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Improving Wheat Yield and Water-Use Efficiency by Optimizing Irrigations in Northern China

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Abstract: Achieving the goal of increasing both crop yield and water-use efficiency with a better irrigation regime is a major challenge in semi-arid areas. In this study, we presented a two-season field experiment (October 2018–June 2019 and October 2019–June 2020) that considered drought stresses, i.e., no irrigation (W0), irrigated in jointing (W1), both in jointing and flowering (W2) after re-greening, and wheat varieties (S086; J22). The results showed that a 45.5% excess of irrigation water input did not promote wheat yield (W1 vs. W2). S086 was beneficial for the usage of soil water consumption under a low amount of irrigation water in both seasons. In addition, irrigation positively affected the activities of superoxide dismutase and catalase in flag leaves ($p < 0.05$). A decrease in irrigation helped to increase the concentrations of soluble sugar and proline and decrease the amount of malondialdehyde content for S086. For the water- and irrigation-water-use efficiency, W1 was significantly increased by 20.6–21.7% and 38.3–39.3% in 2018–2019 and 23.4–24.4% and 43.8–44.7% in 2019–2020, respectively, as compared to W2. Additionally, a higher yield for S086 than J22 was found under deficit irrigation. Consequently, our study suggested that the S086 variety combined with a total amount of irrigation water of 165 mm might be recommended to meet the win–win goal of high crop yields and water-use efficiency for reducing ground water depletion in the future.

Keywords: limited irrigation; drought stress; yield; water-use efficiency; northern China

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1. Introduction

Intensified winter wheat planting is the primary cropping system in northern China, which produces >67% of the wheat in China [1]. Northern China is a typical semi-arid area with an average annual precipitation of 556 mm, but only 27–32% (150–180 mm) of this falls during the winter wheat growing season [2]. Consequently, precipitation cannot meet the requirements, and a lack of adequate water thus causes up to a 200–300 mm shortage of water during the whole winter wheat growing season [3,4]. The irrigation water for flood irrigation measurements, which is pumped from deep groundwater 3–5 times per wheat season, accounts for 80% of the total agricultural water used in this region [5]. In this region, flood irrigation that is used by many farmers causes up to 60% of the irrigation water lost by evaporation or leaching, and this poses a serious threat for sustainable agricultural production [6]. As a result, the groundwater level is declining rapidly at a rate of 0.8–1.5 m yr^{-1} in this region [3,7], which has become an important issue that is restricting sustainable development [8,9]. Therefore, formulating optimal irrigation approaches and improving water-use efficiency in northern China are essential for future agriculture. Since the 1990s, limited irrigation methods have been implemented and proposed to reduce the use of groundwater without decreasing the wheat yield in this region [10]. Because of the important status of wheat in food consumption over the previous 40 years, a focus on improving the productivity of irrigation water is probably the most common strategy for resolving future water-related challenges by adapting proper agricultural management and implementing irrigation-water-saving measures [11,12].

Deficit irrigation, defined as the application of irrigation water below the full-crop evapotranspiration (ET) level, is an important practical strategy to affect water-use efficiency and wheat yields, its quality is based on the key growth stages in which the irrigation water is applied, and it has been globally applied for wheat and other crop fields, particularly in dry regions such as northern China [13–15]. A reduction in or a total loss of seasonal irrigation treatments may cause drought stress, which can stimulate wheat roots to grow into deeper soil (below the 80 cm soil layer) layers and then utilize the soil water and nitrogen found in the deep soil [8]. Additionally, an appropriate scheduling of irrigation minimizes the effects of water stress on crop yields and increases the productivity from water [16]. Li et al. [8] reported that irrigating after the flowering stage could reduce the consumption of pre-anthesis water and ensure the soil water supply at the critical stage, thus increasing water-use efficiency. Jha et al. [17] reported that plants that experienced water stress during the flowering and vegetative growth stages had significantly lower yields and biomass. However, Davarpanah and Ahmadi [12] reported that irrigation at the jointing stage was the most efficient irrigation event for achieving a high yield in all climate conditions. Zhang et al. [18] found that water-saving irrigation contributed to a high plant N-use efficiency and improved the mitigation of greenhouse gas emission and soil N losses. In addition, the physiological indicators of wheat leaf, for example, enzymes in flag leaves such as superoxide dismutase, peroxidase, catalase, and malondialdehyde (MDA), are directly affected by irrigation regimes. Moreover, the responses of crop yield production and the sensitivity of the physiological indicators of wheat leaf to irrigation regimes remain unclear. Thus, the main purpose of this study was to (1) assess the effects of irrigation on soil water consumption, winter wheat yield, water-use efficiency, and the sensitivity of the physiological indicators of wheat leaf; then to (2) determine the traits of two wheat varieties with high yields, such as the WUE and yield; and to (3) explore the influence of the interaction of year, variety, and irrigation events on wheat yield and water-use efficiency. Furthermore, this knowledge will aid in the development of appropriate irrigation management strategies and the selection of appropriate wheat varieties in accordance with future agriculture goals in northern China.

2. Materials and Methods

2.1. Experiment Area

This study was conducted in Quzhou County, Hebei Province (36°86′ N, 115°02′ E, Figure 1a) during the two wheat seasons of 2018–2019 and 2019–2020. Quzhou is a typical area with the most serious water shortage in northern China with an annual average temperature of 16.8 °C. The long-term average annual precipitation is 541.31 mm, and most of this rainfall occurs in the summer and comprises 65–80% of the total. The soil parameters, precipitation, and air temperature values are shown in detail in Table 1 and Figure 1b.

Table 1. Soil conditions of 0–20 cm soil layer.

Year	Bulk Density ($g\ cm^{-3}$)	SOM ($g\ kg^{-1}$)	TN ($g\ kg^{-1}$)	Av-N ($mg\ kg^{-1}$)	Av-P ($mg\ kg^{-1}$)	Av-K ($mg\ kg^{-1}$)
2018–2019	1.48	14.12	1.21	110.41	16.41	150.15
2019–2020	1.46	15.35	1.44	100.56	11.62	137.62

Note: SOM, soil organic matters content; TN, total nitrogen content; Av-N, the concentration of available nitrogen; Av-P, the concentration of available phosphorus; Av-N, the concentration of available potassium.

