agronomy

Article

Effect of Activated Water Irrigation on the Yield and Water Use Efficiency of Winter Wheat under Irrigation Deficit

Huan Wang [1,2], Jun Fan [1,2,*] and Wei Fu [1,2]

[1] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Xianyang 712100, China; wanghuan123@nwafu.edu.cn (H.W.); weifuu0518@nwafu.edu.cn (W.F.)
[2] College of Natural Resources and Environment, Northwest A&F University, Xianyang 712100, China
* Correspondence: fanjun@ms.iswc.ac.cn

Abstract: Activated water irrigation has been widely investigated as an effective production increasing measure. However, the response of activated water irrigation in plant growth and water use efficiency (WUE) with the irrigation amount is not well understood. Here, a pot experiment was conducted to determine the effects of activated water irrigation on winter wheat growth, yield, and WUE under irrigation amount. Twelve treatments included four irrigation water types, (i) tap water (TW), (ii) tap water with magnetization (MW), (iii) tap water with oxygenation (OW), (iv) tap water with magnetization and oxygenation (M&OW), and three irrigation amounts, (1) 80% of the field capacity (FC), (2) 65%FC, and (3) 50%FC. The results indicated that activated water irrigation improved the plant height, leaf area, aboveground biomass, and photosynthetic characteristics at each growth stage of winter wheat. However, the yield and WUE varied with water type and irrigation amount. With 80%FC, the yield and WUE of MW were significantly greater by 35.7% and 53.9% than TW. The yield and WUE of OW were greater by 11.4% and 23.1% than TW. With 65%FC, the yield of MW, OW, and M&OW were greater by 43.9%, 46.3%, and 14.6% than TW, respectively. WUE of MW, OW, and M&OW were greater by 37.0%, 37.0%, and 11.1% than TW, respectively. With 50%FC, the yield of OW and M&OW were significantly greater by 77.3% and 122.7% than TW. WUE of OW and M&OW were significantly greater by 41.4% and 75.9% than TW ($p < 0.05$). Overall, the research provides clear evidence that OW is an effective way to increase yield and WUE, MW and M&OW should be applied in suitable soil water conditions.

Keywords: irrigation amount; activated water; oxygenated water; magnetized water; growth characteristic; yield; water use efficiency

Citation: Wang, H.; Fan, J.; Fu, W. Effect of Activated Water Irrigation on the Yield and Water Use Efficiency of Winter Wheat under Irrigation Deficit. *Agronomy* **2022**, *12*, 1315. https://doi.org/10.3390/agronomy12061315

Academic Editor: Anna Tedeschi

Received: 5 May 2022
Accepted: 27 May 2022
Published: 30 May 2022

1. Introduction

Economic development and an increasing population accelerate the demand for freshwater resources, as do environmental challenges such as uncertain global climate change and soil salinization, therefore, the shortage of such resources has become a worldwide problem [1–3]. About 70% of the global freshwater resources are used for agricultural irrigation [4]. For example, as a large country with a population of 1.3 billion, China has less than 2200 cubic meters of water per capita, only a quarter of the world average, and is one of the 13 countries that lack sufficient water for agriculture [5]. The arable area in the northern region is about 65% of the total arable area in China, but irrigation water resources in that area are less than 20% of the total [6]. This unbalanced distribution of irrigation water is mainly attributed to the uneven distribution of rainfall in time and space, especially in the arid and semi–arid rain–fed agriculture regions in the Loess Plateau [7,8]. The increasing demand for food brought about by the rapid growth of the global population has made irrigation water shortage a problem that cannot be ignored. Therefore, food production must be based on improving water efficiency and developing new agricultural water sources. Over the years, many countries have improved water management. However, there is still a prominent imbalance between the supply and demand of agricultural water, highlighting the need to continue to develop new water sources and improve water use efficiency (WUE).

Around the world, one of the main factors of crop yield decline is irrigation deficit [9,10]. Cui et al. [11] found that deficit irrigation effectively saves water, improves the WUE, and resolves the contradiction of water needs and supply in semi–arid regions. Bloch et al. [12] indicated that deficit irrigation plays an essential role in improving the drought tolerance of crops and affects the production and distribution of dry matter. It has been affirmed that deficit irrigation successfully improved the WUE of maize [13] and the yield of wheat [14]. Research on tomatoes indicated that deficit irrigation (alternate partial root–zone irrigation) significantly increased the WUE_i (photosynthesis rate/transpiration rate) compared with conventional irrigation [15]. At the same time, the research on sugar beet showed that the yield was 9.0% and 11.0% lower in deficit irrigation of 75% and 50% evapotranspiration than in normal irrigation [16]. Generally, water deficit mainly influences dry matter allocation. Ma et al. [14] indicated that the photosynthetic products of grain crops are directly transferred to the grains or stored in the vegetative parts, which helps increase grain yield. The photosynthate translocation may be influenced, and the yield may be reduced in unfavorable conditions.

Activated water is treated water using physical techniques. It significantly changes the physical and chemical properties of water, thereby improving the activity of water molecules. In recent years, magnetization, oxygenation, and other irrigation water activation technologies have been widely researched as simple, low–energy, low–input, non–polluting, and efficient water treatment technologies [17–20]. These methods improve the physical and chemical characteristics of irrigation water, improve the physiological efficacy of irrigation water and enhance the transmission of irrigation water from soil to crops.

Over the last century, some research has focused on magnetized water, which is obtained by passing ordinary water through a magnetic field [21]. When the liquid water flows through a magnetic field, some of the physical and chemical properties of the water are changed. The average distance between the water molecules increases and some hydrogen bonds are weakened or even broken. This results in an increase in the number of free monomer water molecules and dimer water molecules [22,23]. At the same time, the chemical bond angle and the radius of the water–ion colloid decrease [19], surface tension and viscosity coefficient decrease [24], pH, osmotic pressure and solubility increase, and the dissolved oxygen increases [25]. Another method is a newly developed oxygenation technique that can effectively increase the amount of oxygen dissolved in irrigation water. Most current oxygenation methods mainly rely on hydrogen peroxide, Venturi tubes, compressed air, and micro–nano bubble water oxygenation [26].

The application of magnetic fields plays an important role in altering crop growth. Irrigation with magnetized water increased seeds germination [27]. Grewal et al. [28] found that magnetic treatment of irrigation water supplied to snow pea and chickpea seeds enhanced the early growth and nutrient contents of seedlings. Related studies indicated that irrigation with magnetized water improved stomatal conductance, photosynthetic rate, leaf area, specific leaf area, and plant chlorophyll content [29,30]. Magnetized water for irrigation has been recommended to improve plant yield and productivity [31,32], save irrigation water and increase WUE [33,34]. Compared with control plants, the gibberellin, kinetin, nucleic acid, and transfer efficiency of photoassimilates in the bean plants irrigated with magnetized water were significantly improved [31].

Adequate oxygen supply effectively alleviated the obstruction of root respiration caused by soil hypoxia and promoted the absorption of water and nutrients by crop roots [35–37]. Previous studies [38–41] have shown that supplying sufficient oxygen to the soil had positive implications for crop growth and WUE. Many activated water irrigation experiments were conducted on different crops. Research on chickpeas showed that aerated subsurface drip irrigation had a higher yield and WUE than irrigation by other means [42]. Research on tomatoes showed that the fruit yield was 21% higher under aerated water irrigation than the control. Aerated irrigation improved the reproductive performance of tomatoes through early flowering and fruiting [43]. Liu et al. [44] found that micro– and nanobubble water oxidation significantly had higher yield, irrigation water use efficiency, vitamin C, and soluble sugar of tomatoes by 16.9%, 16.9%, 17.7%, and 39.2%, and of cucumbers by 22.1%, 22.1%, 16.7%, and 19.4%, than with no gas addition. Zhu et al. [45] found that under the condition of oxygenated brackish water irrigation, the germination rate, germination potential, germination index, vigor index, and plant height of wheat were significantly higher than those of brackish water treatment.

Previous experiments about the effects of magnetized and oxygenated water irrigation on crop growth have been conducted under full irrigation conditions [31,32,42–46]. However, irrigation water is lacking in arid and semi–arid areas of the world, fewer observations have been reported on the effects of magnetized and oxygenated water irrigation on crop growth under irrigation amount. Zhao et al. [47] investigated the three irrigation levels of magnetized water and oxygenated water on winter wheat growth and found that 96 mm magnetized water irrigation was the optimal measure to save water and increase irrigation efficiency on the Guanzhong Plain, China. Further study is required to better understand how activated water irrigation influences crop growth, yield, and WUE in different water resource conditions.

The objectives of the current study were to (i) determine the effects of activated water on wheat growth and yield under different irrigation amounts, and (ii) propose the most suitable type of activated water for wheat growth in different irrigation amounts. Accordingly, we conducted a pot experiment in an artificial climate chamber with four irrigation water types and three irrigation amounts, aimed at providing a reference for alleviating the shortage of irrigation water in arid and semi-arid areas.

2. Materials and Methods

2.1. Experimental Site

The pot experiment was conducted from November 2018 to May 2019 in an artificial climate chamber at the Institute of Soil and Water Conservation, Chinese Academy of Sciences (34°16′ N, 108°4′ E). The indoor relative humidity and CO_2 concentration were maintained at 70% and 400 ppm. The temperature during the day and night were 25 °C and 20 °C. LED light was used in this study and the light intensity was controlled at 6000 lx; the photo period was 12 h d^{-1} (from 7 a.m. to 7 p.m.).

