

Article

Optimized Sowing Date and Seeding Rate for Simultaneous Improvement of Yield and Quality of Late-Sown Winter Wheat in the Southern North China Plain

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Abstract

Sowing date and seeding rate are key agronomic measures for regulating yield formation and quality accumulation in winter wheat, especially in the context of global warming, which has led to delayed sowing becoming the norm. Clearly identifying optimal combinations of sowing date and seeding rate under late-sowing conditions is crucial for achieving coordinated improvement in both high yield and quality. Therefore, this study used the strong-gluten wheat cultivar ‘Shaannong 33’ and conducted a two-factor split-plot field experiment in the southern North China Plain (Nanyang, Henan) during 2019–2021. Three sowing dates (early sowing: 27 October; intermediate sowing: 31 October–2 November; late sowing: 6–8 November) and four seeding rates (180×10^4 , 240×10^4 , 300×10^4 , and 360×10^4 plants ha^{-1}) were tested to systematically analyze the effects of sowing date and seeding rate on wheat yield and its components, grain processing quality, and starch physicochemical properties. The results showed that sowing from late October to early November (approximately 25 October to 2 November in 2019–2020 and 25 October to 31 October in 2020–2021) combined with a seeding rate of $240\text{--}300 \times 10^4$ plants ha^{-1} maintained yield at a comparably high level across both growing seasons while improving processing quality indicators such as protein content, wet gluten content, and dough stability time for the strong-gluten cultivar ‘Shaannong 33’. However, the optimal sowing window varied between years: in 2019–2020, both D1 (27 October) and D2 (2 November) produced comparable yields, whereas in 2020–2021, D2 (31 October) was superior for both yield and quality. This inter-annual variability highlights the influence of climatic conditions on the optimal sowing window. Further delaying the sowing date to after 6 November led to decreases in yield and quality parameters; however, increasing the seeding rate to 360×10^4 plants ha^{-1} partially compensated for yield loss. In addition, late sowing significantly increased amylopectin content, swelling power, and pasting indicators such as peak viscosity and final viscosity while decreasing amylose content and pasting temperature, which is beneficial for improving cooking and eating quality. Correlation analysis indicated that the amylose/amylopectin ratio was the core factor determining starch pasting properties, while protein content showed a significant negative correlation with starch pasting indicators, reflecting the resource competition effect between grain protein and starch. Yield differences between the two years were mainly driven by changes in spike number per unit area, while inter-annual climate fluctuations (especially precipitation and temperature) significantly affected spike formation capacity. Overall, sowing date and seeding rate have a synergistic regulatory effect on yield and quality of late-sown wheat for the strong-gluten cultivar ‘Shaannong 33’. It is recommended to adopt a sowing date of 25–31 October with the seeding rate controlled at $240\text{--}300 \times 10^4$ plants ha^{-1} to achieve



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synergistic improvement of yield and quality under late-sowing conditions in the southern North China Plain for this cultivar.

Keywords: sowing data; seeding rate; winter wheat; yield; quality

1. Introduction

Wheat is one of the three major staple food crops globally, with approximately 35–40% of the world's population relying on it as their main food source. Continuously improving wheat yield and quality is a core goal for ensuring food security [1,2]. China is the world's largest wheat producer and consumer, accounting for over 19% of global wheat production and contributing about 20% to domestic grain consumption. Its stable yield and quality improvement have strategic significance for national food security and global grain market stability [3]. The southern North China Plain is the core advantageous production area for winter wheat in China. In this region, the wheat sowing area in Henan Province has remained stable at over 5.66 million hectares annually, with both yield and quality ranking among the top in the country [4]. However, influenced by multiple factors such as previous crop harvest timing, agricultural machinery operations, autumn floods and droughts, and climate warming, late sowing of wheat has become a normalized production issue in this region [5,6]. Historically, the optimal sowing window for winter wheat in the southern North China Plain was from 5 October to 15 October, based on the requirement of accumulating 400–600 °C·d of growing degree days before winter dormancy to ensure robust tiller development and safe overwintering [7]. Over the past two decades, however, climate warming has progressively shifted the suitable sowing period. Autumn temperatures in this region have increased by approximately 0.3–0.5 °C per decade, meaning that sowing within the traditional window now often results in excessive pre-winter accumulated temperature (>700 °C·d), leading to vegetative overgrowth, reduced frost tolerance, and increased winter damage risk [6,8]. Concurrently, the widespread adoption of maize–wheat double cropping systems and delayed maize harvests have further postponed wheat sowing, while more frequent autumn flooding events have exacerbated these delays [5]. Consequently, actual sowing dates in the region have progressively shifted to late October or even early November, making late sowing a persistent production challenge rather than an occasional anomaly. Sowing within the traditional window now tends to increase the risk of pre-winter overgrowth and frost damage, while excessively late sowing causes insufficient pre-winter accumulated temperature and weak populations, restricting the synergistic improvement of yield and quality [7,9]. Therefore, it is urgent to clarify suitable agronomic regulation measures under late-sowing conditions.

The sowing date is a crucial agronomic measure for regulating wheat growth and development, yield formation, and quality accumulation [3,10,11]. If the sowing date is too early, the crop is prone to be affected by rising temperatures, resulting in vigorous seedlings and an overly large population, which increases the risk of winter damage [6]. If the sowing date is too late, there will be insufficient pre-winter accumulated temperature, resulting in fewer tillers and poor population quality, which is not conducive to safe overwintering and strong seedling establishment [12].

Meanwhile, the sowing date significantly affects grain protein and starch accumulation and component composition by altering the temperature and light conditions during grain filling, thereby changing wet gluten content, sedimentation value, dough stability time, and starch pasting properties, exerting an important regulatory effect on processing quality [9,11,13]. However, in field experiments, the effects of sowing date are often

confounded with inter-annual climatic variability, as temperature and radiation conditions during specific phenological stages—particularly grain filling—can vary substantially between years and may exert a stronger influence on quality traits than the relatively small shifts in sowing date itself [14,15]. Therefore, multi-year experiments combined with detailed climatic data analysis are required to disentangle the genuine effects of sowing date from those of inter-annual climatic variation.

The seeding rate directly determines population structure and is the core means for achieving yield compensation and quality stability in late-sown wheat [7]. Low seeding rates make it difficult to form sufficient spike numbers, resulting in insufficient population productivity. Appropriate density increases can effectively compensate for the tillering deficit caused by late sowing and stabilize yield by increasing the spike number per unit area [16,17]. However, excessive seeding rates intensify competition among individuals for light, temperature, water, and nutrients, reduces the rate of tiller ear formation, increases unproductive tillers, and leads to decreased kernel number per spike and 1000-kernel weight [15,18]. Excessive seeding rates also affect grain matter accumulation and quality formation [19]. Therefore, an appropriate seeding rate can optimize population structure, coordinate individual and population relationships, and achieve efficient resource utilization and synergistic improvement of yield and quality.

In summary, the sowing date and seeding rate have significant regulatory effects on yield components and quality traits of late-sown winter wheat. However, systematic research on their coupled effects under late-sowing conditions in the southern North China Plain remains relatively weak. Although numerous studies have examined the individual effects of sowing date or seeding rate on wheat yield and quality, the results have been inconsistent due to differences in cultivars, climatic conditions, and agronomic backgrounds [7,14]. Moreover, most previous studies have focused either on yield components or on a limited set of quality traits, with few systematically examining the coupled effects of sowing date and seeding rate on both processing quality and starch physicochemical properties, particularly for strong-gluten wheat under late-sowing conditions in the warm-temperate transitional zone of the southern North China Plain. Furthermore, the interactive effects between agronomic management and inter-annual climatic variability on quality formation remain poorly understood, as most studies have been conducted over a single growing season or have not explicitly analyzed year-to-year climatic differences. Therefore, this study aimed to (1) systematically evaluate the effects of sowing date and seeding rate under different annual climatic conditions on the yield components, grain processing quality, and starch physicochemical properties of the strong-flour variety ‘Shaanong 33’; (2) identify optimal combinations of sowing date and seeding rate that achieve synergistic improvement of both yield and quality under late-sowing conditions; and (3) provide a theoretical basis and technical support for high-yield, high-quality, and high-efficiency cultivation of late-sown wheat in the region.

