table 1. During harvest, plants were gently uprooted, and the roots were carefully shaken to measure root and shoot length for further analysis.

Table 1. Soil chemical properties before the experiment for maize cultivation.

pH	EC (µS. cm^{-1})	OM	N	Alkanity (as HCO_3)	P	K	Na	Ca	Mg	SO_4^{2-}	Cl^-
		(%)		ppm							
7.7	1210	3.21	0.09	202	3.19	11.5	155	214	35	1272	274.8

EC: Electrical Conductivity; OM: Organic Matter.

2.3. Water treatment and maize irrigation timing

Across the entire growth period (31 June 2022 –10 October 2022), irrigation timing for seed maize and field maize depends on the irrigation method, the type of soil, and the climate of each region. In this study, we used normal tap water which was separated into two parts including magnetized water (M) and normal tap water (C). To evaluate the different irrigation water requirements of seed maize and field maize, we treated seed and field maize with three different levels of irrigation with and without magnetized water including 2.31, 1.73, and 1.15 inches per foot during the cultivation period, which was labeled with 100, 75, and 50 percent, respectively. We considered 6 plots for each group with three replications and maize seedlings were irrigated in an organized method during the growth period similar to all tested seedlings.

2.4. Preparation of magnetized water

Magnetic water treatment directs water to pass through a strong magnetic field. We prepared the magnetized water by passing tap water through the magnetization device. The magnetic device is constructed from a 23 mm diameter copper tube with a 2-meter pipe length. To hold magnets and copper tubes, we designed a clamp and installed it on the system. By placing 70 neodymium magnets with size 50×20×30 mm on 4 integrated pipes, we provided constant magnetic strength water and passed through a strong and uniform magnetic field. Each integrated pipe is placed nearly 30 times between the magnets, from inlet to outlet (Only once per second). Fig. 1 shows the experimental setup which was packed and installed after the water tank.

2.5. Measurement of growth parameters

To determine the growth status of seedlings under the tested situation, we recorded The number of seed germination, shoot length, ear length, number of seeds per ear, and weight of ear.

2.6. Measurement of photosynthetic pigments

Chlorophyll and carotenoid content were measured (In the stem stage) according to the method (Lichtenthaler, 1987). In this method, 200 mg of fresh leaf tissue was cut into small pieces, ground, and macerated with 5 ml of acetone 80% (v/v). Samples were filtrated with Whatman paper and the final volume of the extract reached 10 ml with acetone 80% (v/v). After this period, a rate of 2 mL each was collected to determine the absorbance in a spectrophotometer at 470, 647, and 663nm. The concentration of these pigments was calculated using Lichtenthaler (1987) equations and expressed in mgg^{-1} FW (fresh weight).

2.7. Proline measurement

Proline concentration was measured (In the stem stage) by Bates et al. (1973) method. For this assay, 500 mg of fresh leaves were ground in 10 ml of 3% sulfosalicylic acid and completely homogenized. After filtration, extract (2 ml) was mixed with 2 ml of ninhydrin solution and 2 ml of glacial acetic acid and placed in a hot water bath (100°C) for one hour. By placing the test tubes in an ice bath, reactions were stopped. Then, 4 ml of toluene was added and the solution was vigorously mixed for 15 seconds. The supernatant phase containing toluene and proline was separated from the aqueous phase and its absorbance was determined by a spectrophotometer at a wavelength of 520 nm. The concentration of proline in each sample was calculated based on a calibration curve and expressed as micromole per gram of fresh weight.

2.8. Determination of total phenol and anthocyanin

The total phenolic content of the leaf extract was determined by the Folin–Ciocalteu method (Wojdylo *et al*., 2007). Briefly, 100 mg of dry leaves was extracted with 20 ml methanol 80% and kept in a water bath at 70 degrees for 3 hours. After filtration, 1 ml crude extract was mixed thoroughly with 2 mL of Folin–Ciocalteu reagent (10%) for 5 min, followed by the addition of 2 mL of 20% (w/v) sodium carbonate. The mixture was kept in the dark for 60 min, and absorbance was measured at 760 nm. The total phenolic content was calculated from the calibration curve, and the results were expressed as mg of gallic acid equivalent per g dry weight.

