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Optimizing Nitrogen Application for Enhanced Yield and Quality of Strong-Gluten Wheat: A Case Study of Zhongmai 578 in the North China Plain

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Abstract: This study was designed to determine the optimal nitrogen application rate for strong-gluten wheat cultivation in the North China Plain. Employing Zhongmai 578, a strong-gluten wheat variety, a field experiment was conducted with the following four nitrogen levels: 0 kg/ha (N0), 150 kg/ha (N1), 210 kg/ha (N2), and 270 kg/ha (N3). The research focused on examining the impact of nitrogen application on the photosynthesis, yield, and quality of strong-gluten wheat. The findings revealed that the N2 treatment (210 kg/ha) yielded the highest results compared to the N0 treatment. Photosynthetic parameters, including chlorophyll content in wheat flag leaves, generally exhibited an increase followed by a decrease, peaking at 7 days after anthesis (except for the transpiration rate, which peaked at 14 days post-anthesis). In the first year, quality indices such as water absorption, capacity, sedimentation value, ductility, protein, and wet gluten initially increased and then decreased with rising nitrogen levels. Conversely, in the second year, these quality indices, including hardness, showed a progressive increase with elevated nitrogen application. These results indicate that enhanced nitrogen application can significantly improve the photosynthetic characteristics of strong-gluten wheat, thereby augmenting both yield and quality. Within the parameters of this experiment, an application of 210 kg/ha of nitrogen emerged as the optimal rate, promoting the superior yield and quality of strong-gluten wheat in the North China Plain.



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Keywords: strong-gluten wheat; photosynthetic characteristics; nitrogen application; quality; North China Plain

1. Introduction

Wheat, a pivotal staple crop, plays a crucial role in global food security, with its yield directly impacting this critical area [1,2]. High-gluten wheat, in particular, serves as a fundamental resource in the production of staple foods, contributing significantly to the creation of superior quality breads. Moreover, it provides essential gluten-rich flour for processing various traditional foods, such as noodles and steamed bread. In light of the rising living standards globally, the demand for high-quality, strong-gluten wheat has increased markedly [3]. This surge underscores the importance of enhancing wheat cultivation techniques and understanding the theoretical aspects to meet this growing need.

Photosynthesis is an important indicator of plant growth and development, as well as an important source of material for crop growth and development and seed formation [4]. It has been shown that photosynthesis is the main factor affecting yield formation [5], and 90–95% of wheat production is obtained directly or indirectly from photosynthesis [6]. The net photosynthetic rate reflects the accumulation of organic matter in plants, and the thousand grain mass is a major factor affecting wheat yield [7]. Chlorophyll is necessary for plants to carry out photosynthesis and is the main site where photosynthesis takes place. Chlorophyll is necessary for the production of organic matter and the release of oxygen in

plants, and there is a direct link between the level of chlorophyll and the accumulation of chemical energy in plants as well as the release of energy from compounds. Chlorophyll content is a good response to plant growth and development and is closely related to photosynthetic rate. In studies of most plant physiological traits, chlorophyll content has a direct correlation with photosynthesis effects and the photosynthesis products produced, thus contributing to further plant growth [8].

Genetic factors and agronomic practices significantly influence wheat yield and grain quality. Among these practices, nitrogen fertilization plays a pivotal role in wheat's growth and development, acting as a critical determinant in the formation of both yield and quality [9,10]. In recent years, the use of nitrogen fertilizers has escalated, leading to increased production costs and diminished efficacy in enhancing yield. Furthermore, the application of chemical nitrogen fertilizers poses environmental concerns. Issues such as volatilization, denitrification, and leaching into the soil have been observed, resulting in environmental pollution and a reduction in fertilizer utilization efficiency [11–13]. Extravagant uptake of nitrogen reduces the rate of nitrogen translocation from the nutrient organs to the seed [14], affects the formation and translocation of photosynthetic products, and leads to oversized crop populations [15] and increased competition for source stores [16]. Excessive application of nitrogen also affects the starch-pasting characteristics and quality of cereal grains [17] and excessive application of nitrogen fertilizers not only does not give full play to its fertilizer efficiency and raises the cost of agricultural products, it also causes serious economic losses. This situation underscores the need for optimized nitrogen management strategies in wheat cultivation to balance agricultural productivity with environmental sustainability.

Consequently, selecting high-quality, strong-gluten wheat varieties, complemented by suitable cultivation practices, is instrumental to achieving the dual objectives of high yield and quality in strong-gluten wheat production [18]. It has been observed that moderate nitrogen application can enhance the photosynthetic performance of wheat leaves [19]. Research indicates that nitrogen application can increase the relative chlorophyll content in leaves (measured as SPAD values), thereby improving photosynthetic capacity. However, excessive nitrogen application can lead to a premature decline in the photosynthetic capacity of the flag leaves in later growth stages, adversely affecting both yield and quality [20]. Further studies have demonstrated that [21] judicious nitrogen fertilizer application can stimulate the growth of stems, leaves, and other nutrient organs. This promotes sustained plant photosynthesis, enhances seed nitrogen uptake, and improves wheat yield and quality [21–23]. Findings by Liu et al. have highlighted that moderate (N210) nitrogen application significantly increases the number of spikes, grains per spike, and overall wheat yield, substantially impacting seed quality [24,25]. Similarly, research by Shasha Li and colleagues corroborates that moderate nitrogen application can effectively improve wheat yield and seed quality [26].

