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Effects of Post-Anthesis Temperature and Radiation on Grain Filling and Protein Quality of Wheat (*Triticum aestivum* L.)

Zhenzhen Zhang, Zhipeng Xing , Nianbing Zhou, Chen Zhao, Bingliang Liu, Dinghan Jia, Haiyan Wei, Baowei Guo and Hongcheng Zhang *

Jiangsu Key Laboratory of Crop Cultivation and Physiology/Jiangsu Co-Innovation Center for Modern Production Technology of Grain Crops, Research Institute of Rice Industrial Engineering Technology, Agricultural College Yangzhou University, Yangzhou 225009, China

* Correspondence: hc Zhang@yzu.edu.cn; Tel.: +86-0514-87974595

Abstract: Due to climate change, global warming, and reduced radiation, there is an urgent need for research to explore the effects on wheat grain filling and protein-related quality. In this study, two spring and two semi-winter varieties were analyzed. Six sowing dates were set in the experiment, at 10-day intervals from the beginning of the local sowing window. The seedling population of the first sowing date (S1) was 300×10^4 plants ha^{-1} , which was observed to have increased by about 10% by the subsequent sowing date. During the experiment, due to the different dates of sowing, the treatments were in different growth stages; so, all the treatments were grown under different day and night temperatures and radiation to study the effects on post-anthesis grain filling and protein quality. The results showed that the sowing date decreased the effective accumulated temperature (EAT) and the cumulative radiation after anthesis and increased the daily average, maximum, and minimum temperatures. The decrease in the EAT of 94.99°C d and the increase in the daily average temperature of 1.59°C after anthesis resulted in a decrease in the wheat grain weight of 4.5 g and an increase in the grain filling rate of 0.029 mg d^{-1} . This may be due to the shortening of the wheat filling time with the increase in the day/night temperatures. Compared with the normal sowing date, the later sowing date caused a decrease in the EAT and an increase in the T_{mean} , which led to an increase in the wheat protein content, wet gluten content, and sedimentation value. There was a positive correlation between the grain filling rate and the protein content in the wheat. Compared with radiation, temperature significantly regulates wheat grain filling and protein formation. These results can be used to guide the sowing date to obtain a higher quality of wheat protein in the future climate change.



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Keywords: temperature; radiation; grain filling characteristics; protein

1. Introduction

After the green revolution, most of the countries have sufficient grain crop productivity; so, now the additional research focus is on crop quality [1]. Improving the nutrition and processing quality of wheat plays an important role in the current social development. Protein is one of the most essential nutrients for humans. The protein content and quality affect the gluten content, sedimentation value, and processing and nutritional qualities of wheat [2,3]. The protein in wheat grain is not only controlled by genetic factors but is also affected by environmental factors [4].

Climate change activities severely affect the nutritional value of wheat grain protein via its photosynthesis, grain filling, nutrient use efficiency, and micronutrient transport [5]. According to the climate model, Gaffen et al. predicted that temperatures could continue to rise, accompanied by frequent extreme weather, as well as reduced solar radiation due to the increased aerosol concentrations and pollutants in the atmosphere [6]. The time from flowering to maturity is the key period for forming grain yield and quality [7]. Additionally,

the temperature and radiation during this period are particularly important for wheat grain filling and protein formation. Therefore, a detailed understanding of the effects of post-anthesis climate change on wheat grain filling and protein-related characteristics is essential for global food and nutritional security.

Previous researchers have conducted a lot of research on the effects of climate change on wheat after anthesis [8]. It is mainly studied through two cultivation methods—one is by changing the wheat growth [9], and the other is by using an artificial climate chamber to provide different temperatures or light in the key growth period of wheat [10]. There are different results for the various test methods. Some studies have shown that when the sowing date is postponed, the effective accumulated temperature of the total growth period of wheat decreases, the daily mean temperature increases, and the cumulative radiation increases gradually [11]. Previous studies have shown that the change of the sowing date is the closest to the future temperature and radiation changes. Therefore, by changing the sowing date, simulation studies on the changes in temperature and light in the future may explore the effects of temperature and radiation on the filling rate and protein-related quality of wheat.

However, previous studies on grain filling and protein content revealed that when the sowing date was delayed, the filling rate increased, the grain weight decreased, and the protein content increased slowly [12,13], whereas with the postponement of the sowing date, the grain weight of wheat decreased, the filling rate decreased, and the protein content decreased gradually [14]. A high temperature after anthesis can accelerate the grain filling rate and shorten the filling time of wheat [15]. An increase in temperature can be beneficial to the synthesis of protein content [16]. Furthermore, less light during the filling stage is beneficial to the increase in protein content [17]. However, with regard to the effects of temperature and radiation on grain filling and the protein quality of wheat, the results are not consistent [16,18].