2. Materials and Methods

2.1. Study Site

This experiment was conducted at the Nanyang Wheat Experiment and Demonstration Station of Northwest A&F University during 2019–2021. The station is located at Wolong Farm, Liaohe Town, Wolong District, Nanyang City, Henan Province (112°24′ E, 32°56′ N), which is in the transition zone from subtropical to temperate climate. The annual sunshine duration is 1897.9–2120.9 h, the frost-free period is 220–244 d, the mean annual temperature is 14.4–15.7 °C, and the mean annual precipitation is 709.5–1168 mm. Precipitation is abundant but unevenly distributed across seasons, with 70% concentrated in the summer flood season. During the wheat growing seasons of 2019–2020 and 2020–2021, average

temperatures were 11.63 °C and 10.94 °C, and precipitation was 272.0 mm and 348.6 mm, respectively (Figure 1). The previous crop was silage maize, which was chopped and used as green manure before pollination. The tested soil was loam, with physicochemical properties in the 0–20 cm soil layer: organic matter 15.30 g kg⁻¹, total nitrogen 1.21 g kg⁻¹, alkali-hydrolyzable nitrogen 40.10 mg kg⁻¹, available phosphorus 22.41 mg kg⁻¹, and available potassium 115.25 mg kg⁻¹.

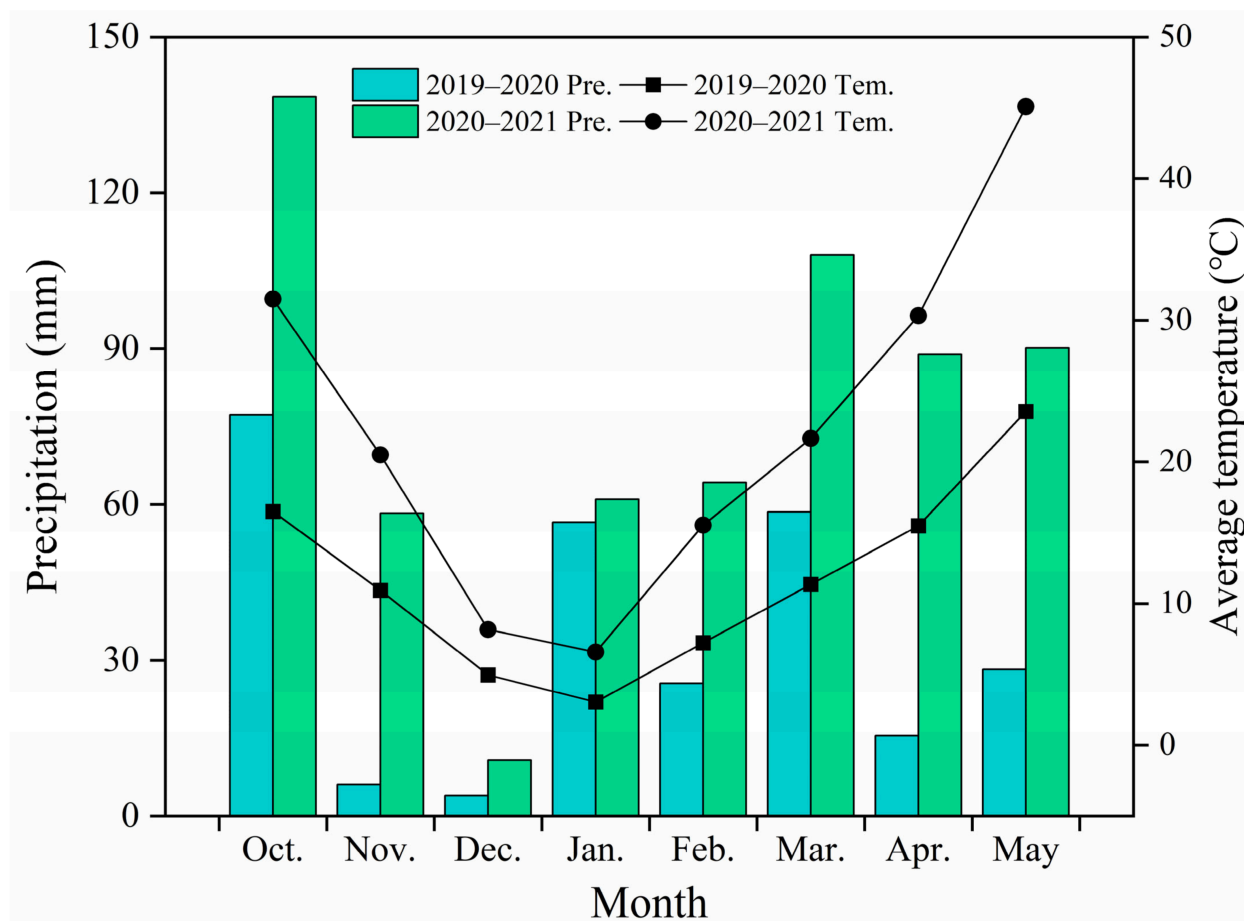


Figure 1. Monthly precipitation and average temperature for 2019–2020 and 2020–2021 winter wheat growing seasons.

2.2. Experimental Design and Materials

This experiment adopted a two-factor split-plot design, with sowing date as the main plot and seeding rate as the subplot. Sowing dates were set at 7-day intervals. For 2019–2020, sowing dates were 27 October (D1), 2 November (D2), and 8 November (D3). For 2020–2021, sowing dates were 25 October (D1), 31 October (D2), and 6 November (D3). Four seeding rate levels were set based on basic seedlings: 180×10^4 plants ha⁻¹ (R1), 240×10^4 plants ha⁻¹ (R2), 300×10^4 plants ha⁻¹ (R3), and 360×10^4 plants ha⁻¹ (R4). These rates were adjusted based on seed germination rate and expected field emergence rate to achieve the target basic seedling densities. Each plot area was 4.5 m² (3 m $\times$ 1.5 m), with three replications, totaling 36 plots. Plots were separated by 0.5 m buffer rows between adjacent plots and 1.0 m alleys between blocks to minimize inter-plot competition and edge effects. Manual rowing and strip sowing were performed with a row spacing of 25 cm. Basal fertilizers applied were 150 kg ha⁻¹ urea (46% N) and 750 kg ha⁻¹ compound fertilizer (N:P:K = 15:15:15). The tested wheat variety was Shaannong 33, a semi-winter strong-gluten variety with semi-prostrate seedlings and dark green leaves. It has good plant-type structure, compact plant type, thick and strong stems, and strong lodging

resistance. Spikes are rectangular, with dense upper spikelets, and the middle spikelets set 4–5 kernels. Grains are white with a horny endosperm and show good late-season greening. It is moderately resistant to stripe rust and powdery mildew. Irrigation was performed timely according to soil moisture conditions, and pest, disease, and weed control was consistent with local field production practices.

2.3. Sampling and Measurements

2.3.1. Yield and Its Components

These yield-related traits were determined in both the 2019–2020 and 2020–2021 growing seasons. At the winter wheat harvest stage, a representative 1 m double row (1 m $\times$ 0.5 m, since row spacing was 25 cm) was selected from the central portion of each plot (avoiding edge rows) for spike count investigation. Spike number per hectare was calculated by multiplying the counted spikes by the conversion factor (10,000 m² ha⁻¹/0.5 m² = 20,000), as the sampled area of 1 m $\times$ 0.5 m = 0.5 m². Meanwhile, 20 spikes were randomly selected to calculate kernels per spike (kernel number per spike = total kernels counted from 20 spikes/20). After harvest, 1000-kernel weight was measured three times from grains of each plot, and the average was taken. For yield determination, only the central four rows of each plot were harvested, leaving one border row on each side (25 cm) as guard rows to minimize edge effects from neighboring plots and alleys. The harvested area was 3 m $\times$ 1.0 m = 3.0 m² (4 rows $\times$ 25 cm row spacing $\times$ 3 m length), and grain yield was converted to kg ha⁻¹ on a 13% moisture basis using the formula: yield (kg ha⁻¹) = harvested grain weight (kg) $\times$ (10,000 m² ha⁻¹/3.0 m²) $\times$ [(100 – actual moisture %)/(100 – 13)].

2.3.2. Grain Processing Quality

Grain processing quality traits were determined in both the 2019–2020 and 2020–2021 growing seasons. Grains harvested at the maturity stage of winter wheat were placed in seed containers for two months to complete post-physiological ripening. Then, flour was ground using a multifunctional grinder (Y400, Zhejiang Laobenxing Environmental Protection Technology Co., Ltd., Hangzhou, China) and passed through an 80-mesh sieve. Wet gluten content was determined using a gluten quantity and quality index determination system (GM2200, Perten Instruments Company of Sweden, Stockholm, Sweden). The dough stability time was measured using the Mixolab 2 system (Chopin, Villeneuve-la-Garenne; Tripette & Renaud, Villeneuve-la-Garenne, France), and the test results were considered qualified when the dough torque value was within 1.05–1.15 Nm. The sedimentation value was determined using a near-infrared grain analyzer (Diode Array 7250, Perten, Stockholm, Sweden).

