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Irrigation with Activated Water Promotes Root Growth and Improves Water Use of Winter Wheat

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Abstract: Magnetic or oxidation treatment of irrigation water can promote the transport of water and nutrients by the root system, improve the efficiency of water and fertilizer use and potentially increase yields. Hydroponic and field experiments were conducted to explore how irrigation with magnetized and/or oxidized water affects grain yield and water-use efficiency (WUE) in winter wheat with an emphasis on physiological changes in the root system. Hydroponic cultivation of winter wheat with pure groundwater and brackish water included the following treatments: control group (CK–G, CK–B); magnetization (GM, BM); oxidation (GO, BO); and the combination of magnetization and oxidation (G(M+O), B(M+O), G(O+M), B(O+M)). Field experiments only tested irrigation with various types of groundwater, including the control group (IG), magnetization treatment (IGM), oxidation treatment (IGO), and the combination of the two treatment methods (IG(M+O), IG(O+M)). Hydroponic cultivation revealed that the magnetic treatment and oxidation of both groundwater and brackish water can significantly improve the root vigor of winter wheat, i.e., improvements of 100.5–253.7% and 100.4–213.9% were seen in the groundwater and brackish treatment groups, respectively, relative to the control group. The root length density (RLD) of wheat increased by 67.6% (GM), 79.4% (GO), 7.5% (BM), and 40.0% (BO) relative to the respective control groups (CK–G and CK–B). Moreover, the root weight density (RWD) for BO and B(O+M) treatments improved significantly (66.7% and 55.4%, respectively) relative to CK–B. The maximal increases in root surface area density (RSD) were observed in treatments GO and B(O+M), which showed values 125% and 100%, respectively, higher than what was measured for the control groups. The root/shoot ratios of the GO and G(O+M) treatments improved significantly (by 75.3% and 62.0%, respectively) relative to CK–G. The results of field experiments showed that wheat in the IGO and IG(O+M) plots absorbed more water from the soil than wheat in the of IG plots (increases of 13.9% and 16.9%, respectively). Furthermore, the IGO and IG(O+M) treatments produced significantly higher grain yields and WUE than the IG plots, with IGO producing the maximum yield ($11.7 \times 10^3 \text{ kg ha}^{-1}$) and IG(O+M) the highest observed WUE ($30.3 \text{ kg ha}^{-1} \text{ mm}^{-1}$). Hence, the research provides clear evidence that the irrigation of winter wheat with magnetized and/or oxidized water can increase grain yields and WUE.

Keywords: magnetization; oxidation; root vigor; root length density; grain yields; water-use efficiency



Citation: Zhao, G.; Zhou, B.; Mu, Y.; Wang, Y.; Liu, Y.; Wang, L. Irrigation with Activated Water Promotes Root Growth and Improves Water Use of Winter Wheat. *Agronomy* **2021**, *11*, 2459. <https://doi.org/10.3390/agronomy11122459>

Academic Editor: Alberto San Bautista

Received: 18 October 2021

Accepted: 30 November 2021

Published: 2 December 2021

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1. Introduction

The shortage of water resources on a global level limits agricultural development, and may severely threaten global food security in the coming decades [1–3]. The oppositional juxtaposition between growing demand for production and water shortages has become increasingly prominent in agricultural production [4,5]. Wheat production has stagnated in 37% and 56% of the production areas around the world and in China, respectively [6].

Most of the areas dedicated to winter wheat production in China are characterized by the uneven distribution of water resources over time and space, while the period of crop growth is not usually synchronized with the rainy season [7]. Both of these characteristics mean that these regions of winter wheat production are highly dependent on irrigation with groundwater [8]. This deep irrigation and exploitation of groundwater resources adversely affected the region [9,10], with the water table decreasing by 0.5–3 m/year in the northwest part of China over the last 20 years [11]. Furthermore, the use of surface irrigation methods (furrow and border irrigation) and excessive water consumption in agricultural production translate to especially low water-use efficiency (WUE) and irrigation water-use efficiency (IWUE) in northwestern China [12,13]. Hence, it is imperative that agricultural organizations and researchers in these areas explore efficient, environmentally friendly agricultural technologies that will improve crop productivity and WUE while conserving water and the local environment. The identification of effective solutions will greatly help the region transition to sustainable agriculture.

Magnetized water production has begun to attract significant attention from the agricultural sector [14,15], mainly because it can alter the molecular structure of water and the composition of the aquatic environment through a physical technique [16,17]. Furthermore, it can improve the capacity for water to interact with other substances [18]. Water becomes magnetized after flowing through the magnetic environment comprising permanent magnets of a certain velocity positioned perpendicular to the magnetic force line. Studies have indicated that the magnetic treatment of irrigation water can benefit crop growth and yield along with water properties, which could make it possible to utilize lower quality water in agriculture [19,20]. Treatment approaches relying on oxidation have also been tested in agriculture, and irrigation with oxidized water has demonstrated promising results [21,22]. Although multiple studies have shown that magnetized water can promote the growth and yield of crops such as wheat, corn and soybean, there are still doubts about how effective this practice is [20,23–25]. Most skeptics state that the biological effects of magnetized water, as well as the mechanisms through which it improves growth and yield, remain unclear, which limits its application to agriculture. The oxidized water refers to water which only retains the positive charge and positive ions after being passed through an oxidation system. Several systematic studies have highlighted various examples of how using oxidized water to irrigate crops can benefit agriculture. For example, Wang et al. [18] showed that irrigation with oxidized water can improve WUE, reduce soil salt stress and increase yields. Irrigation water that has been improved by physical technology can be defined as activated water. By improving the physicochemical properties (the pH and dissolved oxygen concentration of water increase after activation, while the viscosity coefficient and surface tension decrease), the magnetic or oxidation treatment improves the action, and ultimately advances the transmission, of irrigation water from soil to crops. The size of crystalline particles and sedimentation after treatment will reduce, and more particles will be suspended in the water. This will decrease the likelihood of precipitated solid substances blocking irrigation and crop capillary channels, and help maintain a smooth flow of nutrient solution, thus enhancing the absorption of water by plants [25].

The root system is the primary organ through which plants uptake available water and nutrients [9,26,27]. The roots of winter wheat are affected by soil water status [28,29], and improvements in soil water use efficiency mainly depend on the development of the root system [1,30]. Various irrigation practices can stimulate roots to grow into deeper soil layers, and thus, can enhance the uptake of water from the subsoil layers [31]. The key root morphological characteristics are root length density, root weight density and root surface area density, all of which directly influence the functioning of the root system and crop production [9,32]. Root growth was found to be significantly associated with shoot biomass, which contributes to higher grain yields and WUE [33].