Moreover, in the past we only studied the sowing date or the regulating temperature and light through the climate chamber, but there were few studies on the effects of temperature and radiation on protein under the sowing date [19,20]. Therefore, this study's aim is to analyze different temperatures and radiation levels after anthesis by postponing the sowing date and controlling the planting density and to study the response of the grain filling characteristics and protein-related quality to different temperatures and radiation levels. The main objectives of this study are (1) to explore the effects of different temperatures and radiation levels after anthesis on wheat grain filling and (2) to study the protein and protein-related quality of wheat.

2. Materials and Methods

2.1. Experimental Site and Design

Field experiments were conducted from October 2017 to June 2018 and October 2018 to June 2019 in Jianhu County, Yancheng City, Jiangsu Province, China (N33°47', E119°77', 4 m altitude). Jianhu County lies in the transition zone between the subtropical and warm temperate zones. Its annual average sunshine duration, precipitation, and average temperature were 2172 h, 1032 mm, and 14 °C, respectively. The experimental field was clay loam, and the basic fertility of the surface soil (0–20 cm depth) was as follows: organic matter (26.8 g kg^{−1}), rapidly available phosphorus (45.6 mg kg^{−1}), total nitrogen (1.59 g kg^{−1}), and rapidly available potassium (96.6 mg kg^{−1}). The pH of the soil during the experiment was 6.82.

Two spring varieties (Yangmai23 and Yangmai25) and two semi-winter varieties (Huaimai 33 and Nongmai 158), which are widely cultivated in Jiangsu Province, China, were used in the experiment. Yangmai 23 (YM23) is from the Jiangsu Jin Tu Di seed industry; Yangmai 25 (YM25) is from the Jiangsu Li Xia He area Agricultural Science Research Institute; Huaimai 33 (HM33) is from the Huaiyin Agricultural Science Institute; and Nongmai 158 (NM158) is from the Jiangsu Shen Nong Da Feng seed industry. Six sowing dates were set in the experiment; these were October 31 (S1), November 10 (S2), November 20 (S3), November

30 (S4), December 10 (S5), and December 20 (S6) [9]. The seedling population of the first sowing date was set as $300 \times 10^4 \text{ ha}^{-1}$, which was increased by 10% for each delayed sowing date [21]. During this period, the seedlings were manually thinned. The slow- and controlled-release fertilizer of the wheat (N:P:K = 26:15:8) and 750 kg ha^{-1} and 75 kg ha^{-1} of urea (229.5 N ha^{-1} in total) were applied to the experimental field as the base fertilizers, but no fertilizer was used in the later stages [22]. All the fertilizers were evenly applied in the 0–15 cm tillage layers during sowing, with a row spacing of 22 cm and a sowing depth of about 2 cm. The plot area was 15 m^2 ($3.3 \text{ m} \times 4.5 \text{ m}$), with two replicates.

2.2. Measurement Items and Related Calculation Methods

The spikes with the same flowering were marked in each experimental plot. From the 10th day after flowering, 30 wheat ears were taken every 5 days, killed for 20 min at 105°C , dried to a constant weight at 80°C , and threshed and weighed by hand, and then, the grain weight was recorded [23].

In this experiment, the Angstrom–Prescott (AP) equation was used to calculate the solar radiation [24]:

$$Q = QA(a + bs)$$

where Q ($\text{MJ m}^{-2} \text{ d}^{-1}$) is the total solar radiation reaching the surface, QA ($\text{MJ m}^{-2} \text{ d}^{-1}$) is the astronomical radiation, “s” is the percentage of sunshine (%), and “a” and “b” are the empirical coefficients.

The formula for calculating the cumulative solar radiation (CSR) at each growth stage is as follows:

$$\text{CSR} = \sum Q \times \text{days of growth stage (d)}$$

The formula for calculating the effective accumulative temperature (EAT) in each growth stage is as follows:

$$\text{EAT} = \sum (T1 - T0) \times \text{days of growth stage (d)} \quad [T1 > T0, \text{ when } T1 < T0, (T1 - T0) \text{ is calculated as } 0]$$

where $T1$ and $T0$ (the lower limit temperature of wheat growth is 0°C) are the mean daily and biological zero temperatures, respectively.

The logistic equation was used to fit the process of grain filling: $y = A/(1 + Be^{-Kt})$ [25].

