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Effects of Different Soil Moisture-Holding Strategies on Growth Characteristics, Yield and Quality of Winter-Seeded Spring Wheat

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Abstract: Drought during the overwintering period threatens the emergence rate and restricts the yield under the "winter-seeded spring wheat" cultivated model in the Hetao Plain Irrigation District in Inner Mongolia. To address this issue, from 2017 to 2019, six treatments were set up in the field to study the emergence rate, growth attributes, grain quality, yield and its percentage of winter-seeded spring wheat. These treatments were the (1) application of water-retaining agents under winter sowing (WRA), (2) soil amendments under winter sowing (SA) and wheat seed presoaking with amino acid water-soluble fertilizer under winter sowing (SP), (3) straw mulching under winter sowing (SM), (4) film-mulching hole sowing under winter sowing (FMHS), (5) blank control under winter sowing (CKW) and (6) conventional blank control under spring sowing (CKS). The results showed that the emergence rate of winter-seeded treatment was lower than CKS treatment, the emergence of WRA, SA, SM, and FMHS treatment increased by 5.4%, 2.3%, 6.5% and 10.8% compared with CKW treatment, respectively. The winter-seeded treatment is earlier than CKS treatment in the growth process, in which FMHS treatment is between 12 d and 16 d earlier in the emergence period, between 13 d and 15 d earlier in the maturation period, between 8 d and 12 d earlier than the CKW treatment in the emergence period, and between 8 d and 10 d earlier in the maturity period. Compared with CKW treatment, WRA, SA, SM, FMHS and CKS treatments increased yield by 13.49%, 11.42%, 14.75%, 21.61% and 28.15%, respectively. FMHS treatment significantly reduced the total water consumption and significantly improved water use efficiency. The protein content, wet gluten content, sedimentation value, dough ductility and maximum resistance in CKS treatment were significantly lower than other winter sowing treatments. The protein percentage and wet gluten percentage in FMHS treatment were the highest, and the difference with CKW treatment was significant. In summary, film-mulching hole sowing in winter improves soil water and the emergence rate, significantly accelerates the growth process of wheat, increases yield and promotes grain quality.

Keywords: winter-sowing spring wheat; moisture-holding strategies; Hetao irrigation district; yield; soil moisture

Citation: Zhao, Z.; Li, M.; Wu, Q.; Zhang, Y. Effects of Different Soil Moisture-Holding Strategies on Growth Characteristics, Yield and Quality of Winter-Seeded Spring Wheat. *Agronomy* **2022**, *12*, 2746. https://doi.org/10.3390/agronomy12112746

Academic Editor: Shulan Zhang

Received: 25 September 2022
Accepted: 3 November 2022
Published: 5 November 2022

1. Introduction

The Hetao irrigation district is one of the most important regions for spring wheat production in Inner Mongolia, China. The annual sowing area accounts for more than 50% of the total area of local food crops [1]. However, the spring wheat in the region usually suffers from insufficient rainfall and cold stress. Moreover, a remarkable resurgence of air temperature always leads to rapid degradation of frozen soil in early spring, making it difficult to sow the spring wheat in time. There are also problems regarding spikes in the development of spring wheat in the district, including a long seedling stage, a short spike differentiation period and insufficient time for grain filling stage. Moreover, dry-hot wind and heat-forced maturity have been threatening local spring wheat production [2]. Furthermore, there are still more than 2 months of frost-free days after the harvest of spring wheat, thus, the light and heat resources cannot be used efficiently [3].

A "turning the traditional spring sowing into winter sowing" cultivated model has been proven to escape the damage from soil collapse and dry-hot wind during plant development [4]. Winter-seeded wheat matures earlier than spring wheat, which can make full use of the natural resources in the "less than two seasons, more than one season" region in northern China, relieving time constraints for multiple cropping after wheat [5,6]. However, the low soil moisture in spring is a major limiting factor for the emergence rate of winter-seeded wheat [7,8]. The application of water-retaining agents and soil amendments have positive effects on improving soil structure and maintains soil water, gas and heat, finally enhancing the soil water-holding capacity [9–11]. For example, Wu et al. showed that the application of soil amendments reduced field N losses by improving the physical structure of the soil, ultimately increasing the yield of wheat and maize [12]. The application of straw and plastic film mulching greatly inhibits soil water evaporation, which is beneficial to increase the water use efficiency [13–16]. Moreover, soil surface covering management significantly improves the soil temperature of the tillage layer, thereby creating an ideal environment for seed germination, advancing the emergence stage and extending the growing period [17–20]. Consequently, adopting apposite soil moisture-holding measurements is vital for popularizing the "spring wheat winter-sowing" cultivated model, and expanding the multiple cropping index after wheat as well as farmland-use efficiency in the Hetao irrigation district.

At present, most studies concentrated on the effect of different soil moisture conservation on winter wheat and spring wheat, whereas research on the "spring wheat winter-sowing" cultivated model in the traditional spring wheat region in China is still rare. Therefore, it is essential to maintain soil moisture during the overwintering period and improve the cold and drought resistance ability of wheat. The target for this study was to evaluate the impacts of different soil moisture-holding strategies on soil water content, seed germination in next spring, growth process, yield and quality formation of winter seeded wheat. The results will be helpful to the principle and technology of high-yield cultivation of winter-seeded spring wheat in the Hetao irrigation district.