Currently, extensive research has been conducted on the impact of varying nitrogen application rates on the yield and quality of strong-gluten wheat; however, studies focusing specifically on the photosynthetic aspects of this wheat variety remain limited. In this experimental study, we selected a strong-gluten wheat variety, Zhongmai 578, and established four different nitrogen application rates. The objective was to investigate the effects of nitrogen application on the following key parameters: chlorophyll content in flag leaves, net photosynthetic rate, stomatal conductance, transpiration rate, inter cellular CO₂ concentration, and, ultimately, the yield and quality of the strong-gluten wheat. This study aims to provide a theoretical foundation and technical guidance for cultivating high-yield, high-quality strong-gluten wheat in the plains region of North China.

2. Materials and Methods

2.1. Experimental Design

The study was executed at the Jiaozhou Modern Agricultural Demonstration Park, Qingdao Agricultural University (35.53° N, 119.58° E), spanning two consecutive years from October 2021 to June 2023. The site has a semi-humid monsoon climate and the soil type is

sandy ginger black soil. Monthly precipitation and average monthly temperatures during winter wheat fertility in 2022 and 2023 are shown in Figure 1. The effective precipitation during the reproductive period of winter wheat was 92.2 mm and 124.6 mm in 2021–2022 and 2022–2023, respectively. The soil organic matter, total nitrogen, alkaline dissolved nitrogen, quick-acting phosphorus, quick-acting potassium and soil pH in the 0–20 cm layer before sowing are shown in Table 1. The wheat variety chosen for this experiment was Zhongmai 578. Four nitrogen fertilizer gradients were established, designated as 0, 150, 210, and 270 kg/ha, corresponding to treatment groups N0, N1, N2, and N3, respectively. Urea (with a nitrogen content of 46%) was used as the nitrogen fertilizer source for all treatments except N0, and a base application of 90 kg/ha was applied. Additional N1, N2, and N3 applications occurred at the jointing stage, coordinated with irrigation. The irrigation was 120 mm throughout the reproductive period, with two irrigations at the nodulation and flowering stages. Both phosphorus fertilizer (P_2O_5 : 12%) and potassium fertilizer (K_2O : 50%) were applied uniformly across all plots at a 90 kg/ha rate as a base fertilizer, with calcium superphosphate acting as a phosphate fertilizer, potassium sulfate as a potash fertilizer, and urea as a nitrogen fertilizer. The experimental design, detailed in Table 2, employed a single-factor randomized block design with three replications. Each plot covered an area of 20 m² with a row spacing of 20 cm. The wheat variety undergoing testing is the high-quality, strong and high-yielding wheat variety Zhongmai 578, which is semi-wintering, with a full-life span of 219.5 to 229.6 days. In 2017–2018, it participated in the regional trial of the waterland group in the northern part of the winter wheat area of the Yellow River and Huaihe River, with an average yield of 7434 kg/ha, which was 2.8% higher than that of the control Jimai 22; the average yield was 7434 kg/ha. In the 2018–2019 renewal trial, the average yield was 8997 kg/ha, with a 3.6% increase in yield over the control Jimai 22; in the 2019–2020 production trial, the average yield was 8328 kg/ha, with a 1.5% increase in yield over the control Jimai 22 [27].

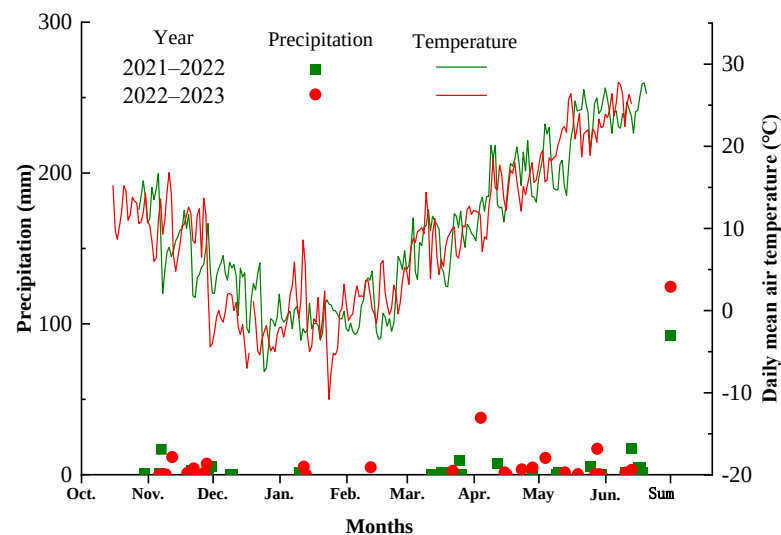


Figure 1. Temperature and precipitation during wheat growing period.

Table 1. Basic physical and chemical properties of 0~20 cm soil layer of experiment field before sowing.

Growing Season	Organic Matter (g/kg)	Total Nitrogen (g/kg)	Alkaline Dissolved Nitrogen (mg/kg)	Quick-Acting Phosphorus (mg/kg)	Quick-Acting Potassium (mg/kg)	pH
2021–2022	18.11	0.79	96.2	17.2	142.2	7.50
2022–2023	16.73	0.76	94.6	17.6	139.9	7.52

Table 2. Experimental design.