The Guanzhong Plain is a typical irrigated area located in the middle of Shaanxi Province and is the main area for winter wheat production within China. Spring and summer droughts, which are influenced by the monsoon climate and exacerbated by the

intensified exploitation of water, have seriously decreased winter wheat yields on the plain. This has severely restricted the development of sustainable agriculture in the area [12]. Therefore, the area needs efficient technological solutions that can improve crop yields and WUE under water limitations and serve as a basis for sustainable agricultural development. Up to now, the response of crop root growth and physiological characteristics to activated water irrigation needs to be clarified. The main purpose of this study was to clarify the how winter wheat responds to irrigation with water that has been treated with magnetization and oxidation, as well as a combination of the two. More specifically, root morphology and vigor were studied in hydroponic experiments, while grain yields and WUE were studied via field experiments. We hoped to provide insight into how irrigation with magnetized and/or oxidized water can benefit winter wheat production.

2. Materials and Methods

2.1. Site Description and Experimental Design

2.1.1. Hydroponic Experiments

Hydroponic experiments were carried out in a greenhouse of Northwest Agricultural and Forestry University, Shannxi Province, China, between June–September 2019. The Xiaoyan 22 wheat variety was tested.

Both pure groundwater (mineralization degree of 0.14 g/L) and brackish water (mineralization degree of 3 g/L, composed of NaCl and pure groundwater) were tested. They were subjected either to magnetization or oxidation, or both. The water pass through the magnetization or oxidation circulatory system for 0.5 h. The experiments also included controls for both types of water. Following treatment, the water was used to prepare a nutrient solution that would be used in the hydroponic cultivation system [34]. The experimental design is shown in Table 1.

Table 1. The different water treatment schemes applied in the hydroponic experiments.

Treatment	Test Water	
	Pure Groundwater	Brackish Water
CK	CK–G	CK–B
Magnetization	GM	BM
Oxidation	GO	BO
Magnetization + oxidation	G(M+O)	B(M+O)
Oxidation + magnetization	G(O+M)	B(O+M)

Note: CK means the control check. CK–G and CK–B mean that the wheat received groundwater and brackish water, respectively, without any treatment. GM and GO describe cultivation with groundwater that was magnetized and oxidized, respectively. G(M+O) and G(O+M) describe cultivation with groundwater that was magnetized and then oxidized and groundwater that was oxidized and then magnetized, respectively. BM, BO, B(M+O) and B(O+M) describe the aforementioned treatments, with the exception of using brackish water.

Seeds that were clean and of uniform size were selected for conventional seedling cultivation. The seeds were washed after being soaked in hydrogen peroxide, and then placed in a dish with filter paper at the bottom. Each treatment had five replicates, and each treatment contained 300 seeds. The water was replaced once a day with water from various treatments. After five days, the seedlings with consistent and robust growth were selected and cultivated with the nutrient solution prepared from the treated water [34]. The cultivation conditions were: temperature of 25 °C/20 °C (day/night); humidity between 60–70%; natural light; and the nutrient solution was changed every five days. The volume of the nutrient solution in cultivation box was 5000 cm³. The experiment had a complete randomized block design, and each treatment (containing 45 wheats) had five replicates.

2.1.2. Field Experiments

Field experiments were performed to assess how different irrigation water types affected crop growth and WUE. The field experiments were carried out during 2018–2019 and 2019–2020 at the Caixinzhuang experimental farm of the Northwest Agricultural and

Forestry University on the Guanzhong Plain at the southern end of the Loess Plateau, China ($34^{\circ}18' \text{ N}$, $108^{\circ}05' \text{ E}$, 523.7 m above sea level). The area has a mean annual temperature of 12.9° C and mean annual precipitation of 650 mm. Most of the precipitation, which accounts for 65% of total annual precipitation, is concentrated between July–September. The day, monthly precipitation and precipitation frequency of rain events for various precipitation classes are presented in Figure 1. The available phosphorous, hydrolysable nitrogen and available potassium in the 0–20 cm layer before the experiment were 5.7 mg kg^{-1} , 7.0 mg kg^{-1} and 133.8 mg kg^{-1} , respectively. The sand content, silt content and clay content were 31.8%, 51.7% and 16.5%, respectively. The winter-wheat cultivar Xiaoyan 22 used in this experiment is widely grown in this area. The wheat was sown on 15 October 2018 and 13 October 2019 at a planting density of 187.5 kg ha^{-1} .

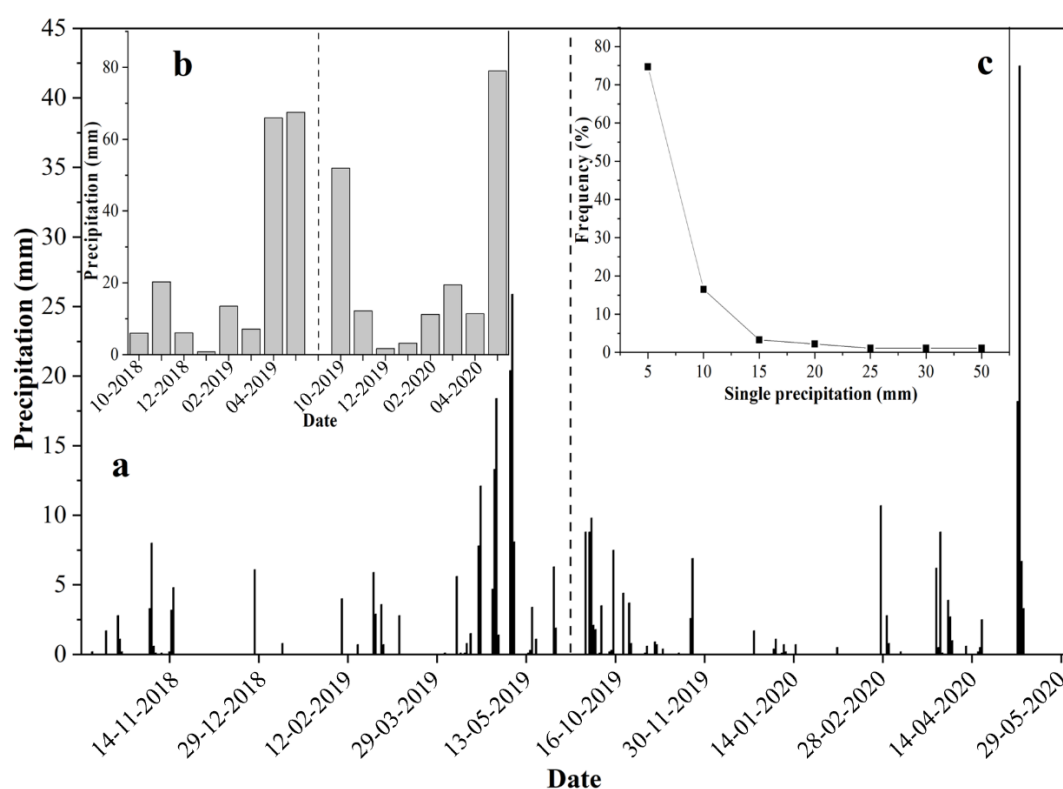


Figure 1. The daily (a) and monthly (b) precipitation and precipitation frequency (c) during the winter wheat growth period from October 2018 to June 2019 and from October 2019 to June 2020 in field experiments.