The soil in the pot experiment was farmland soil collected from the top 20 cm in Yangling, Shaanxi. The collected soil was air–dried and passed through a 2 mm sieve to remove visible roots and organic residues and was mixed thoroughly before use. The soil had a pH of 8.2, total N of 1.06 g kg^{-1}, total P of 0.19 g kg^{-1}, and organic matter of 8.28 g kg^{-1}, field capacity of 24.0% (gravimetric), permanent wilting point of 8.5% (gravimetric), soil bulk density of 1.44 g cm^{-3}. The soil texture is medium loam.

2.2. Experimental Design and Management

2.2.1. Experimental Design

Twelve irrigation treatments (Table 1) were tested during the winter wheat jointing, heading, filling, and maturity stages. There were three irrigation amounts: (1) 80% of the field capacity (FC), (2) 65%FC, and (3) 50%FC. There were four irrigation water types: tap water (TW), magnetized water (MW), oxygenated water (OW), and magnetized and oxygenated water (M&OW). There were five pots for each treatment type defined in Table 1. The 60 cylindrical PVC pots (40 cm height, 20 cm diameter, without drainage holes) were randomly placed in the artificial climate chamber. Each pot was filled with air–dried soil at an initial bulk density of 1.35 g cm^{-3}. The same three cutting rings (volume 100 cm^3, inner diameter 5.05 cm) were used to collect undisturbed soil to determine the field capacity of the soil.

Table 1. Design of the activated water irrigation experiment.

Treatment	Irrigation Water Type	Irrigation Amount
TW_{80}	Tap water	80%FC
TW_{65}	Tap water	65%FC
TW_{50}	Tap water	50%FC
MW_{80}	Magnetized water	80%FC
MW_{65}	Magnetized water	65%FC
MW_{50}	Magnetized water	50%FC
OW_{80}	Oxygenated water	80%FC
OW_{65}	Oxygenated water	65%FC
OW_{50}	Oxygenated water	50%FC
$M\&OW_{80}$	Magnetized and oxygenated water	80%FC
$M\&OW_{65}$	Magnetized and oxygenated water	65%FC
$M\&OW_{50}$	Magnetized and oxygenated water	50%FC

Notes: TW_{80}, TW_{65}, and TW_{50} represent irrigation with tap water with the irrigation amounts 80%FC, 65%FC, and 50%FC, respectively. MW_{80}, MW_{65}, and MW_{50} represent magnetized irrigation water with the irrigation amounts 80%FC, 65%FC, and 50%FC, respectively. OW_{80}, OW_{65}, and OW_{50} represent oxygenated irrigation water with the irrigation amounts 80%FC, 65%FC, and 50%FC, respectively. $M\&OW_{80}$, $M\&OW_{65}$, and $M\&OW_{50}$ represent magnetized and oxygenated irrigation water with the irrigation amounts 80%FC, 65%FC, and 50%FC, respectively. FC, field capacity.

The details of field capacity measures were as follows. Connecting the cutting ring full of fully saturated field soil with the cutting ring full of quartz sand, the cutting ring with soil was on the top, the quartz sand cutting ring was on the bottom, and the upper cutting ring was pressed with a brick. After 8 h, 15.0–20.0 g of soil was taken out from the cutting ring to determine the soil moisture content, which was determined to be the field capacity [45]. The field capacity of the soil was 24.2% and the standard deviation of the three repeats was 1.30%.

Each pot contained 8.5 kg of air–dried soil. Urea (containing 40% N), superphosphate (containing 16% P_2O_5), and potassium sulfate (containing 60% K_2O) were used as base fertilizer and mixed with the soil before potting. The dosages of the three fertilizers were 4.3 g pot^{-1}, 18.1 g pot^{-1}, and 5.5 g pot^{-1}, respectively, and fertilizers were applied once before sowing. A plastic tube (50 cm height, 2 cm diameter) was inserted into the pot, and the irrigation water entered the soil through the plastic tube in the growth period. We called the irrigation way "bottom–up irrigation".

2.2.2. Experimental Management

The test crop was a commonly used local winter wheat variety (Xiaoyan 22), and the wheat was sown on 5 November 2018 and harvested on 20 May 2019. From sowing to the three–leaf stage, the winter wheat was irrigated with different water types, but soil water content was maintained at nearly 80%FC (approximate 19.4% soil water content) to ensure the normal growth of wheat in the early stage. Surface-to-bottom irrigation and bottom-up irrigation were combined to ensure the growth of the wheat and to promote root growth. At the three–leaf stage, taking into account the diameter of pot and to ensure normal plant growth, superfluous plants were pulled out to leave nine plants with uniform growth in each pot. After entering the jointing stage, the wheat was treated with different irrigation amounts, and the irrigation frequency was every two days using bottom–up irrigation. The irrigation volume of each pot was obtained by subtracting the current soil moisture content from the pre-determined treatment soil moisture. The current soil moisture content was obtained by weighing (0.1 g), and the plant weights were neglected.

2.2.3. Irrigation Water

The tap water was local tap water from Yangling, Shaanxi. Magnetized water was obtained by cyclic magnetization of tap water through a 3000 Gs magnetic field. Details were as follows. The 3000 Gs custom magnetic ring (3.0 cm inner diameter, 3.4 cm outer diameter, 3.2 cm height) was placed on the inlet pipe of the peristaltic pump. Moreover, the inlet and outlet pipes (2.7 cm inner diameter, 0.3 cm thickness) of the peristaltic pump were placed in the same container filled with tap water. The cyclical movement of the tap water in the container was driven by the operation of the peristaltic pump. The rotational speed of the peristaltic pump was 400 r min^{-1}, and 45 L tap water was circulated for 1 h.

The water obtained by passing tap water through the micro–nano bubble generator to increase the oxygen content in the water was called oxygenated water. The inlet and outlet pipes (2.7 cm inner diameter, 0.3 cm thickness) of the micro–nano bubble generator were placed in the same container filled with tap water, and 45 L tap water was also circulated for 1 h.

The magnetized and oxygenated water was obtained by magnetizing the water first and then oxygenating. The rate and parameter settings were the same as magnetized water and oxygenated water. The preparation of magnetized water and oxygenated water is shown in Figure 1. The preparation methods here were similar to Yang et al. [48].

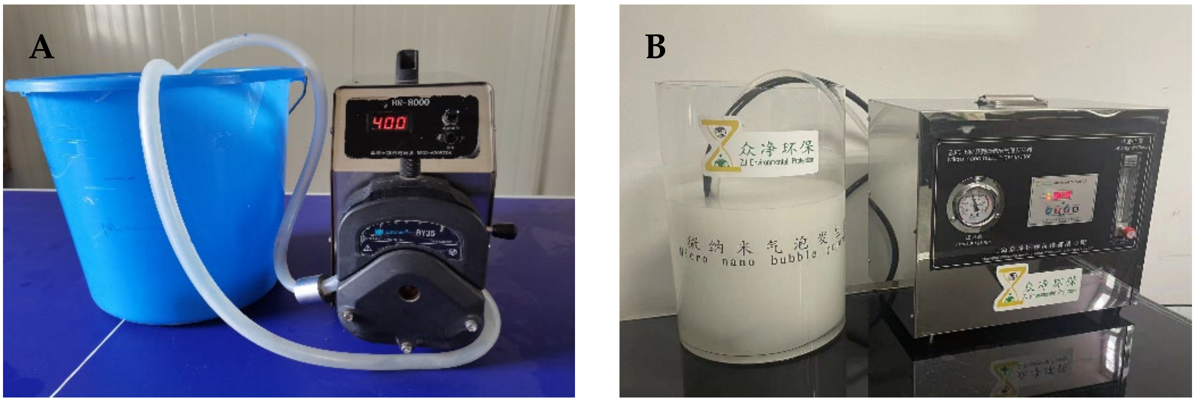

Figure 1. The preparation of magnetized water (**A**) and oxygenated water (**B**).

2.3. Sampling and Measurements

In the jointing stage, heading stage, filling stage, and maturity stage, the growth and physiological indexes of the wheat were measured.

2.3.1. Growth Characteristics

Plant height, aboveground biomass, and leaf area were measured at different growth stages. The same three plants per pot were selected to measure plant height at different stages. Plant height was measured with a ruler. One wheat plant per pot was randomly harvested at different growth stages to measure leaf area and aboveground biomass. The total leaf area was determined by a leaf area instrument (LI–3100A, Li–Cor, Lincoln, NE, USA). The aboveground biomass was measured by drying wheat plants at 65 °C to a constant weight.

2.3.2. Physiological Characteristics

The same three plants were selected in each pot, and the photosynthetic rate (P_n), stomatal conductance (G_s), and transpiration rate (T_r) of the winter wheat were measured using the LI–6400 Portable Photosynthesis System (LI–Cor, Lincoln, NE, USA) at different growth stages. SPAD–502 Minolta chlorophyll meter (Spectrum Technologies, Plainfield, IL, USA) was used to measure the SPAD values of the flag leaves at different stages. These physiological characteristics were measured in–vivo without harvesting the plants.

