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Effects of water and nitrogen coupling on photosynthetic characteristics and yield of winter wheat in film hole irrigation fields

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A B S T R A C T

Investigating impacts of combined moisture and nitrogen on photosynthetic characteristics and yield of winter wheat by film hole irrigation, this study conducted the planting experiment of winter wheat with film hole irrigation under different irrigation amount so as to study fertilizer amount was studied and the effects of winter wheat plant height, chlorophyll content, rate of photosynthesis, rate of transpiration, stomatal conductance and other photosynthetic characteristics. Analyses of yield and water use efficiency of winter wheat under water and nitrogen interaction were carried out. The reports showed that under film hole irrigation, the plant height of winter wheat initially increased and thereafter decreased with increasing the moisture content, with the plant height of the medium water treatment being significantly higher than that of the other ones, and this trend gradually decreased with the increasing fertilization application, indicating that the variation of water failed to significantly affect plant height under high fertilizer level ($P > 0.01$); the increase of nitrogen application was beneficial and could improve the sensitivity of winter wheat to environmental changes, which was reflected in the increase of both net photosynthetic rate and transpiration rate ($P < 0.01$), and it could last for a long time to keep the stomatal conductance of winter wheat at a high level constantly; the diurnal variation of photosynthesis in high water and medium nitrogen presented a "unimodal-type" curve; the diurnal change of photosynthesis in medium water and medium nitrogen as well as in low water and high nitrogen showed a "bimodal" curve; the water use efficiency of winter wheat leaves in medium nitrogen and high water could be significantly increased when the irrigation amount was the same ($P < 0.05$); water–nitrogen scheme for medium nitrogen and medium water was the best solution to save water, reduce nitrogen and increase grain yield under the experimental conditions of film hole irrigation of winter wheat. Its grain yield was 3,763.01 kg/ha^2 and the total water utilization efficiency and irrigation water utilization efficiency reached the maximum. The results of this study can provide scientific basis for water and fertilizer management of winter wheat under the film hole irrigation mode.

Keywords: Film hole irrigation; Water nitrogen coupling; Photosynthetic characteristics; Yield; Winter wheat

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1. Introduction

Irrigation and fertilizer are the two most important factors for crop growth and development in agricultural production, and they are also the easiest to control. However, for a long time, water shortage has seriously restricted the productivity of economic crops in China, and the flood irrigation techniques used in production has caused a large amount of water loss [1–4]. In terms of chemical fertilizer use, chemical fertilizers have changed from insufficient inputs in the past to excessive application in some areas, resulting in a series of environmental problems, such as decreased fertilizer utilization, soil compaction, surface pollution and groundwater pollution [5,6]. This high-consumption and low-efficiency production method not only brings about waste of resources, ecological degradation and environmental pollution, but also restricts the sustainable development of Chinese agriculture. Facing the frequent droughts, increasing water scarcity, and reduction of arable land in China, it is essential for China to implement the water and fertilizer coupling, promote the comprehensive management of water and farmland, and complement fertilizer and water with each other so as to comprehensively improve the efficiency of water and fertilizer utilization and promote agricultural productivity and efficiency.

At present, some important progress has been made in the researches on the coupling effect of crop water and fertilizer at home and abroad [7–12]. Studies have shown that an adequate supply of nitrogen and phosphorus is conducive to the development of vegetative organs such as roots, stems, and leaves, and the coordinated development of plant populations. Also, it can make up for the adverse effects of water stress, including reduced leaf area and slow leaf extension, which is beneficial to dry matter production and reduce yield loss [13]. Li et al. [14] studied the effects of water deficit and nitrogen fertilization on the growth and nitrogen uptake of winter wheat. As the results showed, water shortage at any growth stage hindered the plant height, leaf area and the accumulation of dried matter and the intake of nitrogen in winter wheat. Shangguan et al. [15] observed the water status and photosynthetic effects of winter wheat leaves using nitrogen and water stress. It was found that high nitrogen could easily lead to a reduction in crop photosynthetic rate, and the reduction effect is more pronounced with increasing drought intensity.

Film hole irrigation is a low-cost integrated irrigation and fertilization method, which is to place the film on the bed surface and irrigate the crops through the planting holes of crops [11,16–19]. Water and fertilizers can enter the soil through irrigation holes in the film. The irrigation has similar characteristics with drip irrigation, but there is no clogging problem due to the larger irrigation holes. At present, the related reports at home and abroad mainly focus on water saving, yield increase, heat preservation, moisture preservation and irrigation water use efficiency [14]. However, the soil environment after sub-film irrigation is more complex than that of conventional irrigation. Chemical reactions of nitrogen in the soil are influenced by such factors as soil moisture, temperature, aerobic properties, microorganisms, root growth and distribution of crops. There are few research results on the optimization and overall planning of fertilizer and water in film hole irrigation and the coupling of water and fertilizer. Based on this, in order to further explore the law behind the water saving, fertilizer conservation and yield increase under the coupling condition of water and nitrogen in film hole irrigation, this research established a field experiments with different application levels of nitrogen and the interaction of moisture control to investigate the effects of film hole irrigation on the photosynthesis characteristics, yield as well as water use efficiency of the winter wheat [20]. In this way, a theoretical basis is provided for the rational irrigation and nitrogen fertilizer application optimization scheme in the film irrigation farmland.

2. Materials and methods

2.1. Laboratory overview

It was conducted from October 2018 to June 2019 at the agricultural water use trial field at the Key Laboratory of Water-Saving Agriculture in Henan Province, North China University of Water Resources and Hydro-power. The winter wheat variety for the test was 'Yumai 68', which was sown on October 13, 2018, and harvested on June 5, 2019. The location of the experimental field is 113°46'E, 34°47'N, 110.4 m above sea level, with an annual precipitation of 637.1 mm, an annual sunshine duration of 1,500 h, an average annual temperature of 14.5°C, an annual frost-free period of 220 d and an annual evaporation of about 2,000 mm. With a silt loam soil, the soil bulk density was 1.35 g/cm^3 with field capacity (FC) of 24.58%. The soil had a total nitrogen (TN) of 0.055%, organic matter (OM) of 0.79%, Olsen's phosphorus (OP) and utilised potassium (AK) of 12.4 mg/kg and 102.6 mg/kg in the field, respectively. The experiment was taken as a field experiment for winter wheat irrigation with film holes. The test area covered an area of 20 m × 1.1 m. The soil surface was leveled according to the film hole irrigation technology. The soil surface was levelled and then covered with membrane holes according to the film hole irrigation technique, and a diameter of 5 cm, a distance of 15 cm from the centre of the holes and a row spacing of 15 cm. and the sowing depth was 10 cm. The winter wheat variety is 'Yumai 68'. In order to avoid the interference of mutual water leakage in the test sections, the researchers set a 1.1 m protective row spacing between the communities. Experiments were randomized and repeated three times. The test site had a length of 60 m and covered an area of 3,600 m^2. The land was flat and easy to irrigate and drain. It was equipped with a motorized waterproof shed that could be opened and closed. The shed was equipped with 18 bottom test pits. The opening of the shed was adjusted to prevent the effect of precipitation during the growth phase of regulated irrigation. Fig. 1 shows a schematic diagram of the sowing of winter wheat under film hole irrigation. The precipitation data were obtained from the automatic weather station set up at the test site (Table 1).