2.3.3. Protein Content, Starch Content, and Their Properties

Consistent with the above settings, protein content was measured in both growing seasons; all starch-related physicochemical indices were only determined using grain samples from the 2020–2021 growing season. Starch was extracted from flour using the hand-washing method [20]. The crude starch was mixed with 0.25% NaOH and allowed to stand at room temperature for 4 h, then centrifuged. After washing with distilled water and anhydrous ethanol and centrifuging three times, the starch was dried and passed through a 100-mesh sieve for storage. Protein and total starch content were determined using a near-infrared grain analyzer (Diode Array 7250, Perten, Stockholm, Sweden). Subsequently, 0.2 g of starch (recorded as *m*₀) was placed into a pre-weighed 10 mL centrifuge tube (tube weight recorded as *m*₁). A total of 5 mL of distilled water was added to the centrifuge tube, mixed by shaking for 10 s, water-bathed at 70 °C for 4 min, mixed by shaking for 20 s, water-bathed at 70 °C for another 6 min, then boiled for 10 min, and cooled in running water

for 3 min. After centrifugation at 8000 r/min for 10 min, the supernatant was discarded, excess water was removed, and the tube was dried at 70 °C for 40 min and then placed in a desiccator to cool for half an hour and weighed (recorded as m_2). The precipitate in the tube was dried to constant weight and weighed (recorded as m_3). Swelling power and water solubility were calculated using the following formulas [21]:

$$\text{Swelling power (g/g)} = \frac{m_2 - m_1}{m_3 - m_1}$$

$$\text{Water solubility (\%)} = \frac{m_0 + m_1 - m_3}{m_0} \times 100\%$$

Amylose and amylopectin contents were determined using the dual-wavelength method on purified starch extracted from whole-grain flour [22]. The results are expressed as percentages of the extracted starch (i.e., starch-basis). Total starch content was determined for whole-grain flour using a near-infrared grain analyzer (Diode Array 7250, Perten, Stockholm, Sweden) and is expressed as a percentage of whole-grain flour (i.e., whole-grain basis). Starch pasting properties were measured using an RVA viscosity analyzer (RVA 4500, Perten Instruments, Stockholm, Sweden). The sample water content was input into the software, which automatically calculated the required sample mass and distilled water volume. Sample mass was accurate to at least 0.01 g and water volume accurate to above 0.1 mL to reduce error. The sample and distilled water were placed in a disposable aluminum sample container, then placed in a stirrer, and the stirrer paddle was vigorously moved up and down 10 times through the sample. The sample container was placed at the designated position on the instrument, the tower cap was pressed down, and the instrument started running. Parameters obtained included peak viscosity, breakdown viscosity, low viscosity, final viscosity, setback viscosity, and pasting temperature.

2.4. Statistical Analysis

All data were initially organized using Microsoft Excel 2019. Analysis of variance (ANOVA) was performed using SPSS 21.0 based on a two-factor split-plot design, with sowing date as the main-plot factor and seeding rate as the subplot factor, to evaluate the main effects and their interaction. To account for inter-annual variability, year was included in the model as a random factor. Multiple comparisons among treatments were conducted using Duncan's new multiple range test at $p < 0.05$. Correlations among indicators were analyzed using Pearson correlation analysis. Mantel tests were employed to assess the strength of associations between the set of explanatory variables and the set of response variables using R 4.5.3 with the 'vegan' package. All figures were generated using OriginPro 2024 (Version 10.1.0, OriginLab Corporation, Northampton, MA, USA).

3. Results

3.1. Yield and Its Components

Significant differences in winter wheat grain yield were observed between the two years ($p < 0.05$, Figure 2 and Table S1). Although kernels per spike and 1000-kernel weight did not differ significantly between the two years, the spike number per unit area in 2020–2021 was significantly lower by an average of 23.05% compared to 2019–2020, leading to a significant reduction of 5.94% in winter wheat grain yield in the 2020–2021 growing season.

The sowing date significantly affected winter wheat yield ($p < 0.05$), but the trend varied between the two years (Figure 2d and Table S1). In the 2019–2020 season, yield significantly decreased with delayed sowing. Compared to D3, yields under D1 and D2 treatments were significantly increased by 13.12% and 9.27%, respectively ($p < 0.05$),

while the difference between D1 and D2 was not significant. With increasing seeding rate, yield first increased and then decreased. However, the trend of yield change with increasing seeding rate varied slightly among sowing dates. For D1 and D2, the highest yield occurred at the R2 seeding rate; for D3, the highest yield occurred at the R4 seeding rate. In the 2020–2021 season, yield first increased and then decreased with delayed sowing. Compared to D3, yields under D1 and D2 treatments were significantly increased by 8.77% and 10.59%, respectively ($p < 0.05$), while the difference between D1 and D2 was not significant. The pattern of yield change with seeding rate was similar to that in 2019–2020. Regarding sowing date and seeding rate combinations, the top five treatments for yield in 2019–2020 were D1R2 > D2R2 > D1R4 > D1R1 > D1R3 and in 2020–2021 were D1R2 > D2R1 > D2R4 > D2R2 > D2R3, with no significant differences among these treatments. This indicates that an appropriate delay of the sowing date does not lead to a substantial yield reduction in either growing season, with comparable yield performance observed between D1 and D2 in both years.

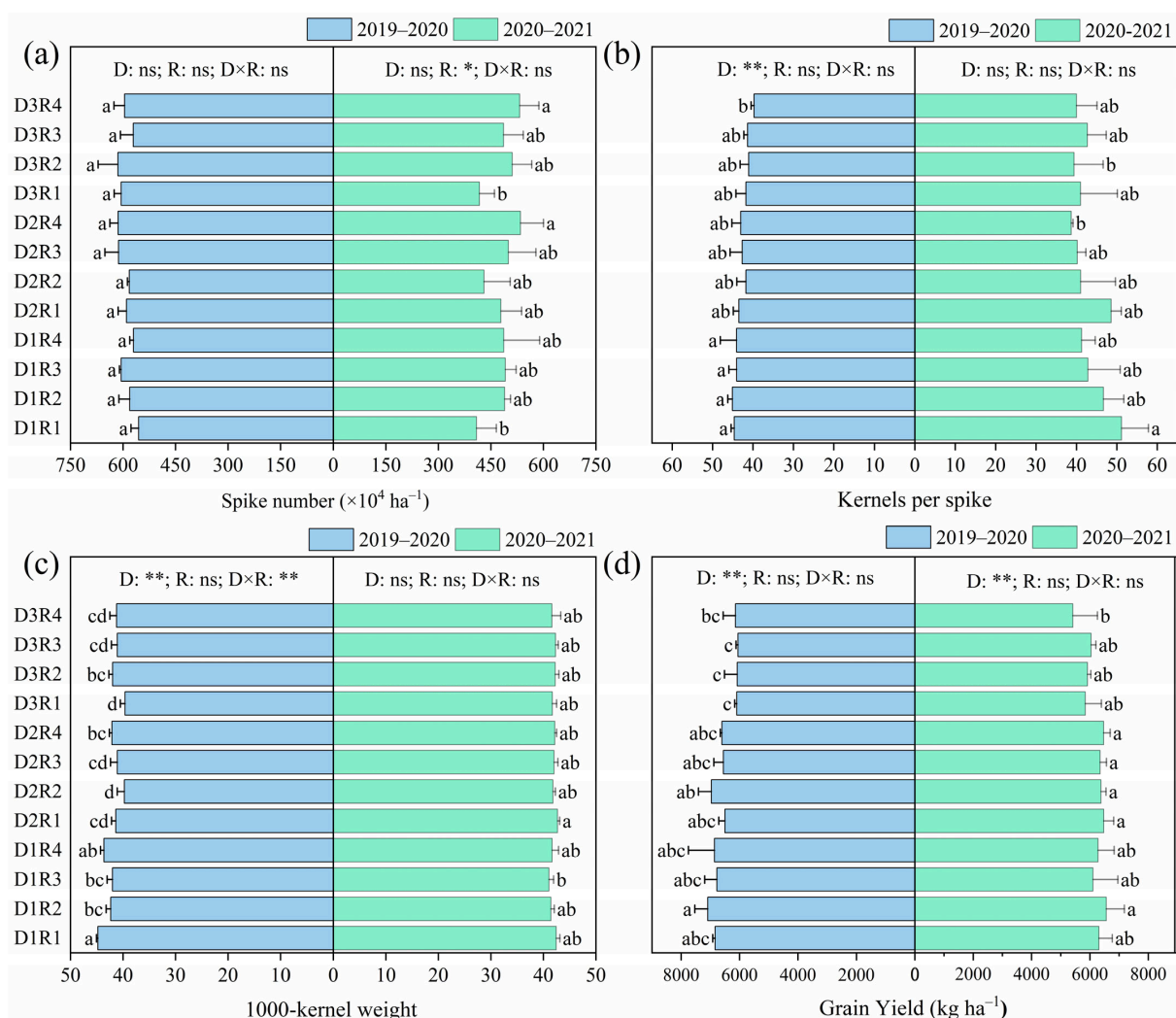


Figure 2. Effects of different combinations of sowing date and seeding rate on grain yield and its components. Subfigure (a–d) respectively represent the spike number, the kernels per spike, 1000-kernel weight and the grain yield of two wheat growing seasons. D and R, respectively, represent sowing date and seeding rate. Different lowercase letters after the numbers indicate significant differences between different treatments. * and ** indicate significant differences at the 0.05 and 0.01 levels, respectively. ns indicates that the difference is not significant. The top-performing combinations for each trait are explicitly listed in the corresponding Results section for readers' reference.