Nitrogen Fertilizer Levels	Base Fertilizer (kg/ha)			Nitrogen Topdressing Amount at Jointing Stage (kg/ha)
	Nitrogen Fertilizer	Phosphate Fertilizer	Potash Fertilizer	
N0	0	90	90	0
N1	90	90	90	60
N2	90	90	90	120
N3	90	90	90	180

2.2. Measurement Items and Methods

2.2.1. Relative Chlorophyll Content (SPAD)

Five representative wheat plants were selected from each plot at the flowering stage and at 7, 14, 21, and 28 days post-flowering to assess the relative chlorophyll content [28]. The chlorophyll content of flag leaves was quantified using a SPAD-502 chlorophyll meter (Minolta, Osaka, Japan).

2.2.2. Photosynthetic Properties of Flag Leaf

Photosynthetic parameters, including the net photosynthetic rate (P_n), stomatal conductance (G_s), transpiration rate (Tr), and inter cellular CO_2 concentration (C_i) of flag leaves, were measured. These measurements were taken under natural light conditions using a LI-6400 portable photosynthesizer (LI-COR, Lincoln, NE, USA) at 10:00 a.m.–11:00 a.m. on days 0, 7, 14, 21, and 28 after flowering. For each treatment, six representative wheat plants were selected, with the process being replicated thrice.

2.2.3. Determination of Quality Traits

Quality parameters of selected, cleaned wheat kernels were analyzed using the MATRX-I Fourier near-infrared quality analyzer (Germany). This analysis included measurements of kernel water absorption, capacity, sedimentation value, ductility, hardness, protein content, wet gluten, and other relevant traits.

2.2.4. Determination of Wheat Yield

Yield-related parameters, such as the number of spikes per plant, number of grains per spike, and the weight of a thousand grains, were recorded at wheat maturity. For yield measurement, a 3 m² area was selected from each plot.

2.2.5. N Accumulation and Use

Samples for the determination of dry matter accumulation at maturity were ground, digested in concentrated sulfuric acid, and the total N content of the plants was determined using the semi-micro Kjeldahl method. The formula for calculating N uptake and use is as follows [29]:

$$\text{N accumulation} = \text{N content (\%)} \times \text{dry matter accumulation};$$

N use efficiency (NUE, kg/kg) is calculated by dividing the seed yield by the plant N accumulation;

N fertilizer bias productivity (PFP, kg/kg) is defined as the seed yield per unit of N applied;

N fertilizer agronomic use (NAE, kg/kg) = (N applied area seed yield – N free area seed yield)/N applied

N harvest index (%) (NHI) = total seed N accumulation/total plant N accumulation

2.3. Data Processing

Data obtained from the experiments were systematically processed using Microsoft Excel 2021. Graphical representations of the data were created using Origin 2021 software, ensuring a clear and precise visualization of the results. Statistical analyses, including Analysis of Variance (ANOVA), were conducted utilizing SPSS 18.0 software. This comprehensive approach to data analysis and representation facilitated a robust and thorough evaluation of the experimental findings.

3. Results

3.1. Effect of Different Nitrogen Application Treatments on Photosynthetic Characteristics of Wheat Flag Leaf

3.1.1. Influence of Nitrogen Fertilization on Chlorophyll Content (SPAD Value) in Flag Leaves of Wheat

Figure 2 illustrates the dynamic trend in chlorophyll content, which generally increased initially and then decreased over time. In the first year of the study, chlorophyll content peaked at 7 days post-flowering across all nitrogen fertilizer treatments, followed by a gradual decline from 14 to 28 days. During the second year, the peak values of different treatments varied, but a consistent decrease was observed from 14 to 28 days post-anthesis. Specifically, at 28 days post-anthesis, the chlorophyll content in treatments N1, N2, and N3 was higher by 28.68%, 81.15%, and 68.44%, respectively, compared to the N0 treatment. Over the two-year period, the N1, N2, and N3 treatments consistently outperformed the N0 treatment. The variations among the three treatments (N1, N2, and N3) were inconsistent across different years and specific days post-flowering. However, the highest chlorophyll content was generally noted in the N2 treatment, with the exception of the 21-day post-flowering period in the first year. This suggests that moderate nitrogen application significantly enhances the chlorophyll content in the flag leaves of wheat.

