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Regulating panicle nitrogen fertilizers for qualities of rice with different grain filling rate in China

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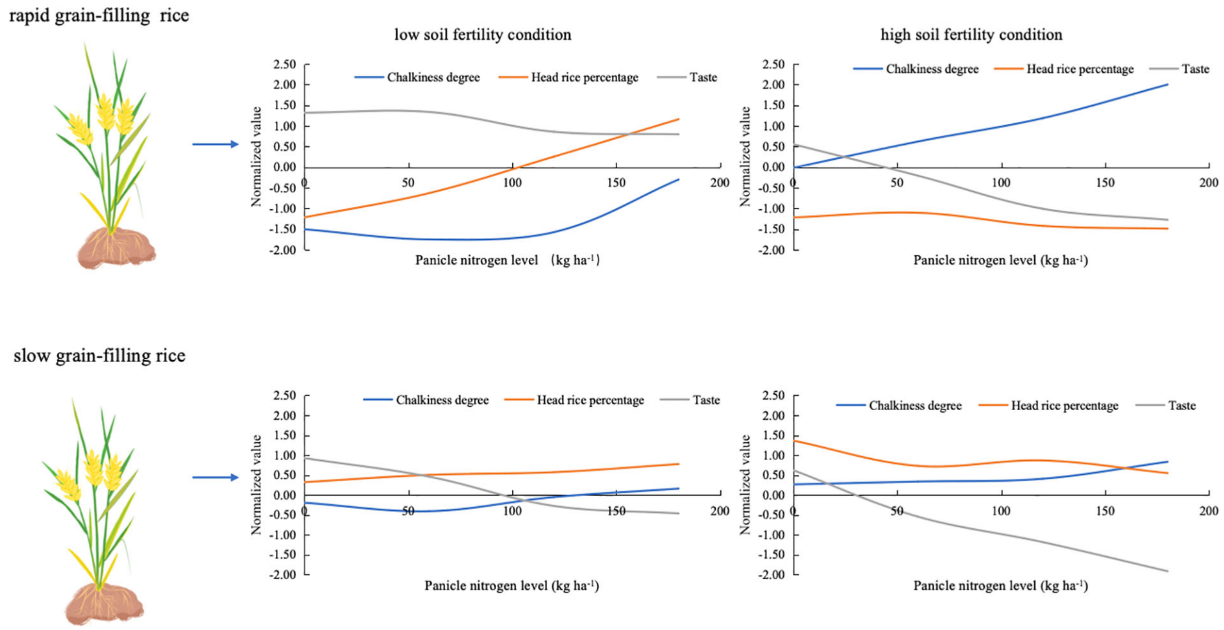
Introduction: Panicle nitrogen fertilizer is an important agronomic measure to regulate rice quality. Grain filling is crucial for the formation of rice quality. However, there are few studies on the effects of panicle nitrogen application on rice quality of soft japonica rice with different grain filling rate.
Methods: In this study, two field experiments were carried out, two soft japonica rice varieties, Ningxiangjing 9 (N9) with rapid grain-filling rate and Ningjing 8 (N8) with slow grain-filling rate, were used under four panicle nitrogen levels.
Results and discussion: N9 exhibited significant increase in chalkiness rate and chalkiness degree under medium to high panicle nitrogen levels, while panicle nitrogen fertilizer application had relatively smaller effects on N8. With the increasing panicle nitrogen level, N9 demonstrated greater improvement in processing quality compared to N8 under environmental with lower soil fertility, Conversely, N9 showed smaller reduction in processing quality compared to N8 under environmental with higher soil fertility. With increasing nitrogen application rates in panicle fertilizers, N8 showed greater decreases in taste quality under medium to high nitrogen levels compared to N9. In conclusion, the key to achieving high-quality rice production in the field lies in formulating differentiated panicle nitrogen fertilizer management strategies based on the grain filling rate characteristics of the varieties.