The mineralization degree of the local groundwater is 0.14 g/L. The artificial preparation of brackish water for irrigation can lead to soil salinization and destroy the soil environment. Therefore, brackish water irrigation experiments were not carried out, and only pure groundwater was used for the irrigation experiments. Five different types of irrigation water differing in treatment were tested during the overwintering (15 January 2019 and 2 January 2020, respectively), jointing (3 April 2019 and 23 March 2020, respectively) and filling (20 May 2019 and 22 May 2020, respectively) stages of wheat production (Table 2). The single irrigation amount was 60 mm, while the total irrigation amount was 180 mm. The drip irrigation system was used, and the irrigation levels were calculated by the number of taps and the drip rate. The experiment employed a complete randomized block design, and each treatment had three replicates [35]. Each plot was $4 \text{ m} \times 4 \text{ m}$, and adjacent plots were separated by 1 m.

Table 2. The treatments and irrigation parameters used in the field experiments.

	Type of Irrigation Water	Single Irrigation Amount (mm)	Total Irrigation Amount (mm)
IG	Pure groundwater	60	180
IGM	Magnetized water	60	180
IGO	Oxidized water	60	180
IG(M+O)	Magnetized + oxidized water	60	180
IG(O+M)	Oxidized + magnetized water	60	180

Note: IG means irrigation with pure groundwater. IGM and IGO describe irrigation with magnetized and oxidized groundwater, respectively, and the total irrigation amount is 180 mm. IG(M+O) and IG(O+M) describe irrigation with groundwater that was magnetized and then oxidized and irrigation with groundwater that was oxidized and then magnetized, respectively.

2.2. Magnetization and Oxidation of Water

The system for magnetizing water consisted of a water-supply tank, pump, outlet pipe (polyethylene pipe) and magnet. A permanent magnet (20 cm length, 10 cm height, 8 cm width) with a field intensity of 3000 G was used in this study. The permanent magnet was mounted on the outer wall of the outlet pipe (about 1.0 m from the water outlet), and the water was magnetized as it passed through the pipe (The thickness and diameter of the pipe were 0.5 cm and 10.0 cm, respectively). Flow rate was $6.3 \times 10^{-3} \text{ m}^3/\text{s}$. The oxidation system included an oxidation processor (Eco1st Technology Group, <http://irrigationenhancer.com/> (accessed on 20 May 2018)), grounding resistance, wire and pump. As water flowed along the oxidation processor, the walls became enriched with electrons, which were then channeled underground to the electrode through grounded wires.

2.3. Sampling and Analysis

2.3.1. Hydroponic Plant Indices

The chlorophyll content of hydroponic wheat leaves was measured in SPAD (soil plant analysis development) units. The SPAD values of the flag leaves were measured with a SPAD-502 Minolta chlorophyll meter (Spectrum Technologies, Plainfield, IL, USA), with 10 leaves subjected to measurements at every sampling point.

At the jointing stage, the roots of five plants from each hydroponic tank were randomly selected to measure root vigor. Fresh 0.5 g root tip samples were taken from each wheat plant. The root vigor of wheat was assessed by measuring the amount of triphenyl tetrazolium chloride (TTC) in the roots [36,37].

Root samples were collected from wheat plants at the jointing stage, grown in each of the water types described in Table 1. The live roots were carefully separated from dead roots according to instructions by Gregory [38]. The images at a resolution of 300 dpi were obtained by scanning with Epson scanner (version V370, Epson, Inc., Beijing City, China). WinRHIZO software (version 5.0, Regent Instruments, Inc., Quebec City, QC, Canada) was used to determine root length, root surface area and root diameter from root images. The root tissue density, root fineness, root length ratio, root mass ratio, root length density, root weight density, root surface area density and root/shoot ratio were calculated based on equations presented by Shahzad et al. [39].

2.3.2. Soil Water Content and Soil Water Storage under Field Experiments

The volumetric soil water content (SWC) was monitored from the center of each plot at the greening, jointing, filling and maturity stages at 10-cm intervals to a depth of 3 m using a neutron meter (IH-II, Didcot Instrument Co., Wallingford, UK) on the field plots with three replicates. The neutron probe could reach this depth by inserting it through a tube while connected to the neutron meter on the surface via a wire. Firstly, the calibration curve of soil volumetric water content in the study area was obtained, and then the soil volumetric water content of 0–300 cm soil layers was calculated according to the calibration curve. Soil water content was measured every 15 days. If it rained on the planned sampling date, the sampling was appropriately delayed. The maximum root depth of the wheat

during flowering was > 2.0 m, so monitoring SWC at a depth of 3 m was conducive to analyzing deep soil water differences [40,41]. The SWC was determined by weighing the samples before and after oven-drying [26].

Soil water storage was calculated using the following equation [42,43]:

$$\text{SWS} = \sum_i^n h_i \times \rho_i \times b_i \times 10/100 \quad (1)$$

where SWS (mm) is soil water storage, h_i (cm) is the thickness of the soil layer, ρ_i (g cm^{-3}) is the bulk density in each layer, b_i is the percentage of soil water by weight, n is the number of soil layers and $i = 10, 20, 40, \dots, 300$. To ensure the accuracy of the bulk density, we excavated a 3 m deep profile in the center of the study area for stratified sampling.

2.3.3. Wheat Production

Plant samples were randomly collected from a 1.0 m^2 section in each plot to measure spike number, grains per spike, 1000-grain weight and grain yield at maturity [5].

2.3.4. Soil Water Consumption, WUE and IWUE

Crop evapotranspiration (ET) during growth was calculated using the water-balance equation [44]:

$$\text{ET} = \text{P} + \text{I} + (\text{SWS1} - \text{SWS2}) - \text{D} - \text{R} \quad (2)$$

where ET (mm) is the crop evapotranspiration, P (mm) is total rainfall during the growing season, I (mm) is the total amount of irrigation, SWS1 (mm) is SWS at planting, SWS2 is SWS at harvest, D is deep percolation of soil water below the measurement depth and R is the surface runoff. The groundwater table remained at a depth of about 100 m below the surface during the experiment based on well monitoring around the study area, so capillary water which moves up from the deep layer to the root zone could be neglected. According to Lin et al. [45], the amount of rainfall was not enough to percolate into the soil layer below 300 cm depth. Additionally, we measured soil water content in the 0–300 cm layer, and calculated available soil water to a depth of 300 cm, so D could also be neglected. Runoff was never observed because the experimental field was flat.