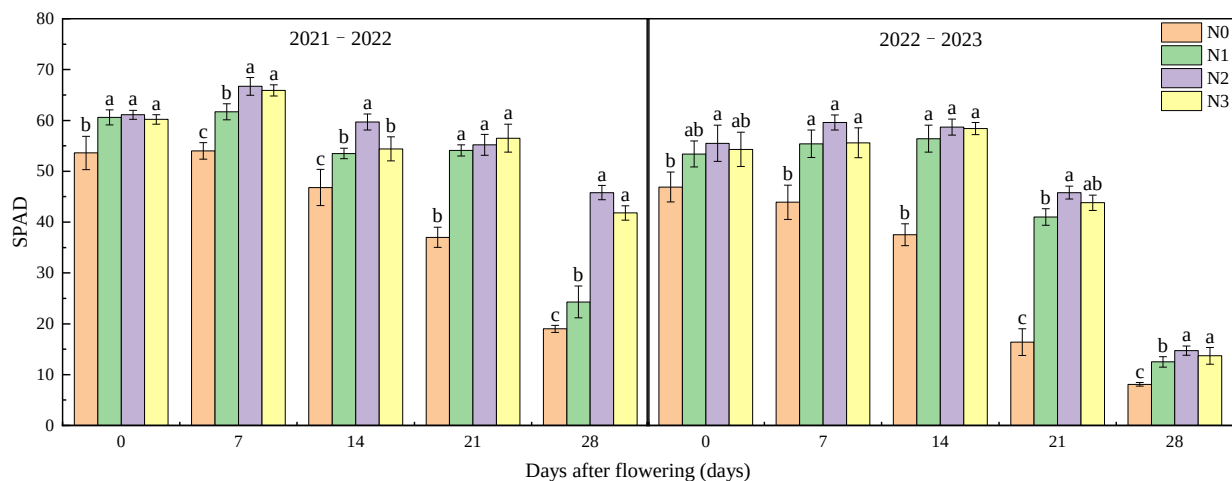


Figure 2. Changes in chlorophyll content of wheat flag leaves after flowering. Different letters indicate a significant difference ($p < 0.05$, Tukey's test).

3.1.2. Impact of Varied Nitrogen Applications on Net Photosynthetic Rate in Flag Leaves of Wheat

As depicted in Figure 3, nitrogen application was found to significantly enhance the P_n of wheat flag leaves. Over the course of the two-year experiment, the P_n of flag leaves initially increased and then decreased as the days post-flowering progressed. The peak in P_n was observed at 7 days after anthesis. At the onset of anthesis (0 days), the P_n for each treatment displayed the following trend: $N3 > N2 > N1 > N0$. At 7 days post-anthesis, the trend altered slightly, with N2 and N3 demonstrating higher rates than N1 and N0. From 14 to 28 days post-anthesis, the N2 treatment consistently exhibited the highest P_n . Notably, at 28 days post-anthesis, the P_n in the N2 treatment remained at a comparatively high level,

significantly surpassing that of the other treatments. In terms of comparative analysis over the two years, the Pn in the N2 treatment was higher by 10.67% and 18.72% than N3 in the first and second years, respectively.

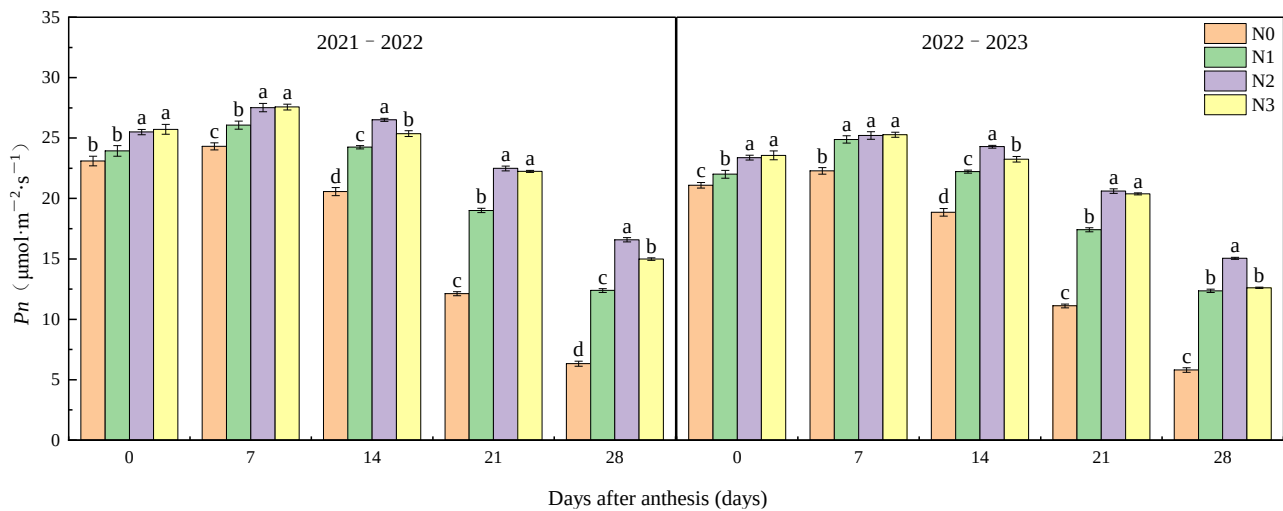


Figure 3. Changes in net photosynthetic rate of wheat flag leaf after anthesis. Different letters indicate a significant difference ($p < 0.05$, Tukey's test).

3.1.3. Variation in Stomatal Conductance of Wheat Flag Leaves Due to Different Nitrogen Treatments

Figure 4 presents the trends in G_s of wheat flag leaves over two years. The G_s exhibited a pattern of increase followed by a decrease as the days after anthesis progressed. The peak in G_s was observed at 7 days post-anthesis. Throughout all stages of post-anthesis, the G_s in treatments N1, N2, and N3 were consistently and significantly higher than that in the N0 treatment. No significant differences were noted between the N2 and N3 treatments, except at seven days post-flowering in the first year when N3 was significantly higher than N2. From 0 to 7 days post-anthesis, the G_s in each treatment were ranked as $N3 > N2 > N1 > N0$. From 14 to 28 days post-anthesis, the order changed to $N2 > N3 > N1 > N0$. At 28 days post-flowering, the G_s in N1, N2, and N3 were 49.67%, 70.64%, and 65.12% higher than the N0 in the first year and 49.52%, 70.53%, and 64.98% higher than the N0 in the second year, respectively.

