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Effects of irrigation and planting patterns on photosynthetic capacity and grain quality of winter wheat**

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Abstract. With the shortage of water resources in recent years, water has become an important factor that limits the photosynthetic capacity and grain quality of winter wheat in the North China Plain. The experiment was conducted in 2011-2014, and the design of the two-factor split-plot was adopted, with three irrigation levels (0, 90, and 180 mm) for the main plot and three planting patterns (single-single row, single-double row, double-double row) for the subplot. The chlorophyll content index, net photosynthetic rate, and dry matter weight of winter wheat at different growth stages were measured, and the quality parameters of the grain were also measured after the harvest. The result indicated that irrigation increased the chlorophyll content index, net photosynthetic rate, grain protein, coarse starch and whiteness, which were favourable for producing dry matter and for seed formation. The chlorophyll content index, net photosynthetic rate, dry matter weight and gluten index of double-double row were higher than those of single-single row. Therefore, the 90 mm irrigation combined with the double-double row planting pattern is a good agronomic practice for winter wheat production, and beneficial for the improvement of flour quality in the North China Plain.

Keywords: *Triticum aestivum* L., chlorophyll content index, dry matter weight, farinograph parameter

INTRODUCTION

Winter wheat (*Triticum aestivum* L.) is the main cereal crop of the North China Plain (NCP), which is the main winter wheat-producing area in China. Water is crucial for wheat growth and development; a lack of water severely restricts crop growth, thereby affecting crop quality (Hasanuzzaman *et al*., 2012). However, the shortage of water resources at present is the main factor affecting the stability and sustainability of agricultural production (Mo *et al*., 2017). During the winter wheat growth period, the crop only receives 25-40% of its water requirement in China (Fang *et al*., 2010); therefore, the efficiency of water resource utilization urgently needs to be improved. Cao *et al*. (2017) studied the continuous expansion of the scale of agricultural production and the gradually increasing water-stress index, particularly in the Huang-Huai-Hai Plain. Agriculture is the biggest consumer of water resources; therefore, it is necessary to improve water management in agriculture to increase agricultural productivity in order to meet the food requirements of a growing population (Kharrou *et al*., 2011; Ierna and Mauromicale, 2018).

Row spacing is an important agronomic measure that determines plant spatial distribution, which affects plant canopy structure, and dry matter production; thus, row spacing ultimately influences biomass production (Mattera *et al*., 2013). Reasonable planting patterns are beneficial for improving the microclimate of farmlands and promoting the growth and development of crops (Wang *et al*., 2016). Han *et al*. (2016) have shown that a wide-precision planting pattern results in higher winter wheat photosynthetic capacity compared with the conventional cultivation planting patterns. The photosynthetic characteristics of maize at the milking stage are improved by the narrow-wide row planting pattern (Liu *et al*., 2011); meanwhile, studies on tobacco (Bilalis *et al*., 2015), rice (Chauhan and Johnson, 2010), and mung bean (Rao *et al*., 2015) show that a narrow row planting results in a higher photosynthetic capacity than wide row planting.

Planting patterns and water affect the accumulation of the photosynthate and the grain quality of wheat, which directly reflects flour quality. Bonfil and Posner (2012)

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point out that the quality of wheat is determined by the grain properties, protein content and starch content. Protein and gluten determine the end-use quality of flour and are closely related to the process of bread-making (Anjum and Walker, 2000; Branlard *et al*., 2001; Day *et al*., 2006). It is not surprising that wet gluten content and the gluten index have been the subject of intense attention by bakers and millers (Triboi *et al*., 2003). It may be assumed that the current research results are mainly concentrated on the level of nitrogen and the effect of different wheat varieties on the grain quality of the wheat (Liniņa and Ruža, 2012). Apart from some studies which have focused on dough quality in "fresh and frozen" food products (Boehm *et al*., 2004), the effects of irrigation and planting patterns on grain quality are rarely studied.

In this study, we studied the chlorophyll content index (CCI), dry matter weight, and net photosynthetic rate (Pn) at different growth stages, and the quality related parameters of grain of winter wheat. This research aims to clarify the effect of irrigation and planting patterns on photosynthetic characteristics and grain quality, optimize irrigation and planting patterns, and provide a reference for the efficient production and high grain quality of agriculture in the NCP.