2.3.3. Yield Components, Total Water Consumption (TWC), and WUE

After four periods of sampling and measurements, the remaining five wheat plants in each pot were harvested. The number of spikes and kernels per pot were estimated by manual counting. The grain yield per pot was determined by threshing, air-drying, and then weighing. Soil water mass at harvest (W_h) was measured with the gravity method, and the soil sample was collected at 0–20 cm in each pot.

The TWC (mm) during the growing period was calculated as:

$$TWC = (W_s + W_i - W_h)/(\rho_w \times S) \quad (1)$$

where W_s is the soil water mass before sowing (kg), W_i is the sum of the water mass irrigated to each pot during the whole growth period (kg), and W_h is the soil water mass at harvest (kg). ρ_w is the density of water, 1.0 g cm^{-3}. S is the surface area of the pot, 3.14×10^{-2} m^2.

The WUE (kg ha^{-1} mm^{-1}) was calculated as:

$$WUE = (Y \times 10)/(S \times TWC) \quad (2)$$

where Y (kg) is the grain yield of the remaining five plants per pot, S is the surface area of the pot, 3.14×10^{-2} m^2. TWC is the total water consumption during the whole growth period (mm).

The harvest index (HI) was calculated as [49]:

$$HI = Y/Y_b \quad (3)$$

where Y (kg) and Y_b (kg) are the grain yield and the biomass yield of the remaining five plants per pot.

2.4. Statistical Analysis

Data were analyzed with SPSS 19.0 software (SPSS Inc., Chicago, IL, USA) at $p < 0.05$. One–way ANOVA and Duncan's multiple comparisons were used to determine significant differences between the treatments. The figures were plotted with Origin 9.3 (OriginLab Corporation, Northampton, MA, USA).

3. Results

3.1. Growth Characteristics

3.1.1. Plant Height

Activated water irrigation significantly increased the plant height in the jointing stage over tap water irrigation with 50%FC (TW_{50}) ($p < 0.05$), as shown in Figure 2. The plant height of magnetized water irrigation with 50%FC (MW_{50}), oxygenated water irrigation with 50%FC (OW_{50}), and magnetized and oxygenated water irrigation with 50%FC ($M\&OW_{50}$) significantly higher by 29.5%, 65.1%, and 29.2%, respectively, over TW_{50} in the jointing stage. Oxygenated water irrigation (OW) had a higher plant height in each growth stage than tap water irrigation (TW) at three irrigation amounts. The plant height of magnetized water irrigation with 80%FC (MW_{80}) were 13.1%, 1.2%, and 1.0% higher than tap water in 80%FC (TW_{80}) in the jointing stage, heading stage, and filling stage, respectively. However, compared with TW_{50}, $M\&OW_{50}$ had a lower plant height in each growth stage. Both magnetized water irrigation with 65%FC (MW_{65}) and magnetized and oxygenated water irrigation with 65%FC ($M\&OW_{65}$) had a higher plant height at each growth stage compared with tap water with 65%FC (TW_{65}).

3.1.2. Leaf Area

Activated water irrigation produced a greater total leaf area at different growth stages than TW. The total leaf area of winter wheat decreased gradually with the decrease of irrigation amount and was highest in the filling stage, as shown in Figure 3. In the filling stage, the leaf area of MW_{80}, oxygenated water irrigation with 80%FC (OW_{80}), and magnetized and oxygenated water irrigation with 80%FC ($M\&OW_{80}$) were 1.1%, 39.3%, and 4.6% higher than TW_{80}, respectively.

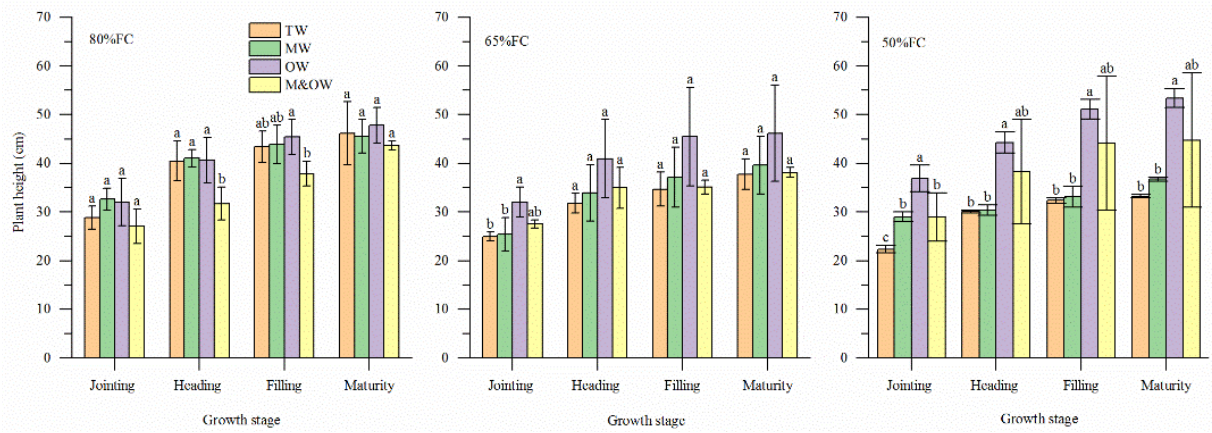

Figure 2. Effect of tap water (TW), magnetized water (MW), oxygenated water (OW), and magnetized and oxygenated water (M&OW) irrigation on plant height of winter wheat with 80%FC, 65%FC, and 50%FC irrigation amounts in the different growth stages. Different letters above the bars indicate significant differences among treatments in the different growth stages at $p < 0.05$. The error bars indicate standard deviations.

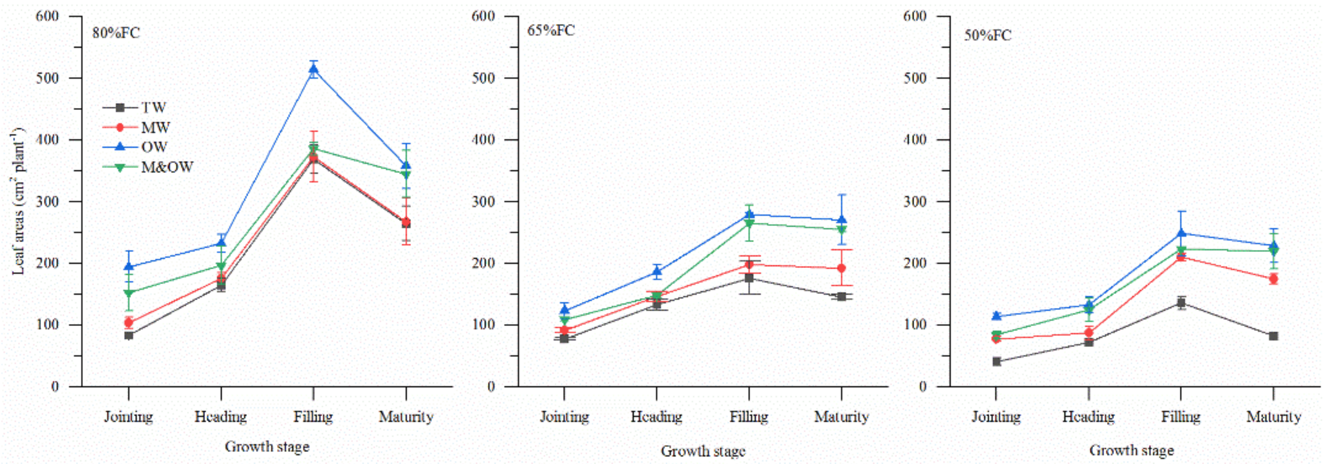

Figure 3. Effect of tap water (TW), magnetized water (MW), oxygenated water (OW), and magnetized and oxygenated water (M&OW) irrigation on total leaf area per plant of winter wheat with 80%FC, 65%FC, and 50%FC irrigation amount in the different growth stages. The error bars indicate standard deviations.

The leaf area of MW_{65}, oxygenated water irrigation with 65%FC (OW_{65}), and $M\&OW_{65}$ were 12.2%, 58.3%, and 50.7% higher than TW_{65} in the filling stage, respectively. The leaf area of MW_{50}, OW_{50}, and $M\&OW_{50}$ were 54.6%, 82.9%, and 64.2% higher over TW_{50} in the filling stage, respectively.

3.1.3. Aboveground Biomass

Activated water irrigation produced a greater aboveground biomass of winter than TW, and the aboveground biomass was influenced by irrigation amount in each growth stage, as shown in Figure 4. In the filling stage, the aboveground biomass of OW_{80} and $M\&OW_{80}$ were 27.9% and 17.1% higher over TW_{80}. In addition, the aboveground biomass of MW_{65}, OW_{65}, and $M\&OW_{65}$ in the filling stage were 28.0%, 69.7%, and 33.0% higher over TW_{65}, respectively. The aboveground biomass of MW_{50}, OW_{50}, and $M\&OW_{50}$ in the filling stage were 88.0%, 114.1%, and 112.3% higher over TW_{50}, respectively.