KEYWORDS

booting stage, precise fertilizer application, grain filling rate, eating quality, soft japonica rice



GRAPHICAL ABSTRACT

1 Introduction

China is one of the world's largest producers and consumers of rice. To address food security challenges, China's rice breeding and cultivation strategies have long prioritized yield improvement, resulting in relatively low proportion of high-quality rice (Hu et al., 2021; Gu et al., 2024). With rising living standards, consumers increasingly favor japonica rice with superior quality and excellent eating qualities, leading to growing demand (Wang et al., 2017). However, in southern China's high-temperature and high-humidity environments, japonica rice exhibits relatively poor grain appearance and eating quality. Over the past two decades, driven by innovations in rice research and breeding technologies, Jiangsu Province has significantly accelerated its high-quality rice breeding process, yielding a series of premium japonica varieties with excellent eating qualities. These include representative cultivars such as Nanjing 46, Nanjing 9108, Ningxiangjing 9, Ningjing 8, Suzhouxiangjing 3, and Suzhouxiangjing 100.

The grain filling process not only determines rice yield but also critically influences grain quality, yet research on the relationship between grain filling dynamics and rice quality remains limited. Zhang J. et al. (2021) found that in hybrid medium-indica rice, the average and maximum filling rates of inferior grains showed positive correlations with chalky grain rate, chalkiness degree, and amylose content. Notably, the timing of maximum filling rate in inferior grains positively correlated with brown rice rate, milled rice rate, and head rice rate. Both average and maximum filling rates exhibited significant or highly significant positive correlations with processing quality, while the timing of maximum filling rate and active filling period showed significant negative correlations with processing quality. Yin et al. (2013) demonstrated that enhancing early filling rates of inferior grains and improving filling rates of both strong and weak grains during peak and later filling stages could simultaneously optimize rice processing and appearance qualities.

Panicle fertilizer, the primary nitrogen source during the booting stage, plays a crucial role in starch granule formation and grain filling. Chen et al. (2021) observed that panicle fertilizer application improved processing quality but degraded eating quality by reducing gel consistency and taste values. Yang et al. (2020) reported that excessive panicle fertilizer reduced starch branching enzyme activity, leading to fewer short-chain branches in amylopectin and impaired starch gelatinization. High nitrogen levels also adversely affected starch optimization by increasing RVA profile breakdown values while decreasing peak viscosity, hot paste viscosity, cool paste viscosity, and disintegration value. The conflict between high yield and premium quality cultivation lies in the divergent nitrogen requirements for panicle differentiation stages to enhance yield versus quality (Wang et al., 2021). Few studies have investigated how nitrogen panicle fertilizer levels regulate rice quality through grain filling characteristics across different filling-rate genotypes. Therefore, this study uses two representative soft-japonica rice cultivars with contrasting filling rates from Jiangsu Province to investigate how nitrogen panicle fertilization affects appearance, processing, and eating qualities. This research provides critical guidance for optimizing quality control strategies in premium japonica rice production.

2 Materials and methods

2.1 Experimental locations

Field trials were conducted at two sites in 2022 during the rice cropping season, including Experimental Base of the Jiangsu Academy of Agricultural Sciences in Lishui (31。39'5.299"N, 119。1'39.464"E) and the Jingxian Farm in Jiangyan District (32。34'1.164"N, 120。5'47.116"E), Taizhou City, Jiangsu Province. The Lishui experimental field had soil fertility characterized by pH (7.0), available nitrogen (60.40 mg kg^{-1}), available potassium (80.41 mg kg^{-1}), available phosphorus (10.33 mg kg^{-1}), and organic matter content (16.09 g kg^{-1}). The Jiangyan experimental field featured sandy loam soil with a pH of 7.1, available nitrogen (85.40 mg kg^{-1}), available potassium (116.1 mg kg^{-1}), available phosphorus (13.2 mg kg^{-1}), and organic matter content (23.6 g kg^{-1}). Meteorological data during the crop growth periods at two trial sites are presented in Figure 1.

2.2 Experimental materials

Two representative late-maturing japonica rice varieties with synchronized heading dates and significant differences in grain filling rates were selected for the trials: Ningxiangjing 9 (N9) with high grain filling rate and Ningjing 8 (N8) with relative low grain filling rate. Their characteristics are detailed in Table 1.

2.3 Experimental design

A split-plot design was employed, with nitrogen fertilizer application during the panicle initiation stage as main plot and rice varieties as subplot. The main plot included four panicle nitrogen levels (0, 60, 120, and 180 kg ha^{-1}, respectively), applied equally as promotive fertilizer (at the fourth leaf stage) and reproductive fertilizer (at the second leaf stage). The subplot consisted of the two rice varieties. Each subplot was 20 m^2. The experiment was replicated three times. 180 kg ha^{-1} nitrogen (Urea) was applied as basel and tiller fertilizer, phosphorus pentoxide (90 kg ha^{-1} as P_2O_5) was applied as basel fertilizer, and potassium oxide (120 kg ha^{-1} as K_2O) was applied equally as basel and panicle fertilizer. Seeds were sown on May 15 and the seedlings were transplanted in June 5. The transplanting row spacing was 25 cm and plant spacing was 13.3 cm. Plastic film mulching was applied to plot boundaries before land preparation to prevent fertilizer leaching. Each subplot had independent inlet and outlet channels, and irrigation was managed through alternate wetting and drying.

