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Effect of Border Width and Micro-Sprinkling Hose Irrigation on Soil Moisture Distribution and Irrigation Quality for Wheat Crops

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Abstract: Micro-sprinkling irrigation is a small-flow irrigation technology that uses the grouped outlets on the micro-sprinkling hoses to spray the pressure water evenly in the field. Plants' barriers during the middle to late growth period of winter wheat significantly reduce the irrigation quality of the micro-spray system. It is still unclear whether soil border width in wheat fields can alleviate the negative effect. In this study, a popularly-used variety (c.v. ZM 369) was adopted to test the mitigation effect of soil borders on irrigation quality, as well as soil moisture distribution, in wheat fields. Two irrigation quotas (i.e., 75 mm and 45 mm per time) and three border widths (i.e., 2.3 m, 3.3 m, and 5.3 m) were arranged in a randomized block design in the experimental years of 2020–2022. Soil moisture distribution and irrigation quality during the middle to late growth period of winter wheat (i.e., jointing to heading stage and grain filling stage) were investigated, as well as the effects on grain yield and water use efficiency (WUE). The results showed that irrigation water distribution in the direction perpendicular to micro-spray tapes generally decreased with the distance from tapes increasing. The maximum difference between the irrigation amount and water collected under the canopy was 134 mm. The uniformity coefficient of soil moisture distribution was increased by 25.8% with a 5.3 m border width compared to a 2.3 m width. Although an irrigation quota of 75 mm was beneficial for ensuring better irrigation uniformity and more stable grain yield, grain yield and WUE were produced with an irrigation quota of 45 mm. In conclusion, it is appropriate to increase border width and adopt a small quota for the micro-spray system in the North China Plain for wheat crops.

Keywords: uniformity coefficient; canopy interception; water saving; water use efficiency

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1. Introduction

Micro-spray irrigation is a widely used irrigation method developed after sprinkling and drip irrigation [1]. With the increase of the nation's investment in civil projects and the reduction in the cost of sprinkler irrigation equipment and tapes, micro-sprinkling hose irrigation has been favored by local farmers in recent years, especially in the well-irrigated area of the North China Plain (NCP). More and more farmers are willing to accept the field water-saving technique upgrade and transformation due to soaring labor costs. Micro-sprinkling hose irrigation has the unique advantage of reducing labor and input costs. The irrigation system uses low-pressure to deliver water to micro-spray emitters through water pipes and tapes and adopts grouped multiple holes to emit water to soils, which markedly saves electricity costs in irrigation. The technique breaks the limitation that a large irrigation quota is essential for traditional flood irrigation to guarantee good irrigation uniformity, whereas micro-sprinkling hose irrigation can achieve a higher uniformity at the expense of a small irrigation quota [2]. Moreover, the low-pressure technique of the irrigation system saves water resources and labor costs. The irrigation system is also conducive to the integration of water and fertilizer [3].

At present, micro-sprinkling hose irrigation for cereal crops mostly refers to the conventional spray irrigation system. It had the traits of "frequent irrigation with small quota." On the contrary, traditional flood irrigation had the characteristic of "less irrigation with a large amount." Nevertheless, in some areas, improper irrigation regimes and schedules of the micro-sprinkling hose irrigation system often occur, regardless of the implementation of the advanced irrigation system. That is, some of the farmers still adopted traditional irrigation regimes and schedules with "larger water amount and lower irrigation times" for the micro-spray system, resulting in a reduction in grain yield and farmers' benefits [4]. Of course, there are still some problems to be solved in the use of micro-sprinkling hose irrigation. For example, the irrigation quality was greatly affected by wind during irrigation, and the thin and soft micro-sprinkling hose was very easy to twist and fold after irrigation. Therefore, windless or breezy weather was often selected for irrigation, and the sprinkler belt didn't roll up until the end of the growth period after irrigation. In a word, how to develop a scientific and reasonable micro-sprinkling hose irrigation system based on local conditions to achieve the dual goals of water saving and yield increasing has attracted more and more scholars' attention.

Applying the micro-spraying system to irrigate winter wheat crops during the growth period can better solve the problems existing in traditional flooding irrigation and is conducive to increasing grain yield and WUE [5–9]. When the planned irrigation quota is determined, the tape length and working pressure can be reasonably selected according to the hydraulic performance of a micro-spraying system, such as the longitudinal slope of the field, micro terrain, soil permeability, and other factors as well [10–13]. The spraying width of micro-spraying tapes is closely related to the tape length and working pressure, which largely determines the field layout spacing of the micro-spraying tapes. Under the condition that the tape length and working pressure are already known, a larger field spacing is more beneficial to give a full display of the advantages of rapid supplementary irrigation of the micro-spray system. However, its irrigation quality and uniformity are often difficult to be effectively guaranteed. In addition, the plant barriers during the middle to late stages of wheat crops significantly reduced the spraying width and seriously affected the irrigation uniformity of the micro-spraying system [14,15]. Under the condition of traditional flood irrigation, border establishment is necessary to guarantee better irrigation quality [16,17]. It was found that reasonable field specifications, leveling land and optimizing irrigation methods could effectively reduce the waste of irrigation water resources and improve the efficiency of irrigation water [18]. However, there have not been final conclusions on whether it is necessary to build borders for a micro-sprinkling hose irrigation system so far. Our study first combined the border building with micro-sprinkling hose irrigation to test the potential positive effect of border width on irrigation quality. We hypothesized that soil moisture distribution in wheat fields could be improved with micro-sprinkling hose irrigation integrated with border planting. The objective of the study is to investigate the mechanism of border planting and irrigation quota improving soil moisture distribution, increasing irrigation quality, and boosting grain yields and WUE. The experimental results can provide a theoretical reference for designing a scientific and reasonable micro-sprinkling hose irrigation system for winter wheat crops in the NCP.