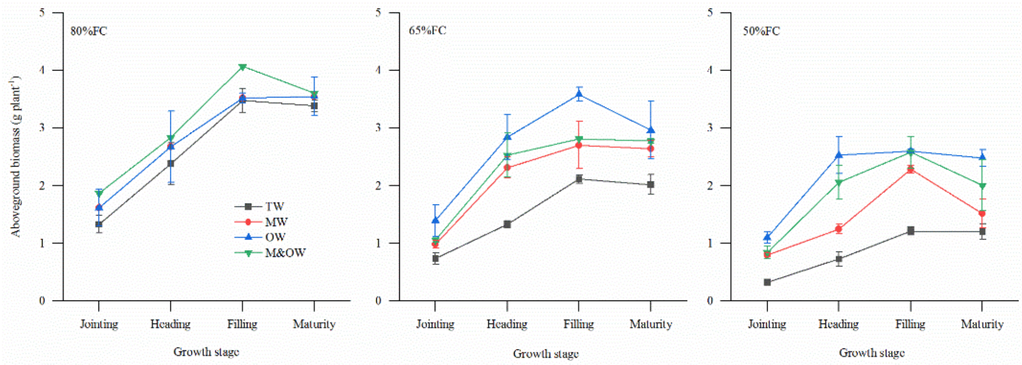

Figure 4. Effect of tap water (TW), magnetized water (MW), oxygenated water (OW), and magnetized and oxygenated water (M&OW) irrigation on aboveground biomass of winter wheat with 80%FC, 65%FC, and 50%FC irrigation amounts in the different growth stages. The error bars indicate standard deviations.

3.2. Physiological Characteristics

The SPAD value of winter wheat was significantly affected by irrigation amount, water type, as well as the interaction between irrigation amount and water type ($p < 0.01$), as shown in Figure 5. In different growth stages, the SPAD value was highest in the filling stage and lowest in the maturity stage, and decreased with the decreasing of irrigation amount. The SPAD value of winter wheat was higher in activated water irrigation than TW in each irrigation amount. Moreover, the effect of activated water irrigation on SPAD value with 50%FC was more obvious than with 80%FC and 65%FC. At the jointing stage, the SPAD value of MW_{50}, OW_{50}, and $M\&OW_{50}$ were 7.5%, 14.6%, and 10.8% higher over TW_{50} ($p < 0.05$). At the heading stage, the SPAD value with MW_{50}, OW_{50}, and $M\&OW_{50}$ was significantly greater by 8.8%, 13.6%, and 10.3% than with TW_{50} ($p < 0.05$). At the filling stage, the SPAD value with MW_{50}, OW_{50}, and $M\&OW_{50}$ was significantly greater by 5.9%, 10.2%, and 8.2% than with TW_{50} ($p < 0.05$).

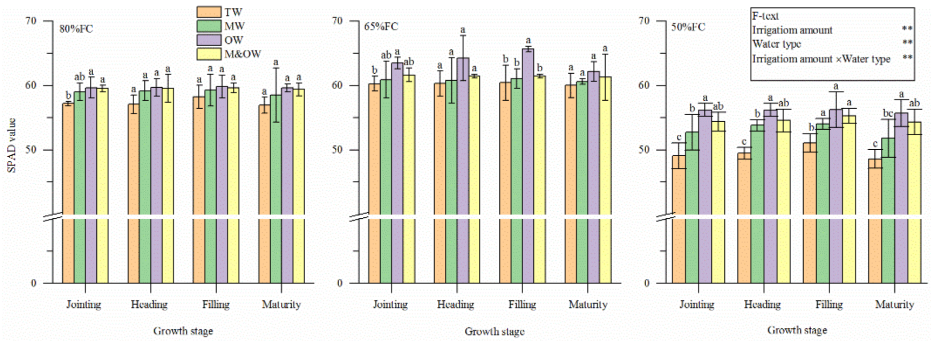

Figure 5. Effect of tap water (TW), magnetized water (MW), oxygenated water (OW), and magnetized and oxygenated water (M&OW) irrigation on SPAD value of winter wheat with 80%FC, 65%FC, and 50%FC irrigation amounts in the different growth stages. Different letters above the bars indicate significant differences among treatments in the different growth stages at $p < 0.05$. Irrigation amount × water type represents the effect of interaction between irrigation amount and water type. ** identifies significant differences at $p < 0.01$, respectively, and ns identifies no significant differences. The error bars indicate standard deviations.

Net photosynthetic rate (Pn), stomatal conductance (Gs), and transpiration rate (Tr) of winter wheat were significantly affected by irrigation amount and water type, but the interaction between irrigation amount and water type had no significant influence on Pn, Gs, and Tr of wheat ($p < 0.05$), as shown in Figures 6–8. In general, increasing the irrigation amounts and irrigation with activated water effectively improved the Pn, Gs, and Tr of wheat. At the heading stage, the Pn, Gs, and Tr were 14.5%, 17.7%, and 40.8% higher with

OW_{50} than with TW_{50}. The Pn, Gs, and Tr were 25.7%, 53.3%, and 32.1% higher with OW_{65} than with TW_{65}. The Pn, Gs, and Tr were 24.1%, 57.1%, and 45.8% higher with OW_{50} than with TW_{50}.

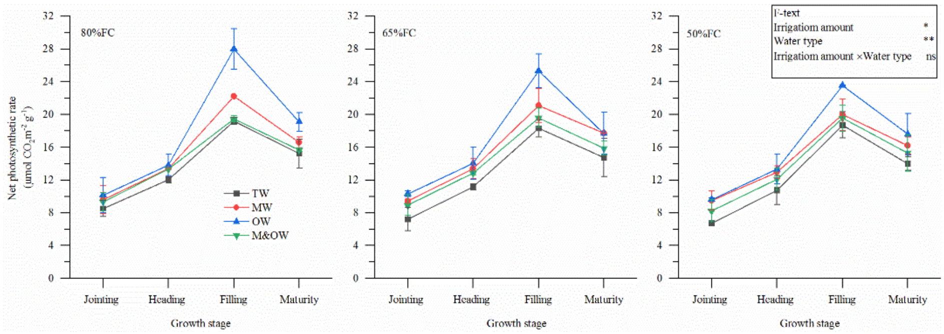

Figure 6. Effect of tap water (TW), magnetized water (MW), oxygenated water (OW), and magnetized and oxygenated water (M&OW) irrigation on net photosynthetic rate of winter wheat with 80%FC, 65%FC, and 50%FC irrigation amounts in the different growth stages. Irrigation amount × water type represents the effect of interaction between irrigation amount and water type. * and ** identify significant differences at $p < 0.05$ and $p < 0.01$, respectively, and ns identifies no significant differences. The error bars indicate standard deviations.

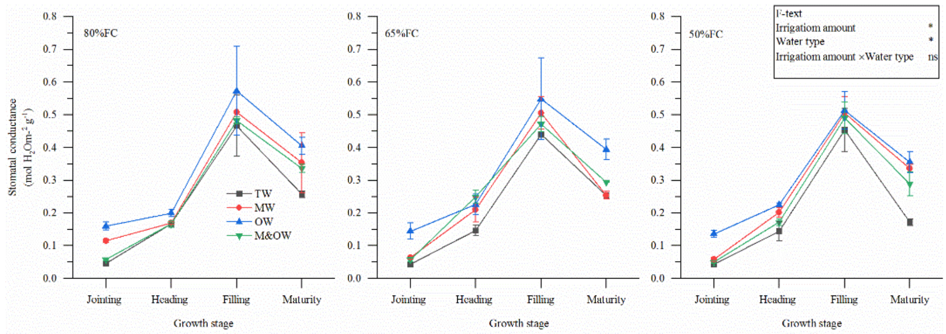

Figure 7. Effect of tap water (TW), magnetized water (MW), oxygenated water (OW), and magnetized and oxygenated water (M&OW) irrigation on stomatal conductance of winter wheat with 80%FC, 65%FC, and 50%FC irrigation amounts in the different growth stages. Irrigation amount × water type represents the effect of interaction between irrigation amount and water type. * identifies significant differences at $p < 0.05$, respectively, and ns identifies no significant differences. The error bars indicate standard deviations.

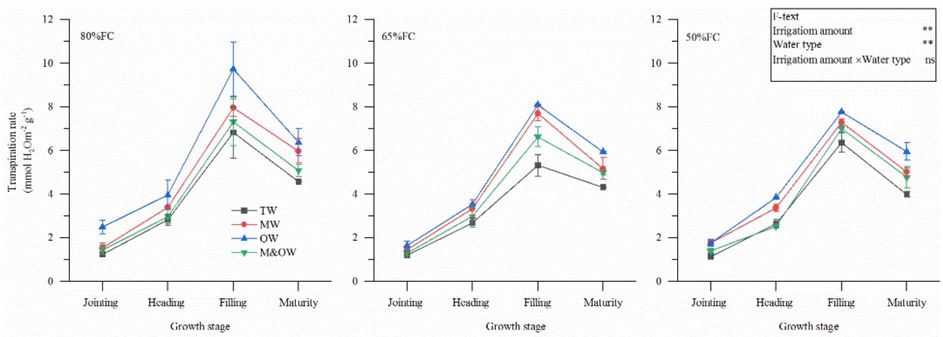

Figure 8. Effect of tap water (TW), magnetized water (MW), oxygenated water (OW), and magnetized and oxygenated water (M&OW) irrigation on the transpiration rate of winter wheat with 80%FC, 65%FC, and 50%FC irrigation amounts in the different growth stages. Irrigation amount × water type represents the effect of interaction between irrigation amount and water type. ** identifies significant differences at $p < 0.01$, respectively, and ns identifies no significant differences. The error bars indicate standard deviations.