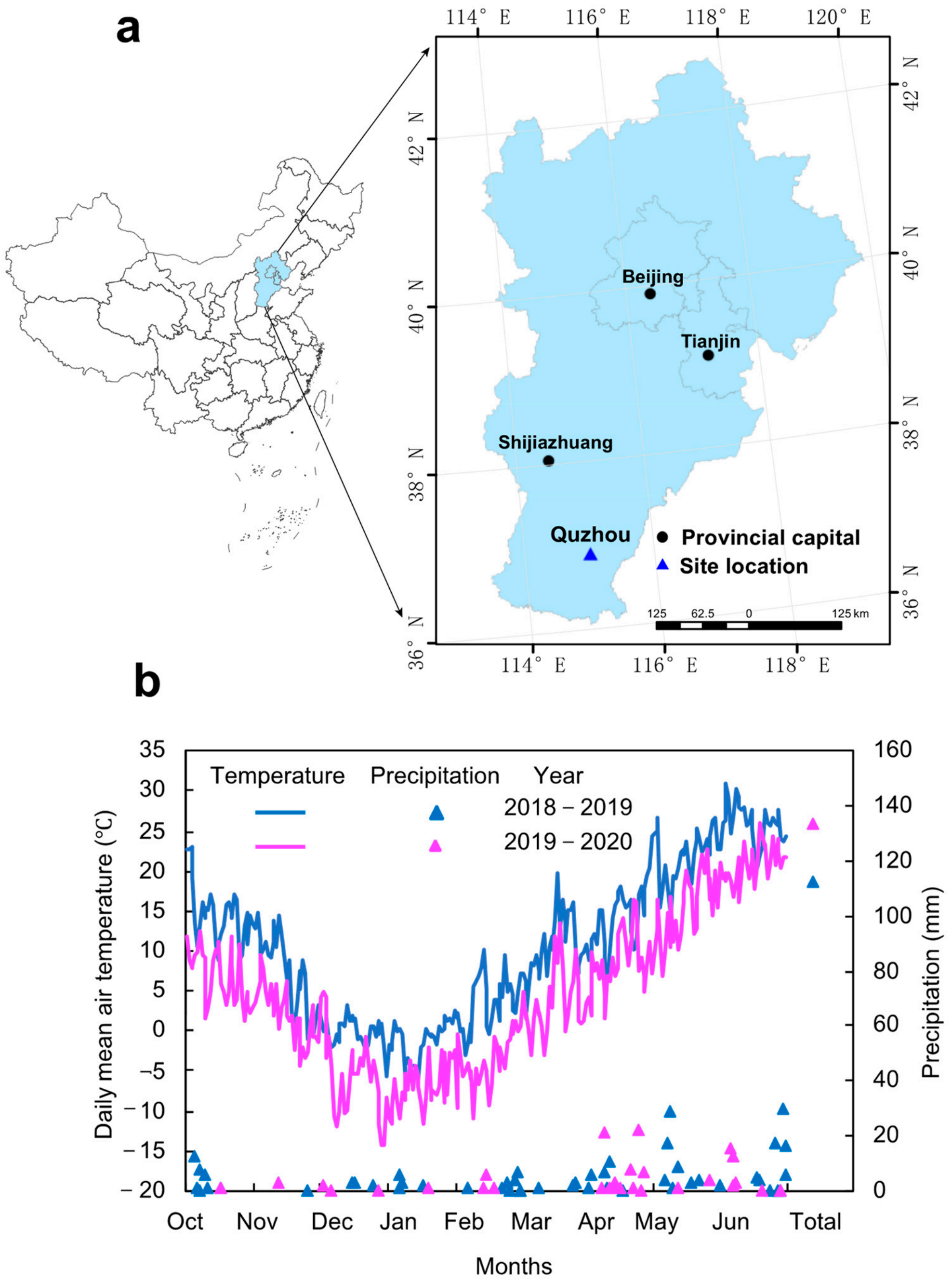

Figure 1. (**a**) The location map of the study area and (**b**) daily precipitation and average daily air temperature during the study period.

2.2. Experimental Design

First, we selected two popular local wheat varieties, i.e., J22 and S086. J22 is an extensively planted variety with steady yield especially in northern China, and S086 is a drought-resistant variety identified by the Institute of Dry Farming, Hebei Academy of Agricultural Sciences, Baoding, China (2015). Secondly, three limited irrigation treatments were considered, i.e., W0, no irrigation after re-greening; W1, irrigation during the jointing stage at 75 mm; W2, irrigation during the jointing and flowering stages at 75 mm for each irrigation, in a total of 150 mm. In this study, all the treatments were irrigated before the winter growth period with the same amount at 90 mm. More irrigation details are shown in Table 2. In this study, wheat variety was maintained in the main plot and irrigation treatments were allocated into sub-plots under a split-plot design. Therefore, six treatments with three replicates, resulting in a total of 18 plots (each with an area of 10 m length × 6 m width), were considered. For fertilizer, 150 kg N ha^{-1}, 120 kg P_2O_5 ha^{-1}, and 90 kg K_2O ha^{-1} were applied along with the wheat sowing, and then 60 kg N ha^{-1} was top-dressed at the jointing stage. Wheat was sown with a row spacing of 15 cm after deep ploughing on 15 October 2018 and 20 October 2019 and harvested on 12 June 2019 and 13 June 2020. Precipitation during the wheat growth period between 2019 and 2020 was 133.7 mm, close to the annual average precipitation of this region.

Table 2. Irrigation amount (mm) in different growth stages during 2018–2020.

Year	Varieties	Treatment	Overwinter 18 December	Jointing 20 March	Flowering 15 May	Total
2018–2019/ 2019–2020	S086	W0	90	0	0	90
		W1	90	75	0	165
		W2	90	75	75	240
	J22	W0	90	0	0	90
		W1	90	75	0	165
		W2	90	75	75	240

Note: The dates cited are the time of irrigation events for each growth stage. W0, no irrigation events after overwintering stage; W1, irrigated in jointing stage; W2, irrigated in jointing and flowering stages.

2.3. Data Collection and Calculation

2.3.1. Crop Yield

To determine the crop yield, the spikes were all counted in one 1 m^2 area of each plot before harvest. The grain number per spike was then counted from 30 randomly selected plants in each plot. The 1000-grain weight was determined by weighing 1000 grains from each plot. At maturity, all the wheat plants in a 3 m^2 area in each plot were harvested, threshed, and then dried at 80 °C for crop yield calculation. In addition, the actual crop yield was calculated with a 12.5% moisture basis.

2.3.2. Soil-Water-Holding Consumption and Water-Use Efficiency

Three soil samples were collected in a 0–200 cm soil layer at 20 cm intervals and then mixed for soil water content analysis at sowing, overwintering, jointing, flowering, filling, and maturity stages. The soil gravimetric water content (%) was measured by oven-drying at 105 °C for 48 h. The soil-water-holding consumption (SWC, mm) was calculated as the final soil-water-holding amount (harvest stage) minus the initial one (seeding stage).