For the anthocyanin assay, we collected fresh leaves (1 g) at the end of the growth period, extracted them, and measured them using the method of Jordan et al. (1994). In detail, leaves were homogenized in 10 ml of acidified methanol (HCl: MeOH, 1:99, v/v) and centrifuged. The absorbance of the extract was determined at 530 nm with a spectrophotometer and anthocyanin content was estimated per mgg^{-1} FW (fresh weight).

2.9. Determination of soluble and insoluble sugars

To determine the soluble sugars, we used the described method by Kochert (1978), which is performed by the sulfuric acid-phenol method. Based on this method, acid hydrolysis of soluble sugars occurs and leads to the formation of a furfural compound, which produces a colored complex with phenol. Briefly, 100 mg of dry leaves (In the stem stage of leaves) were mixed in 5 ml of 70% ethanol and kept in the refrigerator for one week. After that, 0.5 ml of supernatant was mixed with 1.5 ml distilled water and 1 ml of phenol 5% and vigorously mixed by the vortex. Then, 5 ml of concentrated sulfuric acid was added and kept at room temperature for 30 min. Absorbance was recorded at 485 nm and soluble sugar values of the samples were evaluated using a standard curve related to glucose. The values were expressed based on milligrams per gram of dry weight. To measure the insoluble sugar, we used the remaining sediment on the filter paper related to the ethanol solution in the previous method. First, the sediment was dried and then weighed and mixed with 10 ml of distilled water in a test tube. Samples were placed in a hot water bath at 100°C for 15 min. After filtration, the solution reached a final volume of 25 ml with distilled water. Then, 2 ml of solution was vigorously mixed with 1 ml of phenol 5% by a vortex. Finally, 5 ml of concentrated sulfuric acid was added and kept at room temperature for 30 min. The standard curve for starch was obtained at 485 nm by a spectrophotometer, and finally, the content of insoluble sugars was measured. After 100 days from the planting date, the crop was harvested. The analysis of all data was done using Prism software.

3. Results and discussion

3.1. Magnetized water triggers the emergence of maize plants from seed earlier and more

First, we evaluated the effects of magnetized water on the germination factor of seeds in pots and maize fields. For this purpose, we treated seed maize in the plot and field with two types of irrigation with and without magnetized water, which was 3.2 inches per foot 10 days after seed planting. It means that irrigation was performed to complete the need for water for seed germination (100%). In a pot, we observed that MW could significantly affect the seed germination and growth index of maize (Fig. 2A). Then, we performed field cultivation to quantify these parameters according to statistical procedures for agricultural research. Obtained results indicated that 91% of total seeds germinated 10 days after planting, however, the germination percentage of seeds in normal tap water treatment was 68% (Fig. 2B,C). Therefore, the magnetized water can increase the germinating rate of seeds and significantly reduce the number of seeds planted per area for seeds originating from a common source.

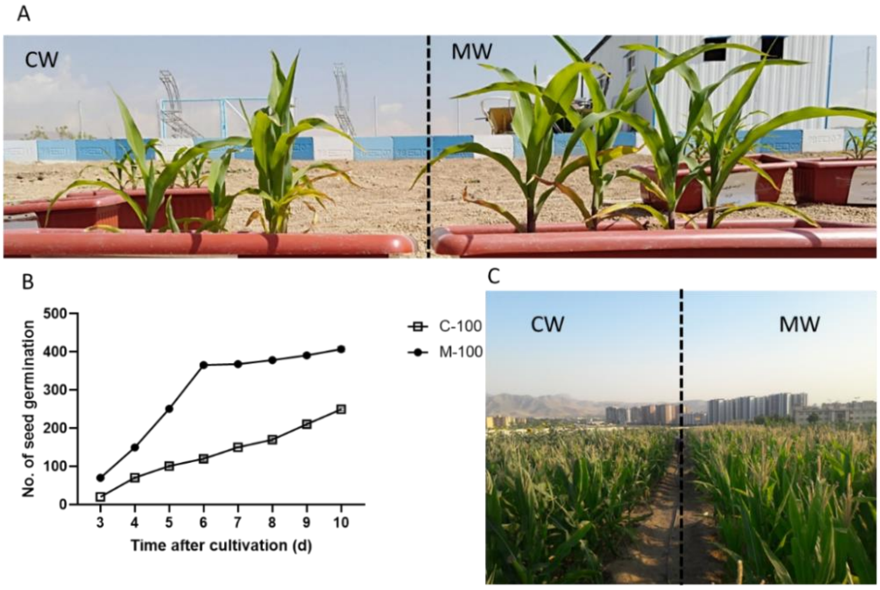

Figure 2. Seed maize germination in water treated with and without a magnetic field according to complete requirement of water (100 %). (A) Pot planting of maize seed, (B) The rate of seed germination, (C) Maize Cultivation in fields.