3.3. TWC, Wheat Yield, and WUE

Activated water irrigation produced lower TWC with 80%FC, and higher TWC with 65%FC and 50%FC, as shown in Figure 9. The TWC with MW_{80}, OW_{80}, and $M\&OW_{80}$ were lower by 10.4%, 10.3%, and 12.8% than with TW_{80}. The TWC with MW_{65}, OW_{65}, and $M\&OW_{65}$ were greater by 4.5%, 8.2%, and 3.2% than with TW_{65}. The TWC with MW_{50}, OW_{50}, and $M\&OW_{50}$ were greater by 10.9%, 26.7%, and 27.1% than with TW_{50}.

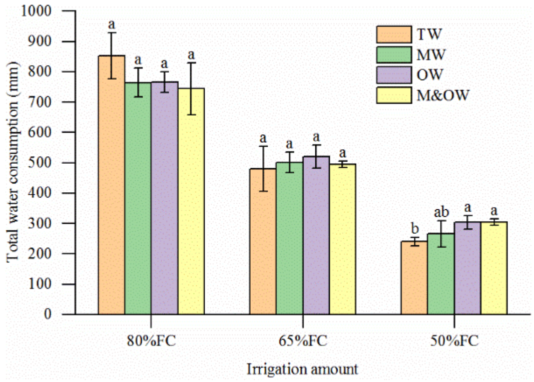

Figure 9. Effect of tap water (TW), magnetized water (MW), oxygenated water (OW), and magnetized and oxygenated water (M&OW) irrigation on total water consumption with 80%FC, 65%FC, and 50%FC irrigation amount. Different letters above the bars indicate significant differences among treatments at $p < 0.05$. The error bars indicate standard deviations.

The yield, yield components, and WUE of winter wheat were significantly affected by irrigation amount and water type ($p < 0.01$), as shown in Table 2. Spikes per pot of MW_{80}, OW_{80}, and $M\&OW_{80}$ were greater by 16.4%, 23.6%, and 19.3% than TW_{80}, respectively, while there was no significant difference among them ($p < 0.05$). The yield of MW_{80} and OW_{80} were greater by 35.7% ($p < 0.05$) and 11.4% ($p > 0.05$) than TW_{80}, while the yield of $M\&OW_{80}$ was significantly less by 27.1% ($p < 0.05$). WUE of MW_{80} and OW_{80} were greater by 53.9% and 23.1% than TW_{80}, while $M\&OW_{80}$ was less by 15.4%.

Table 2. The yield, yield components, water use efficiency (WUE), and harvest index (HI) of winter wheat with different water irrigation.

Irrigation Amount	Treatment	Spikes per Pot	Kernels per Pot	Yield ($\times10^{-3}$ kg pot^{-1})	WUE (kg ha^{-1} mm^{-1})	HI (%)
80%FC	TW_{80}	14.0 ± 1.0 a	304.0 ± 29.1 b	7.0 ± 1.3 b	2.6 bc	23.0 a
	MW_{80}	16.3 ± 2.5 a	417.7 ± 15.7 a	9.5 ± 0.9 a	4.0 a	22.9 a
	OW_{80}	17.3 ± 0.6 a	354.7 ± 40.0 b	7.8 ± 0.5 ab	3.2 ab	22.9 a
	$M\&OW_{80}$	16.7 ± 2.3 a	144.7 ± 19.1 c	5.1 ± 1.0 c	2.2 c	13.9 b
65%FC	TW_{65}	12.0 ± 1.7 b	123.3 ± 7.6 c	4.1 ± 0.1 b	2.7 b	15.9 b
	MW_{65}	13.0 ± 1.0 ab	262.0 ± 21.5 a	5.9 ± 0.3 a	3.7 a	22.0 a
	OW_{65}	15.7 ± 1.5 a	167.0 ± 2.7 b	6.0 ± 0.7 a	3.7 a	23.7 a
	$M\&OW_{65}$	13.3 ± 1.5 ab	187.7 ± 16.0 b	4.7 ± 0.2 b	3.0 b	15.8 b
50%FC	TW_{50}	7.3 ± 0.6 b	114.3 ± 5.1 b	2.2 ± 0.2 b	2.9 c	17.9 c
	MW_{50}	7.3 ± 0.6 b	84.3 ± 3.1 c	1.8 ± 0.2 b	2.2 c	17.0 c
	OW_{50}	8.3 ± 0.6 b	117.0 ± 9.5 b	3.9 ± 0.8 a	4.1 b	21.9 b
	$M\&OW_3$	10.7 ± 0.6 a	181.3 ± 27.6 a	4.9 ± 0.7 a	5.1 a	24.7 a
Irrigation amount		**	**	**	**	ns
Water type		**	**	**	**	**
Irrigation amount × Water type		ns	**	**	**	**

Notes: Irrigation amount × water type represents the effect of interaction between irrigation amount and water type. The number following ± is the standard deviation. Values followed by different letters within a column are significantly different among treatments in the same irrigation amount ($p < 0.05$). ** identifies significant differences at $p < 0.01$, respectively, and ns identifies no significant differences.

With 65%FC, irrigation with activated water had more spikes and high yield and WUE. Spikes per pot, yield, and WUE of OW_{65} were significantly higher, by 30.8%, 46.3%, and 37.0%, than TW_{65}, respectively ($p < 0.05$). The yield and WUE of MW_{65} were significantly greater, by 43.9% and 37.0%, respectively, than TW_{65} ($p < 0.05$).

Yield and WUE of OW_{50} were significantly greater, by 77.3% and 41.4% than TW_{50} ($p < 0.05$). Yield and WUE of $M\&OW_{50}$ were significantly greater, by 122.7% and 75.9%, than TW_{50} ($p < 0.05$). However, kernels per pot, yield, and WUE of MW_{50} were lower, by 26.2%, 18.2%, and 24.1%, respectively, than with TW_{50}, and kernels per pot were significantly lower ($p < 0.05$).

The HI ranged from 14.9% to 24.7%, and was affected by water type and an interaction effect between irrigation amount and water type (Table 2). With $M\&OW_{80}$, HI was significantly lower, by 59.9%, than with TW_{80}. HI with MW_{65} and OW_{65} was significantly higher, by 37.5% and 50.0%, than with TW_{65}. HI with OW_{50} and $M\&OW_{50}$ were 22.2% and 38.9% higher than with TW_{50}, whereas there was no significant difference between MW_{50} and TW_{50} ($p < 0.05$).

4. Discussion

4.1. Response of Wheat Growth Traits to Irrigation Water Type and Irrigation Amount

In this study, irrigation with MW had a positive effect on plant height, leaf area, SPAD value, photosynthetic rate, stomatal conductance, and transpiration rate. These results indicated that MW promoted the growth of winter wheat. Similar results were obtained in previous studies. It was found that MW effectively increased plant height and specific leaf area of cowpea [30], increased each part biomass of a plant (straw yield and grain yield) [29], increased the chlorophyll content of soybeans and two varieties of peppers [50], and significantly improved the photosynthetic rate of plants [30]. The probable reasons were as follows. On the one hand, the hydrogen bonds between the water molecules treated by a magnetic field were broken and free monomer small molecules were formed. These small free monomer molecules had a hexagonal structure, which easily penetrated biological cell walls and entered plant cell membrane channels, thereby promoting crop growth [23,51]. On the other hand, the magnetic field increased the synthesis of gibberellin, indole acetic acid, and cytokinin, and decreased abscisic acid in plant cells, which in turn promoted the division and enlargement of crop cells, and promoted crop growth. Furthermore, with MW irrigation, the wheat leaf area increased. Larger area leaves had the ability to absorb and capture more light energy, and the increasing leaf chlorophyll content had a positive effect on increasing photosynthetic rate and material synthesis [52–55].

The results of our study showed that irrigation with OW at three irrigation amounts promoted the growth of wheat plant height, leaf area, leaf SPAD value, net photosynthetic rate, stomatal conductance, and transpiration rate, as well as aboveground biomass at different growth stages, especially in 50%FC. The results were consistent with previous studies on irrigation with aerated water [56,57]. Bhattarai et al. [43] found that the transpiration rate of tomato leaves was significantly increased using subsurface aeration drip irrigation. Zhao et al. [58] indicated that aeration treatment on "Red Globe" grape had a positive effect on the net photosynthetic rate, stomatal conductance, and transpiration rate of the leaves in the same growth stage. The possible reasons were as follows. Firstly, OW increased oxygen content in the root zone, improved the soil respiration, and promoted the activity and reproduction of aerobic microorganisms [58], which rapidly decompose soil organic matter and accelerate the mineralization rate, thus promoting the uptake and utilization by crops [59]. Secondly, the higher leaf areas and SPAD value found using OW, enhanced the ability to absorb and convert light energy, and increased the photosynthetic rate, which in turn promoted the accumulation of dry matter [60]. Thirdly, the size of the oxygenated water complex was 50 µm or less, which is smaller than the traditional water complex, and the bubbles can stay in the water for a long time, thereby changing the absorption characteristics of the root surface and improving the absorption of nutrients by plants [61,62].

M&OW irrigation promoted the growth of wheat plant height with 65%FC and 50%FC (Figure 2), but it had an inhibitory effect with 80%FC (Figure 2). The possible reason was that the M&OW irrigation promoted the formation of wheat tillers, especially at 80%FC.