2.2. Experimental protocol and experimental design

The crops were sown on October 29, 2018, with a planting density of 1,381,200 plants/hm^2, and was harvested

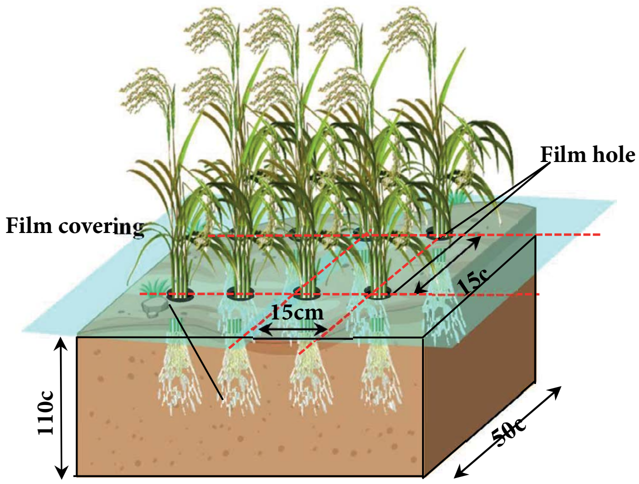

Fig. 1. Layout of film hole irrigation.

Table 1
Rainfall from of each month during the experiment (mm)

Age	2018			2019					Sum-rainfall
Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	
Rainfall	0.3	22.6	11.1	12.9	8.5	2.3	28.4	2.1	88.2

uniformly at the maturity stage on May 26, 2019. Three irrigation levels were set in the experiment, namely, high water (W1) of 750 mm; medium water (W2) of 650 mm; and low water (W3) of 550 mm. Irrigation was not carried out during the wintering period of winter wheat. For deficit irrigation, four fertilization levels were set-low fertilizer (N_1, N 120 kg/hm², P2O5 180 kg/hm², KCl 180 kg/hm²) for each adjustment degree; medium fertilizer (N_2, N 240 kg/hm², P_2O_5 180 kg/hm², KCl 180 kg/hm²); high fertilizer (N_3, N 360 kg/hm², P_2O_5 180 kg/hm², KCl 180 kg/hm²); no fertilizer (N_0, N 0 kg/hm², P_2O_5 180 kg/hm², KCl 180 kg/hm²) – for a total of 36 treatments with 3 replicates per treatment. All irrigation levels started from the greening period, and the soil mass moisture content was measured based on the drying method. The nitrogen fertilizer used in the experiment was urea, the basal fertilizer was 1/2 urea + all P_2O_5 and KCl, and the other 1/2 urea was top-dressed in the early stage of turning green.

2.3. Observation content and statistical methods

2.3.1. Observation content

The plant height, leaf area, chlorophyll content index, photosynthetic characteristics and grain yield of winter wheat are measured and determined at each growth stage of it.

2.3.1.1. Determination of physiological growth traits in winter wheat

Five winter wheat plants were randomly selected from each treatment and labelled to differentiate between the four growth stages of winter wheat (jointing stage, heading stage, flowering stage and filling stage) [21]. The plant height was measured with a ruler; flag leaves were measured with a Sys-Spad-5 portable chlorophyll meter chlorophyll content index.

2.3.1.2. Determination of photosynthetic characteristics

The photosynthetic properties of flag leaves were measured every 8–10 d from the jointing stage (March 21, 2019) to the maturity stage (May 11). The FT-GH30 portable photosynthesis measurement system produced by Shandong Fengtu Company in China, was used for the measurements, and the light intensity was provided by the system's artificial light source LED, which was set to 1,500 mmol m²/s, and the measurement time was from 9:00 to 11:00 in the morning of the same day. In addition, during the jointing period of winter wheat, a day with fine weather and few clouds was selected, and the diurnal variation was measured every 2 h from 9:00 to 17:00; 6 plants were selected for each treatment, and the photosynthetic rate (P_n) of leaves, transpiration rate (T_r), stomatal conductance (G_s) was measured respectively. The calculation formula of leaf water use efficiency (LWUE) is: LWUE = P_n/T_r.

2.3.1.3. Determination of wheat grain filling process

In the flowering stage of winter wheat, plants with similar growth and flowering on the same day should be selected for listing and identification. After flowering, samples were taken every 4 d. Three main stem ears of each treatment were blanched at 105°C for 20 min and dried through at 80°C until the mass was constant and threshed. During the measurement, the mass of the sample was weighed by a high-precision scale of 1‰ and converted into the mass of 100 grains.

2.3.2. Data processing and analysis

The test data were statistically calculated and plotted using Microsoft Excel 2019 and Surfer 16, and ANOVA was performed using SPSS statistical software. The Duncan method was used to test the significance of differences between different test protocols at the levels of $P < 0.05$ and $P < 0.01$, respectively.

3. Results and analysis

3.1. Plant height and chlorophyll content index of winter wheat under film hole irrigation

Figs. 2 and 3 are charts showing the changes of plant height of winter wheat under the film hole irrigation with different irrigation and nitrogen applications at the jointing-heading-flowering-grain-filling stage, respectively.

The letters H, M, L in the graph represent the abbreviations of high water, medium water and low water respectively in the graph of irrigation treatment; the letters None, L, M, H in the graph represent the abbreviations of no nitrogen, low nitrogen, medium nitrogen and high nitrogen respectively in the graph of fertilization treatment, the same below.