In the 2019–2020 season, sowing date significantly affected the kernels per spike and 1000-kernel weight, while the interaction of sowing date and seeding rate only significantly affected the 1000-kernel weight (Figure 2a–c). Both kernels per spike and 1000-kernel weight significantly decreased with delayed sowing. In the 2020–2021 season, seeding rate significantly affected the spike number per unit area and kernels per spike. Spike number per unit area showed a linear increasing trend with increasing seeding rate, while kernels per spike showed a linear decreasing trend.

The optimal sowing date for yield varied between the two years. In 2019–2020, D1 (27 October) and D2 (2 November) produced comparable yields, with no significant difference between them, while D3 (8 November) resulted in significantly lower yield. In 2020–2021, D1 (25 October) and D2 (31 October) also yielded comparably, with no significant difference between them, while D3 (6 November) was significantly lower. However, the optimal sowing window was slightly narrower in 2020–2021 (25–31 October) compared to 2019–2020 (27 October–2 November), reflecting the influence of inter-annual climatic conditions, particularly the lower average temperature and higher precipitation during the 2020–2021 growing season (Figure 1), which may have delayed crop development and reduced the window for optimal establishment. This inter-annual variability underscores the need for flexible, climate-adaptive sowing recommendations rather than fixed calendar dates.

3.2. Protein Content and Processing Quality

Substantial year effects were observed for processing quality traits (Table 1). The 2020–2021 season exhibited significantly higher wet gluten content ($p < 0.01$), sedimentation value ($p < 0.01$), and stability time ($p < 0.01$) compared to 2019–2020. Specifically, average wet gluten content in 2020–2021 was 16.2% higher than in 2019–2020, sedimentation value increased by 12.3%, and stability time increased by 13.0%. However, protein content did not differ significantly between years, averaging 15.47% in 2019–2020 and 15.38% in 2020–2021. The significant year $\times$ sowing date interactions for protein content ($p < 0.05$) and wet gluten content ($p < 0.01$) indicated that the response of quality traits to sowing date was modulated by inter-annual climatic conditions. In 2019–2020, sowing date only significantly affected wet gluten content, seeding rate only significantly affected stability time, and their interaction only significantly affected stability time ($p < 0.05$, Tables 1 and S2). Wet gluten content decreased with delayed sowing, with D2 and D3 being 1.43% and 2.51% lower than D1, respectively. Under the D1 and D2 sowing dates, stability time first decreased and then increased with increasing seeding rate; under the D3 sowing date, stability time first increased and then decreased with increasing seeding rate. In 2020–2021, sowing date significantly affected protein content, wet gluten content, and stability time; seeding rate only significantly affected stability time; and their interaction only significantly affected stability time ($p < 0.05$, Tables 1 and S2). Protein content, wet gluten content, stability time, and sedimentation value all first increased and then decreased with delayed sowing, performing best under the D2 sowing date. D2 showed significant differences from D1 and D3 in protein content, wet gluten content, and stability time. Protein content under D2 was 6.62% and 5.65% higher than D1 and D3, respectively; wet gluten content was 8.50% and 6.42% higher; and stability time was 13.73% and 14.47% higher. Across different sowing dates, the protein content, wet gluten content, and sedimentation value first increased and then decreased with an increasing seeding rate, indicating that both too high and too low seeding rates are detrimental to the improvement of protein content and secondary processing quality. Regarding sowing date and seeding rate combinations, the treatment with the highest protein content was D2R2, while the treatments with the highest wet gluten content, sedimentation value, and stability time were all D2R1, indicating that appropriate delay of sowing date is beneficial for improving processing quality such as

protein content and wet gluten content. Correlation analysis showed that grain protein content was significantly positively correlated with wet gluten content, sedimentation value, and stability time ($p < 0.05$, Figure 3). In summary, sowing before 31 October with a seeding rate of approximately $240\text{--}300 \times 10^4$ plants ha^{-1} resulted in relatively stable performance of processing quality indicators such as protein content and wet gluten content. Sowing too late, i.e., sowing after November, was detrimental to the stability of these indicators.

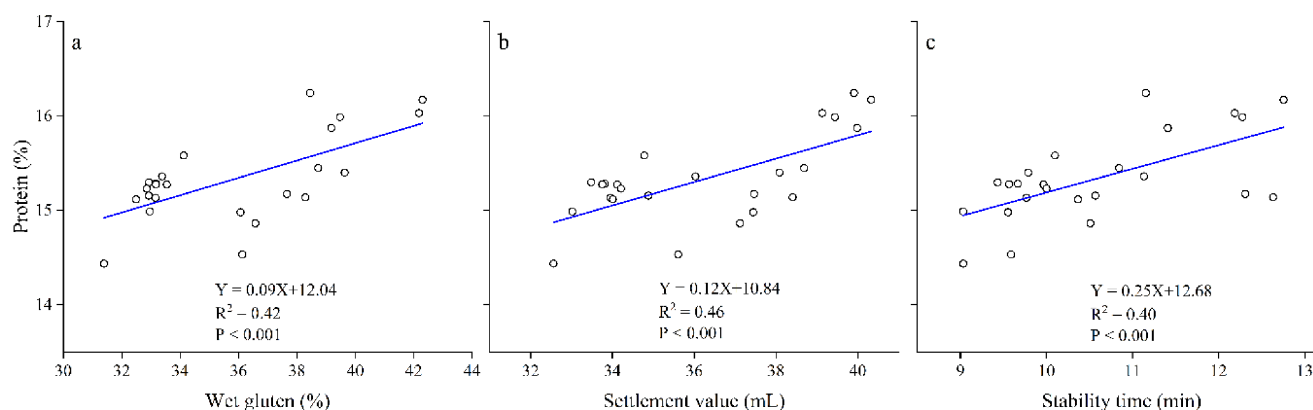


Figure 3. The relationship between grain protein content and processing quality. subfigures (a), (b) and (c) respectively represent the relationships between protein content and wet gluten content, sedimentation value, and stability time.

Table 1. Effects of different combinations of sowing date and sowing density on protein content and main processing quality.

Factor	Protein (%)	Wet Gluten (%)	Sedimentation Value (mL)	Stability Time (min)
Year				
2019–2020	15.18 a	33.01 b	34.05 b	9.89 b
2020–2021	15.49 a	38.72 a	38.47 a	11.25 a
Sowing data (SD)				
D1	15.18 b	35.43 b	35.94 a	10.30 a
D2	15.68 a	36.79 a	36.90 a	11.01 a
D3	15.15 b	35.38 b	35.94 a	10.40 a
Seeding rate (SR)				
R1	15.24 a	35.97 a	35.97 a	10.33 a
R2	15.34 a	35.42 a	35.99 a	9.89 a
R3	15.41 a	36.22 a	36.74 a	10.84 a
R4	15.33 a	35.85 a	36.35 a	11.22 a
ANOVA				
F(Y)	ns	**	**	**
F(D)	*	*	ns	ns
F(R)	ns	ns	ns	ns
F(Y × D)	*	**	ns	ns
F(Y × R)	ns	ns	ns	ns
F(D × R)	ns	ns	ns	ns
F(Y × D × R)	ns	ns	ns	ns

Note: D and R, respectively, represent sowing date and seeding rate. Different lowercase letters after the numbers indicate significant differences between different treatments. * and ** indicate significant differences at the 0.05 and 0.01 levels, respectively. ns indicates that the difference is not significant.

3.3. Starch Content and Physicochemical Properties

3.3.1. Starch Content and Swelling Power

Sowing date significantly affected amylose content, amylose/amylopectin ratio, amylopectin content, and water solubility (Tables 2 and S3, $p < 0.01$) but had no significant

effect on total starch content or swelling power ($p > 0.05$). Amylose and amylopectin contents were determined on extracted starch using the dual-wavelength method and are expressed as percentages of extracted starch (starch-basis); total starch content was determined on whole-grain flour using near-infrared spectroscopy (NIR) and is expressed as a percentage of whole-grain flour (whole-grain basis). Therefore, amylose and amylopectin values represent the composition of the starch fraction, while total starch represents the starch content of the whole grain. Changes in amylose content, water solubility, and amylose/amylopectin ratio with sowing date showed opposite trends to those of amylopectin content and swelling power. Amylose content, water solubility, and amylose/amylopectin ratio significantly decreased with delayed sowing. Compared to D1, amylose content under D2 and D3 decreased by 4.32% and 5.19%, respectively; amylose/amylopectin ratio decreased by 6.72% and 7.45%; and water solubility decreased by 6.72% and 7.91%. For all three indicators, D1 was significantly higher than D2 and D3, with no significant difference between D2 and D3. Amylopectin content and swelling power significantly increased with delayed sowing. Compared to D1, amylopectin content under D2 and D3 increased by 2.03% and 2.44%, respectively, and swelling power increased by 7.60% and 8.00%. D1 was significantly lower than D2 and D3, with no significant difference between D2 and D3. Amylose content, amylose/amylopectin ratio, amylopectin content, swelling power, and water solubility showed no obvious pattern with changes in seeding rate.