Among them, A (theoretical maximum grain weight), B (primary parameter), and K (growth rate parameter) are all fitting parameters of the equation.

$$\text{Average filling rate (G)} = A \times K/6$$

The nitrogen content in the grain was determined using a semi-automatic Kjeldahl nitrogen meter [26], in which the protein coefficient of the wheat was 5.70.

The gluten content was determined using the Perten Instrument gluten washing system [27], and the gluten meter was the Glutomatic 2200.

The sedimentation value of the wheat flour was determined using the Zeleny method [27].

2.3. Experimental Data Collection and Analysis

The daily mean temperature and sunshine hours during the wheat growing season were provided by the Jianhu County Meteorological Station in Yancheng City, Jiangsu Province, China. Based on the analysis of the local meteorological data in the past 10 years, the temperature and radiation in this experiment were within the range of variation.

The data recorded and sorted out using Microsoft Excel 2016 were statistically analyzed using SPSS 22.0 (ANOVA). The means were compared by the least significant difference at the probability level of 0.05 (LSD, $P = 0.05$). The graphs were prepared using Origin 2022.

3. Results

3.1. Effects of Different Sowing Dates on Temperature and Radiation after Anthesis

The post-anthesis temperature of the two types of wheat showed the same rule under different sowing dates, and the rules were similar in different years. (Tables 1 and 2)

With the postponement of the sowing date, the EAT of S1 was lower than that of S2–S6 by -1.9 – 57.1 °C d, 14.4 – 72.9 °C d, 32.6 – 90.7 °C d, 68.4 – 107.3 °C d, and 74.4 – 120 °C d, respectively. The daily mean temperature (T_{mean}), daily maximum temperature (T_{max}), and daily minimum temperature (T_{min}) increased gradually with the postponement of the sowing date, and they increased by 0.32 °C for each delayed sowing date. The realization rule of T_{max} and T_{min} is the same as that of T_{mean} . With the postponement of the sowing date, the CSR of S1 was lower than that of S2–S6 by 1.85 – 54.59 MJ m $^{-2}$, 6.39 – 71.11 MJ m $^{-2}$, 47.11 – 91.73 MJ m $^{-2}$, 49.69 – 118.92 MJ m $^{-2}$, and 52.43 – 140.39 MJ m $^{-2}$, respectively. The change in the daily mean radiation (R_{mean}) dose was not significant during the seeding period.

Table 1. Effects of different treatments on post-anthesis temperature.

		2017–2018				2018–2019			
		EAT (°C d)	T_{mean} (°C)	T_{max} (°C)	T_{min} (°C)	EAT (°C d)	T_{mean} (°C)	T_{max} (°C)	T_{min} (°C)
YM23	S1	758.00	19.95	24.38	15.94	789.30	20.54	25.86	15.69
	S2	753.50	20.36	24.89	16.25	732.20	19.79	24.76	14.92
	S3	743.60	20.66	25.19	16.57	734.40	20.40	25.38	15.60
	S4	705.30	20.74	25.19	16.82	719.10	21.15	26.34	16.06
	S5	684.80	20.75	25.18	16.84	691.20	21.60	26.73	16.66
	S6	674.50	21.08	25.48	17.25	677.90	21.87	27.07	16.85
YM25	S1	767.70	20.20	24.74	16.15	805.70	19.65	24.63	14.93
	S2	761.20	20.57	25.12	16.52	774.10	20.37	25.42	15.44
	S3	729.50	20.84	25.29	16.89	762.00	21.17	26.43	16.07
	S4	705.40	20.75	25.15	16.88	739.00	21.74	26.98	16.61
	S5	692.30	20.98	25.46	17.04	698.40	21.83	27.01	16.84
	S6	678.80	21.21	25.63	17.49	685.70	22.12	27.35	17.05
HM33	S1	789.70	20.78	25.34	16.64	801.50	20.55	25.67	15.58
	S2	753.10	20.92	25.39	16.97	803.40	21.14	26.37	16.13
	S3	716.80	21.08	25.64	17.13	784.80	21.80	27.02	16.71
	S4	699.00	21.18	25.66	17.34	768.90	21.97	27.14	17.02
	S5	713.50	21.62	26.15	17.70	733.10	22.22	27.43	17.15
	S6	705.00	22.03	26.67	18.05	727.10	22.72	28.01	17.69
NM158	S1	777.00	20.45	25.03	16.28	799.30	19.98	25.09	15.09
	S2	729.20	20.26	24.18	17.11	775.40	20.96	26.12	15.97
	S3	708.40	20.84	25.29	16.93	756.80	21.62	26.95	16.42
	S4	692.30	20.98	25.46	17.04	742.30	21.83	27.03	16.89
	S5	678.80	21.21	25.63	17.49	701.00	21.91	27.10	16.92
	S6	686.30	21.45	25.94	17.55	693.00	22.35	27.53	17.36

Table 2. Effects of different treatments on post-anthesis radiation.