From Figs. 2 and 3 it can be seen that the irrigation amount was consistent, and the plant height increased with the increasing nitrogen application, which indicates that the nitrogen application measures as a whole help to promote the growth of winter wheat; when the nitrogen content was consistent, the plant height of winter wheat in medium water was significantly higher than that in high water and low water level ($P < 0.01$) and the growth is listed in the order of large to small: medium water > high water > low water. Appropriate water deficit helped the winter wheat roots and plants to grow. On the

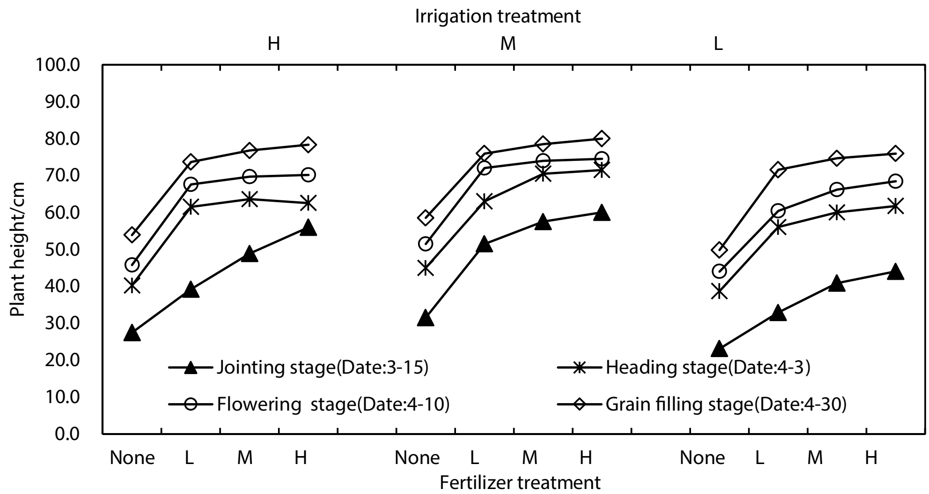

Fig. 2. The plant height of winter wheat with changing fertilizer amount in different stages under the film hole irrigation.

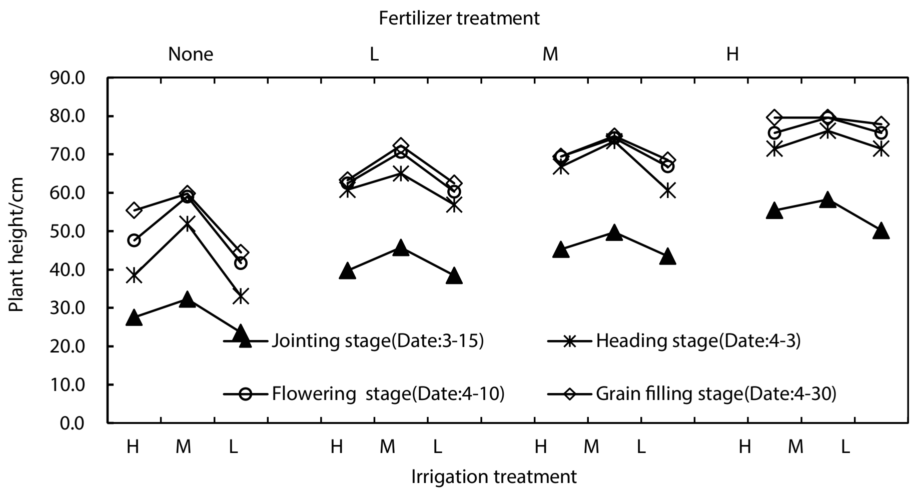

Fig. 3. The plant height of winter wheat with changing irrigation amount in different stages under film hole irrigation.

contrary, too much irrigation tended to lead to increased water content in the soil pore space and poor permeability, which is not conducive to the respiration of the root layer; in the above-mentioned growth stages, the plant height has always shown an increasing trend. All fertilization treatments reached the maximum value at the grain-filling stage (Fig. 3). The irrigation did not have significant influence on plant height ($P > 0.05$).

Figs. 4 and 5 show the changes of the chlorophyll content index of winter wheat under film hole irrigation at four growth stages. It can be seen that under the same irrigation conditions, the chlorophyll content index increased first and then decreased with the increasing nitrogen content, and the chlorophyll content index of the medium fertilizer treatment was significantly higher than that of other fertilization treatments ($P < 0.01$); under the same nitrogen application conditions, the chlorophyll content index of winter wheat in medium water was significantly greater than that in high water and low water, and the order arranged from large to small was: medium water > high water > low water. During the whole growth period, the chlorophyll content of winter wheat rose firstly and then decreased, reaching the maximum value at the flowering stage and decreasing to the minimum value at the grain filling stage.

Significance analysis showed that the interaction of nitrogen application and irrigation had an extremely significant effect ($P < 0.01$) on plant height and chlorophyll index in all four growth stages of winter wheat under film hole irrigation, both in terms of plant height and chlorophyll content index.

3.2. Photosynthetic characteristics and water use efficiency of winter wheat under film hole irrigation

Tables 2 and 3 show the changes of net photosynthetic rate (P_n) and transpiration rate (T_r) of winter wheat irrigated with film holes at different growth stages under water and nitrogen interaction.

From Tables 2 and 3 it can be seen that the interaction of water and nitrogen had a significant effect ($P < 0.05$) on the net photosynthetic rate and transpiration rate of winter wheat at all stages of growth. Among them, the photosynthetic rate of the three growth stages of flowering,

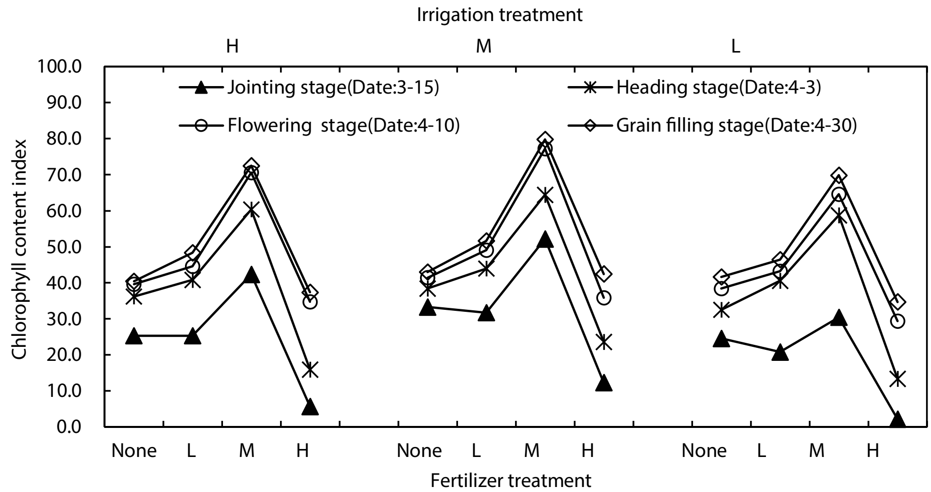

Fig. 4. The chlorophyll content index of winter wheat with changing fertilizer amount in different stages under film hole irrigation.