WUE and IWUE were calculated using the following equations [1]:

$$\text{WUE} = \text{Y} / \text{ET} \quad (3)$$

$$\text{IWUE} = \text{Y} / \text{I} \quad (4)$$

where WUE ($\text{kg ha}^{-1} \text{ mm}^{-1}$) describes water-use efficiency for grain yield and IWUE ($\text{kg ha}^{-1} \text{ mm}^{-1}$) describes the irrigation water-use efficiency. Y (kg ha^{-1}) is grain yield at maturity.

2.4. Statistical Analyses

Prior to the analysis, we tested the normality and homogeneity of variances of the experimental data. The mean values were calculated for each variable and analysis of variance (ANOVA) was used to assess the significance of differences in the measured variables between treatments. If the F-value was significant ($p < 0.05$), multiple comparisons of annual mean values were performed based on the least significant difference (LSD). All of these analyses were performed in SPSS (Statistical Product and Service Solutions, version 13.0, IBM Corporation, Armonk, NY, USA). The graphs were prepared in OriginPro 2016 (OriginLab Corporation, Northampton, MA, USA).

3. Results

3.1. Root Growth under Hydroponic Conditions

3.1.1. Germination Proportion

The proportions of wheat seeds that germinated after hydroponic cultivation with pure groundwater and brackish water subjected to different treatments are shown in Figure 2. The hydroponically-cultivated plants receiving magnetized and oxidized water showed germination proportions that were 24.8% and 31.1% higher, respectively, than what was observed for pure groundwater (CK–G), and 20.9% (BM) and 31.8% (BO) higher, respectively, than what was observed for untreated brackish water (CK–B). The germination proportions for B(M+O) and B(O+M) were 50.0% and 51.7%, respectively. These ratios were 36.4% and 40.9% higher, respectively, than the proportion observed for CK–B ($p < 0.05$). With the exception of the BM treatment, plants which had been treated with magnetized water, oxidized water or a combination of both showed significantly higher germination proportions than CK–G or CK–B ($p < 0.05$) plants.

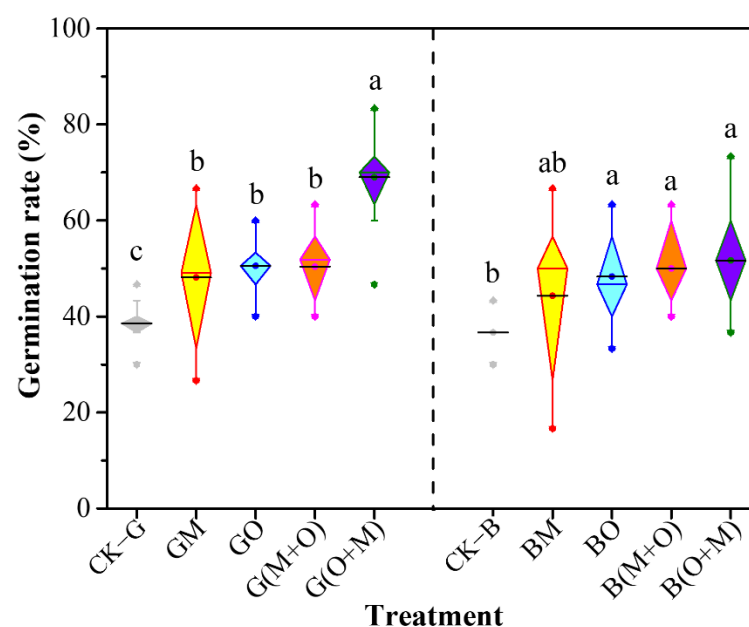


Figure 2. Effects of different water treatments on germination proportions of winter wheat. Analysis of variance (ANOVA) was used to assess the significance of differences in the measured variables between treatments. Different letters above the bars on both sides of the dashed line indicate significant between-treatment differences at $p < 0.05$. Note: The black horizontal line and the color horizontal line represent the mean and median, respectively.

3.1.2. Root Vigor

As shown in Figure 3, both water treatment approaches significantly improved root vigor in winter wheat, with the TTC scores of roots treated with magnetized and oxidized water 100.5–253.7% and 100.4–213.9% higher, respectively, than what was measured for control plants (CK–G and CK–B; $p < 0.05$). However, the two treatments did not differ significantly in root vigor when only comparing plants under the same water class (groundwater or brackish; $p > 0.05$). The GO ($925.1 \mu\text{g g}^{-1} \text{h}^{-1}$) and B(O+M) ($775.2 \mu\text{g g}^{-1} \text{h}^{-1}$) treatments showed the highest root vigor values in the groundwater and brackish water hydroponic systems, respectively. For both types of water, oxidation had a larger impact on root vigor than the magnetic treatment. As such, the root vigor of plants that had received water that was first oxidized and then magnetized (G(O+M) and B(O+M)) differed slightly from the root vigor of plants that had received water which was first magnetized and then oxidized (G(M+O) and B(M+O)). Hence, both of the tested treatment methods

can improve wheat root vigor relative to untreated groundwater or brackish water, with oxidation having a more significant effect than magnetization.

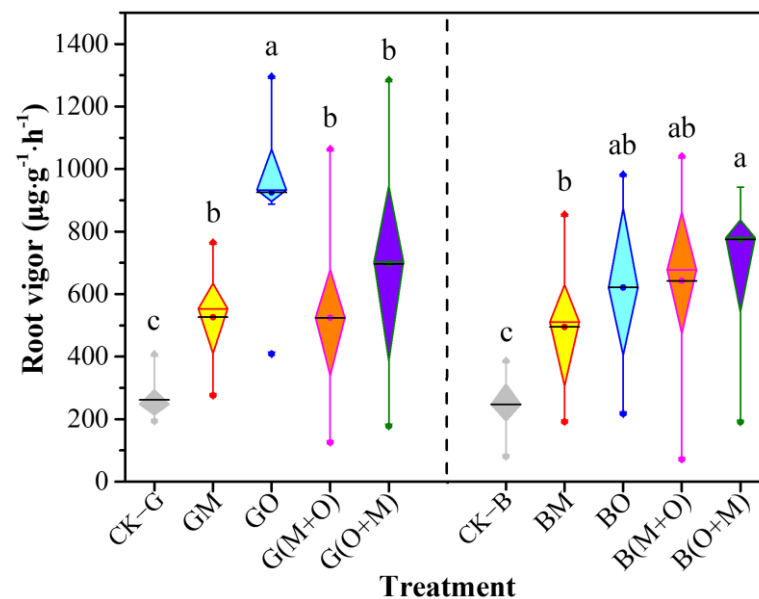


Figure 3. Root vigor of winter wheat cultivated in a hydroponic system with pure groundwater and brackish water that was subjected to two different treatments (magnetization and oxidation). Different letters above the bars on both sides of the dashed line indicate significant between-treatment differences at $p < 0.05$. Note: The black horizontal line and the color horizontal line represent the mean and median, respectively.