MATERIALS AND METHODS

The three-year study was conducted at the Agronomy Experimental Station of Shandong Agricultural University (36°09′ N, 117°09′ E) during the 2011-2012, 2012-2013, and 2013-2014 winter wheat growing seasons, and the precipitation of the three growing seasons were 205.8, 195.8, 158.4 mm, respectively. The soil was a silty loam (pH 6.9), and the soil surface (0-20 cm) characteristics were 16.3 g kg^{-1}soil organic matter, 1.3 g kg^{-1} total nitrogen, 35 mg kg^{-1} available phosphorus, and 95 mg kg^{-1} available potassium; soil bulk density of 1.5 g cm^{-3}; and field capacity of 38.6% (V%). The weather data were obtained from the ET106 Weather Stations (Campbell Scientific, Inc., North Logan, USA).

In this experiment, the design of a two-factor split-plot was adopted. Three irrigation levels for the main plot, namely, 0, 90, and 180 mm, and treatments with the timing and irrigation levels are shown in Table 1. During irrigation, a flow meter was used to measure the amount of water applied. Three planting patterns (single-single row planting pattern, SS; single-double row planting pattern, SD; and double-double planting pattern, DD) for the subplot (Fig. 1). Each experimental plot area was 3 m × 3 m with three replications. The winter wheat (variety Jimai 22) was hand planted at a density of 400 × 10^4 plants ha^{-1} on 9 October 2011, 10 October 2012, and 9 October 2013. The seedlings

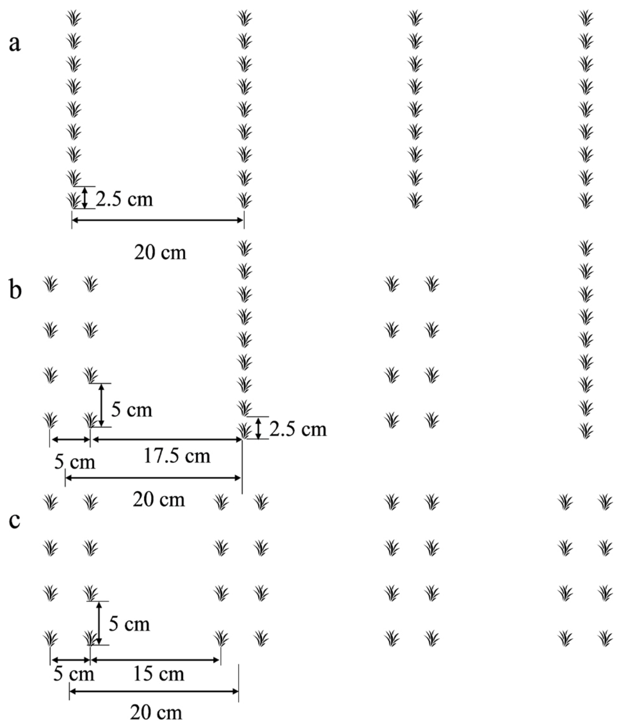

Fig. 1. Schematic diagram showing: a – single-single row (SS), b – single-double row (SD), and c – double-double row (DD).

Table 1. Treatments with the timing and levels of irrigation (mm) for winter wheat in 2012 to 2014

Planting pattern	Jointing stage (GS34) (6 April 2012, 8 April 2013, 29 March 2014)	Heading stage (GS48) (3 May 2012, 3 May 2013, 14 April 2014)	Filling stage (GS70) (15 May 2012, 16 May 2013, 30 April 2014)	Total
	0	0	0	0
Single-single row	30	30	30	90
	60	60	60	180
	0	0	0	0
Single-double row	30	30	30	90
	60	60	60	180
	0	0	0	0
Double-double row	30	30	30	90
	60	60	60	180

were planted in a 2-3 cm soil depth and were thinned by hand 15 days after emergence to achieve uniform final plant population densities (200×10^4 plant ha^{-1}). During the winter wheat field experiment, 225 kg ha^{-1} N, 120 kg ha^{-1} P_2O_5, and 105 kg ha^{-1} K_2O were applied to the field as base fertilizers (235 g of diammonium phosphate and 189 g of potassium sulfate for each plot); the total urea amount was 345 g for each plot, 50% of the total amount (173 g) was applied as a base fertilizer, and the remaining 50% was applied at the jointing stage (GS35) (Zadoks *et al*., 1974). The winter wheat plants were harvested on 9 June 2012, 8 June 2013, and 31 May 2014.