2. Materials and Methods

2.1. Experimental Site

This study was carried out at the Wuyuan Agricultural Technology Extension Center (107°35′ E, 40°30′ N, elevation 1028 m a.s.l.), Bayannaoer City, Inner Mongolia, China, from 2017 to 2019 (location is shown in Figure 1). This area has a typical temperate continental climate. The mean annual air temperature is 8.2 °C, with a maximum of 31.1 °C (July) and a minimum of 17.2 °C (January). Mean annual precipitation is 179 mm (rain and snow). Mean annual pan evaporation is from 1992~2505 mm. The annual sunshine duration is from 3100~3300 h. The frost-free period is from 130~145 d. Rainfall and temperature are shown in Figure 2. All meteorological data comes from the Meteorological Bureau of Bayannaoer City. The soil is clay loam. The initial soil properties at the top 20 cm layer are shown in Table 1. The soil pH was measured with a glass electrode in soil suspensions in distilled water. Soil organic matter was analyzed with H_2SO_4-$K_2Cr_2O_7$ solution. Available N was measured with the alkaline hydrolysis diffusion method. Available P was determined by the 0.5 mol·L^{-1} $NaHCO_3$ extraction-Mo-Sb colorimetric method. Available K was determined by the 0.5 mol·L^{-1} NH_4OAc extraction-flame photometric method.

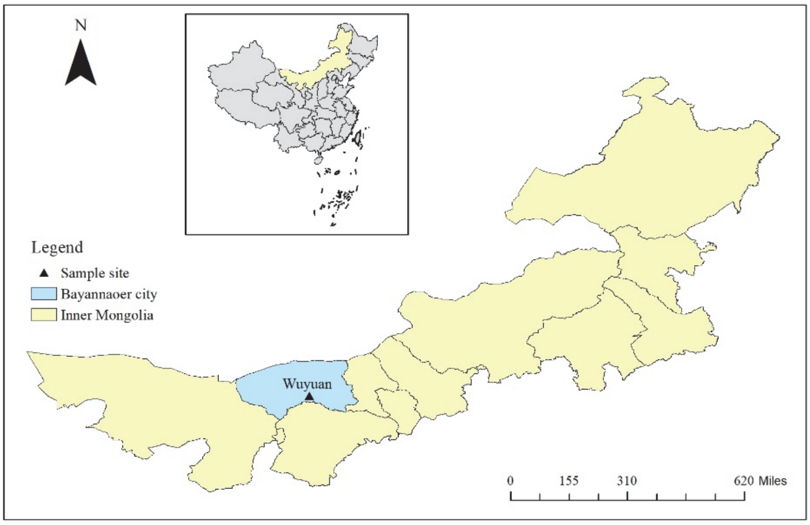

Figure 1. Experimental site.

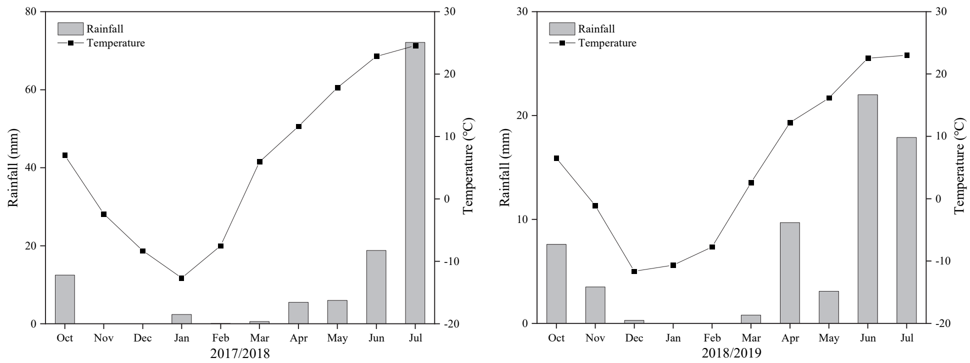

Figure 2. Rainfall and temperature of experimental site. Oct: October; Nov: November; Dec: December; Jan: January; Feb: February; Mar: March; Apr: April; Jun: June; Jul: July.

Table 1. Initial soil properties along with the root zone profile of 0~20 cm layer.

Parameter	2017/2018	2018/2019
pH	7.84	7.81
Organic matter (g·kg^{-1})	22.86	22.79
Available N (mg·kg^{-1})	48.57	48.13
Available P (mg·kg^{-1})	22.94	22.84
Available K (mg·kg^{-1})	121.39	122.01

2.2. Experimental Design

The preceding crop was spring wheat-sowed in winter. The spring wheat cultivar "Yongliang 4" was selected for the present study.