3.1.3. Root Length Density (RLD), Root Weight Density (RWD) and Root Surface Area Density (RSD)

There were significant differences between the water types regarding how the treatment methods affected RLD (Table 3). The treatment methods had a more significant effect in the groundwater hydroponic system than in the brackish water hydroponic system. For example, the RLD of wheat roots increased by 67.6% and 79.4% by the GM and GO treatments, respectively, from the control group (CK–G). The corresponding changes for BM and BO—from CK–B—were 7.5% and 40.0%, respectively. With brackish water, the largest increase in RLD, 57.5% higher than for CK–B, was observed in the B(O+M) treatment.

Table 3. Root length density (RLD), root weight density (RWD) and root surface area density (RSD) of wheat receiving either groundwater or brackish water subjected to two treatment methods.

	Treatment	Root Length Density (cm cm^{-3})	Root Weight Density ($\times 10^{-5} \text{ g cm}^{-3}$)	Root Surface Area Density ($\text{cm}^2 \text{ cm}^{-3}$)
Pure groundwater	CK–G	0.34 c	3.31 b	0.04 d
	GM	0.57 ab	5.75 a	0.07 bc
	GO	0.61 a	5.82 a	0.09 a
	G(M+O)	0.63 a	5.35 a	0.08 ab
	G(O+M)	0.42 b	4.14 b	0.06 c
Brackish water	CK–B	0.40 b	2.49 b	0.05 b
	BM	0.43 ab	3.48 a	0.06 b
	BO	0.56 ab	4.15 a	0.07 ab
	B(M+O)	0.44 ab	3.69 a	0.05 b
	B(O+M)	0.63 a	3.87 a	0.10 a

Table 3. Cont.

	Treatment	Root Length Density (cm cm ⁻³)	Root Weight Density (×10 ⁻⁵ g cm ⁻³)	Root Surface Area Density (cm ² cm ⁻³)
F-value	Water quality	1.01	51.85 **	0.31
	Activation methods	2.40	12.72 **	2.20
	Water quality ×			
	Activation methods	8.18 **	5.93 *	12.49 **

Different letters in the same column indicate significant between-treatment differences at $p < 0.05$. * and ** indicate significant differences at the 0.05 and 0.01 probability levels, respectively.

The relative effect of the treatment methods depended on the type of water treated (Table 3). With groundwater, the RWD obtained with GM and GO was 73.7% and 75.8% larger than the CK–G ($p < 0.05$). With brackish water, the RWD obtained with BM, BO, B(M+O) and B(O+M) were 39.8%, 66.7%, 48.2%, and 55.4% higher, respectively, than the CK–B ($p < 0.05$). The tested treatment methods had a larger effect on the RSD of wheat root in groundwater than in brackish water cultivation systems, with a maximum increase of 0.09 cm² cm⁻³ observed for the GO treatment. In brackish water, B(O+M) had the largest effect on RSD–100.0% higher than measured for CK–B.

3.1.4. Root Morphology

The root morphology parameters (except for root fineness) were significantly different across the water types and treatment methods ($p < 0.05$), while the variation between water types was not significant except for dry root weight (Table 4). The GO and G(O+M) treatments significantly increased the root tissue density (36.7% and 35.0%), root fineness (21.9% and 26.3%), root length ratio (67.2% and 44.1%), and root mass ratio (69.2% and 53.8%) relative to CK–G. Compared to CK–B, the dry root weight of BM, BO, B(M+O) and B(O+M) treatments increased significantly, i.e., by 41.7%, 75.0%, 58.3%, and 50.0%, respectively. The BM and BO treatments showed significant increase in root tissue density (31.8% and 67.6%) and root mass ratio (29.5% and 73.0%) relative to the CK–B treatment. The root length ratios of BM, BO, B(M+O) and B(O+M) did not significantly increase over the CK–B control case.

Table 4. Effects of different treatments on the morphology of the winter wheat root system at the late jointing stage.

	Treatment	Root Dry Weight (g Plant ⁻¹)	Root Tissue Density (g cm ⁻³)	Root Fineness (cm cm ⁻³)	Root Length Ratio (cm g ⁻¹)	Root Mass Ratio (g g ⁻¹)
Pure groundwater	CK–G	0.17 b	0.060 b	641.55 b	301.09 b	0.026 b
	GM	0.28 a	0.066 ab	741.16 ab	400.06 ab	0.037 a
	GO	0.29 a	0.082 a	782.09 a	503.34 a	0.044 a
	G(M+O)	0.27 a	0.068 ab	802.18 a	399.33 ab	0.041 a
	G(O+M)	0.21 b	0.081 a	810.40 a	433.96 a	0.040 a
Brackish water	CK–B	0.12 b	0.044 c	570.22 b	605.92 a	0.037 b
	BM	0.17 a	0.058 ab	727.79 bc	666.83 a	0.062 a
	BO	0.21 a	0.057 ab	898.06 a	761.68 a	0.064 a
	B(M+O)	0.19 a	0.067 a	814.88 ab	664.67 a	0.049 ab
	B(O+M)	0.18 a	0.050 bc	676.76 bc	741.25 a	0.044 ab
F-value	Water quality	51.38 **	20.99 **	0.46	72.85 **	23.67 **
	Activation methods	15.44 **	3.20 *	9.27 **	3.35 *	8.08 **
	Water quality ×					
	Activation methods	3.06 *	2.43	2.50	0.10	2.08

Different letters in the same column indicate significant between-treatment differences at $p < 0.05$. * and ** indicate significant differences at the 0.05 and 0.01 probability levels, respectively.

3.1.5. Root/Shoot Ratios

The root/shoot ratios of wheat under various treatments are shown in Figure 4. The results demonstrate that cultivating wheat with either pure groundwater or brackish water that has been subjected to magnetization and/or oxidation increased root/shoot ratios in winter wheat ($p < 0.05$). Compared to the CK–G control case, the root/shoot ratios for the GM, GO, G(M+O) and G(O+M) treatments all improved significantly, i.e., by 42.4%, 75.3%, 61.0%, and 62.0%, respectively. Figure 4 also shows that treated brackish water had a stronger effect on the root/shoot ratio (a maximum increase of 76% in the root/shoot ratio) than treated pure groundwater.