The CCI of five flag leaves that were characterized by consistent growth and similar features were measured using CCM-200 (Opti-Sciences, Hudson, USA) on a clear day from 9 a.m. to 11 a.m. at GS34, GS39, GS46, GS49, and GS71 in 2011 to 2012, GS32, GS35, GS44, GS49, and GS71 in 2012 to 2013, and GS31, GS35, GS45, GS49, and GS71 in 2013 to 2014. The Pn of the flag leaves were measured by using an LI-6400 portable photosynthetic system (LI-COR Inc., Lincoln, USA) on a clear day from 9 a.m. to 11 a.m. at GS45, GS49, and GS71. The relevant parameters were set as follows: quantum flux density was 1600 μmol m^{-2} s^{-1}, air flow rate was 500 μmol s^{-1}, relative humidity was 60-70%, and the leaf chamber temperature was 30°C, each treatment measured three flag leaves with consistent light direction and growth status. The total radiation levels during 2011-2012, 2012-2013, and 2013-2014 were 2803, 2961, and 3245 MJ m^{-2}, respectively (Table 2). The dry matter weight was measured for GS35, GS45, GS49, GS71, and GS80 by stochastically collecting 15 strains of wheat per treatment. The leaf, stem, and ear were separated in a drying oven at 105°C for 30 min and dried to a constant weight at 80°C.

The farinograph parameters were measured by using a Farinograph-AT (Brabender Technologie Gmbh & Co. KG, Duisburg, Germany). The wet gluten content and gluten index were measured by using a Glutomatic 2200 instrument; the falling number was measured by using an F1500 analyser, while rough fat, coarse starch, flour whiteness was quantified by using an Inframatic 9200 (Glutomatic 2200, F1500 and Inframatic 9200 were supplied by Perten Instruments, Hägersten, Sweden). Sedimentation was measured by using a BAU-A (Beijing Agricultural University Instruments, Beijing, China).

The experimental data were analysed using SPSS 16.0 (SPSS Inc., Chicago, USA) with an ANOVA being used to determine the significant differences between the different treatments. The least significant difference (LSD) was used to compare the means of the three replications, and the effects were considered significant at $p < 0.05$ in the statistical calculations. The Pearson correlation coefficient was used for correlation analysis. All graphs were plotted using Sigmaplot 10.0 (SPSS Inc., Chicago, USA).

RESULTS

From GS31 to GS71, the change trend of CCI decreased first and then increased, with GS71 showing the highest value (except at GS49 in 2011-2012). At GS34 in 2011-2012, GS32 in 2012-2013, and GS31 in 2013–2014, the CCI values of DD were significantly higher than that of SS under rainfall (no irrigation). Three years of results showed that the average CCI values of SS, SD, and DD planting patterns were 41.01, 41.07, and 42.01, respectively, with the DD value exceeding the SS value. The CCI values of DD were 6.76% (2011-2012), 9.63% (2012-2013), and 3.19% (2013-2014) higher than those of SS at GS71, respectively. Under irrigation levels of 0, 90, and 180 mm, the CCI values of DD were 41.61, 42.35, and 42.07, respectively. Compared with those values obtained with 0 mm treatment, CCI values of 90 and 180 mm irrigation treatments increased by 1.78 and 1.11%, respectively. The result showed that 90 mm enhanced the CCI (Fig. 2).

Net photosynthetic rate increased with the level of irrigation. The average Pn values under irrigation conditions of 0, 90, and 180 mm from 2011-2014 were 20.01, 23.75, and 24.76 μmol CO_2 m^{-2} s^{-1}, respectively; and the Pn values of the irrigation treatments were significantly higher than those of the rain-fed treatment ($p < 0.05$). Throughout the growth season, the Pn values of DD were 6.10 and 8.31% higher than those of SS and SD, respectively. Moreover, the Pn values of the 2013-2014 growth season were higher than those of the 2011-2012 and 2012-2013 growth season due to increased solar radiation during the 2013-2014 growth season (Table 1). From GS45 to GS71, the Pn values of the 180 mm treatment were significantly higher than those of 0 and 90 mm treatments in 2012-2013 ($p < 0.05$), with an order of 180 mm > 90 mm > 0 mm irrigation (Table 3). The Pn values at 180 and 90 mm irrigation levels were 3.73 and 18.69% higher, respectively, than those with 0 mm (rain-fed). A significant interaction effect between