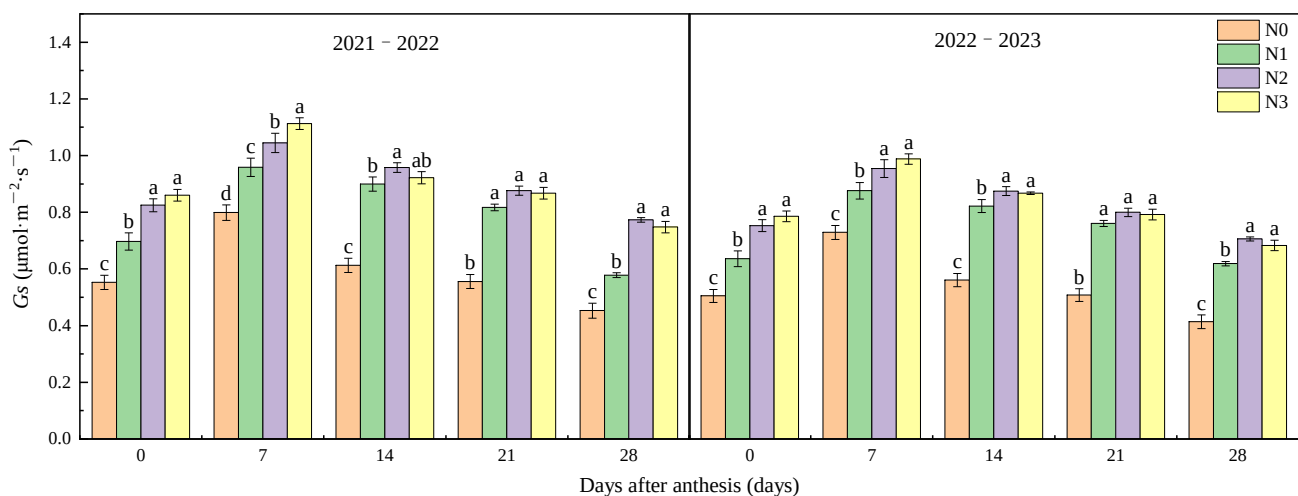


Figure 4. Changes in stomatal conductance of wheat flag leaf after anthesis. Different letters indicate a significant difference ($p < 0.05$, Tukey's test).

3.1.4. Effect of Diverse Nitrogen Fertilization Levels on Transpiration Rate in Flag Leaves of Wheat

Figure 5 illustrates the variation in the Tr of wheat, which initially increased and decreased as the days progressed post-anthesis. The peak Tr was observed at 14 days post-anthesis. In the first year, the Tr for each treatment was relatively high at 28 days post-anthesis, with no significant differences noted among the N1, N2, and N3 treatments. At the onset of anthesis (0 days), the trend in Tr was $N3 > N2 > N1 > N0$, which then shifted to $N2 > N3 > N1 > N0$ from 7 to 28 days post-anthesis, a pattern that remained consistent across both years. Notably, at 14 days post-anthesis, the N2 treatment exhibited a Tr significantly higher than the other treatments. Specifically, in the first year, the Tr in the N2 treatment was 35.91%, 14.10%, and 5.62% higher than the N0, N1, and N3 treatments, respectively. In the second year, these figures were 23.09%, 20.17%, and 5.63% higher for N2 than N0, N1, and N3, respectively.

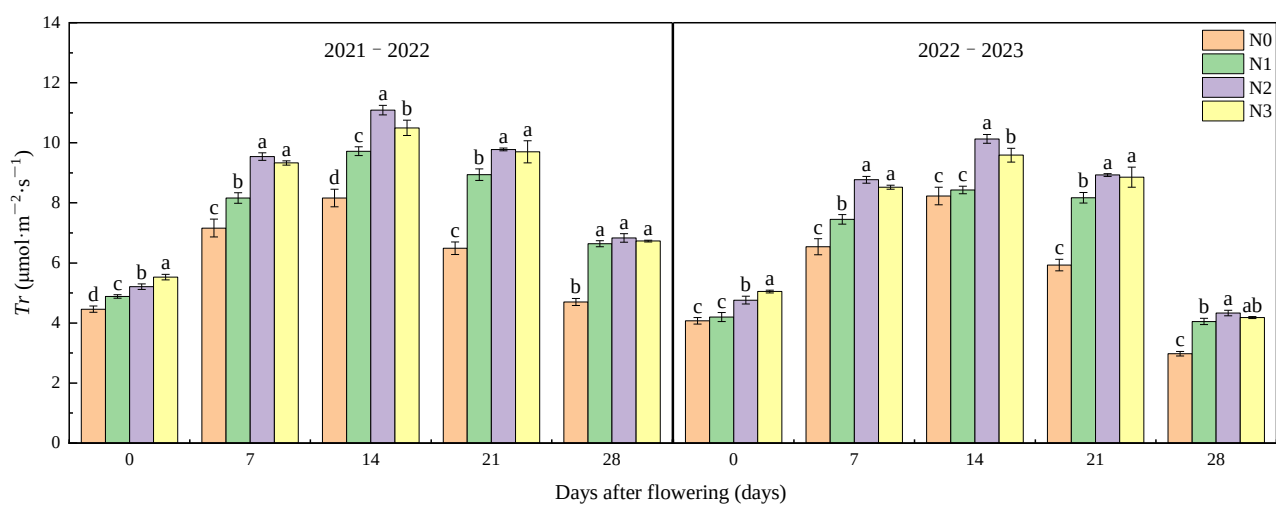


Figure 5. Changes in transpiration rate of wheat flag leaf after anthesis. Different letters indicate a significant difference ($p < 0.05$, Tukey's test).