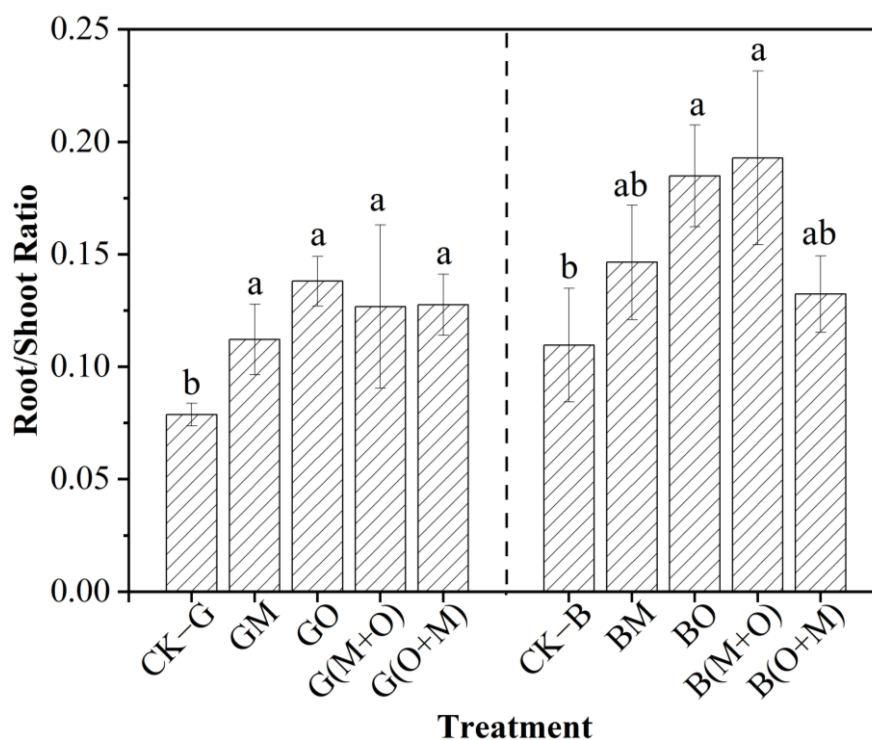


Figure 4. Root/shoot ratios of winter wheat for various treatments. Different letters above the bars on both sides of the dashed line indicate significant between-treatment differences at $p < 0.05$.

3.1.6. Chlorophyll Content (SPAD)

In the groundwater hydroponic system, the leaves of winter wheat plants that had received water treated through magnetization and/or oxidation had significantly higher SPAD values (12.6–25.9%) than the leaves of control on the 80th day of wheat cultivation ($p < 0.05$) (Figure 5). Plant leaves on the 110th day that received magnetized or oxidized brackish water had 14.5–25.0% higher SPAD than control leaves. Both the groundwater and brackish water cultivation systems demonstrated that the GO, BO, G(O+M) and B(O+M) treatments significantly improved the SPAD values of the leaves ($p < 0.05$).

3.2. WUE of the Field Experiments

3.2.1. SWC

As shown in Figure 6, the SWC 60 cm below ground surface in IGM, IGO, IG(M+O) and IG(O+M) plots decreased to different degrees relative to control (IG) plots. At 150 cm below ground, the SWC for the IG(M+O) and IG(O+M) were lower than in the IG case. The abundant rainfall from late April to early May may have been responsible for the high SWC observed in the 20–60 cm layer (Figure 1a). At the filling stage, soil water storage (60–300 cm) in the IGM and IGO plots was 11.6% and 13.9% lower, respectively, than what was observed in the control (IG) plot. Correspondingly, soil water storage (60–300 cm) in the IG(M+O) and IG(O+M) plots at the filling stage was 16.7% and 16.9% lower, respectively,

than what was observed for the control (IG) plot. In other words, the plots irrigated with either magnetized or oxidized water (or water that had been subjected to both treatments) could demonstrate higher water consumption or deeper penetration than plots irrigated with pure groundwater.

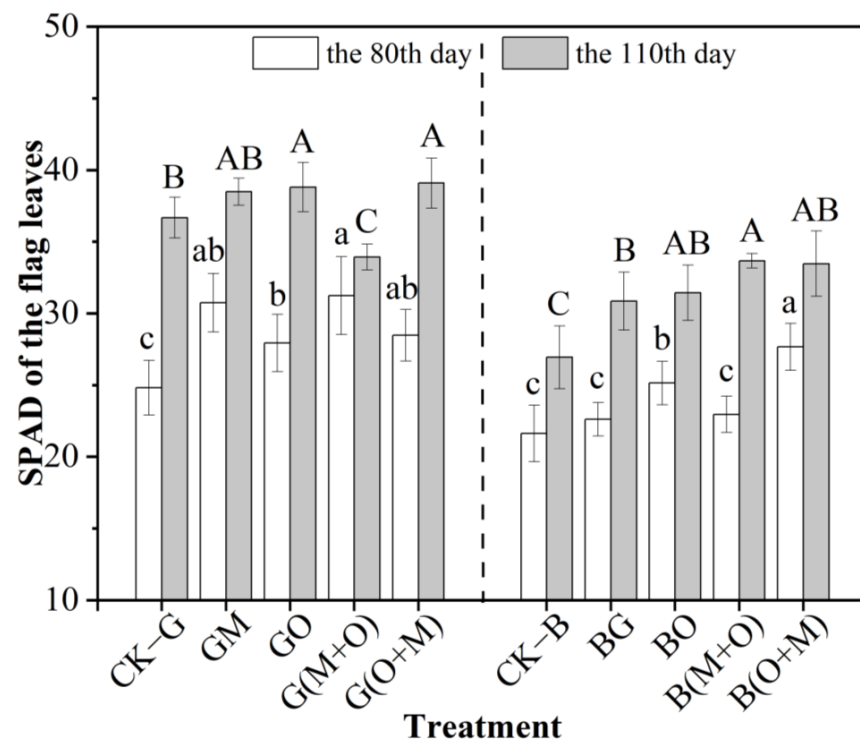


Figure 5. Soil plant analysis development (SPAD) of flag leaves 80 and 110 days after germination. Different letters above the bars on both sides of the dashed line indicate significant between-treatment differences at $p < 0.05$.