2. Materials and Methods

2.1. Site Description

Field experiments were conducted at Xuchang Irrigation Experiment Station, the North China Plain, during the growing seasons of winter wheat in two consecutive years of 2020–2021 and 2021–2022 (34°08′ N, 113°59′ E, a.s.l. 85 m). The place has a continent-temperate monsoon climate. Mean annual precipitation is 701.1 mm, with only 35% of annual precipitation falling in the wheat-growing seasons. The mean annual temperature is 14.7 °C, the frost-free period is 216.4 d, and the annual sunshine hours are 2183 h. The soil is a fluvo-aquic soil with a granular structure, which has silt loam soil in 0–100 cm and sandy loam soil in 100–200 cm. The specific soil structure at different depths is shown in Table 1. Field capacity and soil bulk density in the 0–100 cm soil layer is 25.4% and 1.53 g cm^{-3}. The water table is detected 10–15 m below the soil surface, which is measured by an ultrasonic electronic water level meter.

Table 1. Soil physical properties at the Xuchang experiment station before the field experiment started in 2020.

Soil Layers (cm)	Sand (>0.05 mm) (%)	Silt (0.002–0.05 mm) (%)	Clay (<0.002 mm) (%)	Soil Texture
0–30	42	36	22	Silt loam
30–60	37	39	24	Silt loam
60–100	39	41	20	Silt loam
100–150	53	32	15	Sandy loam
150–200	68	22	10	Sandy loam

2.2. Experimental Design

The field experiments included two sections: (II) a border width experiment in the 2020–2021 season and (II) a soil moisture distribution experiment in the 2021–2022 season. A commonly used variety, ZM 369, was adopted as the experimental material. The previous crop was summer maize in a double-cropping system, where winter wheat was planted after a 2 week fallow period for soil preparations. The row spacing of wheat plants was 18 cm, and the planting rate was 187.5 kg ha^{-1}. The irrigation system was composed of five parts: water sources, head of the irrigation project, water transmission pipelines and pipe fittings, water-metering and observation equipment, and micro-spray tapes and emitters. The type of micro-spray tapes was specific ones designed for wheat plants, characterized by the arrangement of inclined 9 holes on tapes, a folded diameter of 100 mm, a diameter of 63 mm, and a working pressure of 0.2 MPa. To minimize the impact of natural wind, a wind barrier (a double-layer black shading net) with a height of 1.5 m was built in advance around the experimental areas. The irrigation water source was from well water with salinity not exceeding 1.5 g/L, and the irrigation water volume was monitored by a water meter. According to THE Regulations on the Prevention and Control of Crop Diseases and Insect Pests, Decree No. 725 of The State Council of the People's Republic of China, and the suggestions of the local government, the weeds and pests in the community should be controlled.

Wheat seeds in the border width experiment were sown on 20 October 2020 and harvested on 1 June 2021, with a growth period of 224 d. Irrigation quota was set as main plots while border width was set as subplots. All treatments were arranged in a randomized block design with three replicates. Two irrigation quota levels (45 mm, and 75 mm) and three border widths (2.3 m, 3.3 m, and 5.3 m, including border ridge 0.3 m) were set, giving rise to a total of 18 treatments(3 reps × 2 quota levels × 3 border widths). Each plot was 60 m long, while the plot width was equal to the designed border widths for each treatment. Sidewalks were set between the main and sub-blocks. The jointing, heading, and grain-filling stages of winter wheat are 60% FC and 55% FC (where FC = Field Capacity). When treatments reached the lower limits, irrigation would be carried out on a windless day with planned irrigation quotas. In detail, irrigation events took place on 15 April and 9 May 2021, respectively, for the two irrigation levels of 45 mm and 75 mm for the border width experiment (Table 2).

Table 2. First-year boundary test design scheme.