The number of wheat tillers was higher than with TW, and a large amount of water was used for wheat tiller formation. As a result, the plant height reduced (Table 2).

4.2. Response of Yield, TWC, Biomass, and WUE to Irrigation Water Type and Irrigation Amount

Wheat yield and yield components were significantly affected by irrigation amount, water type and the interaction between the two factors (Table 2). With 80%FC, MW and OW produced higher wheat yields, more spikes per pot, and more kernels per pot than TW. These results were similar to the results of Du et al. [63] on potatoes with MW irrigation, and the meta–analysis of Du et al. [64] about OW irrigation. These searchers mainly attributed the improvements to the effect of MW and OW on crop growth. However, the kernels per pot and yield of M&OW_{80} treatment were 52.4% and 27.1% lower than TW_{80}. In the present study, wheat from all pots were harvested at the same time to make sure the growth time per pot was the same. When harvested uniformly, the wheat leaves of M&OW_{80} had not been entirely yellowed, and the grain had not matured, which probably was the main reason for the lower yields in this treatment. This phenomenon indicated that M&OW_{80} prolonged the wheat growth period. With 65%FC, the three types of activated water significantly improved wheat yield and its components. However, with 50%FC, only OW and M&OW significantly increased kernel numbers and yield, while MW had a negative effect on yield. The possible explanations for these results are as follows. On the one hand, sufficient water supply during the winter wheat growth period was beneficial to production increase. However, with 50%FC, wheat had a higher water requirement during the filling stage, and water supplied during irrigation was mainly used for vegetative growth, which hindered grain filling. On the other hand, OW had the ability to increase water absorption and utilization, so a higher yield than obtained with TW was found with OW and M&OW. In addition, although MW increased the number of free monomer water molecules and dimer water molecules, which was more conducive to crop absorption and utilization, lower irrigation water was mainly used for vegetative growth rather than reproductive growth. This hindered the grain filling of MW. Although there were more spikes using MW_3 than with TW_3, most of them were not full or not formed, resulting in a yield reduction [23,51].

The TWC was less with activated water irrigation than with TM_{80}, while TWC was higher with activated water irrigation than with TM_{65} and TM_{50} (Figure 9). This was probably because sufficient water supply promoted the growth of plants, especially with activated water irrigation, and the higher canopy obtained with MW, OW, and M&OW effectively reduced the soil evaporation (Figure 3) and decreased the TWC. However, under 65%FC and 50%FC conditions, the water supply was insufficient, but activated water had the ability to promote root growth and increase the water absorption efficiency [47]. As a result, the higher canopies were found using MW, OW, and M&OW than with TW (Figure 3). Although a higher canopy can effectively reduce soil evaporation, higher crop transpiration also should not be ignored. The higher TWC of activated water irrigation may have attributed the higher crop transpiration than with TW under 65%FC and 50%FC conditions [65,66].

WUE was significantly affected by irrigation amount, water type, and the interaction between the two factors (Table 2). Under 80%FC conditions, WUE with MW and OW was larger by 53.9% and 23.1% than with TW, while WUE with M&OW was less by 15.4% than TW. Under 65%FC condition, the WUE with MW, OW, and M&OW were greater, by 37.0%, 37.0%, and 11.1%, respectively, than TW. Under 50%FC condition, the WUE using OW and M&OW were significantly greater, by 36.7% and 70.0% ($p < 0.05$), than using TW, while the WUE using MW was 26.7% less than with TW. Zhao et al. [67] found that magnetized water irrigation with 120 mm had the highest water use efficiency in the field condition. The results of this study were similar to the studies of others [28,66–68]. The lower WUE reduction using M&OW with 80%FC and using MW with 50%FC might be attributed to the uneven distribution of photosynthetic products and reduction of yield. In addition, the

WUE in our study only took into account yield and neglected the biomass of wheat stalks; this may underestimate the water use efficiency.

Moreover, there was no research on oxygenated water and magnetized and oxygenated water irrigation under different irrigation amounts, further field experiment research should also be conducted in these aspects.

4.3. Applicability Evaluation

In arid and semi–arid areas, the current water–saving measures commonly used in farmland mainly include mulching [69–71] and no–tillage [72,73]. A meta–analysis conducted on non–plastic–film mulching on maize in the Loess Plateau of China showed that plastic–film mulching produces significantly higher maize grain yield, by 56.1% than no–mulching [74]. A recent meta–analysis of the soil tillage practices in Northern China indicated that subsoiling and mulching increased the wheat yield by 16.3 ± 3.2 and 14.9 ± 2.9%, respectively [75]. Previous research showed that plastic mulching significantly increased crop yield and WUE by 24.3% and 27.6%, respectively. However, it left residual plastic in the soil. Residual plastic concentrations between 0 and 240 kg ha^{-1} have limited influence on crop yields, but at residual plastic film >240 kg ha^{-1}, yield decreases [76]. Although no–tillage treatments increased WUE by 16.5–29.1%, continuous no–tillage decreased yields [72].

In our study, compared with TW_{50}, the yield and WUE of OW_{50} were greater by 77.3% and 41.4% (Table 2), respectively. These results indicated that compared with other water–saving measures, irrigation with activated water not only avoided the introduction of contaminants into the soil, but also improved crop yield and WUE.

At present, the preparation equipment of magnetized water and oxygenated water used in field experiments are permanent magnet and Venturi tube [67,77]. The methods were as follows. A permanent magnet was installed on the outer wall of the irrigation water pipe, and the water was magnetized as it passed through the pipe. The Venturi tube was installed on the pipe of the drip irrigation system, the air was sucked through the Venturi tube of the Mazzei injector following Bernoulli's principles, and the air volume in the irrigation water was controlled by the pressure differences for the inlet and outlet. Furthermore, the input of permanent magnet and Venturi tube are very low because these instruments could be used for a long time, for example, 20 years. Activated water irrigation could be considered an effective water-saving measure to increase crop yield.

This study provided a new research idea regarding activated water irrigation research in the field condition, and we recommend to prepare the activated water with permanent magnet and Venturi tube in field conditions. In addition, we will also conduct relevant experiments to verify our current experimental results under field conditions.

5. Conclusions

Activated water promoted the growth of winter wheat under different irrigation conditions. Its use increased wheat plant height, leaf area, aboveground biomass, SPAD value and photosynthetic indicators. The yield and WUE varied with irrigation amounts. With 80%FC, MW and OW produced a higher yield and WUE than TW. With 65%FC, MW, OW, and M&OW had a higher yield and WUE than TW. With 50%FC, OW and M&OW had significantly higher yield and WUE than TW. Overall, activated water irrigation could be considered an effective water–saving measure to increase crop yield.

Author Contributions: Conceptualization, H.W. and J.F.; methodology, J.F.; software, H.W.; formal analysis, H.W.; data curation, H.W.; investigation, H.W. and W.F.; writing—original draft preparation, H.W. and W.F.; writing—review and editing, H.W. and J.F.; visualization, H.W.; supervision, J.F.; project administration, J.F.; funding acquisition, J.F. 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: Not applicable.