Table 2. Effects of different combinations of sowing date and sowing density on starch content and characteristics (2020–2021).

Treatment		Starch Content (%)	Amylose Content (%)	Amylopectin Content (%)	Amylose/Amylopectin	Water Solubility (%)	Swelling Power (g/g)
D1	R1	79.00 ± 0.21 a	32.18 ± 1.60 ab	67.82 ± 1.6 bc	0.48 ± 0.04 ab	26.00 ± 1.48 a	13.74 ± 1.61 ab
	R2	79.40 ± 0.37 a	33.15 ± 0.93 a	66.85 ± 0.93 c	0.50 ± 0.02 a	25.16 ± 1.76 ab	13.01 ± 1.27 b
	R3	79.45 ± 0.82 a	31.97 ± 0.46 ab	68.04 ± 0.46 bc	0.47 ± 0.01 abc	24.90 ± 0.35 ab	13.51 ± 0.66 ab
	R4	79.43 ± 1.05 a	30.56 ± 0.32 bc	69.44 ± 0.32 ab	0.44 ± 0.01 bcd	24.49 ± 1.41 ab	13.11 ± 1.81 ab
D2	R1	78.97 ± 0.07 a	31.61 ± 0.67 abc	68.39 ± 0.67 abc	0.46 ± 0.01 abcd	23.52 ± 1.24 abc	15.13 ± 1.61 ab
	R2	78.84 ± 0.25 a	29.81 ± 1.72 bc	70.19 ± 1.72 ab	0.43 ± 0.03 cd	22.59 ± 1.47 bc	14.86 ± 1.49 ab
	R3	78.87 ± 0.62 a	30.16 ± 2.37 bc	69.84 ± 2.37 ab	0.43 ± 0.05 bcd	24.23 ± 0.68 ab	14.07 ± 0.61 ab
	R4	79.00 ± 0.43 a	30.75 ± 0.62 bc	69.25 ± 0.62 ab	0.44 ± 0.01 bcd	23.45 ± 1.36 abc	13.37 ± 0.71 ab
D3	R1	79.75 ± 0.58 a	31.49 ± 0.17 abc	68.51 ± 0.17 abc	0.46 ± 0.00 abcd	23.77 ± 0.78 abc	15.21 ± 0.53 ab
	R2	79.18 ± 0.25 a	30.05 ± 2.85 bc	69.95 ± 2.85 ab	0.43 ± 0.06 bcd	24.30 ± 1.37 ab	15.34 ± 1.18 a
	R3	78.83 ± 0.34 a	29.41 ± 0.86 c	70.59 ± 0.86 a	0.42 ± 0.02 d	21.53 ± 1.27 c	13.78 ± 1.98 ab
	R4	79.48 ± 1.28 a	30.26 ± 0.82 bc	69.74 ± 0.82 ab	0.43 ± 0.02 bcd	23.00 ± 1.74 bc	13.68 ± 0.58 ab
ANOVA							
F(D)		ns	**	**	**	**	ns
F(R)		ns	ns	ns	ns	ns	ns
F(D × R)		ns	ns	ns	ns	ns	ns

Note: D and R, respectively, represent sowing date and seeding rate. Different lowercase letters after the numbers indicate significant differences between different treatments. ** indicate significant differences at the 0.01 levels. ns indicates that the difference is not significant. Amylose and amylopectin contents were determined on extracted starch and are expressed as percentages of extracted starch (starch-basis). Total starch content was determined on whole-grain flour and is expressed as a percentage of whole-grain flour (whole-grain basis). Values are means ± standard deviations ($n = 3$).

Regarding sowing date and seeding rate combinations, the top three treatments with the lowest amylose content and amylose/amylopectin ratio were D3R3, D2R2, and D3R2; the top three treatments with the lowest water solubility were D3R3, D2R2, and D3R4; the top three treatments with the highest swelling power were D3R2, D3R1, and D2R1; and the top three treatments with the highest amylopectin content were D3R3, D2R2, and D3R2 (Tables 2 and S3). This indicates that amylose content, water solubility, and

amylose/amylopectin ratio decrease with delayed sowing, while amylopectin content and swelling power show the opposite trend.

3.3.2. Starch Pasting Properties

Sowing date and seeding rate significantly affected starch pasting properties (Tables 3 and S4, $p < 0.05$). Peak viscosity, breakdown viscosity, final viscosity, and setback viscosity showed a significant increasing trend with delayed sowing, with a pattern generally similar to that of amylopectin content (Table 2). Compared to D1, peak viscosity under D2 and D3 increased by 7.62% and 9.26%, breakdown viscosity increased by 8.90% and 10.06%, final viscosity increased by 7.09% and 8.80%, and setback viscosity increased by 7.62% and 9.13%, respectively, with no significant differences between D2 and D3. Low viscosity also increased with delayed sowing, but the differences were not statistically significant (Tables 3 and S4). Pasting temperature decreased with delayed sowing, with average values of 86.12 °C, 84.01 °C, and 84.53 °C for the three sowing dates from early to late (Table S4), though the differences were not statistically significant according to ANOVA (Table 3).

Table 3. Effects of different combinations of sowing date and sowing density on starch pasting properties (2020–2021).

Treatment		Peak Viscosity (cP)	Low Viscosity (cP)	Breakdown Viscosity (cP)	Final Viscosity (cP)	Setback Viscosity (cP)	Pasting Temperature (°C)
D1	R1	1443.78 ± 69.99 abc	826.60 ± 74.14 ab	617.16 ± 12.88 bcd	1632.69 ± 77.03 ab	806.07 ± 19.44 abc	89.37 ± 0.24 a
	R2	1469.39 ± 144.57 abc	830.91 ± 92.46 ab	638.48 ± 56.25 abcd	1633.15 ± 153.27 ab	802.24 ± 61.18 abc	83.06 ± 4.98 a
	R3	1366.20 ± 18.01 bc	763.75 ± 51.13 ab	602.44 ± 39.17 cd	1516.92 ± 26.00 ab	753.17 ± 25.63 bc	84.05 ± 9.67 a
	R4	1118.41 ± 87.02 d	533.29 ± 105.41 c	585.12 ± 18.40 d	1149.69 ± 151.75 c	616.70 ± 46.33 d	87.98 ± 1.15 a
D2	R1	1576.16 ± 114.20 ab	881.00 ± 50.29 a	695.16 ± 64.07 a	1738.50 ± 107.00 a	857.50 ± 57.84 a	85.45 ± 1.11 a
	R2	1319.50 ± 219.04 c	682.33 ± 188.90 bc	637.16 ± 30.17 abcd	1403.33 ± 284.72 b	721.00 ± 95.86 c	80.85 ± 5.77 a
	R3	1405.66 ± 65.68 abc	753.50 ± 63.01 ab	652.16 ± 41.52 abcd	1547.16 ± 103.26 ab	793.66 ± 43.84 abc	86.24 ± 0.68 a
	R4	1507.50 ± 111.72 abc	831.16 ± 114.42 ab	676.33 ± 8.81 ab	1664.16 ± 167.62 ab	833.00 ± 54.18 ab	83.52 ± 5.58 a
D3	R1	1579.83 ± 211.43 a	904.00 ± 175.85 a	675.83 ± 35.59 ab	1743.83 ± 275.05 a	839.83 ± 100.37 ab	88.03 ± 0.04 a
	R2	1505.83 ± 90.89 abc	819.33 ± 84.58 ab	683.16 ± 19.35 ab	1656.16 ± 135.93 ab	836.80 ± 56.17 ab	81.40 ± 6.08 a
	R3	1417.00 ± 122.73 abc	750.66 ± 121.76 ab	666.33 ± 32.53 abc	1559.16 ± 156.68 ab	808.50 ± 35.07 abc	82.02 ± 5.50 a
	R4	1394.66 ± 60.78 abc	730.83 ± 70.35 ab	663.83 ± 35.67 abc	1495.66 ± 88.11 ab	764.83 ± 22.37 abc	86.65 ± 2.05 a
ANOVA							
F(D)		**	ns	**	*	**	ns
F(R)		**	**	ns	**	**	ns
F(D × R)		**	**	ns	**	**	ns

Note: D and R, respectively, represent sowing date and seeding rate. Different lowercase letters after the numbers indicate significant differences between different treatments. * and ** indicate significant differences at the 0.05 and 0.01 levels, respectively. ns indicates that the difference is not significant. Values are means ± standard deviations ($n = 3$).