Table 2. Monthly solar radiation (MJ m^{-2}) in the growing season of winter wheat during October 2011 to May 2014

Month	Oct	Nov	Dec	Jan	Feb	Mar	April	May	Total
2011-2012	315	163	219	223	304	419	538	622	2803
2012-2013	390	278	220	232	260	431	561	589	2961
2013-2014	402	277	210	168	298	487	575	828	3245

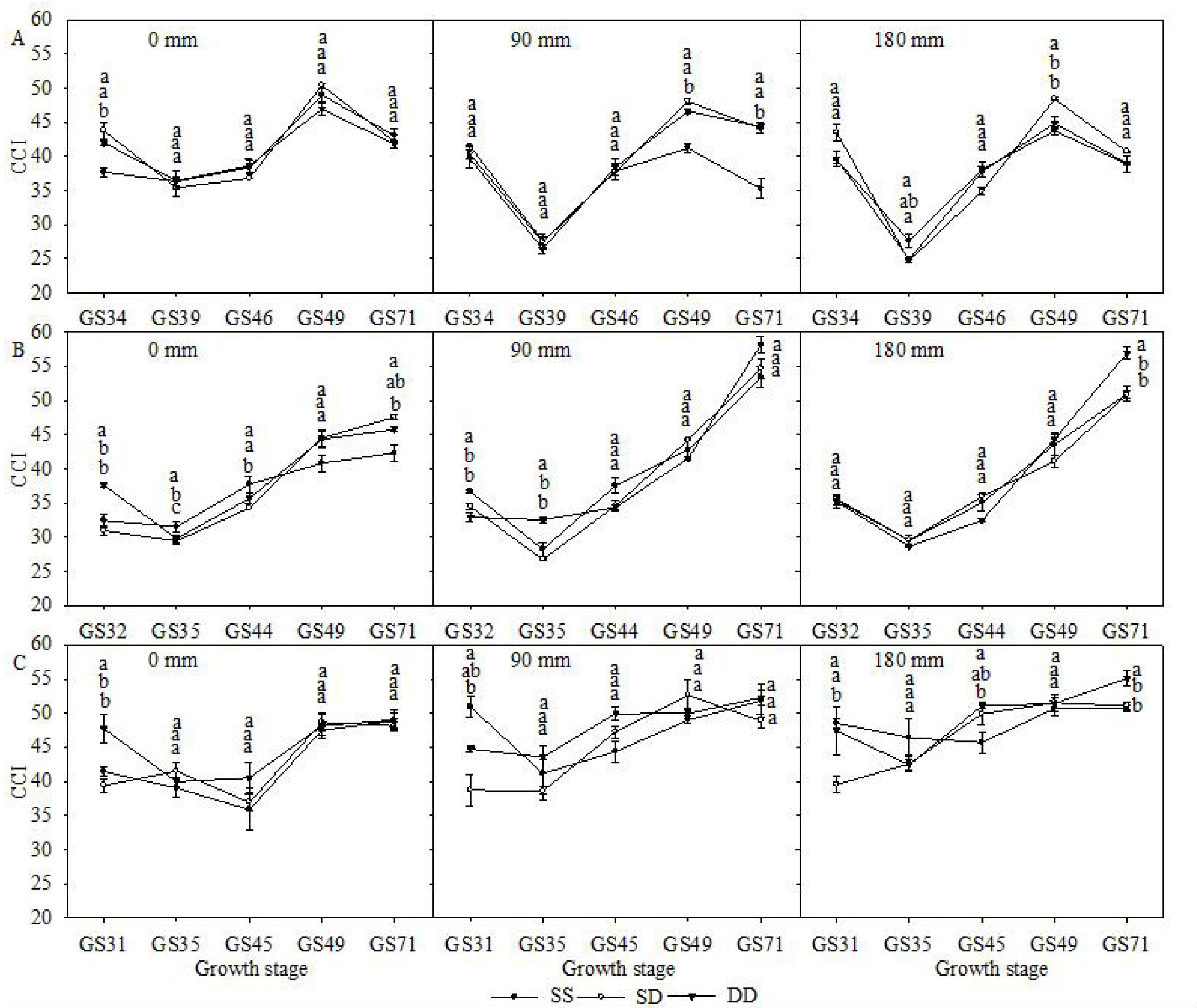

Fig. 2. Effects of planting patterns and irrigation level on the chlorophyll content index (CCI) of winter wheat at different growth stages in 2011-2012 (A), 2012-2013 (B) and 2013-2014 (C). Vertical bars = S.E.

irrigation levels and planting patterns was observed in 2012-2013 ($p < 0.01$). The result indicated that irrigation was beneficial for the increased Pn of winter wheat.