		2017–2018		2018–2019	
		CSR (MJ m $^{-2}$)	R_{mean} (MJm $^{-2}$ day $^{-1}$)	CSR (MJ m $^{-2}$)	R_{mean} (MJm $^{-2}$ day $^{-1}$)
YM23	S1	516.67	13.60	617.65	15.06
	S2	514.00	13.89	563.06	15.22
	S3	510.27	14.17	552.96	15.36
	S4	467.64	13.75	557.26	16.39
	S5	466.98	14.15	506.94	15.84
	S6	443.80	13.87	498.76	16.09
YM25	S1	531.33	13.98	605.56	14.77
	S2	517.08	13.98	603.71	15.89
	S3	493.48	14.10	597.30	16.59
	S4	471.83	13.88	558.45	16.42
	S5	464.42	14.07	514.37	16.07
	S6	440.05	13.75	484.77	15.64
HM33	S1	547.93	14.42	630.69	16.17
	S2	507.01	14.08	625.88	16.47
	S3	476.82	14.02	582.12	16.17
	S4	456.20	13.82	564.48	16.13
	S5	485.71	14.72	529.48	16.04
	S6	495.49	15.48	523.98	16.37
NM158	S1	540.58	14.23	623.08	15.58
	S2	510.52	14.18	602.12	16.27
	S3	480.51	14.13	582.78	16.65
	S4	464.42	14.07	536.10	15.77
	S5	440.05	13.75	504.16	15.75
	S6	461.56	14.42	482.70	15.57

3.2. Effects of Post-Anthesis Temperature and Radiation on Grain Filling Characteristics of Wheat

The grain filling changes of the two types of wheat showed the same rule under the different temperature and radiation treatments, and the rules were similar in different years. (Table 3) With the postponement of the sowing date, the filling rate increased gradually, and the average filling rate increased by 0.018 mg d^{-1} for each delayed sowing date. The theoretical maximum grain weight decreased gradually with the postponement of the sowing date and decreased by 0.9 per delayed sowing date. The B value decreased slowly with the postponement of the sowing date, i.e., the effective filling time was also progressively shortened, with an average decrease of 4.53 per delayed sowing date. The K value increased steadily with the postponement of the sowing date.

Table 3. Effects of different temperature and radiation on grain filling coefficient and average filling rate of wheat.

		2017–2018				2018–2019			
		A	B	K	G	A	B	K	G
YM23	S1	43.71 a	73.92 a	0.190 d	1.38 e	44.07 a	67.66 a	0.190 e	1.39 e
	S2	43.19 ab	67.95 b	0.194 cd	1.39 d	43.44 b	61.77 b	0.194 de	1.40 de
	S3	42.76 b	59.15 c	0.196 cd	1.40 d	42.56 c	56.73 c	0.200 d	1.41 d
	S4	41.77 c	52.17 d	0.203 c	1.41 c	41.49 d	54.41 d	0.206 c	1.42 c
	S5	40.52 d	49.85 e	0.213 b	1.44 b	41.04 d	44.79 e	0.211 b	1.44 b
	S6	39.91 d	47.20 e	0.221 a	1.47 a	39.93 e	39.76 f	0.221 a	1.47 a
YM25	S1	43.80 a	71.54 a	0.191 f	1.39 d	44.35 a	64.90 a	0.191 e	1.41 f
	S2	43.36 ab	69.25 b	0.196 e	1.42 c	43.57 b	60.29 b	0.195 e	1.42 e
	S3	42.42 bc	62.88 c	0.202 d	1.42 c	42.81 c	57.22 c	0.201 d	1.43 d
	S4	41.39 cd	53.44 d	0.207 c	1.43 c	41.90 d	54.40 d	0.209 c	1.46 c
	S5	40.63 d	51.89 d	0.216 b	1.46 b	41.49 d	47.73 e	0.213 b	1.47 b
	S6	40.15 d	48.34 e	0.224 a	1.49 a	40.70 e	45.80 e	0.223 a	1.51 a
HM33	S1	44.86 a	70.84 a	0.190 e	1.42 d	46.90 a	71.09 a	0.182 e	1.42 f
	S2	44.46 ab	65.09 b	0.193 e	1.43 cd	46.08 b	70.01 a	0.187 e	1.44 e
	S3	43.79 b	59.06 c	0.198 d	1.44 c	45.04 c	62.15 b	0.193 d	1.45 d
	S4	42.19 c	50.70 d	0.205 c	1.44 c	43.56 d	58.89 c	0.202 c	1.47 c
	S5	41.10 d	50.64 d	0.216 b	1.48 b	42.02 e	56.58 d	0.211 b	1.48 b
	S6	40.10 e	46.66 e	0.225 a	1.5 a	41.46 e	56.86 d	0.220 a	1.52 a
NM158	S1	44.53 a	71.27 a	0.189 d	1.41 e	46.26 a	71.54 a	0.184 e	1.42 e
	S2	43.53 b	67.89 b	0.196 de	1.42 de	45.07 b	69.12 a	0.190 de	1.43 d
	S3	42.98 b	59.83 c	0.199 d	1.43 d	44.78 c	64.72 b	0.194 d	1.45 c
	S4	41.66 c	53.37 d	0.207 c	1.44 c	42.38 d	60.76 c	0.206 c	1.45 c
	S5	40.60 d	50.88 de	0.216 b	1.46 b	41.44 e	54.92 d	0.214 b	1.48 b
	S6	39.87 e	46.17 e	0.223 a	1.48 a	40.31 f	50.87 e	0.226 a	1.52 a