Treatments	Border Width (m)	Irrigation Quota (mm)	Water Pressure (MPa)	Single Irrigation Water (mm)	Irrigation Time (h)
G1Q2	2.3	75	0.05–0.06	83	0.67
G1Q3	3.3	75	0.06–0.08	79	0.85
G1Q5	5.3	75	0.1	85	1.9
G2Q2	2.3	45	0.05–0.06	47	0.35
G2Q3	3.3	45	0.06–0.08	54	0.60
G2Q5	5.3	45	0.1	48	0.68

During the second experimental year of 2021–2022, a soil moisture distribution experiment was conducted to quantify the negative effect of plant barriers on the irrigation quality of a micro-spraying system. The experiment was carried out on the same plots with the same irrigation quota and border width treatments. In detail, wheat seeds were sown on 27 October 2021 and harvested on 28 May 2022, with a growth period of 213 d. In this experiment, sunny days with no wind were selected at the jointing stage (1 April 2022), filling stage (29 April 2022) and maturity stage (20 May 2022), respectively, to implement micro-sprinkling hose irrigation, respectively. Water penetration under crop canopy within the effective spraying width of micro-spraying tapes was measured. Dynamics of soil moisture content 3 d before and after each irrigation event were automatically monitored using soil moisture sensors. Uniformity coefficients of irrigation water distribution and of soil moisture distribution were consequently calculated after measurement. The specific arrangement of the field experiment is shown in Figure 1.

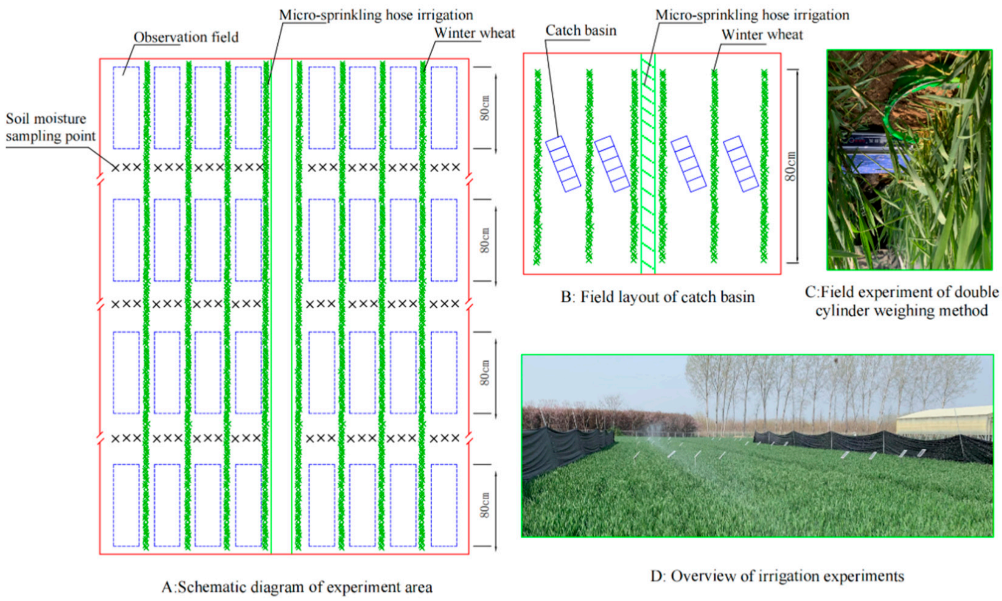

Figure 1. The layout of soil moisture distribution experiment in the second experimental year of 2021–2022.

2.3. Data Collection and Measurements

2.3.1. Soil Moisture Content

Soil moisture content (SMC, $cm^3\ cm^{-3}$) was measured at 10 cm increments to a depth of 100 cm using Insentek soil moisture sensors (Zhejiang Oriental Insentek Technology Co., Ltd., Hangzhou, China). The sensor is a portable wireless sensor based on Frequency Domain Reflectance (FDR), which can realize automatic collection, wireless transmission, portable charging and other functions. The previous study indicated that the Insentek sensor was a reliable tool to represent real SMC values in the field with a root mean square error of 0.927 $cm^3\ cm^{-3}$ between the Insentek sensor and oven-dry method [19]. The oven-drying method was adopted to measure SMC before sowing at 10 cm increments to a depth of 100 cm.

To measure soil moisture distribution, Insentek sensors were installed between rows at the distance of 15 m, 30 m and 45 m from the reference border along the direction of micro-spray tapes. At the same time, soil sampling was also made to measure soil moisture content at similar positions. Moreover, perpendicular to the direction of micro-spray tapes, soil sampling was also made to measure soil moisture content at the distance of 15 m, 30 m and 45 m from the tapes. Soil samples were taken 30 cm away from the Insentek sensors.

2.3.2. Canopy Water Penetration, Irrigation Uniformity and Irrigation Amount

Canopy water penetration was measured using acrylic material flow collecting devices installed at similar positions to Insentek sensors in crop rows under the canopy of the wheat plants [20], which was similar to the commonly used rain gauge method, as shown in Figure 1A. The amount of water in the flow collecting device would be weighed immediately after irrigation and converted into the amount of water per unit area according to the opening area, which was the amount of canopy water infiltration at this point.