Crop evapotranspiration for a given stage (ET) was calculated according to the soil water balance equation:

$$ET = \Delta S + I + P - R - D + CR \tag{1}$$

where ΔS (mm) is soil water extraction based on the difference between two close growth stages, I (mm) is irrigation, P (mm) is rainfall, R (mm) is runoff, D (mm) is drainage deeper than the 200 cm soil profile, and CR (mm) is the capillary rise into the root zone. R and D can be ignored in northern China according to [19,20]. Additionally, the groundwater table at the experimental site is 5–6 m below the ground surface, which was deeper than the root activity depth of these two wheat varieties selected in this paper (0–2.5 m); therefore, the CR is negligible.

ΔS was calculated according to Equation (2):

$$\Delta S = 10\sum_{i=1}^{n} \gamma_i H_i(\theta_{i1} - \theta_{i2}) \tag{2}$$

where n (=10) is the number of soil layers from 0 to 200 cm; γ_i (g cm^{-3}) is the bulk density of the ith soil layer; H_i (cm) is the soil depth of the ith soil layer; θ_{i1} (%) and θ_{i2} (%) are the initial and final gravimetric water content of the ith soil layer, respectively.

The water consumption intensity (CD, mm d^{-1}) and percentage (CP, %) for a given stage are calculated as follows:

$$CD = \frac{ET}{D} \tag{3}$$

$$CP = \frac{ET}{ET_T} \tag{4}$$

where ET (mm) is the crop evapotranspiration for a given stage, D (d) is the duration days for a given stage, and ET_T (mm) is the total ET for the whole growth season.

The water-use efficiency was evaluated based on the use of the total and irrigation water by the crop, which was estimated as crop-water-use efficiency (WUE, kg m^{-3}) and irrigation-water-use efficiency ($IWUE$, kg m^{-3}), as described by Jha et al. [21].

$$WUE = \frac{GY}{ET_T \times 10} \tag{5}$$

$$IWUE = \frac{GY}{I \times 10} \tag{6}$$

where GY is the grain yield (kg ha^{-1}), ET_T is the total evapotranspiration during a growing season (mm), and I is irrigation (mm).

2.3.3. Plant Nitrogen Uptake and Utilization

The 6 wheat plants were collected at overwintering, jointing, flowering, filling, and maturity stages, and then oven-dried and sieved. The total nitrogen (N) content was determined using the Kjeldahl method. In this study, the NUE indicator was used through N partial factor productivity for fertilizer (PFP_N, kg grain kg^{-1} N_{fert}) [10].

PFP_N was defined as the ratio of crop yield to fertilizer N applied (7):

$$PFP_N = \frac{GY}{N_{fert}} \tag{7}$$

where GY is the grain yield (kg ha^{-1}) and N_{fert} is the fertilizer N application rate (kg ha^{-1}).

2.3.4. Physiological Factors of the Flag Leaf

Twenty flag leaves in each plot were randomly collected at 0, 7, 14, 21, and 24 days after the flowering stage in 2018–2019 and 2019–2020 and then stored at −20 °C before the biochemical analysis was conducted based on a previous study [19]. In this study, six related indicators were used: superoxide dismutase (SOD, U g^{-1} h^{-1}), peroxidase (POD, U g^{-1} h^{-1}), catalase (CAT, U g^{-1} h^{-1}), malondialdehyde (MDA, nmol g^{-1}), soluble sugar (SS, mg g^{-1}), and proline (Pro, mg g^{-1}) content of flag leaf according to Troll and Lindsley [22] and Zhang and Kirkham [23].

2.4. Statistical Analysis

The results in the table have been expressed as mean ± standard error of the three replicates of each treatment. Varieties (i.e., S086 and J22) and irrigation practices (i.e., W1, W2, and W3) were applied in the main and sub-plot, respectively. Microsoft Excel 2010 (Microsoft Co., Redmond, WA, USA) was used to arrange the experimental data. The effects of different years, wheat varieties, irrigation practices, and their interactions on crop yield, N and water consumption, and soil water content were analyzed by SPSS 22.0 software (SPSS Inc., Chicago, IL, USA) using a three-way ANOVA at a significance level of 0.05. Significant differences among different irrigation practices under S086 or J22 were tested using the least significant difference (LSD) test at a significance level of 0.05. Significant differences between S086 and J22 under W1, W2, and W3 were tested using an independent t-test at a significance level of 0.05. Simple correlation analysis was performed to determine whether soil water characteristics, yield, and water-use efficiency were related to wheat physiological factors using Origin pro, 2021 (Origin lab, Northampton, MA, USA).

3. Results

3.1. Crop Water Consumption

Water consumption intensity (*CD*), percentage (*CP*), and total water consumption (TWC) were different in differing growth stages and treatments (Table 3). For the filling–mature stage, the CD of W2 was higher ($p < 0.05$) than those of W1 and W0.

Table 3. Crop water consumptions in different growth stages.

Year	Varieties	Treatment	Seeding to Jointing			Jointing to Flowering			Flowering to Filling			Filling to Mature		
			CD	CP	TWCl	CD	CP	TWC	CD	CP	TWC	CD	CP	TWC
			mm d^{-1}	%	mm	mm d^{-1}	%	mm	mm d^{-1}	%	mm	mm d^{-1}	%	mm
2018–2019	S086	W0	0.43 a	26.26 a	70.92 a	2.93 b	41.16 a	111.17 b	3.00 b	10.01 b	27.04 b	3.15 b	31.46 b	84.97 c
		W1	0.40 a	20.14 b	66.43 a	3.61 a	41.63 a	137.32 a	4.68 a	12.76 a	42.08 a	3.83 b	31.39 b	103.53 b
		W2	0.42 a	18.04 b	69.42 a	3.90 a	38.55 a	148.36 a	5.51 a	12.90 a	49.63 a	5.04 a	35.34 a	136.00 a
	J22	W0	0.45 a	27.43 a	72.34 a	3.16 b	44.33 a	116.92 b	2.92 b	8.86 b	23.38 b	2.83 b	29.02 b	76.53 b
		W1	0.46 a	23.32 b	74.92 a	3.84 a	44.18 a	136.93 a	7.12 a	17.73 a	56.98 a	2.98 b	25.06 b	80.51 b
		W2	0.47 a	20.08 b	76.92 a	3.97 a	38.35 a	146.94 a	7.31 a	15.27 a	58.50 a	5.36 a	37.79 a	144.76 a
2019–2020	S086	W0	0.54 a	22.84 a	88.98 a	0.89 b	8.65 b	33.69 b	7.32 c	16.92 b	65.90 c	3.28 b	22.71 b	88.48 c
		W1	0.51 a	18.94 b	84.99 a	1.77 a	15.01 a	67.32 a	16.96 b	34.03 a	152.65 b	4.30 b	25.85 b	115.99 b
		W2	0.56 a	19.28 b	93.02 a	1.83 a	14.40 a	69.48 a	22.24 a	41.50 a	200.19 a	5.39 a	30.15 a	145.43 a
	J22	W0	0.43 a	17.89 a	68.94 a	0.95 b	9.08 b	34.98 b	8.36 c	17.37 b	66.91 c	2.69 b	18.83 b	72.55 b
		W1	0.35 a	13.89 b	57.45 a	1.48 a	13.26 a	54.84 a	18.60 b	35.98 a	148.80 b	3.17 b	19.42 b	80.29 b
		W2	0.35 a	12.34 b	56.21 a	1.52 a	12.37 a	56.35 a	25.88 a	45.45 a	207.03 a	6.14 a	36.42 a	165.91 a