Data followed by different lowercase letters are significantly different at the 5% probability level, as determined by the LSD test.

3.3. Effects of Temperature and Radiation on Protein and Related Quality of Wheat

The changes in the protein and protein-related traits of the two types of wheat under the different temperature and radiation treatments showed the same rule, and the rules were similar in different years (Table 4). There were significant differences in the protein content, wet gluten content, and sedimentation value among the sowing date treatments. With the postponement of the sowing time, the protein content increased gradually, and the protein content increased by 0.21% for each delayed sowing date. With the postponement of the sowing time, the wet gluten content increased gradually, and the wet gluten content increased by 0.45% per delayed sowing date. With the postponement of the sowing time, the sedimentation value increased gradually, and the sedimentation value increased by 1.34 mL for each delayed sowing date.

Table 4. Effects of temperature and radiation on protein and related quality of wheat.

		2018–2018			2018–2019		
		Protein Content (%)	Wetglute Content (%)	Zeleny (mL)	Protein Content (%)	Wetglute Content (%)	Zeleny (mL)
YM23	S1	13.11 d	31.37 e	50.35 d	13.31 d	31.83 d	52.20 d
	S2	13.44 c	31.92 d	52.87 c	13.52 cd	32.33 d	53.45 d
	S3	13.78 b	32.36 c	53.05 c	13.84 bc	33.02 c	56.20 c
	S4	13.91 b	32.44 c	56.15 b	13.95 b	33.38 c	57.00 c
	S5	14.26 a	33.27 b	56.50 b	14.08 ab	33.93 b	58.75 b
	S6	14.49 a	34.32 a	58.60 a	14.34 a	34.60 a	60.25 a
YM25	S1	12.35 e	29.31 f	43.67 e	12.49 e	29.72 d	44.50 e
	S2	12.65 de	29.81 e	46.40 d	12.73 de	30.27 c	46.20 d
	S3	12.93 cd	30.27 d	48.05 c	13.04 cd	30.67 bc	48.00 c
	S4	13.03 bc	30.93 c	49.85 b	13.33 bc	31.14 b	50.02 b
	S5	13.31 ab	31.42 b	51.50 a	13.54 ab	31.92 a	51.72 a
	S6	13.46 a	32.54 a	52.35 a	13.70 a	32.13 a	53.00 a
HM33	S1	12.41 d	29.53 f	54.05 d	12.49 e	29.99 d	54.00 d
	S2	12.82 c	30.29 e	55.90 c	12.86 d	30.48 d	55.83 c
	S3	13.06 c	30.89 d	56.40 c	13.23 c	31.11 c	56.75 c
	S4	13.39 b	31.51 c	58.10 b	13.48 bc	31.69 b	58.25 b
	S5	13.71 a	32.02 b	59.30 b	13.72 ab	32.28 a	59.25 ab
	S6	13.98 a	32.54 a	60.95 a	13.93 a	32.61 a	60.25 a
NM158	S1	12.78 e	31.05 e	55.70 d	12.86 f	31.41 e	55.35 e
	S2	13.10 d	31.55 d	56.85 cd	13.20 e	32.01 d	56.90 d
	S3	13.40 cd	32.04 c	57.55 c	13.55 d	32.50 cd	58.53 c
	S4	13.67 bc	32.35 bc	59.10 b	13.73 c	32.92 bc	59.10 bc
	S5	13.85 ab	32.76 b	60.10 b	13.91 b	33.31 b	60.35 ab
	S6	14.02 a	33.31 a	61.50 a	14.10 a	34.24 a	61.35 a

Data followed by different lowercase letters are significantly different at the 5% probability level, as determined by the LSD test.