3.2. Magnetized water increased maize growth

We tested the volume of different types of irrigation water at maize fields with normal water and magnetized water including 2.31, 1.73, and 1.15 inches per foot, which were labeled with 100, 75, and 50%, respectively. Magnetized water at 100% recorded the higher shoot height (Table 2) and the lowest was recorded in normal water at 50% (Fig. 3A,B).

Concerning shoot length, magnetically treated water showed an increase in plant height over control, although 75 and 50% were not statistically significant. Shoot length data showed that magnetically treated water of 100% recorded significantly higher length than 50%.

Table 2. Variance analysis table of shoot length of single cross 704 corn plant

	DF	SS	MS	F (DFn, DFd)	P value
Interaction	2	1765	882.3	F (2, 12) = 2.101	P=0.1650
Row Factor	1	15534	15534	F (1, 12) = 36.99	P<0.0001
Column Factor	2	25801	12900	F (2, 12) = 30.72	P<0.0001
Residual	12	5039	419.9		

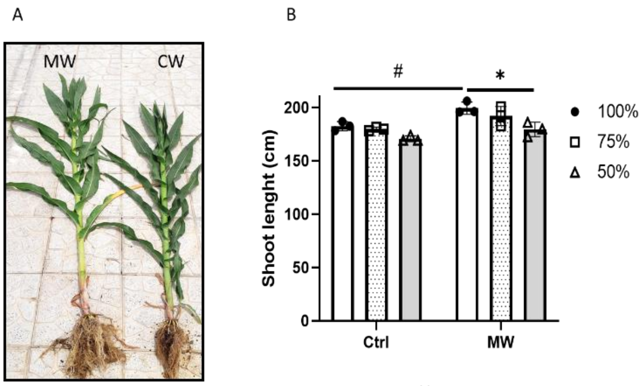

Figure 3. The shoot length maize with different irrigation water requirements including 100, 75, and 50%, respectively. (A) Maize plant treated with 100 MW and 100 CW; (B) shoot length analysis. and inter-subjects, respectively (P<0.05).

3.3. Magnetized water positively regulated ear growth

The magnetic treatment of irrigation water increased the ear length, weight, and the number of seeds per ear vs. control. Statistical analysis of the data reveals significant differences for all the treatments (Table 3). The ear size of plants treated with and without magnetized water 50% was significantly smaller than that of 75 and 100% plants. In plants treated with and without magnetic water treatment, with decreasing water consumption from 100 and 75 % to 50%, we observed a significant decrease in weight and number of seeds per ear (Fig. 4A-C). The length of the ear in magnetized water 100 and 75% was also significantly more than that of controls (Fig. 4B), thus grain yield of magnetic water treatment significantly increased compared with that of normal water treatment (Fig. 4A,C) (Table 3). Therefore, consistent with the weight of the ear, the number of seeds per ear reduced in control when the volume of irrigation water decreased from 100 and 75% to 50%, while the plants treated with magnetized water indicated high levels of length, weight, and number of seed per ear (Fig. 4D).

Table 3. Variance analysis table of ear weight and length single cross 704 corn plant

		DF	SS	MS	F	P value
Ear weight	Interaction	2	1765	882.3	2.101	0.1650
	Row Factor	1	15534	15534	36.99	P<0.001
	Column Factor	2	25801	12900	30.72	P<0.001
	Residual	12	5039	419.9	-	-
		DF	SS	MS	F	P value
Ear length	Interaction	2	15.74	7.87	2.815	0.099
	Row Factor	1	183.6	183.6	65.69	P<0.001
	Column Factor	2	106.2	53.1	19	P<0.001
	Residual	12	33.54	2.795	-	-

100 MW and 100 CW. a significant difference intra- and inter-subjects, respectively (P<0.05, P<0.01, P<0.001, respectively).