Note: CD: water consumption intensity; CP: water consumption percentage; TWC: total water consumption. Definitions of different irrigation treatments (i.e., W0, W1, and W2) are given in the caption of Table 2. The same letter in the same column denotes no significant difference in different irrigation treatments by LSD ($p < 0.05$) for these two varieties.

In 2018–2019, a 55.62% (W1) and 83.54% (W2) higher TWC for S086 and 143.71% (W1) and 150.21% (W2) higher TWC for J22 compared to the W0 treatment were found in the flowering–filling stage, respectively. Additionally, a 31.36% (S086) and 79.80% (J22) higher TWC in W2 compared to W1 was found in the filling–mature stage. Similar to 2018–2019, in 2019–2020, TWC in W2 was highest for all growth stages (Table 3).

The *CP* especially in jointing–flowering was highest during the whole season, comprising 38.6–41.6% (S086) and 38.4–44.4% (J22) in 2018–2019, while that in the flowering–filling stage was highest in all irrigation treatments except the seeding–jointing and filling–mature stages in 2019–2020. During the whole season, TWC was W2 > W1 > W0 during both years (Figure 2).

3.2. Soil-Water-Holding Consumption

For different irrigation treatments, TWC decreased along with the increase in amount of irrigation (as the main source of crop water demand). Additionally, the increase in irrigation amount is related to the increase in TWC and the decrease in soil-water-holding consumption (SWC). In 2018–2019, for S086, the order of SWC in the 20–100 cm soil layer was W0 > W1 > W2, while that in 100–180 cm was W1 > W0 > W2. For J22, the order of SWC in the 20–120 cm soil layer was W0 > W1 > W2, but there was no obvious regularity in the deeper soil layer (Figure 3).

In 2019–2020, the order of SWC in surface soil (0–20 cm) and the 40–120 cm soil layer was W0 > W1 > W2 for S086, although there was a lack of an obvious trend in the deeper soil layer, while that in 20–120 cm was W0 > W1 > W2 for J22 but was not apparently regulatory in the deeper soil layer.

3.3. Dynamics of the Physiological Factors of Flag Leaves

Irrigation increased the activities of superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT) from 7 days and the contents of soluble sugar (SS) and proline (Pro) from 14 days after the flowering stage, but decreased the content of malondialdehyde (MDA) during the whole flowering stage (Figures S1–S6). Accordingly, in W2, the SS content increased by 9.1–19.0% (S086) and 4.3–19.8% (J22) during 2018–2019 and 3.4–8.4% (S086) and 10.2–16.6% (J22) during 2019–2020, compared with the content of W1. The Pro content of W2 was 5.6–11.7% (S086) and 7.3–15.2% (J22) higher than those of W1 during 2018–2019, while it was 9.0–10.4% (S086) and 8.3–12.6% (J22) higher than those of W1 during 2019–2020 (Figures S5 and S6). Year and irrigation significantly affected the POD content ($p < 0.05$), but no interaction was found (Table 4). However, there was no significant effect of year, variety, irrigation, and their interactions on SOD, CAT, MDA, sugar, and Pro content.

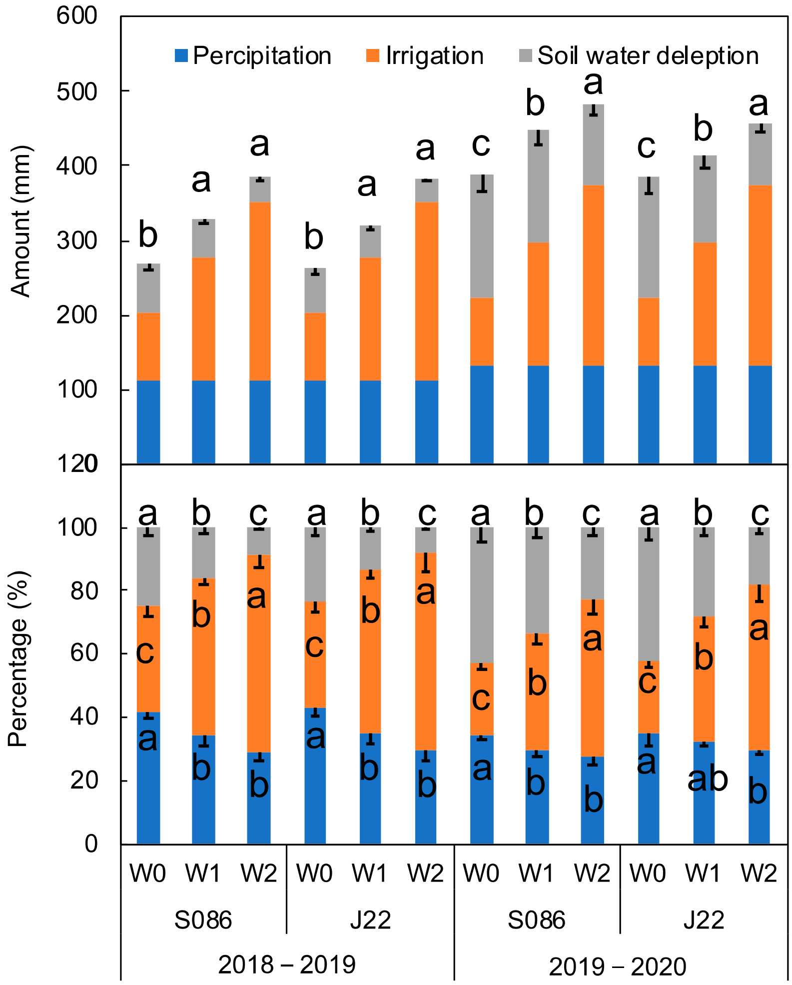

Figure 2. Water consumption and percentage from precipitation, irrigation, and soil water depletion in 0–200 cm soil layer under different treatments. Definitions of different irrigation treatments (i.e., W0, W1, and W2) are given in caption of Table 2. The same letter in each soil layer denotes no significant difference in different irrigation treatments by LSD ($p < 0.05$).