Results showed that dry matter weight gradually increased from GS35 to GS80 and increased with the increase in irrigation level during 2011-2014 (Fig. 3). The planting pattern significantly affected the dry matter weight during the growth stages ($p < 0.05$). During the 2011-2012 growth season, the dry matter weight of SS was significantly lower than those of DD and SD ($p < 0.05$), especially in GS45 to GS80, and the dry matter weight of DD was higher than that of SD. During the 2012-2013 growth season, the dry matter weight of DD was significantly higher than that of SS ($p < 0.01$), except at GS71 under rainfall. The dry matter weight values of DD and SD were higher than that of SS during the total growth period ($p < 0.05$).

Three years of experiments showed that the dry matter weight did not vary significantly between the different irrigation levels at GS35 and GS45. The average dry matter weights at 0, 90, and 180 mm irrigation levels were 965, 1039, and 1050 g m^{-2}, respectively. The dry matter weight increased with the irrigation level. The dry matter weights for the different planting patterns were in the order of DD > SD >SS, and the value of DD was significantly higher than that of SS ($p < 0.05$).

The average results of the 2012-2013 and 2013-2014 growing seasons of 0, 90 and 180 mm were 14.41, 13.87, and 13.61% (grain protein), 66.89, 67.20, and 66.93% (coarse starch), 1.94, 2.02, and 2.00% (rough fat), and 74.54, 74.03 and 74.03 (whiteness), respectively; and the grain protein of the rain-fed treatments (0 mm) was significantly higher than that of irrigation treatments ($p < 0.05$),

Table 3. Effects of planting patterns (PP) and irrigation levels (IL) on net photosynthetic rate (μmol CO_2 m^{-2} s^{-1}) of winter wheat at different growth stages during 2011-2014

Treatments	GS45				GS49				GS71			
	11-12	12-13	13-14	Mean	11-12	12-13	13-14	Mean	11-12	12-13	13-14	Mean
IL (mm)												
0	19.6c	19.3c	20.0b	19.6b	21.4b	13.4c	22.2b	19.0b	19.8b	12.2c	26.6a	19.5a
90	22.3a	22.2b	25.3a	23.2a	20.8b	22.5b	27.2a	23.5a	26.1a	17.1b	29.1a	24.1a
180	20.6b	23.9a	26.5a	23.7a	27.0a	24.9a	28.3a	26.7a	26.1a	18.6a	29.6a	24.8a
PP												
SS	20.3b	22.2a	22.1b	21.5ab	23.3a	21.0a	24.8b	23.1a	23.8a	17.2a	26.5b	22.5a
SD	20.1b	20.6b	23.2ab	21.3b	22.2ab	18.9b	25.0b	22.1a	24.0a	14.3c	28.7ab	22.3a
DD	22.0a	22.6a	26.5a	23.7a	22.9b	21.0a	27.9a	24.0a	24.2a	16.3b	30.1a	23.5a
Source												
IA	0.0001	0.0001	0.0103	0.0035	0.0001	0.0001	0.0001	0.0015	0.0001	0.0001	0.1718	0.2092
PP	0.0001	0.0072	0.1055	0.0907	0.1012	0.0006	0.0145	0.5770	0.5852	0.0001	0.1102	0.9184
IL×PP	0.2286	0.0086	0.9063	0.9996	0.2780	0.0001	0.4354	0.9752	0.0073	0.0001	0.9209	0.9875

SS – single-single row, SD – single-double row, DD – double-double row. Values followed by the different letters in each column are significantly different according to $p < 0.05$.