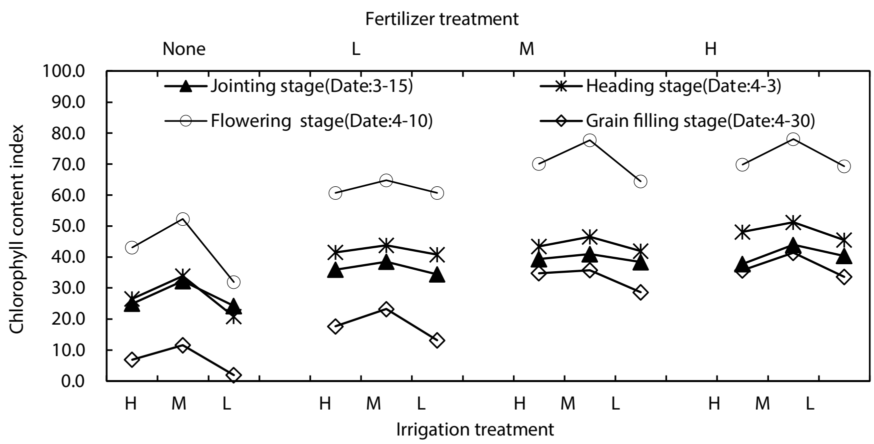

Fig. 5. The chlorophyll content index of winter wheat with changing irrigation amount in different stages under film hole irrigation.

Table 2
The net photosynthetic rate of winter wheat

Irrigation amount (mm)	Nitrogen dosage (kg/hm²)	Net photosynthetic rate P_n (μmol CO_2/m²/s)				
		Jointing period (3.20)	Heading period (3.31)	Flowering period (4.06)	Grain filling period (4.17)	Mature period (4.30)
High water	No nitrogen	5.04 Df	9.27 Ii	17.79 Jj	7.86 Hh	3.46 Ef
	Low nitrogen	13.08 Bc	26.69 Cc	36.17 Cc	32.05 Bb	23.55 Ab
	Medium nitrogen	20.22 Aa	22.50 Dd	30.01 Ee	26.18 Dd	19.41 BCc
	High nitrogen	17.72 Ab	15.33 Gg	22.73 Gg	23.13 Ee	13.12 De
Medium water	No nitrogen	3.15 Dfg	11.04 Hh	20.38 Ii	8.77 Gg	3.77 Ef
	Low nitrogen	9.46 Cde	31.36 Aa	37.72 Bb	36.87 Aa	25.09 Aab
	Medium nitrogen	18.16 Aab	29.81 Bb	31.11 Dd	26.21 Dd	25.47 Aab
	High nitrogen	14.20 Bc	22.11 Dd	39.32 Aa	27.63 Cc	20.33 Bc
Low water	No nitrogen	2.22 Dg	7.69 Jj	11.94 Kk	4.01 Ii	1.16 Fg
	Low nitrogen	7.48 CDe	20.00 Ee	24.77 Ff	27.99 Cc	17.32 Cd
	Medium nitrogen	13.24 Bc	17.40 Ff	22.89 Gg	26.03 Dd	17.65 Cd
	High nitrogen	9.87 Cd	17.06 Ff	21.33 Hh	21.96 Ff	11.78 De
Significance test (F-value)	Irrigation level	**	**	**	**	**
	Nitrogen application level	**	**	**	**	**
	Irrigation × nitrogen application	*	**	**	**	**

Notes: Within the same period of growth, various upper and lower case characters in the same column indicate significantly different at the $P < 0.01$ and $P < 0.05$ levels;
** and * denotes significantly significant difference at the $P < 0.01$ and $P < 0.05$ levels correspondingly, and NS denotes non-significant ($P \geq 0.05$), as Table 3.

Table 3
Transpiration rate of winter wheat

Irrigation amount (mm)	Nitrogen dosage (kg/hm²)	Transpiration rate T_r (mmol/m²/s)				
		Jointing period (3.20)	Heading period (3.31)	Flowering period (4.06)	Grain filling period (4.17)	Mature period (4.30)
High water	No nitrogen	3.91 DEe	5.33 CDcd	5.99 Bb	3.90 Bb	1.35 Bc
	Low nitrogen	5.01 Ccd	7.83 Bb	7.96 ABab	7.95 Aa	5.12 Aa
	Medium nitrogen	5.62 Bbc	6.97 Bb	7.70 ABab	7.65 Aa	2.81 ABbc
	High nitrogen	5.76 Bb	6.99 Bb	7.66 ABab	6.93 ABa	2.34 Bbc
Medium water	No nitrogen	5.30 BCc	5.67 Ccd	5.93 Bb	4.40 Bb	1.58 Bbc
	Low nitrogen	5.57 BCbc	7.04 Bb	6.94 ABb	6.16 ABa	5.15 Aa
	Medium nitrogen	6.04 ABab	8.81 ABa	7.51 ABb	7.41 Aa	4.79 ABa
	High nitrogen	6.40 Aa	9.23 Aa	9.22 Aa	6.25 ABa	4.72 ABa
Low water	No nitrogen	3.46 Ef	4.15 Dd	5.85 Bb	3.23 Bb	0.99 Bc
	Low nitrogen	4.18 De	4.71 CDd	6.40 Bb	6.16 ABab	3.21 ABb
	Medium nitrogen	4.63 CDd	4.93 CDd	6.11 Bb	6.26 ABab	2.70 Bb
	High nitrogen	5.07 Cc	5.97 Cc	5.99 Bb	5.40 ABab	2.16 Bbc
Significance test (F-value)	Irrigation level	**	**	**	*	**
	Nitrogen application level	**	**	*	**	**
	Nitrogen dosage (kg/hm²)	*	**	NS	NS	NS

grain filling and maturity was more significantly affected by the interaction of water and nitrogen. When flowering stage was reached, the net photosynthetic rate and transpiration rate of winter wheat were already the peak of the entire growth and development period the effects of photosynthesis were not consistent due to the light intensity, temperature and chlorophyll content. Gradually as the growth process progresses with increasing temperatures, the photosynthesis of winter wheat progressively increases, the corresponding plant height also increases and chlorophyll content accumulates more rapidly. When flowering occurred, the chlorophyll content was suppressed and began to decline, and photorespiration also declined. At the same irrigation rate, growth stage net photosynthetic rate and transpiration rate of winter wheat increased and then decreased with the increase of nitrogen content. At the jointing stage, the net photosynthetic rate of winter wheat at medium and high nitrogen levels was generally at a higher value regardless of the irrigation rate. At the heading stage, flowering stage, grain filling stage and maturity stage, the photosynthesis rate of low nitrogen winter wheat reached the highest, while that of medium nitrogen in the winter wheat was close to low nitrogen. During the jointing stage, the net photosynthetic rate of winter wheat with high water and medium nitrogen was the highest, because in the jointing stage, winter wheat needed a large number of water demand, and the key raw material for photosynthesis was water. The lower soil water content led to a decrease in the water content of plant cells. Then, the plant started its self-protection function, regulated the osmotic pressure inside and outside the cells, the opening of leaf stomata, and antioxidant systems, enhanced the water absorption and water retention capabilities and maintained cell expansion pressure. The free radicals were removed to protect the cell structure from dehydration. Water deficit regulation impaired the regulatory function of plant organisms, increased the number of reactive oxygen radicals, disrupted the normal material metabolism, disrupted the cell membrane system, increased its osmotic pressure, reduced photosynthesis, directly led to the net photosynthetic rate and transpiration rate, and reduced the water consumption capacity.