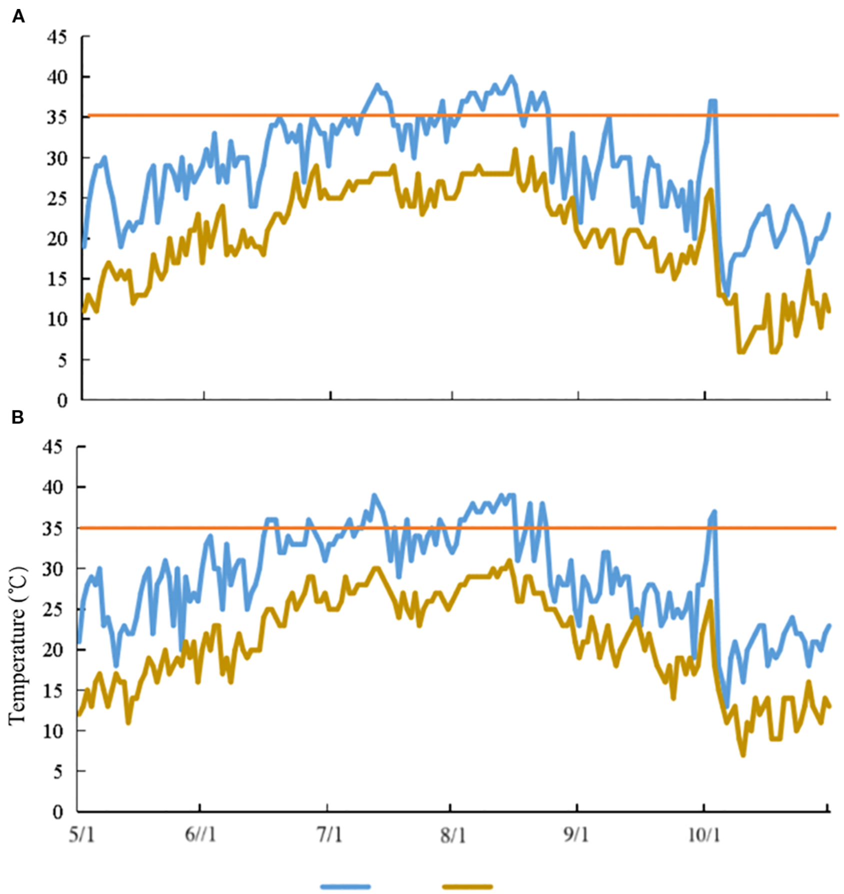


FIGURE 1
Daily max temperature and daily min temperature at Lishui **(A)** and Jiangyan **(B)**.

TABLE 1 Cultivar information of different varieties in different environments.

E	V	Heading date	GRmean ($mg\cdot grain^{-1}\cdot d^{-1}$)	Grain weight (mg)
Lishui	N9	8/22	0.94	23.6
	N8	8/22	0.75	26.1
Jiangyan	N9	9/5	0.99	23.5
	N8	9/9	0.73	27.4

E, V and GRmean means environment, variety and mean grain filling rate, respectively.

All other practices, including pest and disease control, were standardized to align with high-yield production protocols.

2.4 Sampling and determination methods

2.4.1 Growth stage recording

Observe and record the sowing date, transplanting date, heading date (80% flowering date), and maturity date (95% yellowing date) for each variety.

2.4.2 Grain filling dynamics

Select 100 panicles with synchronized heading dates and similar spike sizes from each plot during the heading-flowering stage. Tag and label these panicles. Sample every 5 days starting from the tagging day until maturity. For each sampling, collect 10 tagged panicles, dry them in an oven, and measure grain weight dynamics to calculate the grain filling rate.

The Richards equation W=(1+Be−kt)NA is used to model grain filling processes and calculate the filling rate. Here, W represents grain weight (mg), A is final grain weight (mg), t is days after flowering, and B, K, and N are equation parameters.