From 2017–2018, five winter sowing treatments were set up as follows: the application of water-retaining agents (WRA, produced by Han Limiao Products Co. Ltd., Beijing, China-PAM), the application of soil amendments (SA, produced by Huaxiang Chemical Co. Ltd., Xuancheng, China-Zeolite), straw mulching (SM, cover thickness approximately 3~5 cm), film mulching hole planting (FMHS, artificial polyethylene film, width: 110 cm, thickness: 0.015 mm) and the blank control under winter sowing (CKW). The PAM and zeolite (45 kg·ha^{-1} application rate) were mixed with soil and then scattered along the furrow before sowing seeds in WRA treatment. The natural air-dry and crushed corn straw (7500 kg·ha^{-1} application rate) were used to cover the surface after sowing seeds in SM treatment. The film was used in FMHS treatment, with sowing holes separated by

10 cm and rows separated by 15 cm. Apart from the above treatment, a traditional spring sowing wheat treatment (CKS) was sown in the respective season. The experiment used a completely randomized block design with three replicates per treatment, with an area of 28 m^2 (4 m × 7 m) for each plot. All winter sowing treatments were sown on 14 November 2017 and spring sowing treatments were sown on 17 March 2018. Apart from FMHS treatment, other treatments were sown by manual strip drilling, with row spacing of 15 cm. The seeding rate for each experiment was 450 $kg \cdot ha^{-1}$. For each treatment, 300 $kg \cdot ha^{-1}$ of diammonium phosphate (P_2O_5: 46%) was basal dressed and 375 $kg \cdot ha^{-1}$ of urea (N: 64.4%) was top dressed at the tillering stage with irrigation. All treatments received four irrigations during the whole wheat growth period, and each irrigation amount was 900 $m^3 \cdot ha^{-1}$.

From 2018–2019, five winter sowing treatments were set up the same as from 2017–2018, except the seeds were soaked by 7500 times VDAL trace element water soluble fertilizer dilution (SP, produced by Zhongjiesifang Biological Technology Co. Ltd., Beijing, China). All winter sowing treatments were sown on 25 November 2018 and spring sowing treatments were sown on 19 March 2019. Apart from FMHS treatment, other treatments were sown by a specific machine, with 15 cm row spacing. The seeding rate, application of fertilizer and irrigation was performed the same as from 2017–2018.

2.3. Emergence Rate Measurement and Growth Process Recording

After 10 d from seedling emergence, the samples were collected from three rows that were 1 m in length, and the number of seedlings was recorded. For FMHS treatment, the number of seedlings of five holes was recorded. The number of seeds and emergence rate was calculated according to seeding rate, 1000-grain weight and row spacing (hole spacing). Each growth stage was recorded according to the standard of that reported.

Emergence rate (%): $ER = \frac{a}{b} \times 100$, where a is the number of seedlings germinated and b is the number of seeds sown.

2.4. Soil Moisture Measurements

Soil moisture (three replicates per plot) at 0~200 cm depths was measured gravimetrically at 20 cm intervals by drying in an oven at 105 °C for 12 h 1 d before sowing and harvest. The soil moisture-related indicators are calculated using the following formula:

Soil water content (%): $w = \frac{a - b}{b} \times 100$, where a is fresh soil weight and b is dry soil weight.

Soil water storage capacity (mm): $W = \frac{Di \times Hi \times wi \times 10}{100}$ where D*i* is the soil bulk density ($g \cdot cm^{-3}$), H*i* is the thickness of soil layer collected (cm) and w*i* is the soil water content (%).

Soil water retention rate (%): $SWRR = \frac{W_2}{W_1}$, where W_1 is the soil water storage capacity at the winter sowing stage and W_2 is the soil water storage capacity at the spring sowing stage.

Evapotranspiration (mm): $ET = P + I + \Delta W$, where P, I and ΔW denote precipitation, irrigation and the difference in soil water storage capacity between the winter sowing stage and mature period, respectively.

Water use efficiency ($kg \cdot hm^{-2} \cdot mm^{-1}$): $WUE = \frac{GY}{ET}$, where GY is the grain yield ($kg \cdot hm^{-2}$).

2.5. Grain Yield and Quality Measurements

The grain yield per 2 m^2 (avoiding border rows) was weighed after drying the grains to a safe storage moisture content (13%), then the total yield per hectare was estimated. Three rows 1 m in length were selected, and the number of spikes, grain per spike and 1000-grain weight were counted and weighed for each plot. The grain quality parameters, including grain protein content (Pro), wet gluten content (WGC), water absorption (WA), sedimentation value (SV), test weight (TW), extensibility area (EA), flour yield (FE), dough malleability (DM) and maximum resistance (MR), was determined by placing the whole air-dried grains directly in a Grain Analyzer (Infratec^{TM} 1241, FOSS, Denmark). The analyzer uses near-infrared transmission technology and full-spectrum scanning using holographic digital grating, which can obtain rich spectral information. The calibration database developed with ANN artificial neural net technology has high analytical accuracy. The instrument was pre-calibrated for various quality indicators reading as the Kjeldahl standard. Then, each whole grain sample was poured into the hopper of the Grain Analyzer to reach the reading cell, which was regulated by sensors located under the conveyor. The quality indicators were manually recorded from the reading screen of the machine.

2.6. Statistical Analyses

All data were analyzed by one-way analysis of variance (ANOVA) to identify differences among the treatment means at a 5% probability level. The statistical analysis and Spearman's rank correlation tests were performed using the SAS 9.0 software package (SAS, USA).