Peak viscosity, low viscosity, final viscosity, and setback viscosity showed a significant decreasing trend with increasing seeding rate (Tables 3 and S4, $p < 0.01$). Compared to R1, peak viscosity under R4 decreased by 12.59%, low viscosity decreased by 19.77%, final viscosity decreased by 15.75%, and setback viscosity decreased by 11.54%. In contrast, breakdown viscosity and pasting temperature showed no significant response to seeding rate ($p > 0.05$, Tables 3 and S4). The significant sowing date × seeding rate interactions for peak viscosity, low viscosity, final viscosity, and setback viscosity ($p < 0.01$, Table 3) indicate that the effect of seeding rate on pasting properties depended on the sowing date. Under D1 and D3, peak viscosity, low viscosity, final viscosity, and setback viscosity all showed decreasing trends with increasing seeding rate, but the decreasing trend under D3 was more gradual than that under D1. This indicates that late sowing can reduce the differences in flour pasting performance among different seeding rates. Therefore, when sowing late and the seeding rate is less than 300×10^4 plants ha^{−1}, flour pasting performance is better.

Sowing too early or seeding too heavily is detrimental to the improvement of flour pasting performance, and differences among different seeding rates diminish under late sowing.

In conclusion, under the late-sowing condition, there was a trade-off relationship between wheat yield and quality. For D1, R2 was the optimal seeding rate to balance high yield and processing quality. For D2, R1-R2 gave the best comprehensive performance in yield, protein content, and starch pasting properties. For D3, even R4 only partially compensated yield loss, while quality declined significantly. Overall, the combination of D1-D2 with R2 ($240\text{--}300 \times 10^4$ plants ha^{-1}) represented the optimal choice for balancing yield and quality for 'Shaannong 33'.

3.4. Correlation Analysis

Pairwise Pearson correlation analysis was first conducted to clarify relationships among amylose (AM), amylopectin (AP), total starch, starch physicochemical parameters, and pasting-related traits (Figure 4). AM exhibited an extremely significant negative correlation with AP ($r = -0.80$, $p < 0.001$), while it was positively correlated with the AM/AP ratio ($r = 0.84$, $p < 0.001$). Consistently, AP showed a strong negative correlation with the AM/AP ratio ($r = -0.99$, $p < 0.001$). Total starch content was markedly negatively associated with AM and the AM/AP ratio ($p < 0.001$), indicating that high amylose accumulation restricts the synthesis of total starch in wheat grains. For physicochemical indices, water solubility (WS) was negatively correlated with the AM/AP ratio ($r = -0.58$, $p < 0.01$) and positively correlated with swelling power (SP, $r = 0.54$, $p < 0.001$) and total starch content ($r = 0.66$, $p < 0.001$). All viscosity-related indicators including peak viscosity (PV), low viscosity (LV), breakdown viscosity (BV), final viscosity (FV) and setback viscosity (SeV) were significantly positively correlated with AM and the AM/AP ratio but negatively correlated with AP and total starch ($p < 0.001$). Pasting temperature (PT) shared the same correlation trend with starch composition ($p < 0.01$). Moreover, PV, LV, BV, FV, and SeV were tightly inter-correlated with each other ($r = 0.78\text{--}1.00$, $p < 0.001$). These correlation outcomes reveal that the AM/AP ratio rather than total starch content acts as the core determinant governing starch physicochemical and pasting properties. From a practical breeding perspective, such close mutual dependence across all viscosity-related traits allows breeders to select only PV as a representative screening index instead of measuring multiple viscosity parameters simultaneously, which effectively reduces phenotyping costs during high-quality wheat selection. For field cultivation management, agronomic practices that moderately decrease amylose proportion can increase total starch accumulation, whereas excessive amylopectin synthesis will lower starch pasting quality. Therefore, a moderate AM/AP ratio should be targeted to balance grain starch yield and end-use processing quality in wheat production.

Subsequently, combined Pearson correlation and Mantel tests were performed to dissect linkages among gluten quality, starch-related traits, and yield components and further clarify how protein, starch, and yield shape grain quality at a multi-trait level (Figure 5). The pairwise correlation results demonstrated that gluten-quality indices (WG, SV, and ST) were significantly negatively associated with starch-pasting parameters (PV, LV, BV, FV, and SeV; $p < 0.05$). By contrast, yield-related components including spike number, kernels per spike, and 1000-kernel weight only displayed weak and non-significant correlations with starch physicochemical and pasting traits ($p > 0.05$). Different from pairwise Pearson analysis that only evaluates associations between two single variables, Mantel tests assess comprehensive multivariate relationships between a core target trait and the whole set of starch-related phenotypic variables, which helps us identify the global regulatory effect of protein, starch, and yield on starch quality. The Mantel test results showed grain protein content had strong overall correlations with starch physicochemical and pasting indicators

(Mantel's $r \geq 0.5$, $p < 0.01$). This result physiologically reflected carbon–nitrogen resource competition during the grain-filling period: assimilates allocated to protein biosynthesis compete for carbon skeletons and photosynthates required for starch synthesis, which reshapes the AM/AP ratio composition and consequently reduces pasting performance. Starch content also exhibited significant overall associations with starch-related traits and spike number ($p < 0.05$), suggesting that starch metabolism forms a source–sink feedback with spike development; spike-derived sink strength modulates photosynthate allocation between amylose and amylopectin. However, grain yield showed negligible Mantel correlations with starch-quality parameters ($p \geq 0.05$), further confirming that yield components exert limited direct effects on starch quality. Collectively, our multi-level correlation results provide clear actionable guidance for wheat breeding and cultivation. For quality-oriented breeding programs, the AM/AP ratio and grain protein content are the two highest-priority selection variables, while yield-related traits are not reliable indicators to improve starch quality. In practical cultivation, optimizing nitrogen application rate and timing is an effective strategy to coordinate carbon–nitrogen partitioning, which balances protein formation and starch composition and reconciles grain yield and processing quality.

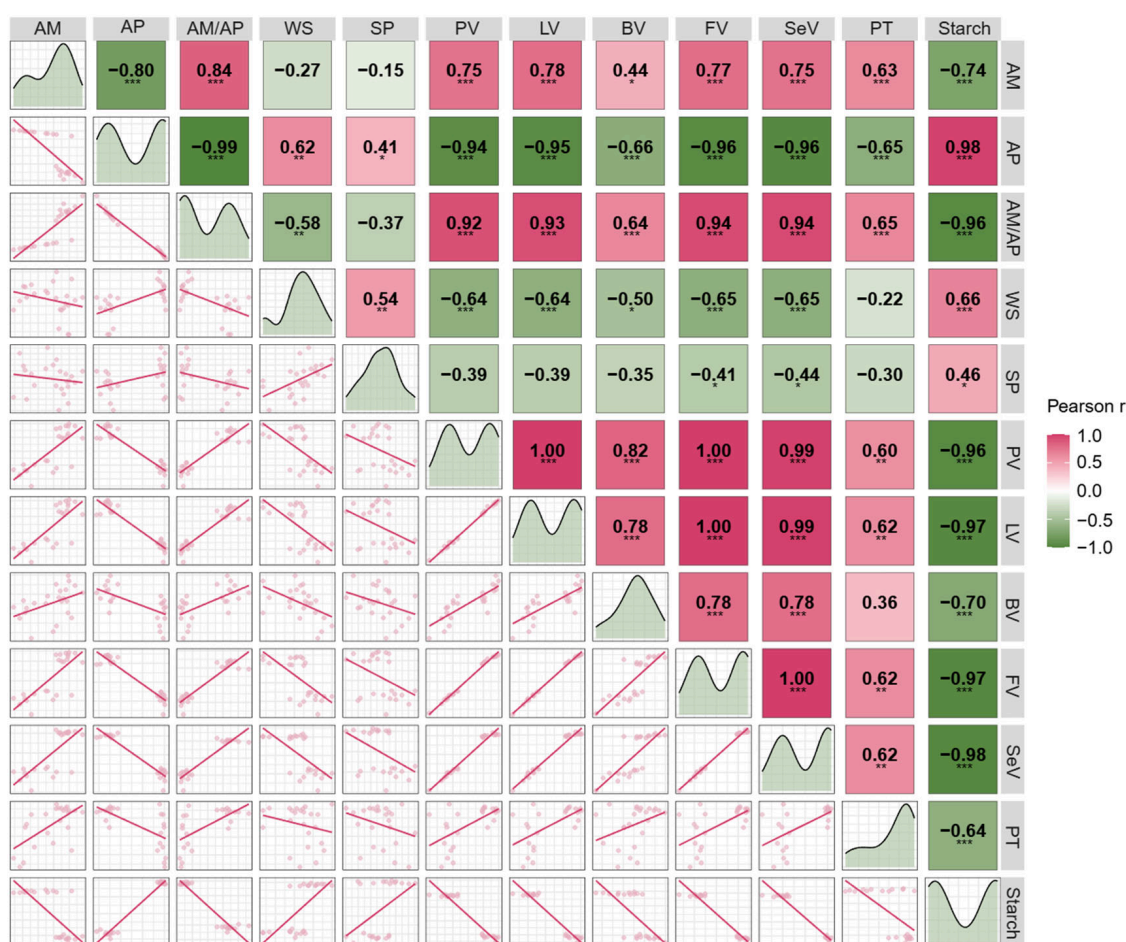


Figure 4. Pearson correlation matrix of starch components, physicochemical properties, and pasting characteristics. Diagonal panels show kernel density distributions of each variable. Upper panels present Pearson correlation coefficients (r) with significance levels indicated by asterisks (* $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$). Lower panels display scatter plots with linear regression lines for each pair of variables. AM: amylose content; AP: amylopectin content; AM/AP: amylose/amylopectin ratio; WS: water solubility; SP: swelling power; PV: peak viscosity; LV: low viscosity; BV: breakdown viscosity; FV: final viscosity; SeV: setback viscosity; PT: pasting temperature; Starch: total starch content.