Table 4 shows the daily average leaf water use efficiency ($\overline{\text{LWUE}}$) of winter wheat.

As can be seen from Table 4, the irrigation and nitrogen application had a very significant effect on the average daily water use efficiency of leaves in the three stages of jointing, heading and flowering of winter wheat ($P < 0.01$). The nitrogen application rate could significantly affect the daily average leaf water use efficiency of winter wheat at both grain filling and mature stages ($P < 0.01$). Only the change of irrigation amount had no significant effect on the daily average leaf water use efficiency of winter wheat ($P \geq 0.05$). The results of ANOVA showed that the water and nitrogen interaction conditions had significant ($P < 0.05$) and highly significant ($P < 0.01$) effects on the daily average leaf water use efficiency of winter wheat at the jointing stage and heading stage, respectively. The leaf water use efficiency of winter wheat gradually increased from the jointing stage, reached the maximum at the flowering stage, and then decreased gradually. There was little difference between the grain filling stage and the mature stage. At the jointing stage, the winter wheat with high water and medium nitrogen had the highest daily average leaf water use efficiency (3.63 μmol/mmol); at the heading stage, the medium water reached the maximum the average daily leaf water use efficiency. It shows that in the three growth stages of jointing-heading-flowering, medium water helped improve the water use efficiency of leaves in the later stage and the daily average leaf water use efficiency (4.87 μmol/mmol) of low nitrogen reached the largest. During the flowering and filling stages, the daily average leaf water use efficiency (4.87 and 5.86 μmol/mmol) of winter wheat with low nitrogen and medium water reached the maximum. In addition, the average daily leaf water use efficiency of winter wheat at maturity showed that nitrogen application significantly increased the average daily water use efficiency of winter wheat leaves.

Table 4
Daily average leaf water use efficiency of winter wheat

Irrigation amount (mm)	Nitrogen dosage (kg/hm²)	Daily average leaf water use efficiency of winter wheat $\overline{\text{LWUE}}$/(μmol/mmol)				
		Jointing period (3.20)	Heading period (3.31)	Flowering period (4.06)	Grain filling period (4.17)	Mature period (4.30)
High water	No nitrogen	1.29 ± 0.15 Fg	1.75 ± 0.38 Ef	2.71 ± 0.57 Cc	1.99 ± 0.12 Cc	2.44 ± 0.46 Bb
	Low nitrogen	2.61 ± 0.09 Cc	3.44 ± 0.18 Bbc	4.16 ± 0.68 ABb	3.96 ± 0.06 Bb	4.39 ± 0.04 ABab
	Medium nitrogen	3.59 ± 0.02 Aa	3.26 ± 0.02 BCc	3.56 ± 1.14 BCbc	3.37 ± 0.17 BCb	6.60 ± 1.23 Aa
	High nitrogen	3.08 ± 0.07 Bb	2.21 ± 0.15 Def	2.71 ± 0.70 Cc	3.57 ± 1.98 Bb	5.35 ± 0.94 ABab
Medium water	No nitrogen	0.59 ± 0.08 Gh	1.97 ± 0.00 Ef	3.14 ± 0.65 BCc	1.97 ± 1.22 Cc	2.27 ± 0.10 Bb
	Low nitrogen	1.69 ± 0.23 Ef	4.50 ± 0.28 Aa	4.97 ± 0.13 Aa	5.76 ± 0.68 Aa	4.66 ± 0.14 ABab
	Medium nitrogen	3.01 ± 0.30 Bb	3.41 ± 0.01 Bbc	3.79 ± 0.16 Bb	3.48 ± 1.14 Bb	5.08 ± 0.65 ABab
	High nitrogen	2.22 ± 0.08 Dd	2.42 ± 0.03 De	3.91 ± 0.09 Bb	3.76 ± 0.70 Bb	4.11 ± 0.51 ABab
Low water	No nitrogen	0.64 ± 0.04 Gh	1.87 ± 0.38 Ef	1.87 ± 0.08 Cd	1.22 ± 0.54 Cc	1.12 ± 0.26 Bb
	Low nitrogen	1.79 ± 0.10 Eef	4.28 ± 0.13 Aa	3.54 ± 0.13 BCbc	4.47 ± 0.10 Ab	5.16 ± 0.52 Aa
	Medium nitrogen	2.86 ± 0.06 BCb	3.57 ± 0.07 Bb	3.43 ± 0.41 BCc	4.10 ± 0.17 Bb	6.25 ± 0.03 ABa
	High nitrogen	1.95 ± 0.20 DEe	2.89 ± 0.15 Cd	3.26 ± 0.04 BCc	4.01 ± 0.39 Bb	5.21 ± 0.10 ABab
Significance test (F-value)	Irrigation level	**	**	**	NS	NS
	Nitrogen application level	**	**	**	**	**
	Nitrogen dosage (kg/hm²)	*	**	NS	NS	NS

3.3. Diurnal variation of photosynthetic characteristics and water use efficiency of winter wheat under film hole irrigation at jointing stage

The diurnal variation of photosynthetic characteristics during the jointing period of winter wheat under membrane aperture irrigation with different irrigation and N application were further analysed. Figs. 6–8 demonstrate the day–night variation of photosynthesis rate (P_n), transpiration rate (T_r) and stomatal conductance (G_s) correspondingly.