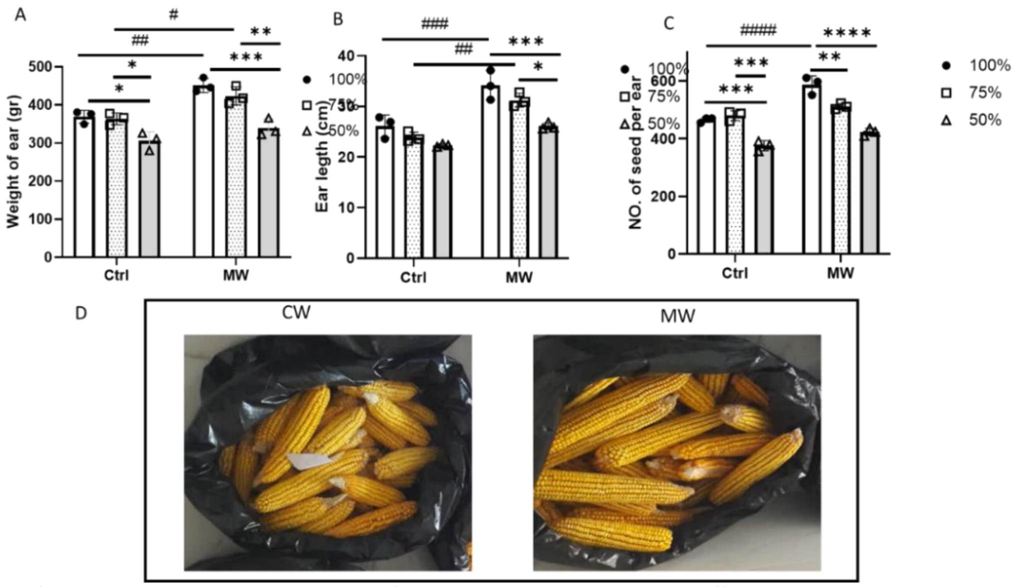

Figure 4. The weight of ear (A), ear length (B), and number of seeds per ear (C) at maize with different irrigation water requirements including 100, 75, and 50%, respectively. (D) Maize ear treated with 100 MW and 100 CW. a significant difference intra- and inter-subjects, respectively (P<0.05, P<0.01, P<0.001, respectively).

3.4. Magnetized water increased photosynthetic pigment content

According to pigment analysis, we observed that magnetized water significantly ($p<0.05$) affected chlorophyll content in the leaves of maize. It was noted that the application of magnetized water 100% remained statistically similar for chlorophyll a, chlorophyll b, and total chlorophyll in maize leaves (Table 4) (Fig. 5A-C). Application of magnetized water on the distribution pattern of 75 and 50% treatments was similar, although, chlorophyll content decreased in an irrigation-dependent manner the lowest was in 50% treatment. Meanwhile, magnetized and normal water 75 and 50% did not differ significantly for all types of chlorophyll but magnetized water 100% differed significantly for chlorophyll a, b, and total chlorophyll compared to both in 50% treatment. Therefore, magnetized water 100% significantly increased the content of chlorophyll a, chlorophyll b, and total chlorophyll in maize leaves over control.

Table 4. Variance analysis table of a, b and total Chlorophyll single cross 704

		DF	SS	MS	F	P value
Chl a	Interaction	2	0.1226	0.06131	2.769	0.1026
	Row Factor	1	0.1014	0.1014	4.580	0.0536
	Column Factor	2	0.3210	0.1605	7.250	0.0086
	Residual	12	0.2657	0.02214	-	-
		DF	SS	MS	F	P value
Chl b	Interaction	2	0.02166	0.01083	2.238	0.1399
	Row Factor	1	0.02830	0.02830	6.083	0.0297
	Column Factor	2	0.06437	0.03219	6.918	0.0100
	Residual	12	0.05583	0.004653	-	-
		DF	SS	MS	F	P value
Total Chl	Interaction	2	0.2474	0.1237	2.719	0.1062
	Row Factor	1	0.2368	0.2368	5.207	0.0415
	Column Factor	2	0.6720	0.3360	7.387	0.0081
	Residual	12	0.5458	0.04548	-	-