3.4. Crop Yield

Irrigation helped to cause an increase in the number of spikes and grains per spike in 2018–2019 (Table 5). Compared to W0, the spikes of S086 increased by 90.51% (W1) and 66.52% (W2). Similarly, the spikes of J22 increased by 75.63% (W1) and 83.90% (W2), respectively, compared to W0. In addition, the 1000-grain weight was significantly affected by year and variety, and their interaction. Additionally, the yield was significantly affected by irrigation practices and the highest wheat yield was found in S086 in all irrigation treatments during these two experimental seasons ($p < 0.05$, Table 4).

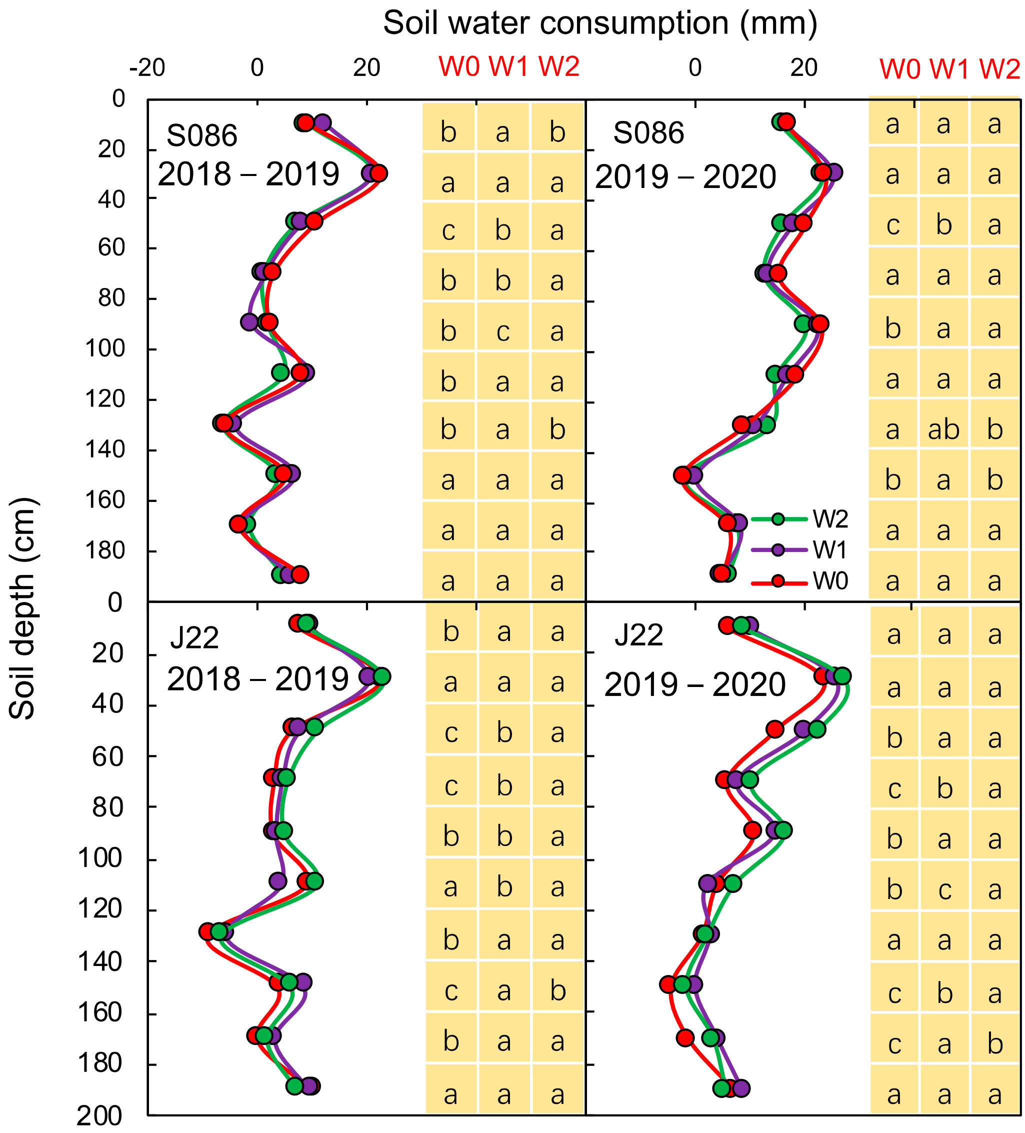

Figure 3. Soil water consumptions under different treatments in 0–200 cm soil layer. Definitions of different irrigation treatments (i.e., W0, W1, and W2) are given in caption of Table 2. The different letters in the same soil layer denote a significant difference in different irrigation treatments by LSD ($p < 0.05$).

3.5. Crop-Water-Use Efficiency

The water-use efficiency (WUE) and irrigation-water-use efficiency (IWUE) were significantly affected by year and irrigation, and their interactions (Table 6). In 2018–2019, the lowest WUE was found in W0 and the lowest IWUE was found in W2, while the highest WUE and IWUE were found in the W1 treatment for both varieties. In 2019–2020, the WUE of W1 was 15.5% ($p < 0.05$) and 9.4% ($p < 0.05$) higher than those in W0 and W2 for J22, respectively. However, the highest IWUE was found in W0, followed by W1 in 2019–2020, which was primarily owing to the higher yield caused by higher rainfall in comparison with that in 2018–2019.

Table 4. Two-way ANOVA of the effects of year, irrigation, and wheat variety on soil water consumption and plant physiological factors 7 days after flowering stage.