As can be seen from Fig. 6, the diurnal variation curves of photosynthetic rate (P_n) of winter wheat under different treatment schemes at jointing stage varied significantly, and the leaves of winter wheat showed different degrees of physiological changes for each irrigation treatment at jointing, heading and flowering stages. The sequence of photosynthetic rate from large to small is as follows: high water > medium water > low water, the "nap" phenomenon of photosynthetic rate in high water was not obvious, presenting a "unimodal" curve. On the contrary, it reached the peak at 12:00 at noon, and the peak was sharp. Therefore, timely irrigation can alleviate the "nap" phenomenon of winter wheat. When the irrigation amount was consistent, nitrogen application significantly increased the photosynthetic rate of winter wheat, and the photosynthetic rate of medium water showed a "bimodal" curve. The duration of "nap" lasted from 10:00 to 14:00, and the photosynthetic rate of medium nitrogen was the highest, while there was no significant difference between low nitrogen and high nitrogen, and the photosynthetic rate of no application was the lowest. Among them, from 10:00 to 12:00, the "nap" phenomenon of low water treatment lasted for a short time. The photosynthetic rate of medium nitrogen was the highest, followed by high nitrogen. The photosynthetic rates of low and no nitrogen application were closer. The effect of nitrogen application rate on photosynthetic rate of winter wheat was more obvious under high water condition at jointing stage. At the three irrigation levels, the photosynthetic rate of medium nitrogen reached the highest.

As can be seen from Fig. 7, diurnal variation curves of transpiration rate (T_R) of winter wheat at jointing stage were different under different water treatment conditions. The transpiration rate of high water reached the peak in a day at 12:00, and then gradually decreased, due to the high

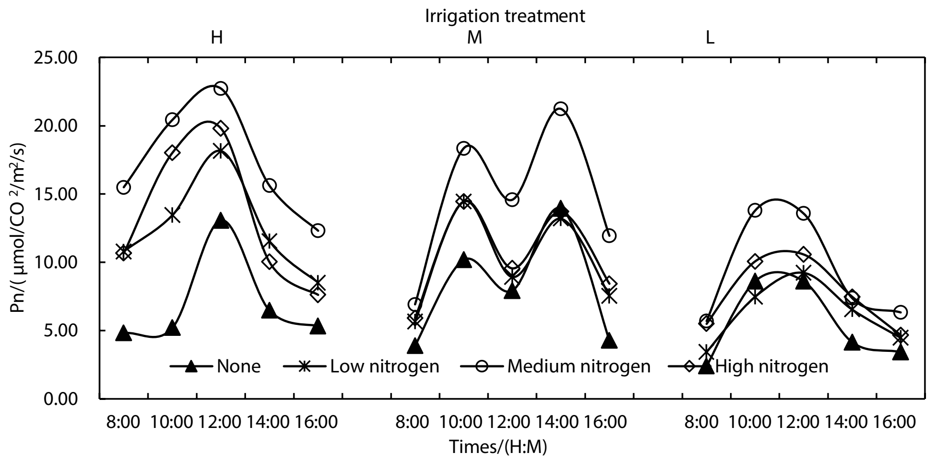

Fig. 6. Diurnal variation curves of photosynthetic rate of winter wheat during jointing period.

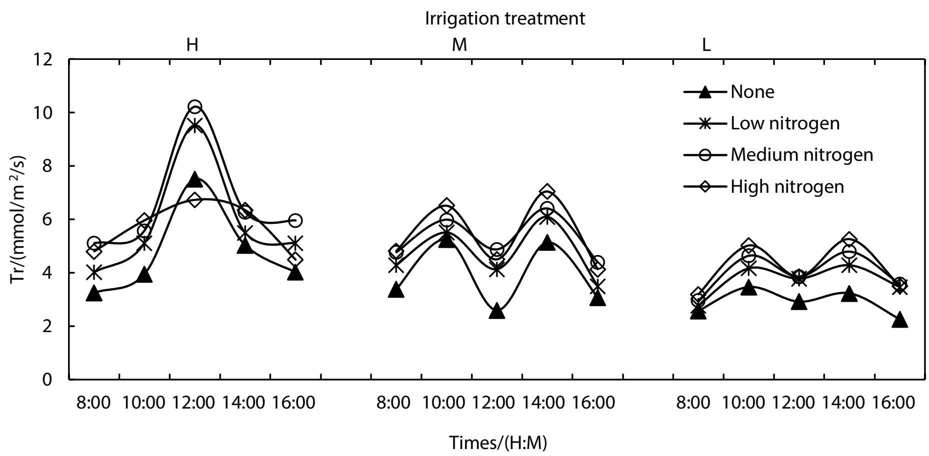

Fig. 7. Diurnal variation curves of evapotranspiration rate of winter wheat during jointing period.

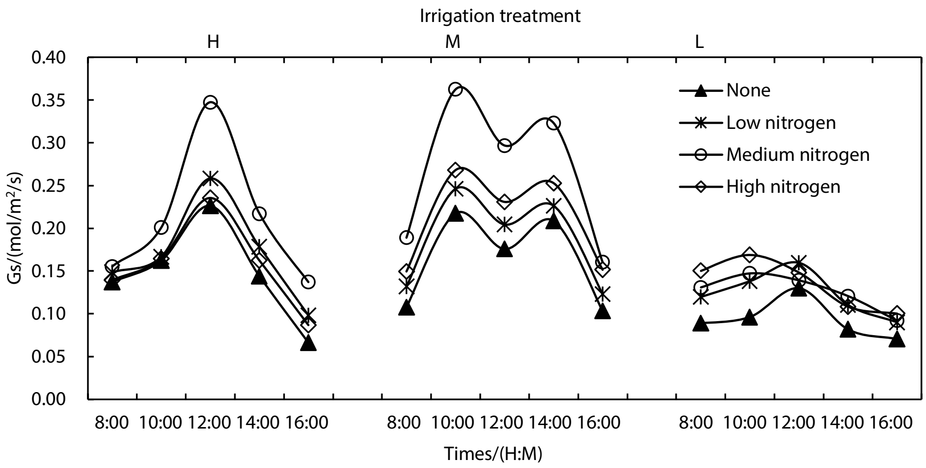

Fig. 8. Diurnal variation curves of stomatal conductivity of winter wheat during jointing period.

temperature and low humidity at noon, which caused winter wheat to rapidly stimulate the corresponding physiological regulation. The phenomenon of "siesta" existed in both the middle and low water levels, that is, there is a valley between 10:00 and 14:00, and the change of valley peak, that is, the difference between the first peak and the valley, indicating that the flag leaves of winter wheat respond to environmental changes with a lag effect when the soil moisture content is low. Under different nitrogen application amount, the peak valley variation range of winter wheat transpiration rare under high water condition from large to small was shown as follows: medium nitrogen > low nitrogen > high nitrogen > no nitrogen application. The range of rare peaks and valleys of transpiration in winter wheat under medium water conditions at different levels of nitrogen application was ranged from large to small: no nitrogen > high nitrogen > low nitrogen > medium nitrogen. Winter wheat without nitrogen was more sensitive to water stress than with nitrogen, and the sensitivity degree increased with the increase of nitrogen application. Under different nitrogen application amount, the peak valley variation range of winter wheat transpiration rare under low water condition from large to small was shown in descending order: high nitrogen > medium nitrogen > low nitrogen > no nitrogen. In conclusion, nitrogen application can significantly improve the sensitivity of winter wheat flag leaves to environmental changes under low irrigation.