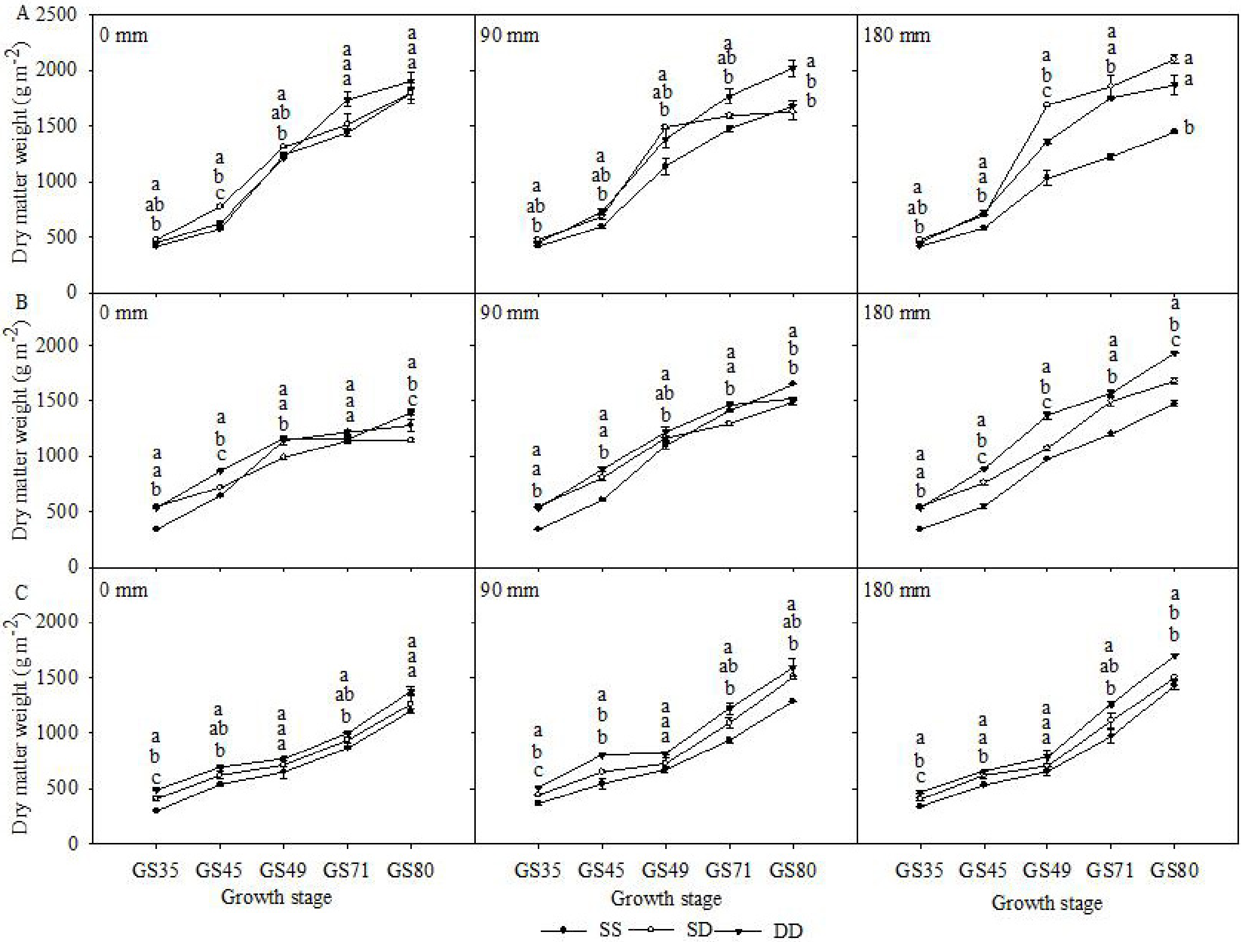

Fig. 3. Effects of planting patterns and irrigation level on the dry matter weight of winter wheat at different growth stages in 2011-2012 (A), 2012-2013 (B) and 2013-2014 (C). Vertical bars = S.E.