2.4.3 Appearance quality

Use the WanShen SC-E Rice Appearance Quality Detection and Rice Quality Judgment Instrument to determine the average length and width of whole grains, chalky grain rate, and chalkiness degree.

2.4.4 Processing quality

Refer to China's National Standard GB/T 1354–2018 for High-Quality Rice to measure brown rice rate, milled rice rate, and whole grain rate.

2.4.5 Total protein and amylose content

Protein content (PC) is determined using a FOSS Kjeltec™ 2300 automatic nitrogen analyzer via the semi-micro Kjeldahl method, followed by conversion using a factor of 5.95.

Amylose content is measured using the Spectrophotometric Method for Rice Amylose (NY/T 2639-2014) and a BDFIA-7000 Amylose Analyzer.

2.4.6 Rice taste and texture characteristics

Evaluate taste value, hardness, elasticity, viscosity, and balance using a rice taste meter (RCTA-11A, Satake, Japan). Procedures: Weigh 30 g of whole grains, rinse with a stainless steel rice washer, transfer to a 50 ml aluminum container with 40 ml distilled water, soak at room temperature for 20 min, steam for 30 min, stir and rest for 10 min, cool in a cooling box for 20 min, equilibrate at room temperature for 1 h 40 min, then measure 8.0 g of cooled rice in a metal cup. Apply pressure for 10 s in both directions to obtain taste value. Each sample is tested four times.

2.4.7 RVA viscosity spectrum of rice

Rice starch viscosity is analyzed using a RVA Viscometer (Perten, Sweden) following AACC 61–01 and 61–02 protocols. Primary parameters include peak viscosity (PV), trough viscosity (TV) and final viscosity (FV). Secondary parameters are breakdown (BD) and setback (SB). Each sample is tested twice, and average values are taken as phenotypic traits.

2.5 Data analysis

Data entry and calculations are performed using Microsoft Excel 2016. Statistical analysis employs SPSS 22.0 with LSD method for multiple comparisons. Origin 19.0 is used for data visualization.

3 Results

3.1 Panicle nitrogen effect on appearance quality

At the Lishui trial site, as panicle nitrogen levels increased, grain length and aspect ratio of different rice varieties showed a decreasing trend, while nitrogen fertilizer had minimal impact on grain width. Chalky grain rate and chalkiness degree increased with higher nitrogen application. Compared to the N0 treatment, N9 exhibited a 46.5% and 85.5% increase in chalky grain rate and chalkiness degree under the N180 treatment, respectively, while N8 showed increases of 15.9% and

12.7%. At the Jiangyan trial site, similar trends were observed: grain length and width decreased with nitrogen topdressing, while chalky grain rate and chalkiness degree followed the same pattern as that at the Lishui trial site. For N9 under N180, chalky grain rate and chalkiness degree rose by 45.7% and 70.3% (vs. N0), and that for N8 increased by 6.4% and 17.9% (Table 2).

3.2 Panicle nitrogen effect on processing quality

In terms of rice processing quality, at the Lishui site, brown rice rate, milled rice rate, and head rice rate all increased with higher nitrogen topdressing levels. Compared to N0, N9 improved by 1.3%, 4.7%, and 18.0% (for brown rice, milled rice, and head rice rates, respectively) under N180, while N8 showed gains of 2.3%, 3.3%, and 3.1%. At the Jiangyan site, however, brown rice rate remained unchanged, while milled and head rice rates decreased with nitrogen application. The milled and head rice rates of N9 under N180 dropped by 2.1% and 2.0% (vs. N0), and the rates for N8 decreased by 3.5% and 5.2% (Table 3).

3.3 Panicle nitrogen effect on nutritive quality

Protein content increased across all varieties with higher nitrogen topdressing. At the Jiangyan site, differences between N120 and N180 were non-significant. For amylose content, N9 showed a trend of initial increase followed by decrease over both years. N8 exhibited an initial increase-decrease pattern at Lishui, but it had significantly higher amylose content under N0 compared to other treatments at Jiangyan (Table 4).

3.4 Panicle nitrogen effect on eating quality

Regarding taste value, at the Lishui site, both varieties showed decreasing trends as nitrogen topdressing increased. N9 had no significant difference in taste value between N0 and N60, but its taste value dropped by 5.5% and 6.3% under N120 and N180, respectively. The taste value of N8 decreased by 5.9%, 15.1%, and 17.4% under N60, N120, and N180. Similar trends were observed at

TABLE 2 Effects of panicle nitrogen levels on appearance quality of early-maturing late-japonica rice with different grain filling rate.