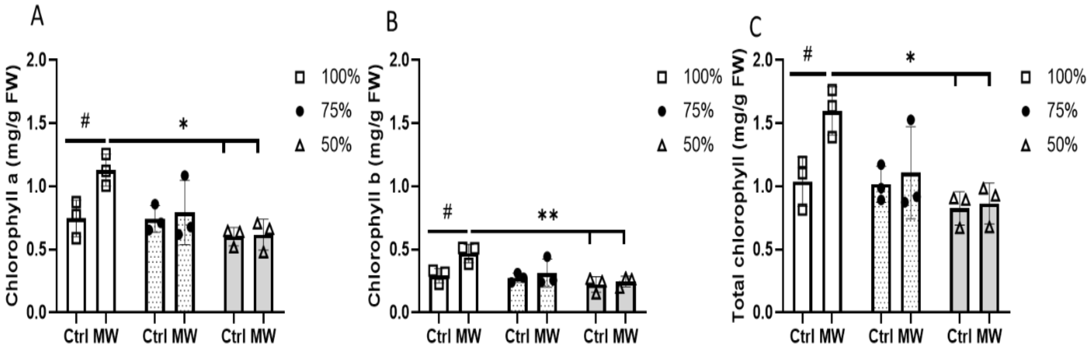

Figure 5. Chlorophyll content in maize cultivated with different irrigation water requirements including 100, 75, and 50%, respectively. (A) chlorophyll a, (B) chlorophyll b, (C) total chlorophyll. *, ** and # indicated a significant difference intra- and inter-subjects, respectively ($P<0.05$, $P<0.01$, respectively).

3.5. Production of anthocyanin and carotenoid is induced by magnetic water

To evaluate the activity of the antioxidant system in response to magnetized water, we assayed the production of carotenoids and anthocyanin in the leaves. Different levels of irrigation water with and without a magnetic field were used to separate the effect of magnetized water from the water quantity used for maize irrigation (Table 5). Our results indicated that carotenoid content significantly enhanced in response to magnetized water 100% over control ($p<0.05$), although its change was not significant in 75 and 50% of treatments (Fig. 6A). For anthocyanin, it was observed that magnetized water 100% differed significantly over control and 50% (Fig. 6B). No significant changes in anthocyanin were noted among 75 and 50 % of treatments over control. Therefore, the magnetic field may promote the accumulation of carotenoids and anthocyanins in maize by enabling their production even when the plant does not perceive the reduced water availability necessary for optimal growth and development.

Table 5. Variance analysis table of carotenoid and anthocyanin single cross 704

		DF	SS	MS	F	P value
Anthocyanin	Interaction	2	16.45	8.225	8.103	0.0059
	Row Factor	1	2.758	2.758	2.717	0.1252
	Column Factor	2	2.127	1.063	1.048	0.3807
	Residual	12	12.18	1.015	-	-
		DF	SS	MS	F	P value
Carotenoids	Interaction	2	0.008581	0.004291	2.175	0.1563
	Row Factor	1	0.008124	0.008124	4.119	0.0625
	Column Factor	2	0.01119	0.005596	2.837	0.0980
	Residual	12	0.02367	0.001972	-	-

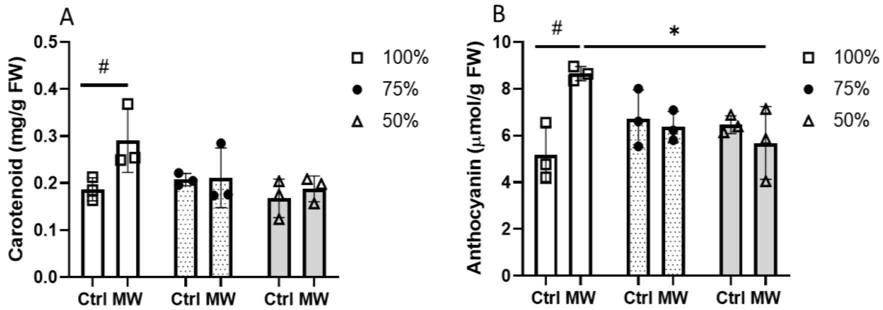

Figure 6. Carotenoids and anthocyanin content in maize cultivated with different irrigation water requirements including 100, 75, and 50%, respectively. (A) Carotenoid, (B) Anthocyanin contents. * And # indicated a significant difference intra- and inter-subjects, respectively (P<0.05).