Table 4. Effects of different planting patterns and irrigation levels on the nutritional quality in winter wheat

Treatment	Grain protein (%)	Coarse starch (%)	Rough fat (%)	Whiteness
Irrigation levels (mm)				
0	14.41a	66.89	1.94b	74.54a
90	13.87b	67.20	2.02a	74.03b
180	13.61c	66.93	2.00a	74.03b
Planting patterns				
SS	14.18a	66.69b	1.95	74.16b
DS	13.95ab	67.29a	2.00	73.95b
DD	13.82b	66.85b	2.00	74.50a
Irrigation levels	0.0001	0.0613	0.0877	0.0113
Planting patterns	0.0002	0.0454	0.2020	0.0194
Irrigation levels × Planting patterns	0.0004	0.0205	0.6001	0.0011

SS – single-single row, SD – single-double row, DD – double-double row. Average for 2012-2014, followed by the different letters in each column are significantly different according to $p < 0.05$.

the rough fat andflour whiteness of the irrigation treatments (90 and 180 mm) were higher than that of the rain-fed treatment (Table 4). The grain protein of SS was 14.18%, and was 1.65 and 2.61% higher than those of SD and DD, respectively ($p < 0.05$). Under the same irrigation conditions, the whiteness of DD was 0.46 and 0.74% higher than those of SS and SD, respectively. The irrigation levels and planting patterns had significant interaction effects on grain protein, coarse starch and whiteness ($p < 0.05$), but there were no significant interaction effects on rough fat ($p > 0.05$).

Irrigation, planting patterns, and their interaction significantly affected the farinograph parameter, gluten index, sedimentation and falling number ($p < 0.05$) (Table 5). The average of SS, SD, and DD were 2.52, 2.72 and 2.48 min (dough development time), 44.42, 47.08 and 50.92 (gluten index), 555.67, 566.33 and 550.67 s (falling number), respectively; and the gluten index of DD was significantly higher than those of SS and SD, and the falling number was inverse ($p < 0.05$). Compared with the rain-fed treatment, irrigation treatments increased by 1.02% (water absorption), 13.61% (dough stability time), 24.90% (gluten index), 6.43% (sedimentation), 4.47% (falling number). Water absorption, flour yield, wet gluten content and sedimentation of 90 mm were significantly higher than those of 0 and 180 mm. The results showed that the 90 mm treatment could improve flour quality.

A significantly positive correlation was observed between the dry matter weight, Pn and falling number (Table 6); the dry matter weight (grain protein) showed a significantly negative correlation to sedimentation (falling number) ($p < 0.05$). Grain protein was significantly negatively correlated with Pn, dry matter weight, coarse starch, gluten index ($p < 0.01$), and positively correlated with sedimentation ($p < 0.01$). The wet gluten content increased with other variables (except for grain protein) and there were no significant differences between them, but the wet gluten content was significantly and positively correlated with rough fat ($p < 0.01$).

DISCUSSION

This study found that planting patterns and irrigation had an influence on the CCI, Pn, dry matter weight and grain quality of winter wheat, and there was a particular correlation between them. The quantification of chlorophyll content provides useful information for investigating the physiological properties of plants (Girma *et al*., 2013). Fang *et al*. (2018) showed that chlorophyll content markedly affects dry matter yield. Excessive irrigation may decrease chlorophyll content (Pirzad *et al*., 2011). Previous studies have shown that the use of the wide-narrow row can significantly improve the CCI and Pn of the flag leaves of winter wheat with increasing irrigation levels (Han *et al*., 2016). In this study, we came to a similar conclusion, the results showed that CCI increases with increasing irrigation levels, whereas the amplification rate decreases. The CCI values of DD and SD were higher than those of SS, and the DD showed the highest values. Planting pattern optimization facilitates the increase in CCI.

Irrigation treatment produced a higher dry matter weight than the non-irrigated treatment. Lin *et al*. (2016) showed that irrigation improves the transfer of pre-flowering assimilates to grains and that narrow row planting may increase the dry matter production of corn. It has previously been shown the leaf area index, the photosynthetically active radiation capture ratio, and radiation use efficiency of DD were higher than those of SD under 90 mm irrigation (Zhang *et al*., 2016), which is beneficial to dry matter

Table 5. Effects of different planting patterns and irrigation levels on the farinograph parameter in winter wheat