Coefficients of irrigation water distribution and of soil moisture distribution were calculated using Christensen's uniformity coefficients [21]. The calculation formula is as follows:

$$C_u = [1 - \frac{\sum_{i=1}^{n} \left| h_i - \overline{h} \right|}{\sum_{i=1}^{n} h_i}] \times 100\% \quad (1)$$

where h_i is the irrigation intensity of the first effective collection tank (mm/h). $\overline{h}$, the water irrigation amount at different positions was determined by a micro-weighing system (Figure 1C). The micro-weighing system consisted of an electronic weighing balance and a double-tube soil column. The precision of the balance was $\pm 10^{-4}$ g. Before irrigation, the undisturbed soil samples attached to wheat plants were loaded into the double tube device in advance, and the inner cylinder and soil samples were weighed. After irrigation, they were taken out immediately and weighed again. The irrigation water amount at this point was determined by the difference between the two weights, and the sampling times were consistent with the irrigation times.

2.3.3. Grain Yield and Water Use Efficiency

In order to study the relationship between irrigation quality and final wheat yield, Collect only at maturity Measure wheat yield, wheat plants from each plot were randomly sampled for the determination of grain yield. Yield measurement sampling areas were set at 15 m, 30 m and 45 m away from the reference border of each plot, and samples were taken at equal intervals along the radial direction of both sides of the micro spraying tapes (4, 6, and 8 samples were taken for 23 m, 33 m and 53 m border width treatments, respectively). After threshing and air drying, the total mass and 1000-grain weight of the samples were determined. Sampled plants in each plot were hand harvested and air dried for 2 wk until constant mass, and then the grain was separated, cleaned, and weighed. Grain yield was calculated on a dry-matter basis (13%) using an electronic balance. Water use efficiency was calculated as the grain yield (in kg ha^{-1}) produced per unit of evapotranspiration. The latter was the sum of soil water at sowing minus soil water at harvest plus the growing season precipitation and irrigation.

2.4. Statistical Analysis

Data were analyzed using an analysis of variance with Statistical Analysis Software (version 19.0, SPSS Inc., Chicago, IL, USA). Significance was declared at the probability level of 0.05 unless otherwise stated. The interactive effect of border widths and irrigation levels was analyzed using ANOVA. The relationships between grain yield, crop evapotranspiration, and water use efficiency of winter wheat were analyzed by means of the

Levenberg-Marquardt Algorithm. Figures were plotted using Original Pro 9.1 (Origin Lab Corporation, Northampton, MA, USA).

3. Results

3.1. Variations in Precipitation, Temperature, and Reference Evapotranspiration

Seasonal precipitation was 131.1 mm and 71.2 mm during the 2020–2021 and 2021–2022 growing seasons of winter wheat, respectively (Figure 2). In the 2020–2021 season, precipitation mainly concentrated during mid-April to early May. For example, rainfall on 20 April and 3 May was 18 mm and 30 mm, respectively, reaching a level of moderate to heavy rain. While during the same period of 2022, the maximum daily rainfall was only 7 mm on 28 April. After the re-greening of winter wheat, daily air temperature rose in a fluctuated way. The average temperature reached its maximum value at maturity, which was 27.5 °C on 1 June 2021, and 26.4 °C on 28 May 2022. Daily reference crop evapotranspiration (ET_0, mm, Penman method) of winter wheat in the growth period of 2020–2021 ranged from 1.23 and 7.19 mm d^{-1}, with the maximum ET_0 occurring on 30 April 2021. The maximum ET_0 value in the 2021–2022 season appeared on 17 May, which was 9.61 mm d^{-1}.

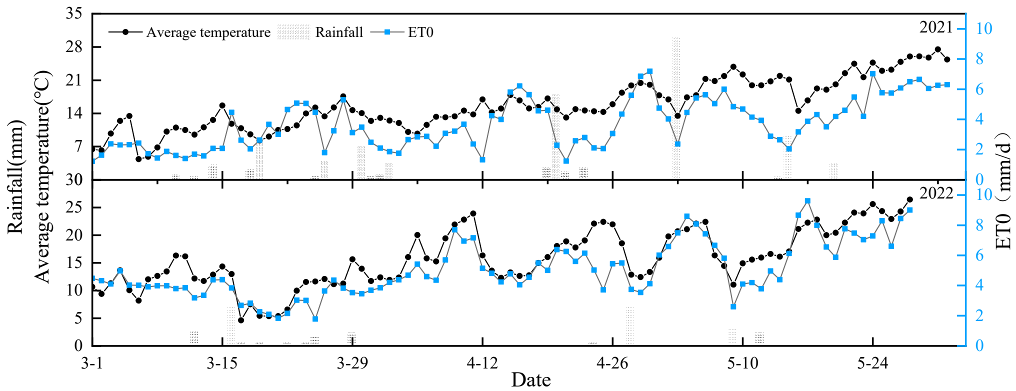

Figure 2. Variations in precipitation, temperature, and reference crop evapotranspiration after winter wheat re-greening.