3.6. Proline and sugar accumulation is dependent on the irrigation regime

To investigate the effect of magnetized water on the osmolyte compounds, we determined the content of proline and sugars in leaves. We found that different levels of irrigation water significantly (p<0.05) affect the proline and sugar accumulation in the leaves of maize cultivated in a field (Table 6). We also evaluated the influence of irrigation rate on the osmolyte compounds of maize leaves. Our results indicated that the application of 75 and 50% of normal water significantly increased the accumulation of soluble sugars over 100% treatment (Fig. 7A). No significant changes of soluble accumulation were noted among different levels of magnetized water 100, 75, and 50%, but magnetized water 100% significantly increased soluble sugars compared to the control.

Meanwhile, the distribution pattern of insoluble sugars was similar to soluble sugars under different levels of irrigation in both treatments (Fig. 7B). It was observed that the decreasing level of normal water from 100 to 50% hiked the insoluble sugars concentration in leaves and it was significant (p<0.01, p<0.05). A maximum enhancement of insoluble sugars was observed where magnetized water 100% was applied over control.

In the case of proline accumulation in leaves, a similar trend of enhancement with a decrease in the application rate of normal water was noted. With decreasing irrigation water related to magnetized and normal treatment from 100 to 50 %, proline accumulated significantly in leaves (Fig. 7C). In 75% of treatments, magnetized water decreased proline concentration over control. Therefore, the accumulation of sugars and proline is more dependent on the water quantity required to supply maize irrigation in the field in combination with magnetic water.

Table 6. Variance analysis table of proline, insoluble sugar and soluble sugar single cross 704

		DF	SS	MS	F	P value
Proline	Interaction	2	3060	153	12.71	0.0011
	Row Factor	1	520	520	4.321	0.0598
	Column Factor	2	5026	2513	20.88	0.0001
	Residual	12	1444	120.4	-	-
		DF	SS	MS	F	P value
Insoluble sugar	Interaction	2	0.06424	0.03212	6.431	0.0126
	Row Factor	1	0.003814	0.003814	0.7635	0.3994
	Column Factor	2	0.07152	0.03576	7.160	0.0090
	Residual	12	0.05993	0.004995	-	-
		DF	SS	MS	F	P value
Soluble sugar	Interaction	2	0.006301	0.003150	4.440	0.0360
	Row Factor	1	0.007729	0.007729	10.89	0.0063
	Column Factor	2	0.03359	0.01680	23.67	P<0.001
	Residual	12	0.008514	0.0007095	-	-

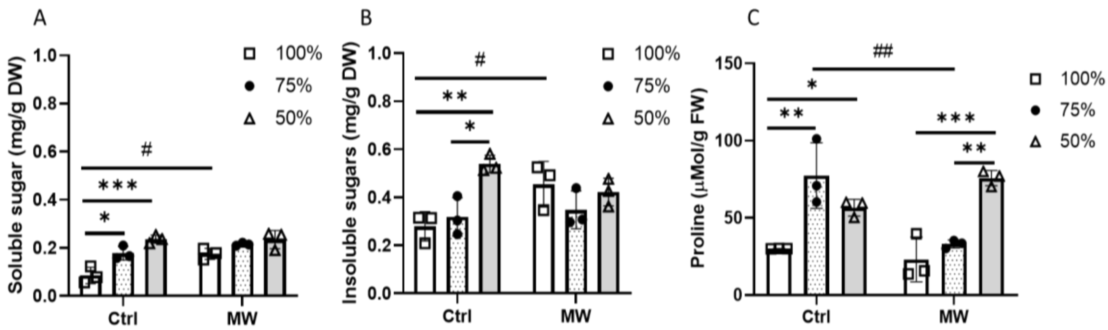

Figure 7. The accumulation of osmolyte compounds at maize with different irrigation water requirements including 100, 75, and 50%, respectively. (A) Soluble sugar, (B) Insoluble sugar, and (C) Proline accumulation. *, **, * and #, ## indicated a significant difference intra- and inter-subjects, respectively (P<0.05, P<0.01, P<0.001, respectively).**