Year	Varieties	Irrigation	TWC	SWC	SOD	POD	CAT	MDA	Sugar	Pro
2018–2019	S086	W0	270.1 ± 88.2	67.5 ± 18.3	461.0 ± 1.6	188.4 ± 8.1	141.4 ± 6.1	20.9 ± 2.5	30.3 ± 2.3	289.5 ± 12.0
		W1	329.8 ± 76.5	52.2 ± 9.9	514.9 ± 12.6	202.0 ± 11.3	160.8 ± 10.1	16.1 ± 2.7	25.0 ± 0.5	259.8 ± 16.2
		W2	384.9 ± 45.2	32.3 ± 7.8	540.7 ± 15.3	225.3 ± 10.3	178.5 ± 2.3	14.7 ± 2.2	23.0 ± 0.5	238.3 ± 15.4
	J22	W0	263.7 ± 21.2	61.1 ± 1.2	473.9 ± 24.3	168.7 ± 5.5	150.0 ± 8.4	17.1 ± 2.1	34.9 ± 1.0	309.6 ± 10.6
		W1	321.3 ± 40.6	43.7 ± 3.9	553.0 ± 22.8	195.7 ± 16.9	176.3 ± 8.1	14.9 ± 1.4	31.3 ± 0.5	261.3 ± 8.4
		W2	383.1 ± 77.5	30.5 ± 11.5	573.5 ± 28.9	218.6 ± 12.4	183.7 ± 5.9	12.9 ± 1.6	28.3 ± 0.0	231.5 ± 4.2
2019–2020	S086	W0	389.6 ± 32.5	165.9 ± 6.1	485.6 ± 6.9	184.3 ± 8.1	125.3 ± 6.9	19.4 ± 1.0	32.0 ± 0.3	229.5 ± 10.6
		W1	448.6 ± 67.9	149.9 ± 13.1	540.3 ± 9.6	216.1 ± 11.3	144.0 ± 9.6	18.1 ± 0.1	26.5 ± 0.1	199.8 ± 11.3
		W2	482.4 ± 78.6	108.7 ± 10.8	563.1 ± 1.0	230.7 ± 10.3	150.0 ± 1.0	14.1 ± 1.2	24.3 ± 0.2	183.3 ± 15.5
	J22	W0	385.3 ± 22.5	161.6 ± 3.2	457.4 ± 8.8	188.1 ± 5.5	118.0 ± 8.8	15.0 ± 0.2	32.6 ± 0.2	229.6 ± 10.2
		W1	413.5 ± 55.2	114.8 ± 4.4	557.6 ± 7.9	206.8 ± 16.9	134.7 ± 7.9	16.8 ± 0.2	28.8 ± 0.3	193.3 ± 11.0
		W2	455.5 ± 49.3	81.8 ± 7.8	580.0 ± 9.5	228.1 ± 12.4	148.7 ± 9.5	22.5 ± 0.0	24.3 ± 0.3	171.5 ± 12.0
ANOVA p value										
Year (Y)			***	***	NS	*	NS	NS	NS	*
Variety (V)			NS	***	NS	NS	NS	NS	NS	NS
Irrigation (I)			***	***	NS	*	NS	NS	NS	NS
Y × V			NS	**	NS	NS	NS	NS	NS	NS
Y × I			NS	***	NS	NS	NS	NS	NS	NS
V × I			NS	NS	NS	NS	NS	NS	NS	NS
Y × V × I			NS	NS	NS	NS	NS	NS	NS	NS

Note: SWC, soil-water-holding consumption; TWC, total water consumption. SOD, superoxide dismutase; POD, peroxidase; CAT, catalase; MDA, malondialdehyde content; SS, soluble sugar content; Pro, proline content. *, **, and *** represent the 0.05, 0.01, and 0.001 significance levels, respectively. NS means no significant effect.

Table 5. Wheat yield and related factors under different irrigation treatments.

Year	Varieties	Irrigation	Spike (×10^4 ha^{-1})	Grains per Spike	Weight (1000-Grain) /g	Yield /kg ha^{-1}
2018–2019	S086	W0	331.95 b	26.33 b	36.68 b	3106.9 ± 212.7 d
		W1	632.41 a	33.00 a	40.79 a	7803.3 ± 413.3 a
		W2	552.75 a	33.67 a	39.57 a	8198.6 ± 178.3 a
	J22	W0	391.35 b	27.67 b	34.85 a	3512.9 ± 228.7 d
		W1	687.31 a	33.67 a	35.70 a	7773.7 ± 801.7 ab
		W2	719.70 a	32.00 a	34.69 a	8110.6 ± 85.0 a
2019–2020	S086	W0	527.67 a	30.61 b	49.28 a	6536.4 ± 206.7 bc
		W1	612.03 a	32.17 a	50.33 a	8182.3 ± 311.3 a
		W2	646.03 a	32.43 a	50.51 a	8286.0 ± 403.5 a
	J22	W0	567.01 a	29.81 b	48.50 a	6502.0 ± 359.2 c
		W1	598.36 a	34.47 a	49.08 a	8062.5 ± 211.8 a
		W2	601.03 a	35.37 a	48.97 a	8122.3 ± 204.5 a
ANOVA p value						
Year (Y)			**	**	***	***
Variety (V)			**	NS	***	NS
Irrigation (I)			***	***	NS	***
Y × V			***	NS	*	NS
Y × I			***	*	NS	***
V × I			NS	NS	NS	NS
Y × V × I			NS	*	NS	NS

Note: Definitions of different irrigation treatments (i.e., W0, W1, and W2) are given in caption of Table 2. The same letter in the same column denotes no significant difference in different irrigation treatments by LSD ($p < 0.05$) for these two varieties. *, **, and *** represent the 0.05, 0.01, and 0.001 significance levels, respectively. NS means no significant effect.

3.6. Combined Effects of Irrigation and Water Consumption on Grain Yield and Water Productivity

Along with the increase in SWC and TWC, POD increased ($p < 0.05$), but the contents of MDA and SS significantly decreased ($p < 0.05$, Figure 4). In addition, the crop yield was significantly affected by the content of SOD, CAT, and SS of flag leaves and then indirectly affected the WUE and PFP. Irrigation water productivity, such as IWUE, was positively correlated with SWC and TWC ($p < 0.05$). However, irrigation would decrease the consumption of soil water, which indicated that deficit irrigation could be beneficial for the increase in antioxidant activity of crops and water productivity.

Table 6. Crop-water- and N-use efficiency in different irrigation treatments.

Year	Varieties	Treatments	WUE (kg m^3)	IWUE (kg m^3)
2018–2019	S086	W0	1.53 ± 0.10 e	3.45 ± 0.24 d
		W1	2.81 ± 0.15 a	4.73 ± 0.25 bc
		W2	2.33 ± 0.05 bc	3.42 ± 0.07 d
	J22	W0	1.73 ± 0.11 de	3.90 ± 0.25 cd
		W1	2.80 ± 0.29 a	4.71 ± 0.49 bc
		W2	2.30 ± 0.02 bc	3.38 ± 0.04 a
2019–2020	S086	W0	2.92 ± 0.09 a	7.26 ± 0.23 b
		W1	2.74 ± 0.10 ab	4.96 ± 0.19 d
		W2	2.22 ± 0.11 c	3.45 ± 0.17 d
	J22	W0	2.91 ± 0.16 a	7.22 ± 0.40 a
		W1	2.70 ± 0.07 ab	4.89 ± 0.13 b
		W2	2.17 ± 0.05 cd	3.38 ± 0.09 d
ANOVA *p* value				
		Year (Y)	***	***
		Variety (V)	NS	NS
		Irrigation (I)	***	***
		Y × V	NS	NS
		Y × I	***	***
		V × I	NS	NS
		Y × V × I	NS	NS

Note: WUE, water-use efficiency; IWUE, irrigation-water-use efficiency. Definitions of different irrigation treatments (i.e., W0, W1, and W2) are given in caption of Table 2. The same letter in the same column denotes no significant difference in different irrigation treatments by LSD ($p < 0.05$) for these two varieties. *** represents the 0.001 significance levels. NS means no significant effect.