3. Results

3.1. Emergence Rate and Soil Water Retention Rate

From 2017–2018, the emergence rate of the CKS treatment achieved 87.1%, significantly ($p < 0.05$) higher than that of winter sowing treatments (Table 2). Among winter sowing treatments, the emergence rate of the CKW treatment was the lowest, which reached only 58.5%, while the WRA, SA, SM and FMHS treatments increased by 5.4%, 2.0%, 4.5% and 9.8% compared with the CKW treatment, respectively. The soil water retention rate of the FMHS treatment was the highest, followed by the SM and WRA treatments, and these were significantly higher than the CKW treatment. However, there was no significant difference between CKW, SA and CKS treatments. From 2018–2019, compared with winter sowing treatments, the emergence rate of the CKS treatment was equally the highest ($p < 0.05$) at 86.8%. The emergence rate was expressed as FMHS > SM > WRA > SP > CKW for winter sowing treatments. The soil water retention rate of FMHS, WRA, SP and SM treatments was significantly ($p < 0.05$) higher than the CKW treatment, whereas the difference was not significant between the CKW and CKS treatments. Correlation analyses revealed that the soil water retention rate under different soil moisture-holding strategies was significantly ($p < 0.01$) associated with the emergence rate.

Table 2. Emergence rate and soil water storage capacity in soil layer between 0 and 200 cm with different moisture–holding treatments.

Year	Treatment	Soil Water Storage Capacity (mm)		Soil Water Retention Rate (%)	Emergence Rate (%)
		Winter Sowing Stage	Spring Sowing Stage		
2017/2018	WRA	263	227	86.34 ± 0.75 (c)	63.9 ± 0.44 (c)
	SA	266	212	79.82 ± 0.86 (d)	60.5 ± 0.79 (d)
	SM	275	246	89.40 ± 0.70 (b)	62.5 ± 1.56 (c)
	FMHS	274	256	93.31 ± 0.79 (a)	68.3 ± 0.62 (b)
	CKW	277	219	78.98 ± 1.45 (d)	58.5 ± 0.87 (e)
	CKS	272	214	78.69 ± 1.31 (d)	87.1 ± 0.44 (a)
2018/2019	WRA	312	267	85.60 ± 2.55 (c)	64.2 ± 0.44 (d)
	SP	318	269	83.16 ± 2.35 (c)	61.3 ± 0.70 (e)
	SM	317	281	88.74 ± 0.43 (b)	67.2 ± 0.66 (c)
	FMHS	314	290	92.38 ± 0.37 (a)	70.6 ± 1.23 (b)
	CKW	309	240	77.67 ± 0.43 (d)	58.8 ± 0.31 (f)
	CKS	325	255	78.84 ± 1.06 (d)	86.8 ± 0.53 (a)
	R			0.889 **	

Alphabets within columns followed by the same letter are statistically insignificant at the 0.05 level. R indicates the correlation coefficient for the water conservation of soil and the emergence rate of wheat. ** Significant at a $p < 0.01$ level. WRA: applied water-retaining agents; SP: applied soil amendments; SM: straw mulching; FMHS: film mulching; CKW: blank control under winter sowing; CKS: traditional spring wheat; SP: soaked by VDAL.

3.2. Growth Stage

There were some distinct differences in the growth process observed among various treatments (Table 3). The emergence stage and mature stage were 4–12 d and 5–12 d ahead of the CKS treatment, respectively. Among the winter sowing treatments, the results of the second year displayed that the seedling date of the FMHS treatment was the earliest, and the emergence stage and mature stages were 5–8 d and 4–7 d ahead of other winter sowing treatments, respectively. The difference in the growth parameters was not obvious among WRA, SA, SM and SP treatments.

Table 3. The growing process of wheat under different moisture-holding treatments.

Years	Treatment	Growth Stages (Days after Sowing)							Days from Seedling to Harvest
		Emergence Stage	Tillering Stage	Jointing Stage	Heading Stage	Flowering Stage	Filling Stage	Mature Period	
2017/2018	WRA	148	166	181	197	204	216	237	89
	SA	149	165	179	195	202	215	236	87
	SM	149	165	179	195	202	214	236	87
	FMHS	143	159	174	190	197	211	231	88
	CKW	150	167	181	197	204	216	237	87
	CKS	31	47	62	80	87	98	120	89
2018/2019	WRA	143	161	178	191	198	212	231	88
	SP	143	160	177	194	197	211	230	87
	SM	144	161	178	191	198	212	231	87
	FMHS	137	154	169	181	189	202	226	88
	CKW	145	164	180	193	199	213	233	88
	CKS	35	53	69	83	89	103	124	89

WRA: applied water-retaining agents; SP: applied soil amendments; SM: straw mulching; FMHS: film mulching; CKW: blank control under winter sowing; CKS: traditional spring wheat; SP: soaked by VDAL.