3.2. Variations in Soil Moisture Content

Before irrigation, soil moisture content (SMC, cm^3 cm^{-3}) decreased at first with soil depth, with the lowest soil water content mainly concentrating in the 40–60 cm soil layers, and then increased with soil depth increasing (Figure 3). After irrigation, SMC dramatically decreased with soil depth in 0–60 cm soil layer and then slightly increased with soil depth increasing. Spatial variation in SMC in 20–60 cm soil layer with 75 mm irrigation quota treatment was significantly larger than that of 45 mm irrigation quota treatment. With the increase of soil depth, SMC in 80–100 cm soil layer basically kept constant regardless of irrigation levels and border widths, implying even the 75 mm irrigation quota might not yield an apparent effect on SMC dynamics in deep layers. With the process of the growth period, soil moisture in 0–80 cm layers was gradually consumed while crop evapotranspiration markedly increased with the air temperature at the filling and maturity stages of wheat plants, accelerating the depletion of soil moisture in the soil profile. It should be noticed that, during the early filling stage of wheat, it might need supplemental irrigation because it was a key stage that impacted the final formation of grain yield.

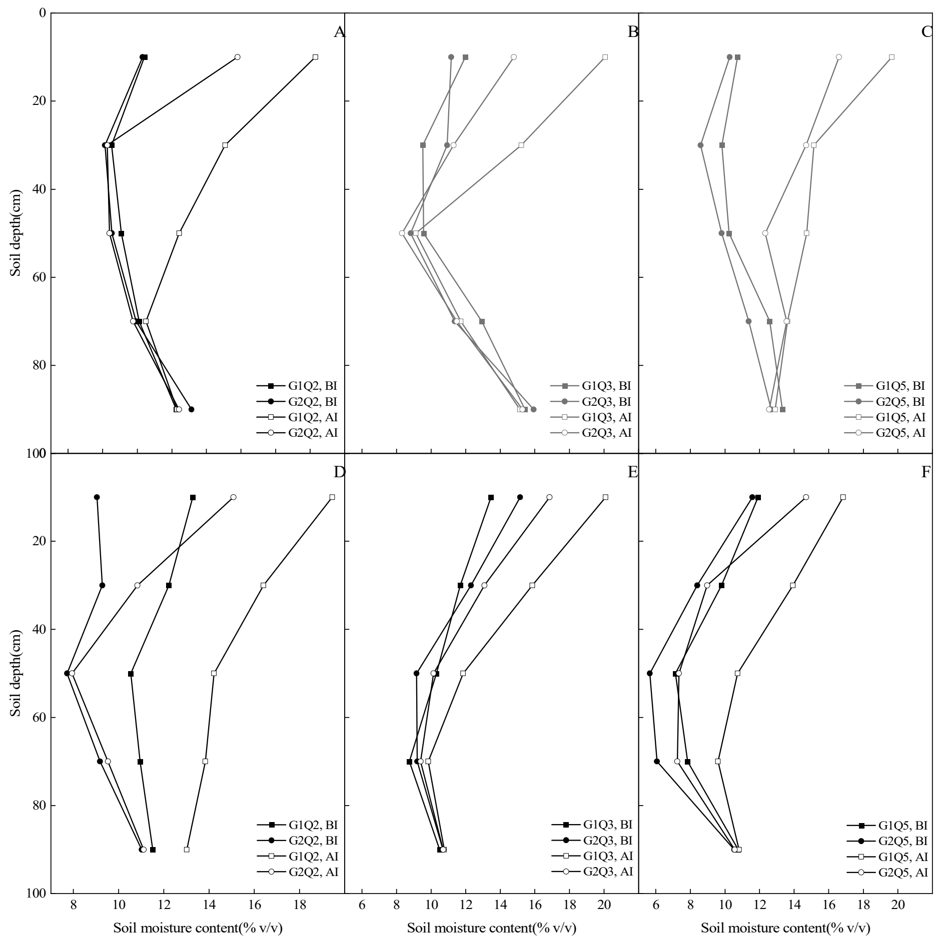

Figure 3. Dynamics of soil moisture content (SMC, $cm^3\ cm^{-3}$) in 0–100 cm soil layers before irrigation (BI) and after irrigation (AI) events at (**A**–**C**) booting stage and (**D**–**F**) filling stage of winter wheat.

3.3. Uniformity Coefficients of Canopy Water Penetration and of Soil Moisture Distribution

Averaged across the two irrigation events during the growing season of 2020–2021, uniformity coefficients of canopy water penetration were 9.7–45.4% and 8.3–42.1%, respectively, for the two irrigation events in April and May (Table 3). Similarly, uniformity coefficients of soil water distribution in the 0–100 cm soil layers were 82.3–95.3% and 53.4–92.9%, respectively. Averaged across the three irrigation events in the growing season of 2021 to 2022, uniformity coefficients of irrigation water distribution, canopy water penetration, and soil moisture distribution were 20.2–43.6%, 17.1–30.8% and 56.9–70.6%, respectively. With the same border width, uniformity coefficients of irrigation water distribution of 75 mm irrigation quota treatments were generally greater than those of 45 mm irrigation quota. The result implied that an increase in the irrigation quota per time was beneficial to the improvement of irrigation quality. Under a low irrigation quota of 45 mm, large variations in irrigation uniformity were observed, which meant that it was difficult to effectively optimize the irrigation quality with micro-sprinkling hose irrigation with a low water quota. However, with the process of the growth period, the uniformity coefficients of irrigation water distribution markedly increased, and the uniformity coefficients of soil water distribution after irrigation remained higher than 56.9%.