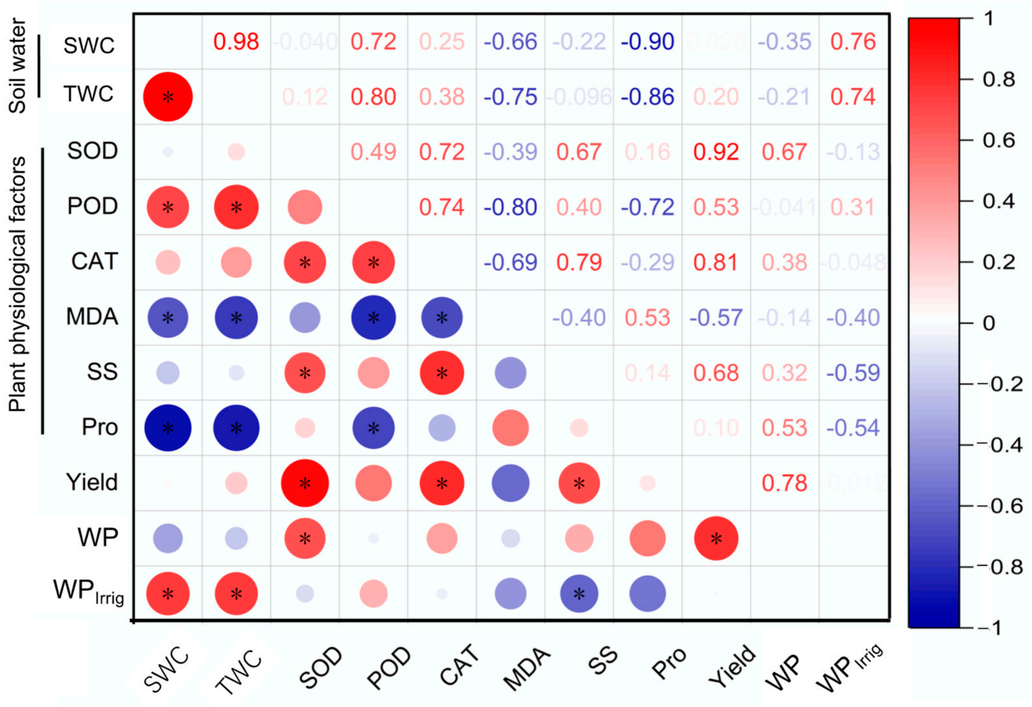

Figure 4. Correlation analysis of physiological factors of flag leaf, yield, and water-use efficiency with soil water consumptions ($p < 0.05$). SWC, soil-water-holding consumption; TWC, total water consumption; SOD, POD, CAT, MDA, SS, and Pro are given in caption of Table 4. * represents the significant correlation at 0.05 levels.

4. Discussion

4.1. Grain Yield and Water-Use Efficiency under Irrigation

Soil water is considered to be the main factor that affects crop yields. Irrigation has a direct impact on soil water content, as well as nutrient availabilities, physiological factors of the flag leaves, and water-use efficiency (Figure 4), which is in line with Ierna and Mauromicale [24].

In semiarid areas, like northern China, water is an important limiting factor in winter wheat yield production [25,26]. Rainfall could effectively supply the demands for crop water and soil water storage, particularly in the winter wheat season. Even though the water required in the winter wheat season still reached up to 200–300 mm [3,27], irrigation was still the main management method to maintain high crop yield production, e.g., the yield of S086 for W0 vs. W1 vs. W2 was 6536 vs. 8182 vs. 8286 kg ha^{-1}, respectively, in 2019–2020 (Table 5), which indicated that irrigation could increase crop yields by as high as 27–164%, and these results have been proven by previous studies [1,2], as Jha, Kumar, and Ines [17] reported that irrigation during dry spells could reduce the wheat yield losses caused by water stress. Additionally, the selection of drought-resistant varieties was also beneficial for irrigation water saving with high crop yield. In this study, the highest yield was found in S086 particularly under one irrigation after the re-greening stage, i.e., W1, owing to the higher drought resistance index in this plant compared to that of J22.

As expected, the grain yield was closely related to spikes, grain numbers per spike, and 1000-grain weight [28–30], as well as superoxide dismutase (SOD) and catalase (CAT) (Figure 4). However, the spikes and grain numbers per spike were highly influenced by irrigation practices ($p < 0.001$; Table 5), which is in line with Xu et al. [31]. As reported, the irrigation 10 days after the jointing stage could decrease the degradation of florets and improve the numbers per spike [32]. Different irrigation methods cause differences in water distribution and nitrogen accumulation, resulting in complex changes in the soil environment, thus altering the environmental responses of plant growth and water-/N-use efficiency [33]. A soil water deficit in the uppermost soil layers during the jointing to anthesis period would seriously decrease the grain numbers and reduce the aboveground biomass at anthesis [31]. The activities of SOD and the contents of malondialdehyde (MDA) and Pro were increased under the water deficit condition, but the activity of CAT was increased after irrigation events, particularly during the 14-day to 21-day period after the flowering stage (Figure S3), which is in line with Mu et al. [34]. Therefore, irrigation contributed to the antioxidant effect of crops in the pre-flowering stage and to nutrient transformations during the later stage of flowering. Moreover, the content of soluble sugar (SS) 14 days after the flowering stage in irrigation treatments contributed to osmoregulation and antioxidant ability in pre-flowering and then to the transformations of nutrients to increase the crop yield during the late-flowering stage (Figure 4), which is consistent with Hui et al. [35]. Above all, irrigation at the stem extension stage (i.e., the jointing stage) of winter wheat is the most effective time to increase grain yield, WUE, plant growth, and photosynthesis [31,32,36].

Compared to W1, the crop yield of W2 (increased one more irrigation event) increased without a significant difference but had a large decrease in the WUE (5.8–12.5%) and IWUE (27.8–30.7%, $p < 0.05$), which is not the appropriate approach to meet future sustainable agriculture [37]. In addition, irrigation was one of the key factors that influence enzymes (i.e., SOD, POD, and CAT) in flag leaves, which were related to the crop-water-use efficiency (Figure 4). Additionally, drought stress is often linked with increases in oxidative stress and decreases in the contents of SS and Pro, which are beneficial to increase the tolerance to drought [38,39]. Our study found that the increase in irrigation amount would improve the content of SOD, POD, CAT, SS, and proline (Pro) but decrease the content of MDA (Figure 4, $p < 0.05$), which might contribute to the resistance to crop oxidation [40]. However, increasing irrigation amount was inversely related to water productivity and use efficiency. Therefore, selections of drought-tolerant varieties were beneficial for the win–win goal of irrigation water reduction and steady yield under drought stress [41]. In our study, when the S086 variety was considered, the reduction in irrigation water amount contributed to the increase in the content of SS and Pro, particularly 0–14 days after the flowering stage ($p < 0.05$, Figures S5 and S6), and then enhanced the ability of drought resistance [40].