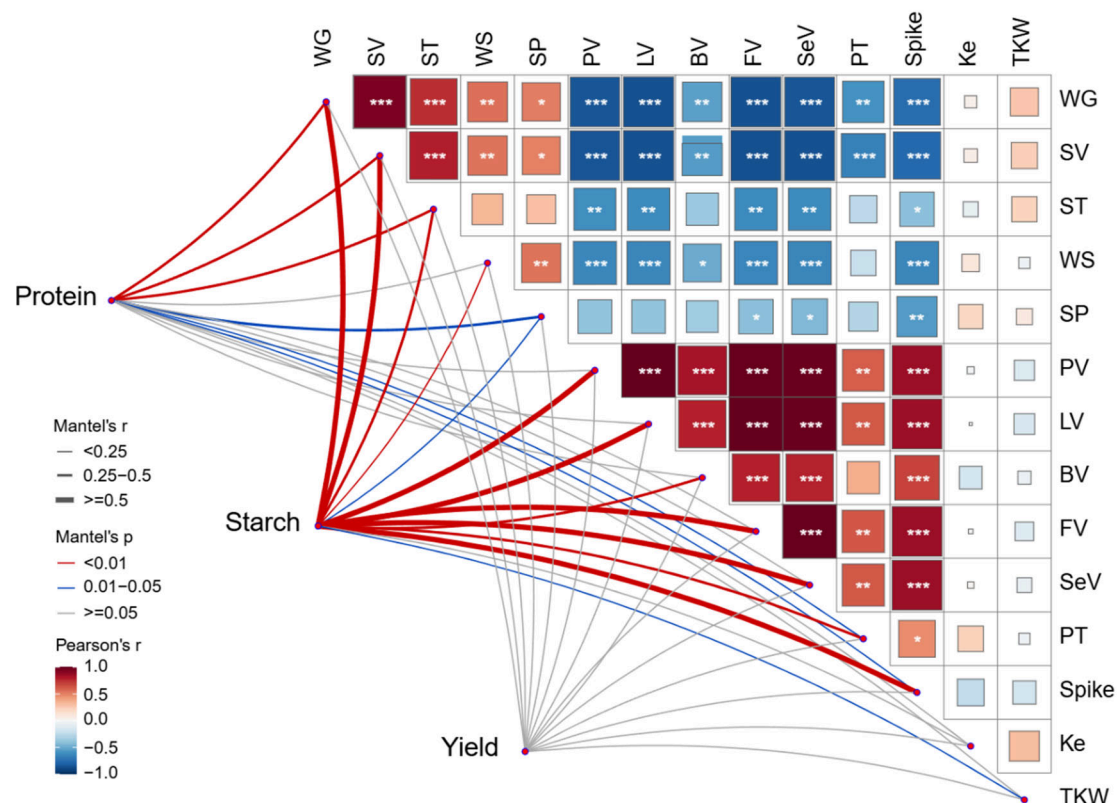


Figure 5. Pearson correlation matrix and Mantel test associations among grain quality traits, starch physicochemical/pasting properties, and yield components. The right panel shows Pearson correlation coefficients (r) between variables, with color gradient from blue to red representing r values from -1.0 to 1.0 . Asterisks indicate significance levels: *** $p < 0.001$, ** $p < 0.01$, and * $p < 0.05$. The left panel displays Mantel test results linking grain protein content, starch content, and grain yield to all measured traits. Line thickness corresponds to Mantel's r value, and line color indicates significance (red: $p < 0.01$, blue: $0.01 \leq p < 0.05$, and gray: $p \geq 0.05$). Abbreviations: WG: wet gluten content; SV: sedimentation value; ST: stability time; WS: water solubility; SP: swelling power; PV: peak viscosity; LV: low viscosity; BV: breakdown viscosity; FV: final viscosity; SeV: setback viscosity; PT: pasting temperature; Spike: spike number; Ke: kernels per spike; TKW: 1000-kernel weight; Starch: grain starch content; Protein: grain protein content; Yield: grain yield.

4. Discussion

4.1. Effects of Sowing Date and Seeding Rate on Winter Wheat Yield and Its Components

A large number of studies have studied the effects of sowing date and seeding rate on wheat yield, with varying results. Ref. [14] showed that yield decreased with delayed sowing and that increasing the seeding rate could reduce the yield loss caused by delayed sowing. However, ref. [23] found that appropriate late sowing not only increased wheat yield but also enhanced lodging resistance. Sowing too early increases the risk of frost damage. Differences in cultivar, region, and climate may have led to the different results of these studies. This study showed that appropriate late sowing did not lead to yield reduction (Figure 2 and Table S1), which is inconsistent with the findings of [14], possibly because different cultivars have different pre-winter accumulated temperature requirements. As a semi-winter cultivar, 'Shaannong 33' has better adaptability to late sowing. However, it is consistent with the findings of [23]. This may be because, against the backdrop of global warming, traditional suitable sowing dates often lead to excessive pre-winter accumulated temperature and increased risk of overgrowth, while appropriate late sowing allows the pre-winter accumulated temperature to return to a more suitable range, thereby reducing frost damage and optimizing population structure [15,24,25]. Seeding rate is a key means of

regulating population structure and mitigating the yield reduction effect of late sowing [26]. This study confirmed that with increasing seeding rate, spike number per unit area showed a linear increasing trend (Figure 2 and Table S1), which is consistent with the findings of [27,28], providing direct evidence for achieving yield compensation through increased density under late-sowing conditions. However, higher seeding rates are not always better. In this study, with the increase in seeding rate, kernels per spike exhibited a continuous decreasing trend (Figure 2 and Table S1). By contrast, 1000-kernel weight only declined from R1 to R3, then slightly increased at R4, and overall was not significantly affected by seeding rate. The reduction in kernels per spike under high-seeding-rate conditions was mainly attributed to intensified intraspecific competition for light, water, and nutrients, which constrained grain development [27,29]. Notably, in this study, when sowing was extremely late (after 6 November), increasing the seeding rate to 360×10^4 plants ha^{-1} still achieved a certain degree of yield compensation, but this compensation effect was limited and could not fully offset the yield loss caused by extremely late sowing (Figure 2 and Table S1). The yield difference between the two years further reveals the importance of climatic conditions. Spike number per unit area in 2020–2021 was reduced by an average of 18.73% compared to the previous year, leading to a significant yield reduction of 5.60% (Figure 2 and Table S1). This may be mainly related to inter-annual fluctuations in precipitation distribution and temperature conditions during the growing season [4]. Therefore, in late-sown cultivation management, the impact of inter-annual climate variability on spike formation capacity should be fully considered. The substantial year difference in yield (5.94% reduction in 2020–2021 compared to 2019–2020) highlights the critical role of inter-annual climatic variability. The spike number per unit area in 2020–2021 was 23.05% lower than in 2019–2020, which was the primary driver of the yield reduction (Figure 2 and Table S1). This reduction is likely attributable to differences in climatic conditions between the two seasons (Figure 1). The 2020–2021 growing season had a lower average temperature and higher total precipitation compared with 2019–2020. The cooler temperatures during tillering and jointing stages in 2020–2021 may have reduced tiller survival and spike formation capacity [4,6]. Previous studies have shown that lower temperatures during the tillering period can significantly reduce the number of productive tillers per plant, ultimately limiting spike number per unit area [12]. Additionally, the higher precipitation in 2020–2021, particularly during the jointing to booting stages, may have increased disease pressure or reduced solar radiation interception, indirectly affecting carbohydrate accumulation and spike development. These findings underscore the importance of considering inter-annual climate variability when developing agronomic recommendations for late-sown wheat.