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

References

1. Schiermeier, Q. The parched planet: Water on tap. *Nature* **2014**, *510*, 326–328. [CrossRef] [PubMed]
2. Zhao, C.; Liu, B.; Piao, S.; Wang, X.; Lobell, D.B.; Huang, Y.; Huang, M.T.; Yao, Y.T.; Bassu, S.; Ciais, P.; et al. Temperature increase reduces global yields of major crops in four independent estimates. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 9326–9331. [CrossRef] [PubMed]
3. Hassani, A.; Azapagic, A.; Shokri, N. Global predictions of primary soil salinization under changing climate in the 21st century. *Nat. Commun.* **2021**, *12*, 6663. [CrossRef] [PubMed]
4. Viala, E. Water for food, water for life a comprehensive assessment of water management in agriculture. *Irrig. Drain. Syst.* **2008**, *22*, 127–129. [CrossRef]
5. Ghose, B. Food security and food self–sufficiency in China: Form past to 2050. *Food Energy Secur.* **2004**, *3*, 86–95. [CrossRef]
6. Deng, X.P.; Shan, L.; Zhang, H.P.; Turner, N.C. Improving agricultural water use efficiency in arid and semi–arid areas of China. *Agric. Water Manag.* **2006**, *80*, 23–40. [CrossRef]
7. Hao, M.-D.; Fan, J.; Wang, Q.-J.; Dang, T.-H.; Guo, S.-L.; Wang, J.-J. Wheat Grain Yield and Yield Stability in a Long–Term Fertilization Experiment on the Loess Plateau. *Pedosphere* **2007**, *17*, 257–264. [CrossRef]
8. Shan, L.; Huang, Z.B.; Zhang, S.Q. *Water–Saving Agriculture*; Tsinghua University Press: Beijing, China, 2000.
9. Monreal, J.; Jiménez, E.; Remesal, E.; Morillo–Velarde, R.; García–Mauriño, S.; Echevarría, C. Proline content of sugar beet storage roots: Response to water deficit and nitrogen fertilization at field conditions. *Environ. Exp. Bot.* **2007**, *60*, 257–267. [CrossRef]
10. Tognetti, R.; Palladino, M.; Minnocci, A.; Delfine, S.; Alvino, A. The response of sugar beet to drip and low–pressure sprinkler irrigation in southern Italy. *Agric. Water Manag.* **2003**, *60*, 135–155. [CrossRef]
11. Cui, N.; Du, T.; Kang, S.; Li, F.; Hu, X.; Wang, M.; Li, Z. Relationship between stable carbon isotope discrimination and water use efficiency under regulated deficit irrigation of pear–jujube tree. *Agric. Water Manag.* **2009**, *96*, 1615–1622. [CrossRef]
12. Bloch, D.; Hoffmann, C.M.; Märländer, B. Impact of water supply on photosynthesis, water use and carbon isotope discrimination of sugar beet genotypes. *Eur. J. Agron.* **2006**, *24*, 218–225. [CrossRef]
13. Geerts, S.; Raes, D. Deficit irrigation as an on–farm strategy to maximize crop water productivity in dry areas. *Agric. Water Manag.* **2009**, *96*, 1275–1284. [CrossRef]
14. Ma, S.-C.; Duan, A.-W.; Wang, R.; Guan, Z.-M.; Yang, S.-J.; Shao, Y. Root–sourced signal and photosynthetic traits, dry matter accumulation and remobilization, and yield stability in winter wheat as affected by regulated deficit irrigation. *Agric. Water Manag.* **2015**, *148*, 123–129. [CrossRef]
15. Wei, Z.; Du, T.; Zhang, J.; Xu, S.; Cambre, P.J.; Davies, W.J. Carbon isotope discrimination shows a higher water use efficiency under alternate partial root–zone irrigation of field–grown tomato. *Agric. Water Manag.* **2015**, *165*, 33–43. [CrossRef]
16. Haghverdi, A.; Yonts, C.D.; Reichert, D.L.; Irmak, S. Impact of irrigation, surface residue cover and plant population on sugarbeet growth and yield, irrigation water use efficiency and soil water dynamics. *Agric. Water Manag.* **2017**, *180*, 1–12. [CrossRef]
17. Chen, W.; Jin, M.; Ferre, T.P.; Liu, Y.; Xian, Y.; Shan, T.; Ping, X. Spatial distribution of soil moisture, soil salinity, and root density beneath a cotton field under mulched drip irrigation with brackish and fresh water. *Field Crops Res.* **2018**, *215*, 207–221. [CrossRef]
18. Chen, X.; Dhungel, J.; Bhattarai, S.P.; Torabi, M.; Pendergast, L.; Midmore, D.J. Impact of oxygation on soil respiration, yield and water use efficiency of three crop species. *J. Plant Ecol.* **2010**, *4*, 236–248. [CrossRef]
19. Khoshravesh–Miangoleh, M.; Kiani, A.-R. Effect of magnetized water on infiltration capacity of different soil textures. *Soil Use Manag.* **2014**, *30*, 588–594. [CrossRef]
20. Luo, J.; He, W.; Qi, S.; Wu, J.; Gu, X.S. A novel phytoremediation method assisted by magnetized water to decontaminate soil Cd based on harvesting senescent and dead leaves of *Festuca arundinacea*. *J. Hazard. Mater.* **2019**, *383*, 121115. [CrossRef]
21. Higashitani, K.; Kage, A.; Katamura, S.; Imai, K.; Hatade, S. Effects of a Magnetic Field on the Formation of $CaCO_3$ Particles. *J. Colloid Interface Sci.* **1993**, *156*, 90–95. [CrossRef]
22. Amiri, M.; Dadkhah, A.A. On reduction in the surface tension of water due to magnetic treatment. *Colloids Surf. A Physicochem. Eng. Asp.* **2006**, *278*, 252–255. [CrossRef]
23. Toledo, E.J.D.L.; Ramalho, T.; Magriotis, Z. Influence of magnetic field on physical–chemical properties of the liquid water: Insights from experimental and theoretical models. *J. Mol. Struct.* **2008**, *888*, 409–415. [CrossRef]
24. Yang, T.; Wang, Q.; Wu, L.; Zhang, P.; Zhao, G.; Liu, Y. A mathematical model for the transfer of soil solutes to runoff under water scouring. *Sci. Total Environ.* **2016**, *569–570*, 332–341. [CrossRef] [PubMed]
25. Shimokawa, I. Oxidative stress and calorie restriction. *Geriatr. Gerontol. Int.* **2004**, *4*, S149–S151. [CrossRef]
26. Abuarab, M.; Mostafa, E.; Ibrahim, M. Effect of air injection under subsurface drip irrigation on yield and water use efficiency of corn in a sandy clay loam soil. *J. Adv. Res.* **2013**, *4*, 493–499. [CrossRef]
27. Ijaz, B. Changes in germination behavior of wheat seeds exposed to magnetic field and magnetically structured water. *Afr. J. Biotechnol.* **2012**, *11*, 2927. [CrossRef]
28. Grewal, H.S.; Maheshwari, B.L. Magnetic treatment of irrigation water and snow pea and chickpea seeds enhances early growth and nutrient contents of seedlings. *Bioelectromagnetics* **2010**, *32*, 58–65. [CrossRef]
29. Moussa, H.R. The impact of magnetic water application for improving common bean (*Phaseolus vulgaris* L.) production. *N. Y. Sci. J.* **2011**, *4*, 15–20.

30. Sadeghipour, O.; Aghaei, P. Improving the growth of cowpea (*Vigna unguiculata* L. Walp.) by magnetized water. *J. Biodivers. Env. Sci.* **2013**, *3*, 37–43.
31. Maheshwari, B.; Grewal, H.S. Magnetic treatment of irrigation water: Its effects on vegetable crop yield and water productivity. *Agric. Water Manag.* **2009**, *96*, 1229–1236. [CrossRef]
32. Savostin, P.V. Magnetic growth relations in plants. *Planta* **1964**, *12*, 327.
33. Al-Khazan, M.; Abdullatif, B.M.; Al-Assaf, N. Effects of magnetically treated water on water status, chlorophyll pigments and some elements content of Jojoba (*Simmondsia chinensis* L.) at different growth stages. *Afr. J. Environ. Sci. Technol.* **2011**, *5*, 722–731. [CrossRef]
34. Mostafazadeh-Fard, B.; Khoshravesh, M.; Mousavi, S.-F.; Kiani, A.-R. Effects of Magnetized Water and Irrigation Water Salinity on Soil Moisture Distribution in Trickle Irrigation. *J. Irrig. Drain. Eng.* **2011**, *137*, 398–402. [CrossRef]
35. Barrett-Lennard, E.G. The interaction between water–logging and salinity in higher plants: Causes, consequences and impli–cations. *Plant Soil* **2003**, *253*, 35–54. [CrossRef]
36. Grable, A.R. Soil Aeration and Plant Growth. *Adv. Agron.* **1966**, *18*, 57–106. [CrossRef]
37. Meek, B.D.; Ehlig, C.F.; Stolzy, L.H.; Graham, L.E. Furrow and Trickle Irrigation: Effects On Soil Oxygen and Ethylene and Tomato Yield. *Soil Sci. Soc. Am. J.* **1983**, *47*, 631–635. [CrossRef]
38. Bhattarai, S.P.; Huber, S.; Midmore, D.J. Aerated subsurface irrigation water gives growth and yield benefits to zucchini, vegetable soybean and cotton in heavy clay soils. *Ann. Appl. Biol.* **2004**, *144*, 285–298. [CrossRef]
39. Goorahoo, D.; Carstensen, G.; Zoldoske, D.F.; Norum, E.; Mazzei, A. Using air in subsurface drip irrigation (SDI) to increase yields in bell peppers. *Int. Water Irrig.* **2002**, *22*, 39–42.
40. Ouyang, Z.; Tian, J.; Yan, X.; Shen, H. Effects of different concentrations of dissolved oxygen or temperatures on the growth, photosynthesis, yield and quality of lettuce. *Agric. Water Manag.* **2019**, *228*, 105896. [CrossRef]
41. Ouyang, Z.; Tian, J.; Yan, X.; Shen, H. Effects of different concentrations of dissolved oxygen on the growth, photosynthesis, yield and quality of greenhouse tomatoes and changes in soil microorganisms. *Agric. Water Manag.* **2020**, *245*, 106579. [CrossRef]
42. Pendergast, L.; Bhattarai, S.; Midmore, D. Evaluation of aerated subsurface drip irrigation on yield, dry weight partitioning and water use efficiency of a broad–acre chickpea (*Cicer arietinum* L.) in a vertosol. *Agric. Water Manag.* **2019**, *217*, 38–46. [CrossRef]
43. Bhattarai, S.P.; Pendergast, L.; Midmore, D.J. Root aeration improves yield and water use efficiency of tomato in heavy clay and saline soils. *Sci. Hortic.* **2006**, *108*, 278–288. [CrossRef]
44. Liu, Y.; Zhou, Y.; Wang, T.; Pan, J.; Zhou, B.; Muhammad, T.; Zhou, C.; Li, Y. Micro–nano bubble water oxygation: Synergistically improving irrigation water use efficiency, crop yield and quality. *J. Clean. Prod.* **2019**, *222*, 835–843. [CrossRef]
45. Zhu, M.; Wang, Q.; Sun, Y.; Zhang, J. Effects of oxygenated brackish water on germination and growth characteristics of wheat. *Agric. Water Manag.* **2020**, *245*, 106520. [CrossRef]
46. Dhungel, J.; Bhattarai, S.P.; Midmore, D.J. Aerated water irrigation (oxygation) benefits to pineapple yield, water use efficiency and crop health. *Adv. Hortic. Sci.* **2012**, *26*, 3–16.
47. Zhao, G.; Mu, Y.; Wang, Y.; Wang, L. Magnetization and oxidation of irrigation water to improve winter wheat (*Triticum aestivum* L.) production and water–use efficiency. *Agric. Water Manag.* **2021**, *259*, 107254. [CrossRef]
48. Yang, X.; Fan, J.; Ge, J.; Luo, Z. Effect of Irrigation with Activated Water on Root Morphology of Hydroponic Rice and Wheat Seedlings. *Agronomy* **2022**, *12*, 1068. [CrossRef]
49. Zhang, P.; Wei, T.; Cai, T.; Ali, S.; Han, Q.; Ren, X.; Jia, Z. Plastic–Film Mulching for Enhanced Water–Use Efficiency and Economic Returns from Maize Fields in Semiarid China. *Front. Plant. Sci.* **2017**, *8*, 512. [CrossRef]
50. Asghar, T.; Iqbal, M.; Jamil, Y.; Haq, Z.U.; Nisar, J.; Shahid, M. Comparison of HeNe laser and sinusoidal non–uniform magnetic field seed pre–sowing treatment effect on Glycine max (Var 90–I) germination, growth and yield. *J. Photochem. Photobiol. B Biol.* **2016**, *166*, 212–219. [CrossRef]
51. Wang, Y.; Zhang, B.; Gong, Z.; Gao, K.; Ou, Y.; Zhang, J. The effect of a static magnetic field on the hydrogen bonding in water using frictional experiments. *J. Mol. Struct.* **2013**, *1052*, 102–104. [CrossRef]
52. Iqbal, M.; Haq, Z.U.; Jamil, Y.; Nisar, J. Pre–sowing seed magnetic field treatment influence on germination, seedling growth and enzymatic activities of melon (*Cucumis melo* L.). *Biocatal. Agric. Biotechnol.* **2016**, *6*, 176–183. [CrossRef]
53. Podleśna, A.; Gładyszewska, B.; Podleśny, J.; Zgrajka, W. Changes in the germination process and growth of pea in effect of laser seed irradiation. *Int. Agrophysics* **2015**, *29*, 485–492. [CrossRef]
54. Racuciu, M.; Creanga, D.; Amoraritei, C. Biochemical changes induced by low frequency magnetized field exposure of vegetal organisms. *Rom. J. Phys.* **2007**, *52*, 645–651.
55. Selim, A.-F.H.; El-Nady, M.F. Physio–anatomical responses of drought stressed tomato plants to magnetic field. *Acta Astronaut.* **2011**, *69*, 387–396. [CrossRef]
56. Shang, Z.-H.; Cai, H.-J.; Chen, H.; Sun, Y.-N.; Li, L.; Zhu, Y.; Wang, X.-Y. Effect of Water–Fertilizer–Gas Coupling on Soil N_2O Emission and Yield in Greenhouse Tomato. *Environ. Sci.* **2020**, *41*, 2924–2935.
57. Zhu, Y.; Cai, H.; Song, L.; Wang, X.; Shang, Z.; Sun, Y. Aerated Irrigation of Different Irrigation Levels and Subsurface Dripper Depths Affects Fruit Yield, Quality and Water Use Efficiency of Greenhouse Tomato. *Sustainability* **2020**, *12*, 2703. [CrossRef]
58. Zhao, F.; Sun, J.; Jiang, Y.; Hu, D.; Yang, X.; Dong, M.; Yu, K.; Yu, S. Effect of rhizosphere aeration by subsurface drip irrigation with tanks on the growth of 'Red Globe' grape seedling and its absorption, distribution and utilization of urea–15 N. *Sci. Hortic.* **2018**, *236*, 207–213. [CrossRef]