Table 3. Uniformity coefficients of canopy water penetration, irrigation water distribution, and soil water distribution for winter wheat in the growing seasons of 2020–2021, and 2021–2022, respectively.

Seasons and Dates		Uniformity Coefficients (%)		
		Canopy Water Penetration	Irrigation Water Distribution	Soil Moisture Distribution
2020–2021	15 April	9.67–45.44	-	82.27–95.27
	9 May	8.27–42.07	-	53.39–92.90
2021–2022	1 April	17.07	20.17	70.55
	29 April	20.29	23.49	56.90
	20 May	30.77	43.64	69.48

3.4. Spatial Distribution of Soil Moisture and Grain Yield

Grain yield and soil moisture distribution at different positions from reference borders were presented in Figures 4 and 5. The range of SMC and grain yield was between 7.03–19.5% and 4495–12,839 kg ha^{-1}, respectively. Average SMC and grain yield near micro-spraying tapes were 10–11.4% and 8004–8139 kg ha^{-1}, respectively, whereas the average values at the 15 m and 45 m distances from the borders were 10.7–11.0% and 7542–8012 kg ha^{-1}, respectively. It was found that SMC near the micro-spraying areas was generally higher at maturity, and grain yield was also greater. The results of correlation analysis showed that the overall consistency between grain yield and soil moisture content was weak (R = −0.241, $p > 0.05$; Figure 6). Correlation between grain yield and border width was also not so good (R = 0.383, $p > 0.05$). However, it showed an increasing trend of grain yield with the increase in border width. Therefore, the appropriate increase of the border width was conducive to grain yield for micro-spraying irrigation.

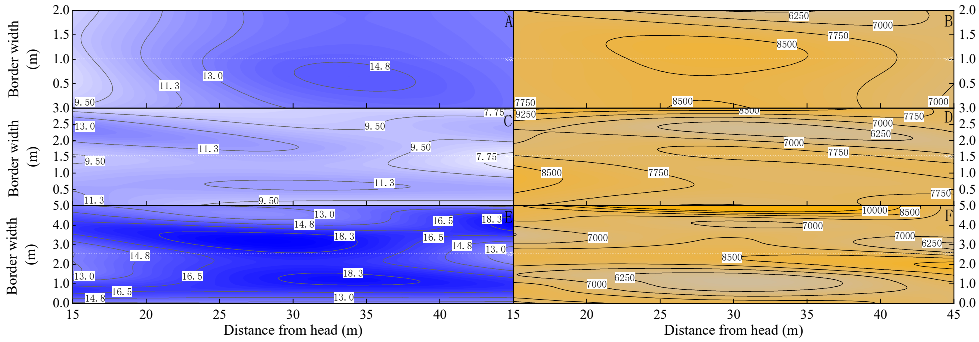

Figure 4. Distribution of soil moisture content (**A**,**C**,**E**) and grain yield (**B**,**D**,**F**) at different positions from the borders with 75 mm irrigation quota.

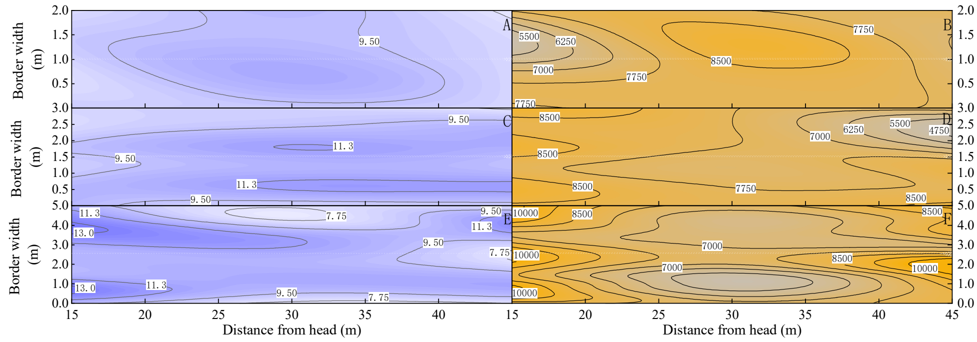

Figure 5. Distribution of soil moisture content (**A**,**C**,**E**) and grain yield (**B**,**D**,**F**) at different positions from the borders with a 45 mm irrigation quota. White lines indicate the positions of micro-spray tapes between borders.