3.4. Correlation Analysis between Temperature, Radiation, and Grouting Characteristics

The correlations between the temperature, radiation, and grain filling characteristics of the two types of wheat were the same, and the annual rules were the same (Figure 1). The EAT was significantly negatively correlated with the A and B values and positively correlated with the K value and grain filling rate. T_{mean} , T_{max} , and T_{min} had similar correlations with the grain filling characteristics, exhibiting significant positive correlations with the A and B values and significantly negative correlations with the K value and grain filling rate. The CSR was significantly negatively correlated with the A and B values and positively correlated with the K value and grain filling rate.

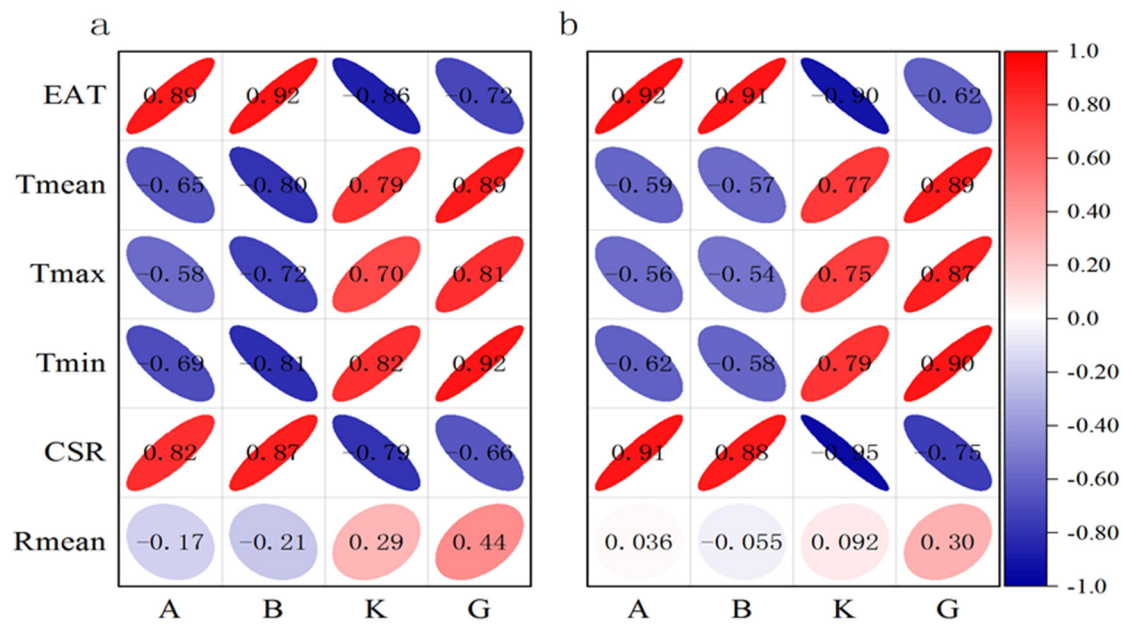


Figure 1. The correlation of temperature and radiation with filling coefficient and filling rate. (a): 2017–2018, (b): 2018–2019; EAT: effective accumulated temperature, T_{mean}: daily mean temperature, T_{max}: daily average high temperature, T_{min}: daily lowest temperature, CSR: cumulative effective radiation, R_{mean}: daily mean radiation; B and K are the filling coefficients, G: the average filling rate during the filling period; the critical values of the correlation coefficient: $r_{0.05} = 0.404$ and $r_{0.01} = 0.5151$.

3.5. Correlation between Temperature, Radiation, and Protein-Related Quality

The correlations between the temperature, radiation, and protein-related quality of the two types of wheat were the same, and the annual rules were the same (Figure 2). The EAT was negatively correlated with the protein content, wet gluten content, and sedimentation value. T_{mean}, T_{max}, and T_{min} were positively correlated with the protein content, wet gluten content, and sedimentation value. The CSR was negatively correlated with the protein content, wet gluten content, and sedimentation value. There were no significant correlations between R_{mean} and the protein content, wet gluten content, or sedimentation value.