3.3. Yield and Yield Components

The analysis of variance indicated notable responses of grain yield and yield components to the different treatments in the 2-year study (Table 4). From 2017–2018, the grain yield and spike number of the CKS treatment were significantly ($p < 0.05$) increased, while the 1000-grain weight and grains per spike were significantly ($p < 0.05$) decreased compared with the winter sowing treatments. Among the winter sowing treatments, the grain yield was highest in the FMHS treatment and lowest in the CKW treatment, ranging from 5165.11 to 4053.31 kg·ha^{-1}. The grain yield of the WRA, SA, SM and FMHS treatments significantly improved by 14.17%, 15.67%, 17.22% and 19.35% compared with the CKW treatment, respectively. The 1000-grain weight of the FMHS treatment was the highest, whereas no significant differences were detected between FMHS and the other winter sowing treatments. The grains per spike were higher ($p < 0.05$) in the FMHS and WRA treatments than in the SA, SM and CKW treatments. Spike numbers ranging from highest to lowest were FMHS > SA > WRA > SM > CKW, with the significant differences between the CKW treatment and the rest of the winter sowing treatments. From 2018–2019, the grain yield, spikes, 1000-grain weight and grains per spike showed a similar trend to the period from 2017–2018 between the CKS treatment and the winter sowing treatments. Among the winter sowing treatments, the grain yield was the highest in the FMHS treatment, followed by the WRA, SM, SP and CKW treatments. The 1000-grain weight of the FMHS treatment was the highest, whereas no significant differences were observed between FMHS and the other winter sowing treatments. The grains per spike of the FMHS treatment were significantly higher than the other winter sowing treatments.

Table 4. Yield and yield components in different moisture-holding treatments.

Year	Treatment	Spikes ($10^4 \cdot ha^{-1}$)	Grains per Spike	1000-Grain Weight (g)	Yield ($kg \cdot ha^{-1}$)
2017/2018	WRA	594 ± 3 (b)	37.3 ± 0.4 (a)	40.40 ± 1.18 (a)	4674 ± 14 (c)
	SA	594 ± 3 (b)	34.9 ± 0.9 (b)	41.90 ± 1.25 (a)	4688 ± 35 (c)
	SM	593 ± 6 (b)	34.1 ± 1.4 (b)	40.78 ± 0.85 (a)	4751 ± 109 (c)
	FMHS	596 ± 3 (b)	36.4 ± 0.5 (a)	42.43 ± 2.02 (a)	4874 ± 4 (b)
	CKW	556 ± 5 (c)	33.6 ± 0.3 (b)	40.17 ± 1.21 (a)	4053 ± 9 (d)
	CKS	655 ± 5 (a)	30.4 ± 0.7 (c)	36.48 ± 1.01 (b)	5054 ± 39 (a)
2018/2019	WRA	494 ± 4 (b)	33.1 ± 1.2 (b)	43.27 ± 0.70 (a)	4739 ± 35 (c)
	SP	491 ± 1 (b)	32.5 ± 0.5 (b)	42.98 ± 0.72 (a)	4502 ± 23 (d)
	SM	496 ± 7 (b)	32.3 ± 0.6 (b)	42.92 ± 0.84 (a)	4716 ± 14 (c)
	FMHS	504 ± 10 (b)	36.9 ± 0.6 (a)	43.45 ± 0.54 (a)	5165 ± 53 (b)
	CKW	412 ± 3 (c)	32.0 ± 0.8 (b)	42.52 ± 0.51 (a)	4200 ± 36 (e)
	CKS	603 ± 10 (a)	29.1 ± 0.4 (c)	36.18 ± 0.66 (b)	5528 ± 35 (a)

Alphabets within columns followed by the same letter are statistically insignificant at the 0.05 level. WRA: applied water-retaining agents; SP: applied soil amendments; SM: straw mulching; FMHS: film mulching; CKW: blank control under winter sowing; CKS: traditional spring wheat; SP: soaked by VDAL.

3.4. Grain Quality

Grain protein %, wet gluten %, sedimentation value, dough malleability and maximum resistance in the CKS treatment were significantly ($p < 0.05$) decreased, whereas no significant differences in water absorption, test weight, extensibility area and flour yield were detected compared with winter sowing treatments (Figure 3). Among the winter sowing treatments, from 2017–2018, the various grain quality traits of the CKW treatment were lower than the WRA, SA, SM and FMHS treatments. The highest value of grain protein %, wet gluten %, dough malleability and maximum resistance was obtained from the FMHS treatment, which was significantly ($p < 0.05$) increased by 8.39%, 6.71%, 5.40% and 16.51%, respectively, compared with the CKW treatment. From 2018–2019, the grain protein % and wet gluten % in the CKW treatment was significantly decreased ($p < 0.05$), compared with other winter sowing treatments. The WRA, SP, SM and FMHS treatment significantly ($p < 0.05$) improved by 4.88%, 8.94%, 8.13% and 9.76% for the grain protein % by 8.57%, 12.24%, 11.43% and 12.65% for the wet gluten %, respectively. The dough malleability and maximum resistance was highest in the FMHS treatment, which were significantly ($p < 0.05$) improved by 5.48% and 8.02% compared with the CKW treatment, respectively. There were no significant differences in sedimentation value among various treatments.