59. Liu, S.D.; Wang, C. Experimental study on the effect of direct oxygen supply on the growth of rice seedling root zone. *Fresenius Environ. Bull.* **2019**, *28*, 4745–4751.
60. Zhu, L.-F.; Yu, S.-M.; Jin, Q.-Y. Effects of Aerated Irrigation on Leaf Senescence at Late Growth Stage and Grain Yield of Rice. *Rice Sci.* **2012**, *19*, 44–48. [CrossRef]
61. Li, H.; Hu, L.; Xia, Z. Impact of Groundwater Salinity on Bioremediation Enhanced by Micro–Nano Bubbles. *Materials* **2013**, *6*, 3676–3687. [CrossRef]
62. Li, Y.; Liao, C.H.; Zhu, Y.Z.; Chen, H.J.; Jin, Q.F. Characteristics of micro–bubble and nano–bubble and their application in environmental pollution control. *Chem. Ind. Eng. Progress.* **2012**, *31*, 1333–1337. [CrossRef]
63. Du, Y.-D.; Gu, X.-B.; Wang, J.-W.; Niu, W.-Q. Yield and gas exchange of greenhouse tomato at different nitrogen levels under aerated irrigation. *Sci. Total Environ.* **2019**, *668*, 1156–1164. [CrossRef]
64. Du, Y.-D.; Niu, W.-Q.; Gu, X.-B.; Zhang, Q.; Cui, B.-J.; Zhao, Y. Crop yield and water use efficiency under aerated irrigation: A meta-analysis. *Agric. Water Manag.* **2018**, *210*, 158–164. [CrossRef]
65. Bhattarai, S.P.; Midmore, D.J. Oxygation Enhances Growth, Gas Exchange and Salt Tolerance of Vegetable Soybean and Cotton in a Saline Vertisol. *J. Integr. Plant Biol.* **2009**, *51*, 675–688. [CrossRef]
66. Pendergast, L.; Bhattarai, S.P.; Midmore, D.J. Benefits of oxygation of subsurface drip–irrigation water for cotton in a Vertosol. *Crop Pasture Sci.* **2013**, *64*, 1171–1181. [CrossRef]
67. Zhao, G.; Mu, Y.; Wang, Y.; Wang, L. Response of winter–wheat grain yield and water–use efficiency to irrigation with activated water on Guanzhong Plain in China. *Irrig. Sci.* **2020**, *39*, 263–276. [CrossRef]
68. 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. [CrossRef]
69. Huang, F.; Liu, Z.; Zhang, P.; Jia, Z. Hydrothermal effects on maize productivity with different planting patterns in a rainfed farmland area. *Soil Tillage Res.* **2020**, *205*, 104794. [CrossRef]
70. Luo, C.-L.; Zhang, X.-F.; Duan, H.-X.; Mburu, D.M.; Ren, H.-X.; Kavagi, L.; Dai, R.-Z.; Xiong, Y.-C. Dual plastic film and straw mulching boosts wheat productivity and soil quality under the El Nino in semiarid Kenya. *Sci. Total Environ.* **2020**, *738*, 139808. [CrossRef]
71. Zhang, P.; Wei, T.; Han, Q.; Ren, X.; Jia, Z. Effects of different film mulching methods on soil water productivity and maize yield in a semiarid area of China. *Agric. Water Manag.* **2020**, *241*, 106382. [CrossRef]
72. Kan, Z.-R.; Liu, Q.-Y.; He, C.; Jing, Z.-H.; Virk, A.L.; Qi, J.-Y.; Zhao, X.; Zhang, H.-L. Responses of grain yield and water use efficiency of winter wheat to tillage in the North China Plain. *Field Crops Res.* **2020**, *249*, 107760. [CrossRef]
73. Yang, H.; Wu, G.; Mo, P.; Chen, S.; Wang, S.; Xiao, Y.; Ma, H.A.; Wen, T.; Guo, X.; Fan, G. The combined effects of maize straw mulch and no–tillage on grain yield and water and nitrogen use efficiency of dry–land winter wheat (*Triticum aestivum* L.). *Soil Tillage Res.* **2019**, *197*, 104485. [CrossRef]
74. Wang, N.; Ding, D.; Malone, R.W.; Chen, H.; Wei, Y.; Zhang, T.; Luo, X.; Li, C.; Chu, X.; Feng, H. When does plastic–film mulching yield more for dryland maize in the Loess Plateau of China? A meta-analysis. *Agric. Water Manag.* **2020**, *240*, 106290. [CrossRef]
75. Wang, J.; Pan, Z.; Pan, F.; He, D.; Pan, Y.; Han, G.; Huang, N.; Zhang, Z.; Yin, W.; Zhang, J.; et al. The regional water–conserving and yield–increasing characteristics and suitability of soil tillage practices in Northern China. *Agric. Water Manag.* **2019**, *228*, 105883. [CrossRef]
76. Gao, H.; Yan, C.; Liu, Q.; Ding, W.; Chen, B.; Li, Z. Effects of plastic mulching and plastic residue on agricultural production: A meta–analysis. *Sci. Total Environ.* **2018**, *651*, 484–492. [CrossRef]
77. Du, Y.-D.; Zhang, Q.; Cui, B.-J.; Sun, J.; Wang, Z.; Ma, L.-H.; Niu, W.-Q. Aerated irrigation improves tomato yield and nitrogen use efficiency while reducing nitrogen application rate. *Agric. Water Manag.* **2020**, *235*, 106152. [CrossRef]