As seen in Fig. 8, the day–night variation in stomatal conductance (G_s) and the rate of transpiration at the jointing stage were approximately the same. When the moisture content was the consistency, stomatal conductance was higher in winter wheat where the nitrogen was applied than in those where no nitrogen was applied. The stomatal conductance of high water gradually increased with rising temperatures from 8:00 am onwards, and showed a "unimodal" curve. Higher soil moisture content made stomatal part of flag leaf of winter wheat open gradually, and peaked at 12:00 noon, which showed as follows: medium nitrogen > low nitrogen > high nitrogen > no nitrogen application; The change of stomatal conductance under low water content was not fluctuated. Because the soil was under drought stress all day long, stomatal conductance fluctuated little under the influence of air temperature and humidity, and reached a small peak from 10:00 to 12:00 the order was: high nitrogen > medium nitrogen > low nitrogen > no nitrogen application. Stomatal conductance showed a "bimodal" curve under medium water condition, which was as follows: medium nitrogen > high nitrogen > low nitrogen > no nitrogen application. Due to soil water shortage, some stomata in flag leaf of winter wheat were activated and close from 10:00 to 14:00 to prevent the increasing ineffective evaporation, resulting in stomatal conductance trough in a period of time. Under medium water treatment, stomatal conductance can effectively prolong the duration (10:00–14:00) to maintain a high value, and nitrogen application amount is more conducive to striking the balance between biomass production.

Fig. 9 shows the diurnal variation of leaf water use efficiency (LWUE) of winter wheat at jointing stage under the interaction of water and nitrogen. It can be seen that the diurnal variation curve of leaf water use is different from that of photosynthetic rate, transpiration rate and stomatal conductance.

As can be seen from Fig. 9, the overall leaf water use efficiency under high water conditions was higher than that of medium and low water treatments regardless of nitrogen application. The leaf water use efficiency of winter wheat at joining stage without nitrogen application did not vary significantly ($P \geq 0.05$), and reached the maximum value (1.73 μmol/mmol) at 12:00. Water use of winter wheat leaves at jointing stage reached the high level in the early stage and low level in the late stage under nitrogen application, reaching the maximum value at 10:00, and the trend from large to small was as follows: average nitrogen (3.62) μmol/mmol > high nitrogen (3.12) μmol/mmol > low nitrogen (2.64) μmol/mmol). The diurnal variation of leaf water use efficiency of winter wheat at jointing stage was not obvious under different nitrogen application rates. Leaf water use efficiency of medium nitrogen was at a high level throughout the whole day. There was a "bimodal" phenomenon, which might be related to the high transpiration rate of flag leaves. The water use efficiency of leaves

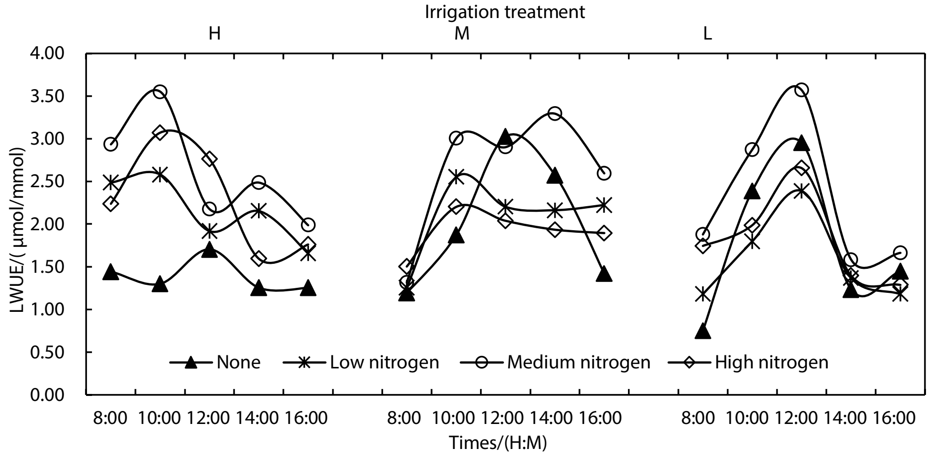

Fig. 9. Diurnal variation curves of LWUE of winter wheat during jointing period.

Table 5
Grain yield and water use efficiency of winter wheat under different fertilization and water stress levels

Irrigation amount (mm)	Nitrogen dosage (kg/hm²)	Grain yield (kg/hm²)	Water consumption/(mm)			Water use efficiency (kg/(hm² mm))		
			Total water consumption	Irrigation amount	Soil water	Total utilization	Irrigation amount	Soil water
High water	No nitrogen	2,368.68 Ii	539.66 Aa	743.72 Aa	106.15 Ee	4.30 Jj	3.12 Ff	21.86 Ii
	Low nitrogen	2,721.46 Gg	526.06 Bb	700.70 Dd	82.91 Ff	5.07 Hh	3.80 Ee	32.17 Dd
	Medium nitrogen	2,990.25 Ff	499.09 Ee	654.84 Gg	81.47 Gg	5.87 Ff	4.48 Dd	35.97 Cc
	High nitrogen	3,326.23 Dd	506.51 Dd	703.84 Cc	72.89 Jj	6.44 Dd	4.64 Cc	44.72 Aa
Medium water	No nitrogen	3,141.44 Ee	508.30 Cc	664.64 Hh	117.94 Bb	6.06 Ee	4.64 Cc	26.11 Hh
	Low nitrogen	3,443.83 Bb	487.33 Gg	733.24 Bb	112.73 Dd	6.93 Cc	4.61 Cc	29.94 Ee
	Medium nitrogen	3,763.01 Aa	460.44 Ii	674.44 Ff	117.20 Cc	8.01 Aa	5.47 Aa	31.47 Dd
	High nitrogen	3,427.03 Cc	467.74 Hh	689.14 Ee	120.65 Aa	7.18 Bb	4.87 Bb	27.83 Gg
Low water	No nitrogen	1,646.32 Ll	496.24 Ff	619.17 Ll	78.87 Hh	3.25 Ll	2.61 Hh	20.45 Jj
	Low nitrogen	1,881.51 Kk	459.35 Jj	625.44 Kk	64.53 Kk	4.02 Kk	2.95 Gg	28.57 Ff
	Medium nitrogen	2402.28 Hh	450.57 Kk	630.34 Jj	62.87 Ll	5.22 Gg	3.73 Ee	37.45 Bb
	High nitrogen	1,982.30 Jj	416.26 Ll	640.14 Ii	75.83 Ii	4.66 Ii	3.04 Ff	25.62 Hh
Significance test (*F*-value)	Irrigation level	**	**	**	**	**	**	**
	Nitrogen application level	**	**	**	**	**	**	**
	Irrigation × nitrogen application	**	**	**	**	**	**	**