3.1.5. Alterations in Inter Cellular CO_2 Concentration in Wheat Flag Leaves Owing to Varied Nitrogen Applications

As delineated in Figure 6, the study observed a fluctuating pattern in C_i within wheat flag leaves post-flowering. Initially, there was a decrease, followed by an increase in CO_2 levels, with the minimum concentration recorded at 7 days after flowering. Across the two years of the experiment, at all evaluated stages, the C_i across different treatments displayed the following consistent order: $N0 > N1 > N2 > N3$. Notably, the N2 and N3 treatments maintained consistently lower C_i levels when compared to the other treatments. The variance between the N2 and N3 treatments was generally insignificant (except at 21 days post-anthesis, where the CO_2 concentration in N2 was significantly lower than that in N3). This pattern suggests that the application of nitrogen has a discernible effect in reducing the C_i in wheat flag leaves.

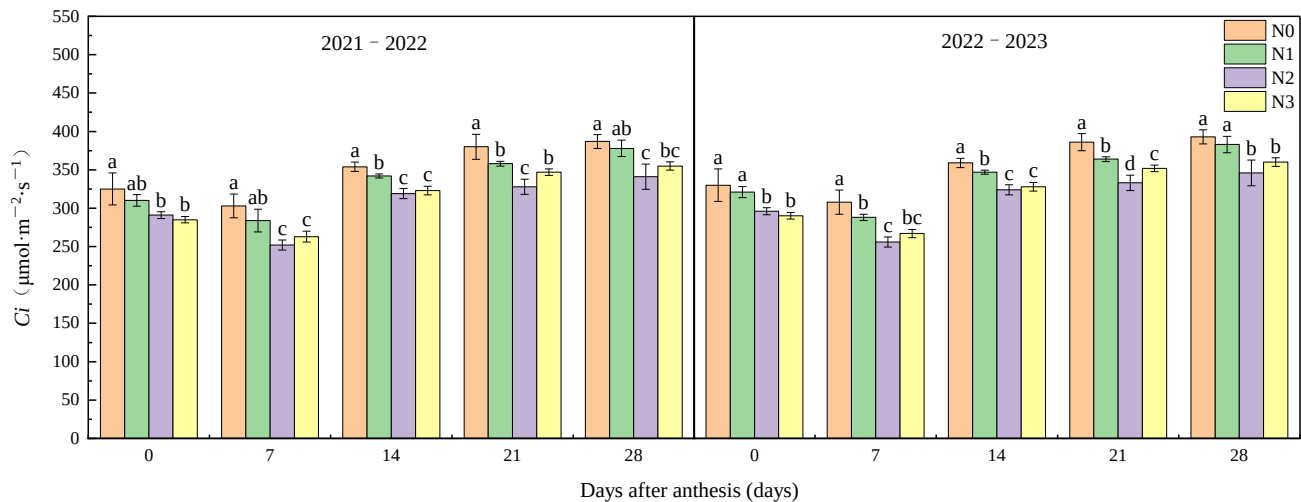


Figure 6. Changes in inter cellular CO₂ concentration of wheat flag leaf after anthesis. Different letters indicate a significant difference ($p < 0.05$, Tukey's test).

3.2. Influence of Nitrogen Treatments on Wheat Yield and Associated Yield Components

Table 3 demonstrates the impact of varying nitrogen (N) application rates on wheat yields over two consecutive years. The yield exhibited a trend of increasing and then decreasing with escalating N application, with the sequence of yield performance being N2 > N3 > N1 > N0. Notably, the highest yield was achieved under the N2 treatment, significantly surpassing the other treatments, with yields recorded at 9210.6 kg/ha and 9127.7 kg/ha in the first and second years, respectively. Over these two years, there was an observed increase in both the number of spikes per plant and the number of grains per spike with increased N application, while the thousand grain weight demonstrated a decreasing trend. This pattern indicates that the enhancement in yield was primarily attributed to the increase in the number of spikes and grains per spike rather than the grain weight.

Table 3. Effects of different treatments on yield and yield components of wheat.

Particular Year	Treatment	The Number of Spikes ($\times 10^4/\text{hm}^2$)	Number of Grains in Spikes	The Thousand Grain Weight (g)	Yield (kg/ha)
2021–2022	N0	429.7 c	26.6 d	52.6 a	5026.7 d
	N1	642.7 b	30.3 c	51.5 b	8447.0 c
	N2	669.3 a	32.3 a	50.6 c	9210.6 a
	N3	689.0 a	31.0 b	49.2 d	8832.6 b
2022–2023	N0	416.8 c	27.5 d	50.9 a	4875.0 d
	N1	623.0 b	31.4 c	49.9 b	8193.2 c
	N2	661.7 a	33.4 a	49.1 c	9127.7 a
	N3	666.2 a	32.1 b	47.7 d	8567.1 b

Note: Different letters indicate a significant difference ($p < 0.05$, Tukey's test).