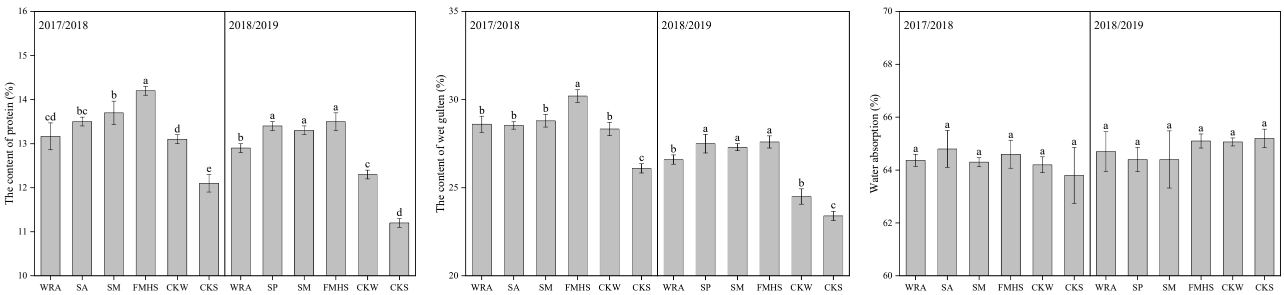

Figure 3. *Cont.*

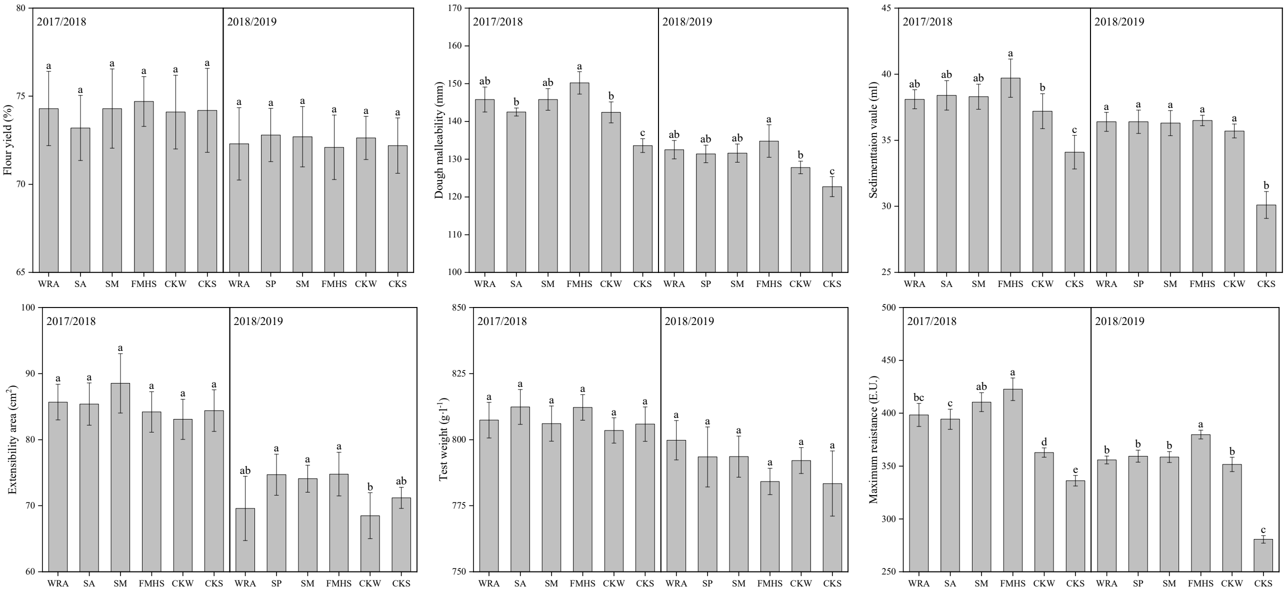

Figure 3. Wheat grain quality with different moisture-holding treatments. WRA: applied water-retaining agents; SP: applied soil amendments; SM: straw mulching; FMHS: film mulching; CKW: blank control under winter sowing; CKS: traditional spring wheat; SP: soaked by VDAL. Different letters (a–e) indicate significant differences among different treatments (p < 0.05).

3.5. Water Use Efficiency

Two-year results showed that the total water consumption in the CKS treatment was higher than that in the FMHS treatment, and slight differences were detected compared with the other winter sowing treatments (Figure 4). The water use efficiency (WUE) was significantly lower in the CKS treatment than the FMHS treatment, but higher than other winter sowing treatments. Among the winter sowing treatments, the total water consumption in WRA, SA, SM and FMHS treatments was reduced by 5.55%, 1.80%, 3.66% and 13.20%, and the WUE was significantly improved by 20.15%, 17.85%, 21.65% and 38.61% compared with the CKW treatment from 2017–2018, respectively. The lowest total water consumption was obtained from the FMHS treatment and the highest from the CKW treatment. The WUE in the FMHS treatment was significantly (p < 0.05) increased, followed by the WRA, SM and SP treatments.