Treatment	Farinograph parameter							
	WA (mL 100^{-1} g)	DDT (min)	DST (min)	FY (%)	WGC (%)	GI	SED (mL)	FN (s)
Irrigation levels (mm)								
0	62.70b	2.63a	2.18	68.46b	34.39c	45.08b	29.33b	554.17c
90	63.95a	2.63a	2.13	69.21a	35.64a	45.50b	31.11a	562.42b
180	63.00b	2.43b	1.98	68.48b	35.23b	50.33a	24.69c	566.75a
Planting patterns								
SS	63.28	2.52b	2.25a	68.48	35.10	44.42c	30.83a	555.67b
DS	63.45	2.72a	2.08b	68.82	34.90	47.08b	30.23a	566.33a
DD	63.73	2.48c	1.97b	68.85	35.26	50.92a	29.03b	550.67c
Irrigation levels	0.0001	0.0002	0.0002	0.0007	0.0001	0.0001	0.0001	0.0244
Planting patterns	0.0001	0.0004	0.0001	0.0523	0.0731	0.0001	0.0032	0.0097
Irrigation levels × Planting patterns	0.0001	0.0001	0.0001	0.0079	0.1740	0.0001	0.0225	0.0001

WA – water absorption, DDT – dough development time, DST – dough stability time, FY – four yield, WGC – wet gluten content, GI – gluten index, SED – sedimentation, FN – falling number, SS – single-single row, SD – single-double row, DD – double-double row. Average for 2012-2014, followed by the different letters in each column are significantly different according to $p < 0.05$.

Table 6. Correlation coefficient between photosynthetic and grain quality factors of winter wheat during 2011 to 2014

	DM	Pn	GP	CS	RF	FY	WGC	GI	SED	FN
DM	1.000	0.555**	-0.615**	0.077	0.396*	0.416*	0.370	0.402*	-0.383*	0.409*
Pn		1.000	-0.538**	0.110	0.325	0.152	0.379	0.327	-0.310	0.411*
GP			1.000	-0.523**	-0.367	-0.275	-0.219	-0.729**	0.531**	-0.481*
CS				1.000	0.255	0.245	0.362	0.358	0.208	0.191
CF					1.000	0.307	0.538**	0.102	0.106	0.346
FY						1.000	0.063	0.026	0.219	0.301
WGC							1.000	-0.088	0.323	0.276
GI								1.000	-0.567**	0.000
SED									1.000	-0.126
FN										1.000

DM – dry matter weight, Pn – net photosynthetic rate, GP – grain protein, CS – coarse starch, RF – rough fat, FY – four yield, WGC – wet gluten content, GI – gluten index, SED – sedimentation, FN – falling number. Correlation is significant at the: *0.05 level, **0.01 level.

accumulation and increasing yield (Mao *et al*., 2017). The experimental results showed that the dry matter weight of DD was significantly higher than that of SS. Therefore, DD is the superior cultivation pattern for dry matter production. Wu *et al*. (2014) showed that water stress exerts a negative effect on Pn and expedites the senescence of the leaf at the flowering stage of wheat. Three years of research have shown that the Pn resulting from the 90 and 180 mm irrigation conditions were higher than those for plots that were only rain-fed. The result indicated that irrigation can increase leaf Pn, thereby improving dry matter yield.

The grain quality of the winter wheat is likely be affected by nutritional quality, the farinograph parameter, varieties and the environment. This study revealed that irrigation treatment would maintain higher grain protein, coarse starch and whiteness than rain-fed agriculture ($p < 0.05$), and the results showed that 90 mm treatment may improve flour quality, which is consistent with previous studies (Waraich *et al*., 2010). In contrast, Vida *et al*. (2014) determined that flour quality is not closely related to the environment for winter durum wheat; however, throughout the winter wheat growing season in the North China Plain, adequate irrigation could increase the water use efficiency, in the decreasing rainfall conditions. The gluten index is significantly correlated with genotype, management and environmental factors Garrido-Lestache *et al*., 2004; Har-Gil *et al*., 2011). The result illustrated that DD could significantly reduce the falling number, increase the gluten index, and improve the processing quality of winter wheat.

CONCLUSIONS

1. The results showed that chlorophyll content index, net photosynthetic rate, dry matter weight increased with higher levels of irrigation, in summary, irrigation improved the quality of the winter wheat.

2. Planting patterns significantly affected chlorophyll content index, net photosynthetic rate and dry matter weight, also double-double row may increase dry matter accumulation by increasing chlorophyll content index and the flag leaves net photosynthetic rate of winter wheat, which has a positive role in improving the grain quality at a later stage.

3. Therefore, with water shortages, a 90 mm irrigation level combined with a double-double row planting pattern was the most beneficial practice revealed by the study for winter wheat production and gain quality in North China Plain.

Conflict of interest: The Authors declare no conflict of interest.

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