3.3. Effect of Different Nitrogen Fertilizer Treatments on Nitrogen Use Characteristics of Wheat

As shown in Table 4, the nitrogen accumulation showed a gradual increasing trend with the increase in nitrogen application in two years, which was manifested as N3 > N2 > N1 > N0. The winter wheat nitrogen utilization efficiency and nitrogen harvest index decreased with the increase in nitrogen application, showing N0 > N1 > N2 > N3. The winter wheat nitrogen fertilizer bias productivity and nitrogen fertilizer agronomic utilization as a whole declined with the increase in N application, showing N1 > N2 > N3 in both years.

Table 4. Effect of different nitrogen fertilizer treatments on nitrogen utilization characteristics of wheat.

Particular Year	Treatment	Nitrogen Accumulation (kg/ha)	Nitrogen Use Efficiency	Nitrogen Harvest Index (%)	Nitrogen Fertilizer Bias Productivity	Nitrogen Use Efficiency (NUE, kg/kg)
2021–2022	N0	115.1 d	43.7 a	79.9 a		
	N1	204.9 c	41.2 b	76.3 b	56.3 a	22.8 a
	N2	264.2 b	35.6 c	70.4 c	44.8 b	20.9 b
	N3	277.7 a	31.8 d	67.2 d	32.7 c	14.8 c
2022–2023	N0	112.7 d	43.3 a	79.1 a		
	N1	200.7 c	40.8 b	75.6 b	54.6 a	22.1 a
	N2	258.8 b	35.3 c	69.7 c	43.5 b	20.3 b
	N3	272.0 a	31.5 d	66.5 d	31.7 c	13.7 c

Note: Different letters indicate a significant difference ($p < 0.05$, Tukey's test).

3.4. Two-Year Comparative Analysis of Wheat Grain Quality Indices under Varied Nitrogen Fertilization Treatment

Table 5 presents a comprehensive overview of the variation in wheat grain quality indices across two years, as influenced by different nitrogen (N) application rates. In the first year, with the exception of grain hardness, all quality indices of wheat grains displayed a pattern of initial increase followed by a decrease as the nitrogen application rate increased. Notably, the N2 treatment achieved the maximum values regarding water absorption, sedimentation value, ductility, and wet gluten content of wheat kernels, significantly outperforming the other treatments. Conversely, in the second year, a gradual increase in each quality index was observed with the rising N application, culminating in the highest values under the N3 treatment. However, it is important to note that, for the second year, except for protein and wet gluten content, the differences between the N2 and N3 treatments were not statistically significant for other wheat kernel quality indices.

Table 5. Effect of different treatments on wheat grain quality.

Particular Year	Treatment	Water Absorption/%	Capacity/(g·L ^{−1})	Sedimentation Value/mL	Ductility/mm	Hardness/%	Protein/%	Wet Gluten/%
2021–2022	N0	55.93 c	780.30 b	20.05 d	101.77 c	45.83 b	11.80 b	26.45 c
	N1	61.76 ab	809.40 a	32.88 b	139.16 b	48.01 b	14.49 a	33.34 b
	N2	61.99 a	809.60 a	35.84 a	151.42 a	51.49 a	14.84 a	36.62 a
	N3	59.44 b	808.57 a	30.45 c	133.42 b	52.39 a	14.49 a	32.62 b
2022–2023	N0	55.56 b	791.43 b	19.26 c	96.30 c	45.11 c	9.92 d	22.67 d
	N1	58.60 a	811.45 a	26.47 b	114.42 b	51.14 b	12.94 c	28.99 c
	N2	59.94 a	819.95 a	28.77 a	156.05 a	53.51 a	13.64 b	30.87 b
	N3	60.00 a	820.58 a	29.37 a	161.74 a	54.07 a	15.05 a	33.85 a

Note: Different letters indicate a significant difference ($p < 0.05$, Tukey's test).

4. Discussion and Conclusions

Photosynthesis constitutes the cornerstone of crop yield formation, with approximately 90% of wheat yield being attributable to photosynthesis, of which the flag leaf's contribution ranges between 20% and 30% [30]. Extensive research, including that by Kang et al. [31] and Qu Wenkai et al. [25], underscores the significant influence of nitrogen on the growth and development of the flag leaf. Proper nitrogen fertilization not only augments the photosynthetic efficiency and chlorophyll content of the flag leaf but also delays its senescence during the grain-filling period, thereby enhancing the leaf area index and optimizing light energy interception [32]. Optimal nitrogen levels can elevate the content of photosynthetic pigments in leaves, activate key enzymes of the photosystem, foster gas exchange, affect chlorophyll fluorescence properties, and thereby improve the overall photosynthetic, physiological, and metabolic processes [33]. This improvement extends to the growth and development of wheat's roots, stems, leaves, and other nutrient