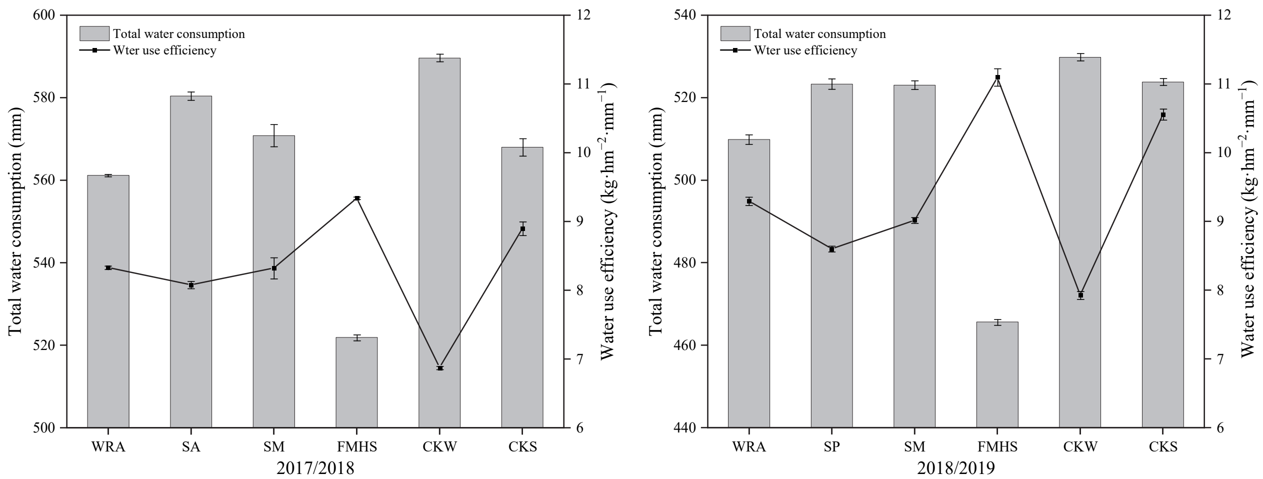

Figure 4. Total water consumption and water use efficiency of wheat under different moisture-holding treatments. WRA: applied water-retaining agents; SP: applied soil amendments; SM: straw mulching; FMHS: film mulching; CKW: blank control under winter sowing; CKS: traditional spring wheat; SP: soaked by VDAL.

4. Discussion

The winter sowing of wheat is susceptible to drought during the overwintering and germination stages in spring, resulting in a prolonged seedling emergence period or loss of activity directly, which affects the field seedling emergence rate, the subsequent population growth and development, as well as the final yield [21]. For achieving a high yield, appropriate measures of soil moisture-holding and temperature maintenance adopted to regulate the soil moisture content during the overwintering period has been an important breakthrough. The results of this study indicated that the emergence rate of the winter-sowing wheat is from 68.3~70.6%, which is an improvement compared with previous studies in the Hetao irrigation area by our team [22]. In addition, a significantly positive correlation with soil moisture retention was identified, which further verified that soil moisture in the following spring is the major limiting factor for the emergence rate with winter-sowing wheat [3]. Previous studies have shown that the application of straw and plastic film mulching can effectively inhibit soil moisture evaporation by cutting off soil-air contact, and the application of water-retaining agents significantly stored water in the soil plowing layer, enhancing the conservation of the soil water content [23,24]. In the present study, we found that the application of straw, plastic film mulching and water retaining agent (PAM) significantly enhanced the seedling emergence rate by improving the soil water retention rate during the overwintering period compared with conventional winter sowing. Drought damage directly leads to seed deactivation when winter-sowing seeds over winter in the form of dormancy. However, less snow in winter and strong wind in spring lead to poor soil moisture in early spring in the Hetao irrigation district. The adoption of surface cover measures can effectively block the contact between soil and atmospheric environmental variables to avoid evaporation so that the soil water and temperature conditions are relatively stable, which can help seeds resist to winter and spring drought, frost and other adverse effects thereby providing favorable conditions for seed germination. This may be the reason for the improvement in the seedling emergence rate.

Numerous studies have revealed that sowing wheat in winter has the advantages of early emergence and early maturation. Wang et al. [25] reported that the growth period of winter-sowing wheat was 13 d longer and 9 d earlier than that of traditional spring-sowing wheat. This study showed that the emergence stage and mature stage of winter-sowing wheat is earlier than spring-sowing wheat. This may be attributed to the sufficient use of the early spring temperature accumulation promoting the early germination of seeds and growth, which eventually accelerated grain maturity. Moreover, this study also found that the seedling stage of the film mulching treatment was approximately 8 d earlier than that of the conventional winter sowing treatment. It can be explained by the improvement in soil moisture and temperature conditions of the film mulching treatment, which promotes the early development of the seed germ and radicle, changing the seed overwintering state. However, the conventional winter sowing of wheat seeds did not show imbibition, resulting in late emergence. Generally, spring wheat harvest time in the Hetao irrigation district is from 15 to 25 July, with between 70 and 80 d available for plant growth after wheat harvest. Very few crops can fully mature due to the limitations of effective accumulated temperature. Changing planting patterns from sowing in spring to sowing in winter can advance the wheat harvest to early July, which makes it possible for multiple crops to fully mature. Based on the results, the establishment of a "spring-wheat winter-sowing" double cropping pattern to further improve annual crop yields and economic benefits still needs further investigation.