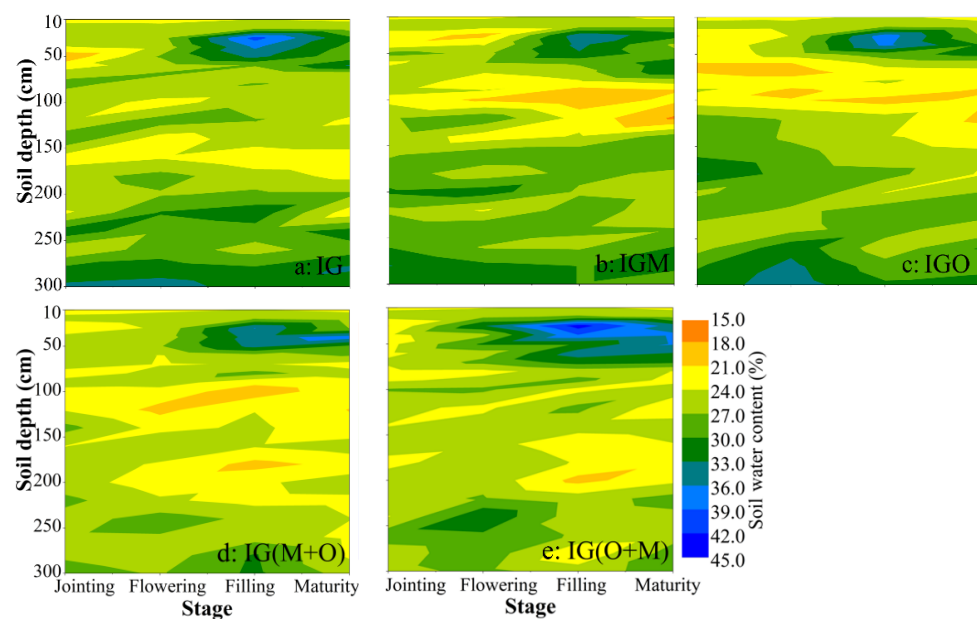


Figure 6. Contour maps of soil water content for plots irrigated with pure groundwater (a) IG treatment, magnetized water; (b) IGM treatment, oxidized water; (c) IGO treatment, magnetized + oxidized water; (d) IG(M+O) treatment and oxidized + magnetized water; (e) IG(O+M) treatment during the period of rapid winter wheat growth (total irrigation amount: 180 mm).

3.2.2. Yield, WUE and IWUE

The yield, WUE and IWUE during the winter wheat growth period in the 2018–2019 and 2019–2020 season under different irrigation regimes are shown in Figure 7. The IGO plots provided yields that were 13.8% and 21.0% higher than the yield of the IG plots ($p < 0.05$), which translates to a difference of $10.7 \times 10^3 \text{ kg ha}^{-1}$ and $11.7 \times 10^3 \text{ kg ha}^{-1}$, respectively. Although the yield increased (10.0% and 11.1%) when the pure groundwater used for irrigation was replaced with magnetized water (IGM), this result did not reach a level of statistical significance ($p > 0.05$). The IG(O+M) plots performed best in terms of WUE, 25.7% ($30.3 \text{ kg ha}^{-1} \text{ mm}^{-1}$) and 21.8% ($27.9 \text{ kg ha}^{-1} \text{ mm}^{-1}$) better than the control (IG) plots. When compared with IG plots, the IWUE of IGO plots in 2018–2019 and IGM plots in 2019–2020 increased by 13.9% and 21.0% ($59.34 \text{ kg ha}^{-1} \text{ mm}^{-1}$ and $97.33 \text{ kg ha}^{-1} \text{ mm}^{-1}$), respectively, with only the improvement reached by the IGM plots achieving statistical significance ($p < 0.05$).

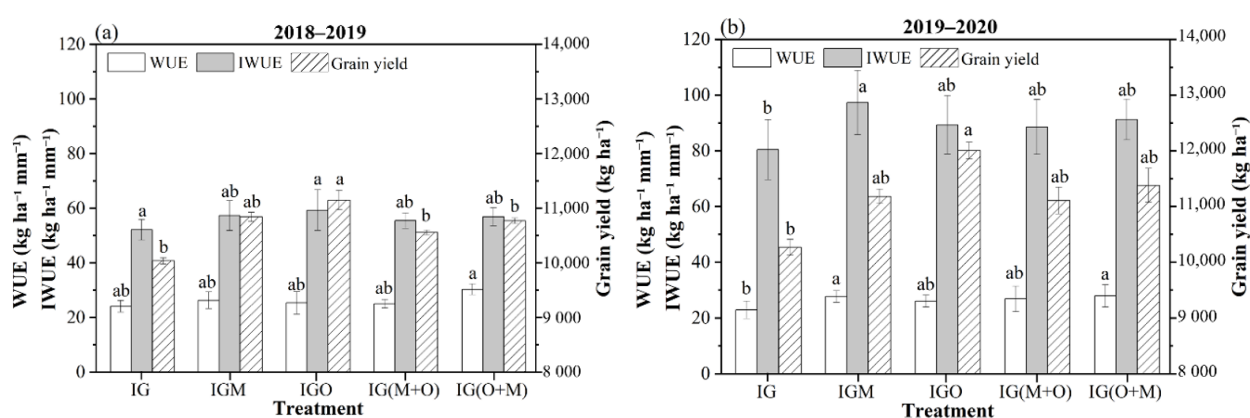


Figure 7. Grain yield, water-use efficiency (WUE) and irrigation water-use efficiency (IWUE) for winter wheat irrigated with water subjected to different treatments (pure groundwater (IG), magnetized water (IGM), oxidized water (IGO), magnetized + oxidized water (IG(M+O)), and oxidized + magnetized water (IG(O+M))) during the 2018–2019 (a) and 2019–2020 (b) growing seasons. Different letters above the bars under the same fill color indicate significant between-treatment differences ($p < 0.05$).

4. Discussion

4.1. Effects of Different Water Treatment Methods on Crop Growth

4.1.1. Effects Related to the Root System

The root system is the most important functional organ for plants to capture available water and nutrients [46]. Roots play a critical role in the plant–soil ecosystem and significantly influence crop growth and grain yield [26,31]. Root growth and physiological function directly affect crop growth, nutritional status, and yield [36,47]. The pH and electrical conductivity (EC) increased after magnetic treatment can modify biological activity in plants, and consequently, influence plant growth [48]. Hence, irrigation with magnetized water can promote the growth of the wheat root system, which, in turn, will improve the utilization of water and nutrients [22,49]. Our results showed that magnetization and oxidation could significantly improve winter wheat root vigor ($p < 0.05$, Figure 3). Similar patterns were also observed for RLD, RWD, and RSD, with the values of all these root traits significantly higher using GO than in the control samples ($p < 0.05$). This could be attributed to the pH and EC changes caused by the tested treatments, which could enhance biological activity, and thereby promote root growth [50]. Wang et al. [18] reported that the pH and EC of the magnetized or oxidized water increased by 3% and 2%, respectively, and the surface tension was significantly reduced (9.1–13.8%).