without nitrogen application was significantly affected by temperature and humidity, that is, showed a unimodal, which may be greatly affected by the changes of net photosynthetic rate. Under high and medium water conditions, leaf water use efficiency of low nitrogen was not much different from that of high nitrogen, and it showed the trend of increasing in the morning and increasing in the afternoon and decreasing in the evening. Under low water content, the water use efficiency of winter wheat leaves with and without nitrogen application showed an inverted "S" shape, indicating that under water stress, photosynthesis had the greatest influence on the difference of water use of winter wheat leaves, and the water use reached the highest under the medium nitrogen. Therefore, the photosynthesis of winter wheat with high water and medium nitrogen, medium water and medium nitrogen, and low water and high nitrogen was strong, and the diurnal variation of photosynthesis under high water nitrogen presented a "unimodal" curve; The diurnal variation of leaf water use efficiency under photosynthesis of medium water and medium nitrogen and low water and high nitrogen showed a "bimodal" curve; under the same amount of water, the average nitrogen content and water use efficiency of winter wheat leaves were the highest; under the same nitrogen application amount, the was not much different from that of high nitrogen, which showed the trend of increasing in the morning and increasing in the afternoon and decreasing in the evening a leaf water use efficiency could be greatly improved under high water conditions.

3.4. Effects of membrane hole irrigation on grain yield and water use efficiency of winter wheat

Table 5 shows grain yield and water use efficiency of winter wheat under different water and nitrogen schemes. According to ANOVA, the statistical effects of grain yield and water use efficiency of winter wheat under the interaction of water and nitrogen were extremely significant ($P < 0.01$) regardless of single factor or double factor interaction. The comparison of water treatments showed that winter wheat grain yield was higher and water use efficiency was greater in medium water than in the other two irrigation levels, and the grain yield of winter wheat under medium water nitrogen condition was the most affected.

It can also be seen from Table 5 that the water use efficiency of medium and low water increased first and then decreased with the increasing nitrogen application. In high moisture conditions, its water use efficiency increased ($P < 0.01$) along with the increasing nitrogen application amount, among which, medium water treatment was the most efficient irrigation water use method. With the decrease of irrigation water, the water use efficiency of soil water decreased gradually. The results of ANOVA showed that the main effects and interaction effects of irrigation and nitrogen application on yield and water efficiency of winter wheat reached highly significant levels ($P < 0.01$). In conclusion, the optimal water-fertilizer ratio for its water saving and weight loss (N) effect was the medium water N treatment under the conditions of film hole irrigation winter wheat large field experiment and under the guaranteed high yield. The grain yield was up to 3,763.01 kg/hm^2, and the total water use efficiency and irrigation water use efficiency reached the highest.

4. Conclusions

Through the coupling field experiment of water and nitrogen in film hole irrigation of winter wheat, this study mainly studied and analyzed the effects of different irrigation amount and fertilizer amount on photosynthetic characteristics and yield of winter wheat under membrane hole irrigation. The main results are shown as follows:

- As the amount of irrigation water increased, the height of winter wheat plants was firstly increased and secondly decreased. The height of plants in the medium water treatment was significantly higher than that in the other water treatments ($P < 0.01$). Plant height under all fertilizer treatments reached a maximum at the filling stage compared to no fertilizer application, but plant height under the high fertilizer treatment was not differentially affected by changes in irrigation water ($P > 0.05$). In the interaction between nitrogen application and irrigation, the diurnal variation difference of daylight rate of winter wheat was the most significant in flowering, filling and maturity stages ($P < 0.05$).
- With the same level of irrigation, both the net photosynthetic rate and transpiration rate of winter wheat first increased and then decreased with increasing nitrogen content. The highest net photosynthetic and transpiration levels were observed at flowering throughout the growth period. In the jointing stage, the net photosynthetic rate of winter wheat in high water and medium nitrogen scheme was the largest, and the transpiration rate of nitrogen in medium water and medium nitrogen reached the maximum, which promoted the material transportation and energy exchange in the plant. On the contrary, with the increase in low moisture content, the rates of net photosynthesis and transpiration in winter wheat were reduced. In winter wheat under the medium nitrogen treatment the net photosynthetic rate at jointing was higher than the other nitrogen treatments regardless of the irrigation amount. In comparison with the other nitrogen treatments, the net photosynthetic rate of winter wheat under the low nitrogen treatment reached a maximum after the heading stage. Nitrogen application rate could significantly affect the water use efficiency of winter wheat at the filling and ripening stages ($P < 0.01$), but irrigation amount had no significant effect on water use efficiency ($P \geq 0.05$).
- The stomatal conductance of winter wheat with nitrogen application was higher than that without nitrogen application, and the stomatal conductance of winter wheat with medium nitrogen application reached the highest under high water and medium water conditions. Nitrogen application was more effective in extending the time to keep the stomatal conductance of winter wheat at a higher level throughout the day, which was more conducive to maintaining the dynamic balance between biomass production. Under low water condition, stomatal conductance of winter wheat decreased with the decreasing nitrogen application amount. The photosynthesis of winter wheat with high water and medium nitrogen, medium water and medium nitrogen, and low water and high nitrogen was strong, and the diurnal variation of photosynthesis under high water nitrogen presented a "unimodal" curve; the diurnal variation of leaf water use efficiency under photosynthesis of medium water and medium nitrogen and low water and high nitrogen showed a "bimodal" curve. At the same amount of irrigation treatment, the highest water use efficiency of winter wheat leaves was found in the medium nitrogen treatment; under the same amount of nitrogen application, high levels of water could improve the water use efficiency of winter wheat leaves.
- Compared with the high water and low water treatment, the grain yield and water use efficiency of winter wheat under medium water were improved. Taking medium water and medium nitrogen treatment as the optimal scheme for saving water and reducing weight (nitrogen) and high grain yield under the experimental conditions of film hole irrigation of winter wheat, the grain yield reached 3,763.01 kg/hm^2, and the total water use efficiency and water use efficiency of irrigation water reached the highest.

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