As Liu et al. [42] reported, irrigation at 120 mm per wheat season is appropriate for future sustainable wheat production with high-yielding in the irrigation region. Additionally, limited irrigation (like deficit irrigation) could cause changes in the soil dry–wet conditions, which was beneficial to increase the drought resistance of crops (e.g., winter wheat, cotton), and then increase the transformation of plants to protein and increase crop yield and qualities, as well as water-use efficiency [14,43]. Thus, the plant system of S086 combined with W1 (165 mm per wheat season) that was recommended in this region was in accordance with the future agriculture goal.

4.2. Influence of Irrigation on Soil-Water-Holding Consumption

In our study, the crop water consumptions in these two winter wheat varieties were different between these two seasons (Table 3). Typically, after the re-greening stage, the physiological growth rate of winter wheat is fast with the increase in water and nutrients demanded. This is also the key period for plant nutrient transformation and grain formation [44]. Additionally, deficit irrigation could increase the SWC by winter wheat (Figure 2) as well, resulting in the increase in root activities and changes in soil microbial communities with more effective usage of the external water besides irrigation water [45].

Therefore, meeting the water requirement of winter wheat in the jointing–filling stage could be the key practice to ensure the normal growth and maintain the soil water storage, which has also been confirmed by other researchers [32,36]. However, SWC primarily differed in the 0–120 cm soil layer in these different irrigation treatments (Figure 2), which is in line with Zhang et al. [2]. In addition, the depletion of deeper soil water was increased when the irrigation water was reduced (i.e., W0 and W1). The SWC in 2019–2020 was higher than the one in 2018–2019, mainly because of the higher rainfall after winter wheat harvested in June 2019 and during April–May in 2020 (Figure 1). Previous studies have reported that severe drought could promote the growth of roots to extract the water in the deeper soil layers as deep as 160 cm for use, but with the cost of limited growth and lower biomass and crop yield [8].

In our study, for no irrigation after re-greening, i.e., W0, the soil water of S086 was higher than that of J22. When irrigated after re-greening, i.e., W1 and W2, the water required for crop growth primarily originated from irrigation water (36.8–62.7%) and increased along with the amount of irrigation amount. In addition, the percentage of irrigation amount to the TWC of S086 was lower than that of J22, which indicated that the S086 variety could be recommended in the regions with low irrigation amount inputs due to the high resistance to water stress. Accordingly, the use efficiency of rainfall and soil water decreased gradually and the irrigation water was still the primary process provided for the crop water demands. Also, the seasonal evapotranspiration would be increased when excessive water was irrigated [46,47].

In our study, during these two wheat seasons, we found no significant difference in crop yield, but a significant difference in total water consumption between W1 and W2 was found, indicating that improved irrigation practices (i.e., W1) can be considered suitable and is recommended for future agricultural production, but other optimized practices should be considered [48], for example, reasonably adjusting or reducing the single irrigation amount in combination with rainfall or delaying irrigation at the jointing stage [32], and improving irrigation strategies with drip irrigation [49,50].

Overall, the results of these two-season experiments indicated that the use of variety S086 under W1 treatment can realize high grain yield and water-use efficiency. However, some studies have pointed out that quantitative irrigation cannot fit the real demands of water for plant growth and have suggested that proper deficit irrigation methods should be carefully considered [15]. For example, our study found a significant influence of year on TWC and SWC mainly due to the different rainfalls between these two years (Figure 1), which caused different soil water supplements for plant demands. Accordingly, further studies are still required to evaluate the combination effects of appropriate irrigation water amounts and rainfall on wheat growth and to maintain high yield for future sustainable agriculture as well as the changes in the micro-environment (e.g., rhizosphere environment, microbial communities) [25], and the interactions among plant physiology, root growth, and microbes.

5. Conclusions

The total water consumption (TWC) and soil water consumption (SWC) by winter wheat under different irrigation treatments all increased along with increasing amounts of irrigation water applied. However, the wheat yields for both W1 and W2 were not significantly higher than those of W0 in both 2018–2019 and 2019–2020 seasons; nonetheless, the highest yield was observed in the S086 variety in all irrigation treatments in both seasons. Also, the SWC in the 0–120 cm soil layer was highly related to wheat growth in all the treatments. During the whole growth period, the crop water consumption was primarily focused on the jointing to filling stage, particularly in the jointing–flowering stages (accounting for 38.4–44.3% of total crop water consumption). Additionally, the drought-resistant variety (i.e., S086) was beneficial for the usage of SWC under a lower amount of irrigation water applied. Meanwhile, irrigation after the re-greening stage might highly promote the physiological growth of flag leaves, i.e., superoxide dismutase and catalase, which could have highly affected crop yield production and water-use efficiency. This study recommended the combination usage of variety S086 and W1 to meet the win–win goal of high crop yield and water-use efficiency with low groundwater consumption. However, further studies are still needed to evaluate the combination effects of an appropriate irrigation water amount and rainfall on maintaining high wheat yield and growth for future sustainable agriculture.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su151310503/s1, Figure S1: Superoxide dismutase (SOD) activities of flag leaf under different irrigation treatments. a, S086 in 2018~2019; b, J22 in 2018~2019; c, S086 in 2019~2020; d, J22 in 2019~2020; Figure S2: Peroxidase (POD) activities of flag leaf under different irrigation treatments. a, S086 in 2018~2019; b, J22 in 2018~2019; c, S086 in 2019~2020; d, J22 in 2019~2020; Figure S3: Catalase (CAT) activities of flag leaf under different irrigation treatments. a, S086 in 2018~2019; b, J22 in 2018~2019; c, S086 in 2019~2020; d, J22 in 2019~2020; Figure S4: Malondialdehyde (MDA) activities of flag leaf under different irrigation treatments. a, S086 in 2018~2019; b, J22 in 2018~2019; c, S086 in 2019~2020; d, J22 in 2019~2020; Figure S5: Soluble sugar (SS) activities of flag leaf under different irrigation treatments. a, S086 in 2018~2019; b, J22 in 2018~2019; c, S086 in 2019~2020; d, J22 in 2019~2020; Figure S6: Proline (Pro) activities of flag leaf under different irrigation treatments. a, S086 in 2018~2019; b, J22 in 2018~2019; c, S086 in 2019~2020; d, J22 in 2019~2020.

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