The formation of high crop production is affected by the compensatory and coordination mechanism of grain yield components [26]. High production of traditional spring-sowing wheat is mainly achieved by obtaining more spikes. However, the spikes of winter-sowing wheat were significantly reduced because of lower numbers of basic seedling density [27]. There are inconsistent results on the effect of winter-sowing on wheat grain yield. The research of Xue et al. [28] showed that wheat sowing in winter significantly reduces the number of basic seedings, resulting in a decrease in the number of spikes and a reduction in yield. The studies by Dong et al. [3] showed that, although wheat sowing in winter reduced the number of basic seedlings, the number of tillers increased, which made its yield level the same as sowing the wheat in spring. Our study showed that the yield of winter-sowing treatments was significantly lower than spring-sowing treatments due to a reduced number of spikes, which contrasts with the result of Dong et al. This may be due to more precipitation improving tillering ability. Spring wheat in the Hetao irrigation area has a higher temperature at the grain filling and maturity stage, named "dry-hot wind", which is one of the main factors restricting the increase in spring wheat production in the area. In the present study, we found that the grain number per spike and 1000-grains weight were significantly higher than the spring sowing treatment, this may be attributed to escaping the damage of the dry-hot wind and high temperatures, providing suitable environmental conditions for spike differentiation and grain filling and achieving the expansion of the individual wheat grain sink. Similarly, the result was demonstrated by previous studies of Zou et al. and Yuan et al. [5,6]. Analysis of wheat yield components showed that the increase in grain number per spike and grain weight compensated for the reduction in grain yield caused by the decrease in the number spikes, but the compensation effect was limited, which is consistent with previous reports [28]. Consequently, if the winter-wheat spike number was guaranteed, this would be worth exploring concerning wheat production potential. Our study also found that the film mulching treatment was the best compared with other winter sowing wheat treatments regarding the number of spikes, 1000-grain weight and grain number per spike. This related to the improvement of the soil environment and soil organic matter mineralization under the film mulching condition, which promoted development of the wheat root, stem and leaf. In addition, higher basic seedling numbers ensures higher spike numbers under the film mulching treatment, which is one of reasons for its high yield performance.

The temperature, sunlight and moisture of wheat from flowering to maturity were mainly environmental factors that affected the formation of grain quality [29]. The result of this study showed that the grain protein content, wet gluten content, sedimentation value, dough malleability and maximum resistance of winter sowing treatments was higher than the spring sowing treatments, and the differences of other grain quality indices were not significant. However, a previous study showed that the grain protein content and wet gluten content were significantly decreased compared with traditional spring wheat in extremely late winter-sowing wheat [25]. The results being inconsistent with ours may be attributable to the different temperatures of winter-sowing wheat at the grain filling stage in different regions. In addition, the grain protein content and wet gluten content in film mulching improved compared with other winter sowing treatments, which is related to soil water maintenance and relieved damage by high temperatures on protein synthase.

Previous studies have revealed that soil evapotranspiration and plant leaf transpiration accounted for 50% of the total water consumption during the whole growth period of wheat. Plastic film mulching can effectively inhibit soil moisture evaporation, improve the transpiration/evaporation ratio and increase the difference in the soil heat gradient, which led to the deep soil moisture moving upward and gathering in the upper layer, finally forming the "moisture-holding effect of water lifting up" [30,31]. Our study showed that the water consumption of winter wheat with film mulching decreased by 16.7% and 16.5% compared with the conventional winter sowing and traditional spring sowing treatment, and the water use efficiency increased by 46.1% and 13.6%, respectively.

5. Conclusions

The winter sowing of wheat in the Hetao irrigation district using film mulching can achieve the best performance. It can overcome the limitation of the overwintering emergence rate to a certain extent and produce larger spikes with more and heavier grains that are of higher quality; therefore, this can be treated as one direction for the further development of local wheat production on the condition that the number of spikes is guaranteed not to decrease. However, a mechanical wheat seed planter should be designed to solve the disadvantages of the film mulching strategy, such as being time-consuming and needing high labor power. Additionally, a lower spike number remains the biggest bottleneck for yield increase in winter-sown wheat. Our future research aims to further improve the basic seedling numbers of sowing wheat in winter by adjusting the sowing rate, sowing date, sowing depth and amount of fertilizer applied based on the film mulching. We believe that when the emergence rate is parallel to that of the traditional sowing of wheat in spring, the winter-sowing wheat yield increase effect will have a positive effect on the innovation of wheat cropping systems in the spring wheat-producing region of northern China.

Author Contributions: Conceptualization, Z.Z. and Y.Z.; methodology, Z.Z.; software, Q.W.; validation, Z.Z., M.L. and Y.Z.; formal analysis, Z.Z.; investigation, Z.Z.; resources, Z.Z.; data curation, Z.Z.; writing—original draft preparation, Z.Z.; writing—review and editing, Y.Z.; visualization, Y.Z.; supervision, Y.Z.; project administration, Y.Z.; funding acquisition, Y.Z. 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 "Research on ecological and physiological mechanisms and matching cultivation techniques of high yield and high efficiency winter planted spring wheat in Hetao irrigation district in Inner Mongolia" (31560365) and Inner Mongolia science and Technology program project "Research on high quality and high yield physiological mechanism and tuning technology of water-saving wheat in the Hetao irrigation area (2019GG236)".

Acknowledgments: We thank Li-guo Jia for his helpful suggestions regarding this manuscript. We also truly appreciate the assistance from the Wuyuan Agricultural Technology Extension Center at Bayannaoer, Inner Mongolia, China.

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

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