organs, fostering better photosynthesis and nutrient accumulation [34]. Shi Yu et al. [35]. showed that, under the condition of 240 kg/ha of total nitrogen fertilizer, the application of 2/3 of nitrogen fertilizer at the nodulation stage was beneficial in improving the photosynthetic characteristics of wheat, and it significantly increased the seed yield by 3.1%–3.8% compared with the base-to-track ratio of 1:1 treatment. Kang Guozhang et al. [31]. found that the moderate application of N fertilizer at the stage of nodulation and spiking can significantly improve the photosynthetic capacity of post-flowering plants and prolong the functional period of post-flowering leaves, promoting the formation of seeds and grouting. Qu Wenkai et al. found that the SPAD value and net photosynthetic rate of two wheat varieties, Jiemai 22 and Yannong 1212, were higher in the treatment of N fertilizer application than in the treatment without N fertilizer. In this study, the chlorophyll as well as the net photosynthetic rate of N1, N2, and N3 were higher than that of N0, which is also in agreement with the results of Qu Wenkai et al. The performance of photosynthetic properties of wheat is regulated by several factors, among which environmental factors such as light, temperature, and carbon dioxide concentration have a direct influence on the photosynthetic properties of wheat. Temperature and moisture are the main ecological factors affecting wheat growth and development [36]. In this study, there were deviations in temperature and rainfall during the two growing seasons of winter wheat. This could also be the reason for the bias in the effects of treatments within the two seasons in parameters such as changes in chlorophyll content of wheat flag leaves after flowering and changes in the net photosynthetic rate of wheat flag leaves after flowering.

In regard to yield components such as the number of spikes, grains per spike, and thousand kernel weight, these parameters are notably sensitive to nitrogen management [37]. While nitrogen fertilization primarily aims to enhance seed yield by improving these components [38], there exists a threshold beyond which additional nitrogen does not increase but somewhat potentially decreases yield [34]. Li Wei et al. [39], concluded that the highest yield was obtained in Shandong by mixing 225 kg/ha total N application (60 d) of slow-release urea (30% basal application and 70% followup application at the greening-planting stage) with ordinary urea at a N application rate of 1:1. This nuanced understanding of nitrogen application's impact on yield is exemplified in our study, which aligns with findings by Zhang Zi Xuan [40], where topdressing with nitrogen at the jointing stage notably improved yield, with an optimal base-topdressing ratio.

Nitrogen utilization is an important index to evaluate the rational use and benefits of nitrogen fertilizers; however, over-application of nitrogen fertilizers will lead to a decrease in the nitrogen fertilizer utilization of the crop and also affect the absorption of other nutrients [41]. Studies have shown that the nitrogen fertilizers use efficiency, and nitrogen fertilizer bioproductivity showed a decreasing trend with the increase in nitrogen application level [42]. In our study, it was found that the nitrogen fertilizer use efficiency, nitrogen fertilizer agronomic use efficiency, nitrogen fertilizer bias productivity, and nitrogen harvest index of wheat decreased with increasing nitrogen application. This is also consistent with the decreasing N fertilizer utilization in winter wheat with increasing N application, as reported by a previous study [43].

Furthermore, nitrogen is a pivotal factor affecting wheat quality, predominantly influencing the protein content within the grain [40]. The protein, a key nutritional quality indicator and a marker for high-quality specialty wheat, along with wet gluten content, is significantly impacted by nitrogen application [44–46]. It has been suggested that a nitrogen application of up to 240 kg/ha can increase the content of β -folds and random curls, thus improving the gluten protein secondary structure [47]. This study's findings, resonating with those of Zhang Jun et al. and Wu Jinzhi et al. [48], demonstrate that nitrogen application at the jointing stage, especially in the N2 treatment, optimally boosts both protein and wet gluten content, thus enhancing the overall quality and processing attributes of wheat.

Nitrogen application promotes soil nitrate nitrogen accumulation [49]. Some scholars have argued that irrigation promotes deep soil nitrate nitrogen aggregation and increased

risk of environmental pollution [50,51]. Yue Wang showed that [52] nitrate N content was low when the N application was less than 150 kg/ha, and the soil nitrate N accumulation increased significantly when the N application was increased to more than 275 kg/ha. Qu Wenkai et al. [25] concluded that, regardless of the fertilizer application rate, the post-harvest soil total nitrogen was mainly concentrated in the 0–40 cm soil layer, adding that the reduction of nitrogen fertilizer rate to 210 and 225 kg/ha effectively suppressed the accumulation of nitrate nitrogen in the surface soil and its migration to the deeper soil, reducing the risk of nitrate nitrogen leaching. The extent to which soil nitrate nitrogen is utilized by the subsequent crop is related to the depth of the soil layer, and nitrate nitrogen beyond the crop's rhizosphere is difficult to utilize effectively. It is generally believed that nitrate nitrogen below 75 cm is difficult to utilize with subsequent crops, increasing the risk of environmental pollution [53,54].

Our research conclusively indicates that nitrogen fertilization at the jointing stage is crucial in improving the photosynthetic attributes, yield, and quality of high-quality, strong-gluten wheat. The N2 treatment in particular (nitrogen fertilizer base chase ratio of 3:4, the amount of irrigation water was 120 mm) had the best effect on promoting wheat growth in the North China Plain. Under the conditions of this experiment, taking into account the photosynthetic characteristics, yield, quality and soil fertility of wheat, the N application rate of 210 kg/ha was the optimal N fertilizer transport method.

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