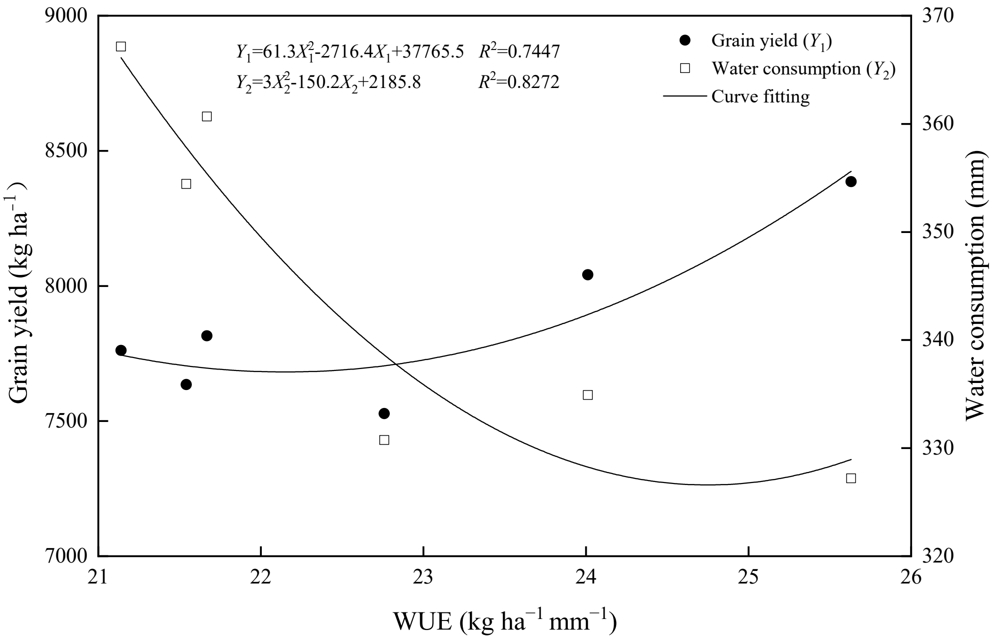

Figure 6. Relationship between grain yield and water use efficiency, and between water consumption and water use efficiency for winter wheat.

3.5. Grain Yield, Water Consumption and Water Use Efficiency

Grain yield, water consumption and water use efficiency (WUE) of winter wheat were 7528–8387 kg ha^{-1}, 327–367 mm and 2.11–2.56 kg m^{-3}, respectively (Table 4). A quadratic function was fitted to the relationship between grain yield and WUE and between water consumption and WUE (Figure 6). Compared with the same border, grain yield with a 75 mm irrigation quota was relatively stable, but total ET_c was high, leading to a lower WUE than that of a 45 mm irrigation quota. When border width increased, the difference in grain yield and ET_c between 45 mm and 75 mm irrigation quota treatments gradually became larger, whereas the difference in WUE was from 0.12 kg m^{-3} (border width 2.3 m) to 0.40 kg m^{-3} (border width 5.3 m). Maximum grain yield and WUE were obtained with a 45 mm irrigation quota. During the growing season of 2020–2021, spike number, ineffective spike number, and grain number per spike were 19.3–19.7, 2.98–3.75 and 28.5–31.5, respectively. Furthermore, it was observed that both the maximum and minimum values of the above-mentioned indicators were observed with the 45 mm irrigation quota treatments, indicating lower irrigation quota induced larger variations in yield components, which was not beneficial for winter wheat to obtain stable yields. The analysis results showed that the water consumption of different border widths was significantly different. There was also a significant difference in water consumption and water use efficiency among different irrigation quotas, respectively. The yield was less affected by border width and irrigation quota, and the difference between treatments was not significant.

Table 4. Yield components, water consumption, and water use efficiency of winter wheat.

Treatments	Spike Number	Grain Number Per Spike	1000-Grain Weight	Grain Yield	Water Consumption	Water Use Efficiency
	($\times 10^4$ ha^{-1})		g	kg ha^{-1}	mm	kg ha^{-1} mm^{-1}
G1Q2	550.0 a	30.0 a	52.6 a	7635.3 a	354.4 b	21.5 b
G1Q3	527.5 a	29.3 a	51.9 a	7761.6 a	367.2 a	21.1 b
G1Q5	535.0 a	29.6 a	52.4 a	7815.5 a	360.7 ab	21.7 ab
G2Q2	510.8 a	31.5 a	51.7 a	7527.6 a	330.7 c	22.8 ab
G2Q3	548.6 a	29.9 a	52.5 a	8041.7 a	334.9 c	24.1 ab
G2Q5	537.0 a	28.5 a	52.1 a	8386.1 a	327.2 c	25.6 a
			ANOVA			
Border width	ns	ns	ns	ns	**	ns
Irrigation quota	ns	ns	ns	ns	**	**
Interaction	ns	ns	**	ns	ns	ns

Note: ns indicates no significant difference between different treatments at the $p > 0.05$ level; ** indicate significant difference between different treatments at the $p < 0.01$ level. Different letters in the same column mean significant difference at $p < 0.05$. No significant interactive effect of border widths and irrigation levels was observed.

4. Discussion

4.1. Irrigation Uniformity Coefficient of Micro-Spraying System

Timely and appropriate supplementation of irrigation water is an effective means to achieve coordinated improvement of crop yields and WUE in water-deficient areas [22–24]. As a low-cost and small-flow irrigation technology in the field, micro-spraying irrigation has great advantages in realizing the high-efficiency and water-saving of pipe irrigation systems. In recent years, the micro-spraying irrigation system has been widely adopted in cereal crops such as wheat and maize in well-irrigated areas of the NCP [25]. With micro-spraying irrigation, SMC in the 0–60 cm soil layers after irrigation decreased with the distance from micro-spray tapes and borders. A similar result was also observed in the literature [26]. In 80–100 cm soil layers, SMC basically kept constant after irrigation events, indicating that the 75 mm irrigation quota did not increase soil percolation in deep layers as expected and was effective in ensuring better irrigation uniformity.