As shown in Figure 4, the substantial increase in the root/shoot ratio of wheat under various treatments was consistent with the results for RLD, RWD and RSD (Table 3). Similarly, it was found that the effect was on the root system rather than on the aboveground

part of the plants [23,51]. It was clearly shown that irrigating winter wheat with magnetized or oxidized water could promote the growth of the wheat root system. Our results also showed that treated brackish water had a positive effect on the root/shoot ratio (Figure 4). It indicates that magnetic treatment or oxidation could efficiently improve the quality of irrigation water in areas plagued by poor water quality. This may be due to the change of the physicochemical properties of brackish water, which could improve the leaching efficiency of soil salt [18,22].

4.1.2. Effects Related to Chlorophyll Content

Photosynthesis is the main driving force underlying the distribution of dry matter and organ formation, as well as the basis for the plant production that determines crop yield [52,53]. SPAD reflects the total chlorophyll content in the leaves, represents the growth of crop leaves and canopy, and is strongly correlated with photosynthesis [54,55]. As shown in Figure 5, SPAD of wheat leaves could be improved by cultivating winter wheat with magnetized and/or oxidized water. Wang et al. [22]—who also irrigated crops with treated water—also reported that irrigation with treated water increased the chlorophyll content in crop leaves, potentially affecting the conversion of carbohydrates in plants and regulating the synthesis and distribution of photo assimilates. A case study by ECO1ST in the United States found that irrigation with oxidized water can decrease the salinity of irrigation water, which is key to mitigating the possible disadvantages of irrigating crops with brackish water and enhancing the uptake of water stored in the soil [21,56].

4.2. Links between Root Traits and WUE Improvement

High yields and WUE in winter wheat require that the root system have a certain absorptive capacity [36]. As such, winter wheat cultivation systems characterized by high yield and low water consumption must promote root growth and maximize the functioning of the wheat root system [57]. Water conditions can significantly influence root growth at the stages of rapid wheat growth, such as jointing and filling, and will subsequently influence grain yields [58,59]. Oxidation and magnetization improved the RLD, RWD and RSD of winter wheat (Table 3). The presented field study results showed that treated water irrigation improved the water use efficiency and grain yield of wheat, and this finding may be related to the utilization of soil water by the root system (Figure 7). This is supported by many comprehensive results [1,21,28,33].

The soil water content of the 60–300 cm soil layers was decreased by both oxidation and magnetization, particularly in the late stages of jointing to maturity (Figure 6). This result, considered together with Figure 3 and Table 3, suggests that the root vigor, along with other root traits, were significantly improved by the GO and G(O+M) treatments. Hence, the grain yields and WUE of the field experiments were improved by irrigation with water that had been magnetized and/or oxidized, treatments that are theorized to promote root growth. The beneficial effects of the magnetic and/or oxidation treatment of irrigation water on soil water absorption could be explained by the lower surface tension and viscosity of the treated water than that of pure groundwater, which would increase water permeability and mobility [60,61]. According to Surendran et al. [20], providing crops with magnetized water can accelerate the activation of enzymes and hormones during the growth process, which may improve the mobilization and transportation of nutrients [48].

4.3. Implications

The results showed that irrigation with magnetized and/or oxidized water can improve water utilization in winter wheat relative to plants that have received pure groundwater (Figure 6). Previous studies of the physical and chemical properties suggest that magnetized and oxidized water is less viscous—and thus, more mobile—than pure groundwater, which would improve the permeability of water in the soil [16,22,50]. In other words, the cultivated winter wheat needs to expend less energy to absorb enough water to meet metabolic needs. As mentioned earlier, the benefits of irrigating crops with magnetized

water are mainly due to a reduction in the surface tension and viscosity coefficient of the treated water [62–64]. In our study, plants which had been treated with magnetized water or oxidized water showed significantly higher germination proportions (Figure 2). Wang et al. [22] summed up the results of previous studies and got a similar conclusion, i.e., beneficial effects of treated irrigation water had been discovered for emergence rate and growing, and many irrigation experiments on corn, wheat and other crops had demonstrated positive biological effects. In addition, root vigor increased following the hydroponic systems including magnetized and/or oxidized water, while the chlorophyll content in the leaves of plants exposed to the oxidized or magnetized water was higher than in the leaves of control plants (Figures 3 and 5). Both of these results suggest that irrigating winter wheat with magnetized and/or oxidized water can promote crop growth and grain formation [51]. Irrigation with magnetized and/or oxidized water could stimulate the activation of enzymes and hormones during crop growth to drive the expression of genes involved in chlorophyll biosynthesis, which would result in the effective mobilization and transportation of water and nutrients. In line with this theory, we have presented evidence that irrigation with magnetized and/or oxidized water improves the absorption of nutrients and water by the winter wheat root system, thus encouraging crop growth and yield.

5. Conclusions

The presented results demonstrate that irrigating winter wheat with activated water strongly improved root growth, grain yield and WUE when compared with the results from irrigation with pure groundwater. Irrigation with oxidized water, along with water that was first oxidized and then magnetically treated, showed the most promising results. Under identical irrigation amounts, plots irrigated with oxidized (along with oxidized and subsequently magnetized) water demonstrated higher grain yields and WUE than control (pure groundwater) plots. Furthermore, root vigor, RLD, RWD and RSD all significantly positively increased in plants receiving magnetized and/or oxidized water. The performed experiments revealed that cultivation with magnetized and/or oxidized water promotes the growth of the root system, increases the root/shoot ratio, and significantly increases the chlorophyll content of leaves. In addition, the magnetic and/or oxidation treatment of brackish water improved the root vigor of winter wheat, which could be expected to positively impact crop production. Therefore, irrigation with activated water affects the physiological characteristics of winter wheat by promoting root growth, which translates to better grain yields and the effective utilization of water. The presented evidence could be pivotal to developing approaches for improving grain yields and WUE in the winter wheat production of northwest China.

Author Contributions: Formal analysis, G.Z.; Funding acquisition, Y.M.; Investigation, G.Z., Y.W. and Y.L.; Methodology, G.Z. and B.Z.; Writing—original draft, G.Z.; Writing—review and editing, Y.M. and L.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (41830754).

Data Availability Statement: Data sharing not applicable.

Acknowledgments: The authors are grateful for the support of the staff of the Caoxinzhuang experimental farm of Northwest A&F University.

Conflicts of Interest: The authors declare there is no conflict of interest.

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