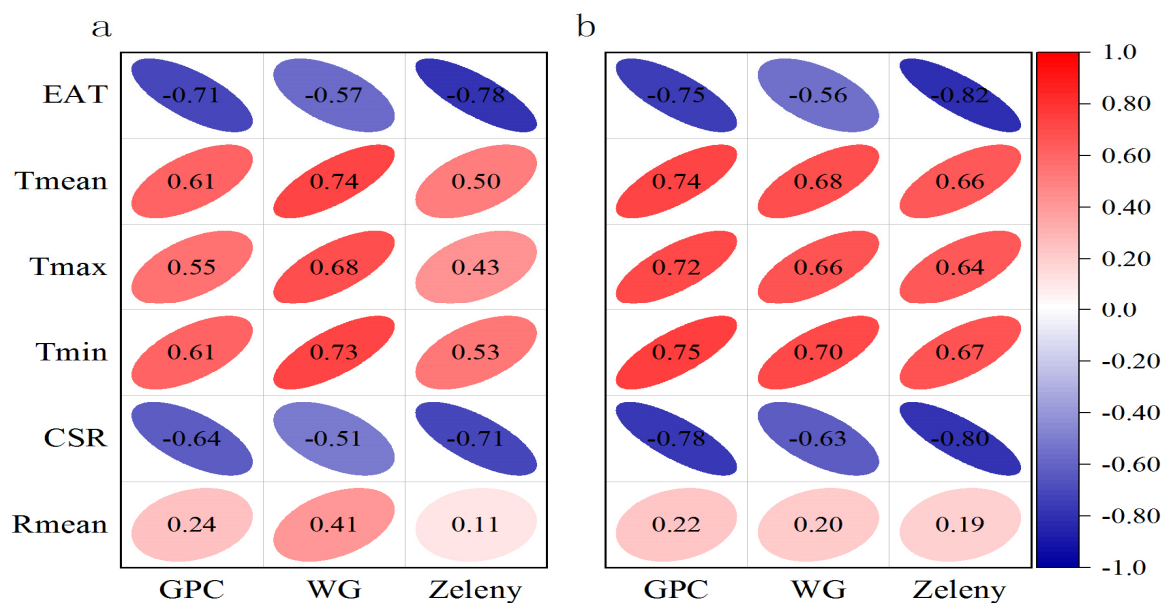


Figure 2. The correlation between temperature and radiation and protein content, gluten content,

sedimentation value. (a): 2017–2018, (b): 2018–2019; EAT: effective accumulated temperature, T_{mean} : daily mean temperature, T_{max} : daily average high temperature, T_{min} : daily lowest temperature, CSR: cumulative effective radiation, R_{mean} : daily mean radiation; GPC: protein content, WG: wet gluten content, Zeleny: sedimentation value. The critical values of the correlation coefficient: $r_{0.05} = 0.404$, and $r_{0.01} = 0.5151$.

4. Discussion

4.1. Effect of Sowing Date on Temperature and Radiation after Anthesis

The shift in the sowing window led to a different quality and quantity of day/night temperature and light intensity during the crop duration. The previous studies used controlled climate chambers for the standardized temperature or radiation variable to study the effect of the factors under consideration on grain filling and protein. In this experiment, by changing the sowing date under the different climatic conditions after flowering, the temperature and radiation were the most significant factors affecting the wheat [9]. A systematic analysis was conducted to study the effects of post-anthesis temperature and radiation on wheat grain filling and protein production. The previous studies showed that the sowing date delays the changes in flowering and ripening time, resulting in changes in the temperature at different stages after anthesis [28]. The current study showed that the postponement of the sowing date led to the postponement of the flowering and maturity dates. For each delayed sowing date, the days from flowering to maturity were shortened by 1.5 days; the daily average temperature increased by $0.32\text{ }^{\circ}\text{C}$; the effective accumulated temperature decreased by $19\text{ }^{\circ}\text{C d}$; and the cumulative radiation decreased by 19.56 MJ m^{-2} . The results of this study are consistent with those of the previous studies. The main reason is that the late sowing delayed the flowering time, resulting in higher T_{mean} , T_{max} , and T_{min} after flowering in the late sowing than in the early sowing [29]. Higher temperature will accelerate the growth and senescence of wheat, leading to the shortening of the growth period from flowering to maturity, and the shortening of the growth period will lead to the gradual reduction in the effective accumulated temperature and accumulated radiation [30].