4.2. Effects of Sowing Date and Seeding Rate on Grain Processing Quality and Starch Properties

The wheat genotype largely determines its quality traits, but the environment, fertilizer management, and cultivation techniques also have significant effects on quality [9,26,30]. Some studies have shown that grain protein content gradually decreases with delayed sowing [19], and wet gluten content and sedimentation value are significantly positively correlated with protein content [31]. Strong-gluten wheat is more susceptible to the effects of sowing date than weak-gluten wheat [32]. However, Ref. [33] found that protein content is highest when sowing at the appropriate time. Ref. [34] showed that with an appropriate seeding rate, wheat protein content, wet gluten content, and sedimentation value are higher, and dough stability time is longer.

This study showed that appropriate late sowing (D2) increased protein content and wet gluten content compared with earlier-sowing (D1) and extremely-late-sowing (D3) treatments, while sowing date produced no significant difference in stability time across the two experimental years (Tables 1 and S2). In the 2020–2021 growing season, protein content,

wet gluten content, and stability time of D2 treatment were significantly higher than D1 and D3 (Table S2), and protein content exhibited significantly positive correlations with wet gluten content, sedimentation value, and stability time (Figure 3). This is consistent with the findings of [32,34]. The improvement in protein content and processing quality with appropriate late sowing can be attributed, at least in part, to the shift in grain filling to later periods when temperatures are typically higher. Moderate heat stress during grain filling has been shown to promote the accumulation of glutenin polymers [35], thereby enhancing dough strength and stability time [36]. This interpretation is supported by our correlation analysis showing significant positive associations between protein content and dough stability (Figure 3) and is consistent with the findings of [25] in similar climatic regions.

The observed responses of starch properties to sowing date reveal important insights into the regulation of starch quality under late-sowing conditions. Compared with D1, both D2 and D3 markedly reduced amylose content by about 5.19% and the amylose/amylopectin ratio by 6.38% while increasing amylopectin content by approximately 2.44% (Table S3). No significant differences in these parameters were observed between D2 and D3. These changes are consistent with the hypothesis that later sowing alters temperature and light resource allocation during grain filling, favoring the upregulation of starch-branching-enzyme activity and promoting amylopectin synthesis at the expense of amylose [37,38]. The decrease in amylose content and increase in amylopectin proportion are the core reasons for the increase in swelling power, rise in viscosity curve, and decrease in pasting temperature [39,40]. The correlation analysis of this study further confirmed that the amylose/amylopectin ratio was extremely significantly negatively correlated with peak viscosity and final viscosity (Figures 4 and 5, $p < 0.001$), indicating that starch composition is a key internal factor determining pasting properties. In addition, this study found that late sowing significantly increased amylopectin content as well as peak viscosity and final viscosity while reducing amylose content (Tables 2, 3, S3 and S4). However, the sowing date did not produce significant differences in swelling power and pasting temperature across treatments. These findings are consistent with previous results reported by [41].

It should be noted that [42] reported an increase in viscosity indicators with increasing planting density, while [43] observed a rise-first-then-fall trend. In this study, viscosity indicators showed a linear decreasing trend with increasing seeding rate (Tables 3 and S4), which differs from previous studies. This discrepancy likely reflects differences in cultivar characteristics (strong-gluten cultivars are more sensitive to density competition) and regional temperature and light conditions [15,30]. Despite this discrepancy, the results of this study indicate that under late-sowing conditions, excessively high seeding rates indirectly inhibits starch accumulation and pasting performance by increasing individual competition intensity.

4.3. Perspectives and Limitations of This Study

Overall, appropriate late sowing (25–31 October) combined with moderate seeding rate ($240\text{--}300 \times 10^4$ plants ha^{-1}) is a feasible combination for achieving synergistic improvement of yield and quality for the strong-gluten cultivar ‘Shaannong 33’. Under this combination, yield was maintained at a relatively high level (Figure 2 and Table S1), while protein content, wet gluten content, and dough stability time remained stable (Tables 1 and S2), and starch pasting properties were significantly improved (Tables 3 and S4). This has positive implications for the processing quality of cooked foods such as noodles and steamed buns made from strong-gluten wheat, as increased amylopectin content and improved viscosity indicators have been shown to be significantly positively correlated with noodle elasticity, smoothness, and specific volume of steamed buns [20,22]. It is worth noting that when the sowing date was further delayed to after 6 November, processing quality indicators showed

a decreasing trend, and even increasing the seeding rate could not fully restore quality at this point (Tables 1 and S2). Therefore, in actual production practice, the sowing date should be controlled before the end of October, with seeding rate as an auxiliary regulatory measure to compensate for yield loss caused by late sowing for this cultivar.

However, this study still has several limitations. First, this study only used one strong-gluten wheat cultivar, 'Shaannong 33'. Whether the results can be extended to weak-gluten, medium-gluten, or other cultivars with different maturity types requires further validation. Second, although the interaction effect between sowing date and seeding rate has been clarified, intermediate physiological indicators related to population structure, photosynthetic matter production, and nitrogen translocation were not systematically measured, limiting the in-depth analysis of the regulatory mechanisms of yield and quality. Third, the starch-related findings in this study were based on a single growing season (2020–2021), which limits the generalizability of these results across different climatic conditions. While the results provide valuable insights into the effects of sowing date and seeding rate on wheat starch properties under the specific environmental conditions of the 2020–2021 season, the responses may vary under different temperature and precipitation regimes. To address this limitation and to disentangle the genuine effects of sowing date from the confounding influence of inter-annual climatic variability, future studies should employ a broader range of sowing dates (e.g., from late September to mid-November) over multiple years (ideally 5–10 years) to capture the full spectrum of climatic variability. Such an approach would enable the identification of critical temperature and radiation thresholds during specific phenological stages, particularly grain filling, that determine quality outcomes, and would allow for the development of robust, climate-resilient agronomic recommendations based on long-term meteorological data rather than fixed calendar dates. Fourth, this study did not include different nitrogen fertilizer management or water management treatments, which have complex interactions with sowing date and seeding rate and are also worthy of attention in integrated cultivation technology systems. Future studies should investigate the interactive effects of sowing date, seeding rate, nitrogen application rate and timing, and irrigation regimes to develop comprehensive integrated cultivation strategies that optimize both yield and quality under varying climatic conditions. Such multifactorial experiments would more closely reflect the complexity of real-world farming systems and would provide more actionable recommendations for farmers.

Despite these limitations, the present study provides several important insights for late-sown strong-gluten wheat production in the southern North China Plain. First, this study comprehensively characterized how sowing date and seeding rate jointly regulate processing quality and starch physicochemical properties, which has rarely been systematically reported in previous studies. Second, our findings clarify the interactive response of yield and quality to agronomic managements under delayed-sowing conditions, revealing the physiological basis for trade-offs between grain yield and quality. Third, we identified that wheat performance under late-sowing conditions is strongly affected by inter-annual climate fluctuation, which highlights that flexible sowing strategies rather than fixed-date management are required for local wheat production. Future research should validate these findings across multiple wheat cultivars with different genetic backgrounds and multi-location trials to improve the wide applicability of our agronomic recommendations.

5. Conclusions

This study used the strong-gluten wheat cultivar 'Shaannong 33' to systematically investigate the regulatory effects of different sowing dates and seeding rates on wheat yield, processing quality, and starch properties under late-sowing conditions in the southern North China Plain. The results showed that appropriate late sowing (approximately

27 October–2 November in 2019–2020, and 25–31 October in 2020–2021) combined with moderate seeding rate ($240\text{--}300 \times 10^4$ plants ha^{-1}) could maintain yield at a comparably high level while improving processing quality indicators such as protein content, wet gluten content, sedimentation value, and dough stability time. However, the optimal sowing window exhibited inter-annual variability: in 2019–2020, both 27 October and 2 November produced comparable yields, whereas in 2020–2021, the window was slightly narrower, with 31 October emerging as the optimal date for both yield and quality. This variability reflects the influence of climatic conditions, particularly temperature and precipitation during crop establishment and grain filling, on the response of wheat to sowing date. Further delaying the sowing date (after 6 November) reduced yield and quality parameters, but the yield loss could be partially compensated by appropriately increasing seeding rate (360×10^4 plants ha^{-1}). In terms of starch properties, moderately late sowing (sown from 31 October to 2 November) significantly increased amylopectin content and peak viscosity by reducing amylose content, whereas the sowing date produced no significant differences in swelling power and pasting temperature. The reduction of amylose content under moderately late-sowing conditions was favorable for improving flour cooking and eating quality. In summary, sowing date and seeding rate have a synergistic regulatory effect on yield and quality of late-sown wheat for the strong-gluten cultivar ‘Shaannong 33’, and appropriate combinations can achieve synergistic improvement of yield and quality against the backdrop of regional climate warming.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy16141378/s1>.

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