The results of this study demonstrated that the magnetic field can increase the seed germination rate and lead to the growth and development of maize in a field. Since maximum crop yield depends on seed germination, it occurs when the dry seed absorbs the water, activates with biochemical reactions, and leads to a normal density of sprouts. The physical and chemical properties of water quality and soil could be affected by magnetic energy that resulted in an increase in water uptake into the cell (Tai *et al*., 2008). For example, the basic properties of water under a magnetic field like ionic strength, pH, and surface tension force could hike the polarizing effect by intensifying the internal vibration of water molecules. Meanwhile, the varieties and the duration of the magnetic field affect the germination percentage. For example, Germination percentage was measured in two maize hybrids including *Zea mays* convar. *mays* cv. Calaria and *Zea mays* convar. saccharata var. Tasty Sweet (Athens, Greece) and magnetic field improved common maize and sweet maize varieties in germination rate after 30 and 45 min treatment (Bilalis *et al*., 2012).

In another study, pre-sowing seed treatments in three maize (*Zea mays* L.) genotypes with electromagnetic fields improved seed vigor and demonstrated positive biostimulation depending on the seed genotype (Aguilar *et al*., 2015). Rapid germination of seeds and seedling growth were reported in other seeds like asparagus (Soltani *et al*., 2006), lentil (Sestili *et al*., 2023), rice (Flórez *et al*., 2004), faba bean (Podleśna *et al*., 2019), sorghum (Nurbaity *et al*., 2019), and soybean (Michalak *et al*., 2019) in response to the influence of a magnetic field. In this study, we used magnetized water to irrigate the maize seeds and our results indicated MW increased the germinating rate of maize seeds 23% more than the control. Consistent with our results, the irrigated cucumber seeds with magnetized water showed an increase in growth compared to the control plants (Hirota *et al*., 1999). Therefore, magnetized water effectively improves the efficiency of maize irrigation in correlation with seed germination.

Plant growth and higher grain yield are the most important factors for the global demand for more food from lesser water resources. Furthermore, abiotic stimuli like drought stress could affect crop yield in response to magnetic water. To investigate the relationship between magnetized water and the quantity of irrigation during the growth and development of maize, we tested the three irrigation regimes including 100, 75, and 50%. According to our results, at magnetic water 100%, the values of maize seed density and weight of ear were 26% and 22% more than the control, respectively, which indicated an obvious effect on ear growth and grain yield. At irrigation 50%, we observed the lowest length, weight, and seed density at both treatments. In confirmation of our results, Rivero et al. (2016) demonstrated a significant increase in biomass production in maize plants treated with magnetic water. Selim and El-Nady (2011) and Al-Khazan et al. (2011) recorded that magnetized water irrigation increases water use efficiency under drought and normal conditions in jojoba as compared to other recommended irrigation. Seed emergence, crop growth rate, and yield of sunflowers significantly improved when magnetic seed enhancement occurred (Afzal *et al*., 2021). Consistent with our results, Alattar et al. (2019) also demonstrated that magnetized water positively affects the growth of maize seedlings, shoot length, stem thickness, and leaves number per seedling over the control. Activations of enzymes and hormones during the growth process resulted probably an improvement in the mobilization and transportation of nutrients under a magnetic field (Maheshwari and Grewal 2009; Surendran *et al*., 2016). For example, higher nutrient uptake with magnetized water in wheat and canola plants was reported (Hozayn *et al*., 2016; Selim and Selim, 2019).

Plant vigor is dependent on the biochemical processes and the magnetic field leads to a change in a chemical reaction with a positive influence on photochemical activity and enzyme activities (Babaloo *et al*., 2018; Baghel *et al*., 2018). Sadeghipour (2016) demonstrated that magnetic water irrigation of cowpea leads to increase in photosynthesis and net photosynthesis rate. Magnetized water can be also involved in chloroplast development through gene expression and cytokinin synthesis (Atak *et al*., 2003) and increasing IAA (Hozayn *et al*., 2011). We also measured the content of chlorophyll a, b, and total chlorophyll in maize plants treated with magnetized water and found magnetized water 100% increased significantly the accumulation of photosynthetic pigments. However, magnetized water 75 and 50% did not change significantly for all types of chlorophyll and total chlorophyll when compared to the control. Some reports demonstrate that chlorophyll accumulation is dependent on the intensity and duration of magnetic field exposure. For example, Racuciu et al. (2007) reported that 100 to 250 mT MF and longer MF exposure reduced photosynthetic pigments but chlorophyll content increased at 50 mT MF.