The irrigation uniformity coefficient is an important indicator to reflect irrigation quality and is also one of the important parameters necessary for planning and designing an irrigation system. It was reported that the hydraulic performance of micro-sprinkling hose irrigation system had little impact on irrigation uniformity at different growth stages of wheat [27]. In fact, the effect of plant barriers on irrigation quality during the middle to late growing period was significant, as reflected by the obvious reduction in uniformity coefficients of soil moisture distribution with border widths increasing. Most of the sprayed water was blocked by wheat stems and leaves close to micro-spray tapes, and the amount of water sprayed away from the micro-spray tapes was generally small. A similar result was also observed in the literature [14]. The results of soil moisture distribution also showed that the average proportion of canopy water penetration to total irrigation water was 51.1% (1 April), 85.1% (29 April) and 69.7% (20 May), respectively. Our result indicated that even during the late growing period of wheat, canopy water penetration was still a major way that the irrigation water reached the ground soil surface. Generally, redistribution of SMC after irrigation made soil moisture in wet layers decrease to varying degrees, which helped soil water move from a high water content area to a low area [28].

4.2. Effect of Border Widths on Irrigation Quality, Grain Yield and WUE

The mean annual precipitation (2010–2020) during the growth period of winter wheat was about 150 mm in NCP, and the water deficit during the growth period was about 300 mm [29]. It was necessary to implement multiple supplementary irrigation technology to achieve high and stable grain yield [22]. Border irrigation is one of the most commonly used approaches for local farmers to water wheat plants in the NCP. Optimizing border widths according to different irrigation approaches is the key to ensuring high irrigation quality. At present, the corresponding sowing, tillage, land preparation, and harvest equipment is quite mature in the market. Since 2020, the mechanization rate of crop cultivation and harvesting in China has reached 71%, of which the comprehensive mechanization rate of wheat, rice and corn harvesting has stabilized at 95%, 85% and 90% [30,31]. It is well-known that plant barriers during the middle to late growth period would significantly reduce the effective spraying radius of micro-spraying irrigation. However, it is still unclear whether the irrigation quality of micro-spraying could be improved by optimizing the design of border widths, which was the low cost of human input and high efficiency of land preparation using mechanized equipment [29]. Previous studies on the effect of border widths on irrigation quality pointed out that the irrigation uniformity coefficient with a 4.0 m border width was significantly lower than that of a 3.0 m border width in the NCP [32]. In east areas of NCP, irrigation amount with a 2.0 m border width was proved least, while its grain yield, WUE and irrigation water use efficiency were the highest, achieving the dual goal of both high yield and low water consumption [33,34]. In this study, uniformity coefficients of soil moisture distribution decreased with the increase of border widths, while grain yield increased with border widths. This finding was probably related to a heavy rainfall event in the mid-filling period in 2021, which provided sufficient rainwater for wheat root uptake.

Spike number, grain number per spike and 1000-grain weight are three major components contributing to grain yields. In this study, 45 mm irrigation quota treatments generated grain yields comparable to 60 mm irrigation quota treatments, indicating that wheat plants can produce similar results at less irrigation quota. Further, a similar experiment in the NCP also found that equivalent grain yield was produced between the control treatment (irrigation quota 60 mm) and 30 mm irrigation quota applied after jointing stages of winter wheat [35], implying that irrigation quota producing similar grain yield had the potential to be reduced by 50%, compared to 60 mm quota. In this study, grain yield and WUE are generally the highest with a 5.3 m border width and 45 mm irrigation quota, indicating that the combination of a 5.3 m border and 45 mm quota is most effective in achieving the dual goal of high grain yield and low water consumption of winter wheat for a micro-spraying irrigation system in the North China Plain.

5. Conclusions

The effect of plant barriers on the irrigation quality of micro-sprinkling hose irrigation is noticeable, especially in the middle to late growth period of winter wheat. The uniformity coefficient of irrigation water distribution generally decreased with the distance perpendicular to the micro-spray tapes increasing. Compared with irrigation water distribution, the uniformity coefficient of soil moisture distribution was 25.8% higher after water redistribution due to the leaves and stems of wheat plants' interception, showing a positive effect of water redistribution on the irrigation quality of the micro-spraying system. Grain yield, total ET_c and WUE of winter wheat were within 7528–8387 kg ha^{-1}, 327–367 mm and 2.11–2.56 kg m^{-3}, respectively. With the increase in border widths, grain yield generally increased. Though grain yields of 75 mm irrigation quota treatments were relatively stable, as indicated by its low variations in grain yields among treatments, 45 irrigation quota combined with 5.3 m border width obtained the maximum grain yield and WUE due to better irrigation uniformity and lower ET_c. In conclusion, the combination of a 5.3 m border and 45 mm quota is most effective in maximizing yield output while minimizing labor input for micro-spraying irrigation for winter wheat in the North China Plain.

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