4.2. Effects of Temperature and Radiation on Grain Filling

Temperature and radiation are the main climatic factors affecting grain filling. Sofield et al. found that temperature determined the length of the wheat grain filling period. In the range of $16\text{--}28\text{ }^{\circ}\text{C}$, when the daily mean temperature increased by $1\text{ }^{\circ}\text{C}$, the grain filling period was shortened by 2.8 days, and the filling rate increased gradually with the increase in temperature [31]. Wiegand et al. determined that when the daily mean temperature increased by $1\text{ }^{\circ}\text{C}$, the grain filling time was shortened by 3.1 days. When the temperature exceeded about $15\text{ }^{\circ}\text{C}$, it was obvious that the effect of grain weight on the grain filling duration was more significant [32,33]. In this study, a logistic growth curve was used to fit the grain filling characteristics of the wheat; the correlations between the temperature, radiation, and grain filling characteristics were analyzed. The results showed that the temperature increased by $0.32\text{ }^{\circ}\text{C}$, the filling time shortened by 1.5 days, and the filling rate increased by 0.018 mg d^{-1} . The current experimental results are similar to the results of the previous findings. The previous studies showed that when the average daily temperature exceeds $25\text{ }^{\circ}\text{C}$, the flag leaves are dehydrated and dried, the water metabolism is seriously maladjusted, and the filling time of the wheat plants is seriously shortened [34]. However, in this study, only part of the treatments had a daily mean temperature of more than $25\text{ }^{\circ}\text{C}$, which might also be the main reason for the shortening of the filling time in this experiment. The filling time was shortened, but the grain weight was reduced less, and hence, the filling rate increased [35]. In this study, it was shown that there was a significant positive correlation between the EAT and the theoretical maximum grain weight. It shows that the increase in effective temperature is beneficial in increasing the grain weight, which is consistent with the study of Momtazi et al. [36,37]. Light can also affect the grain filling rate and grain weight of wheat. The earlier sowing date can obtain higher solar radiation and grain weight, but the longer filling period can affect the filling rate [38,39]. However, some studies have shown that the decrease in radiation reduces the SPAD value of the leaves and

has a negative effect on the characteristics of chlorophyll fluorescence, reducing the grain weight and photosynthetic rate [40,41]. In this study, the grain weight decreased and the grain filling rate increased gradually with the decrease in the total solar radiation, and there were no correlations between the daily average solar radiation and the grain filling rate or the grain weight [42]. This may be because the temperature affects the photosynthesis of wheat leaves; therefore, the higher solar radiation during the day cannot be fully utilized. Therefore, the temperature can affect the grain filling characteristics of wheat more than the solar radiation.

4.3. Effects of Temperature and Radiation on Proteins and Related Properties

Temperature and radiation affect not only the filling rate but also the protein-related quality [43]. The previous studies showed that the increase in temperature can increase the contents of total protein, gliadin, and glutenin in wheat grains and reduce the protein yield [44–46]. There was a significant positive correlation between the protein and the gluten contents [47]. At the same time, it can be concluded that the increase in temperature can increase the gluten content of wheat. Other studies have shown that when the average temperature increases by 1 °C, the protein content increases by 0.435%, and the sedimentation value increases by 1.09 mL. When the temperature rises above 32 °C, it is not conducive to the increase in protein content because high temperature accelerates the cessation of the vegetative and reproductive growth [48,49]. In this study, the temperature increased by 0.32 °C, the protein content increased by 0.21%, the wet gluten content increased by 0.45%, and the sedimentation value increased by 1.34 mL. Although the materials and methods are different, the results of this study are similar to those mentioned above. In this study, the temperature was not more than 32 °C; therefore, the protein content, gluten content, and sedimentation value increased with the increase in temperature. This may be due to the increase in temperature, glutamate synthase activity, and glutenin and gliadin [50]. Previous studies have shown that the decrease in radiation is beneficial to protein formation [51,52]. However, few studies have demonstrated that post-anthesis radiation has no effect on the protein [53]. In this study, the total solar radiation was significantly negatively correlated with the protein and gluten contents and the sedimentation value, but there was no correlation between the daily radiation and the protein and gluten contents and the sedimentation value. This may be because there is no significant rule of daily mean radiation after anthesis in this experiment, which further shows that the effect of temperature on protein formation is greater than that of radiation on protein formation.

5. Conclusions

The delay in the current sowing window led to the gradual decrease in the accumulated temperature and the total cumulative radiation after anthesis and increased daily average, maximum, and minimum temperatures. In the current scenario of climate change, with the change in temperature and radiation, the wheat grain filling rate increased, the grain weight decreased, the protein content increased, the wet gluten content increased, and the sedimentation value increased. The increase in the grain filling rate of the wheat was beneficial to protein formation. Compared with radiation, temperature could better regulate the post-anthesis filling and protein synthesis of the wheat. This study shows that changing the sowing date is the closest way to simulate the changes of temperature and radiation in the future; so, the results of this study can deal with the problem of wheat stubble and high-quality wheat protein under future climate change. In the continuation of the current research findings, there may be the changes in the temperature and radiation, filling rate, and protein synthesis in the whole filling stage, as well as the further exploration of how temperature and radiation affect protein synthesis in the whole filling process.

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