The assimilatory pigment content like carotenoids of rice plants treated with magnetized water significantly increased (Babaloo *et al*., 2018). We also demonstrated that magnetized water 100% significantly enhanced carotenoids and anthocyanin content than the control ($p<0.05$). Dhawi and Al-Khayri (2008) also mentioned that MF increased pigment content and carotenoid in *Phoenix dactylifera* L. (date palm) by 100 mT for 360 min. Furthermore, the higher carotenoid content by MF accumulates by increasing the ROS production and activation of the plant defense system (Abdolmaleki *et al*., 2007; Strzałka *et al*., 2003). However, Mridha et al. (2016) reported that MF exposure for 30-60 min reduced the carotenoid and chlorophyll content and increased ROS production. Hasan et al. (2018) subjected two Moringa species to drought treatment for 30 days including 100% Field capacity (Control), 50% FC (Moderate stress), and 20% FC (Severe Stress). Results indicated that drought stress increased the accumulation of all phenolic compounds, flavonoids, Malondialdehyde (MDA), H_2O_2, and proline content during all the levels of drought stress but magnetic water treatment decreased the antioxidant and oxidant compounds significantly. In our study, the proline content was significantly increased in maize plants under drought stress. Under drought stress, magnetized water 100% did not change significantly proline content than control but magnetic water 75% decreased proline than 75% normal water. Meanwhile, both magnetized water and normal water had 50% increased proline content.

In grapevine, the key enzyme activity of the phenylpropanoid pathway called PAL increased in response to MF and phenolic compounds such as anthocyanin, flavonoids, and phenol accumulated (Zareei *et al*., 2019). Additionally, seawater irrigation stress of *Silybum marianum* (L.) plants could reduce when magnetic field treatment was applied for irrigation and decreased the harmful effects of oxidative damage (Migahid *et al*., 2019). In date palms, Dhawi and Al-Khayri (2008) reported higher proline accumulation in response to magnetic fields, which change the osmotic potential and lead to the enhancement of water absorption (Belyavskaya, 2001). Recently, Naseer et al. (2022) also reported that photosynthetic pigments and soluble sugar contents increased in response to artificial magnetism resulting in the improvement of various growth attributes. Our results indicated that soluble and insoluble sugars were significantly increased under drought stress conditions. Under magnetized water treatment, maize plants exposed to 100% level exhibited a significant increase in soluble and insoluble sugars to control but others did not change significantly when compared to their control. Therefore, using magnetized water in maize plants can counteract the adverse effects of drought stress through the transportation of sugars and modulation antioxidant system with decreasing oxidative damage.

4. Conclusion

We performed our experiment in the field to highlight the influence of magnetized water on the physiological and growth responses of maize. Generally, magnetic field treatment was studied in a laboratory in a defined condition, however, it will be different in agriculture fields for farmers. Our results demonstrate that the installation of magnetic devices before the irrigation network in the field for maize could improve maize productivity by increasing photosynthetic pigments and sugar production. Furthermore, induction of anthocyanin and carotenoid occurs by magnetic water, however, irrigation regimes affect the accumulation of proline and sugars. Therefore, the establishment of maize irrigation strategies requires a scientific basis to enhance water use efficiency and highlight magnetized water treatment as one of the most valuable and economical technologies involved in improving yield and saving water resources.

Conflict of interests

All authors declare no conflict of interest.

Ethics approval and consent to participate

No humans or animals were used in the present research. The authors have adhered to ethical standards, including avoiding plagiarism, data fabrication, and double publication.

Consent for publications

All authors read and approved the final manuscript for publication.

Availability of data and material

All the data are embedded in the manuscript.

Authors' contributions

All authors had an equal role in study design, work, statistical analysis and manuscript writing.

Informed consent

The authors declare not to use any patients in this research.

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