V	E	N	GL	GW	L/W	CR	CD
			mm	mm		%	%
N9	Lishui	N0	5.03 A	2.63 A	1.92 A	16.6 B	3.9 B
		N60	5.04 A	2.65 A	1.90 B	12.5 C	3.2 B
		N120	4.99 B	2.63 A	1.90 B	17.0 B	3.7 B
		N180	4.97 B	2.62 A	1.90 B	24.3 A	7.3 A
		CV	0.7	0.5	0.5	27.9	41.4
	JiangYan	N0	4.89 A	2.83 A	1.73 A	25.6 C	8.1 B
		N60	4.80 B	2.78 B	1.73 A	27.6 B	9.9 B
		N120	4.80 B	2.77 B	1.74 A	31.7 B	11.5 A
		N180	4.83 B	2.80 AB	1.73 A	37.3 A	13.8 A
		CV	0.9	0.9	0.3	16.9	22.4
N8	Lishui	N0	4.84 A	2.73 B	1.77 A	27.0 B	7.6 A
		N60	4.76 B	2.76 A	1.73 B	28.2 B	7.0 A
		N120	4.75 B	2.75 A	1.72 B	29.2 AB	8.0 A
		N180	4.72 B	2.77 A	1.70 B	31.3 A	8.6 A
		CV	1.1	0.6	1.7	6.3	8.6
	JiangYan	N0	4.91 A	2.93 A	1.68 A	31.1 A	8.9 B
		N60	4.85 B	2.89 B	1.68 A	31.4 A	9.1 B
		N120	4.81 C	2.84 C	1.69 A	32.3 A	9.3 B
		N180	4.80 C	2.85 C	1.68 A	33.1 A	10.5 A
		CV	1	1.4	0.3	5.5	17.8

V, E, N, GL, GW, L/W, CR and CD means variety, environment, panicle nitrogen level, grain length, grain width, length/width, Chalky grain rate and chalkiness degree, respectively. N0, N60, N120 and N180 means 0, 60, 120, 180 kg N ha^{-1}, respectively. Different uppercase letters in the same column indicate statistical significance at the 0.05 level among different nitrogen levels. CV means the coefficient of variation.

TABLE 3 Effects of panicle nitrogen levels on milling quality of early-maturing late-japonica rice with different grain filling rate.

V	E	N	BR (%)	MR (%)	HR (%)
N9	Lishui	N0	80.7 B	70.0 B	58.2 C
		N60	80.6 B	70.7 B	60.8 C
		N120	81.2 A	73.3 A	64.7 B
		N180	81.8 A	73.3 A	68.7 A
		CV	0.7	2.4	7.3
	JiangYan	N0	82.7 A	67.0 A	58.2 A
		N60	82.6 A	66.4 AB	58.7 A
		N120	82.5 A	65.7 B	57.3 B
		N180	82.4 A	65.6 B	57.0 B
		CV	0.2	2.3	3.0
N8	Lishui	N0	81.9 B	73.3 D	65.0 B
		N60	82.4 B	74.2 C	65.8 AB
		N120	83.0 AB	75.0 B	66.1 AB
		N180	83.8 A	75.7 A	67.0 A
		CV	1.0	1.4	1.3
	JiangYan	N0	85.2 A	73.3 A	69.6 A
		N60	85.2 A	72.2 B	66.8 B
		N120	85.4 A	71.7 B	67.4 B
		N180	85.6 A	70.7 B	66.0 B
		CV	0.2	3.5	4.3

V, E, N, BR, MR and HR means variety, environment, panicle nitrogen level, brown rice rate, milled rice rate and head rice rate, respectively. N0, N60, N120 and N180 means 0, 60, 120, 180 kg N ha^{-1}, respectively. Different uppercase letters in the same column indicate statistical significance at the 0.05 level among different nitrogen levels. CV means the coefficient of variation.

Jiangyan: N9's taste value fell by 10.1%, 20.6%, and 24.2% (N60, N120, N180 vs. N0), while N8 dropped by 15.2%, 23.6%, and 33.1%. Changes in appearance, viscosity, and balance were consistent with taste value, whereas hardness showed an opposite trend (Table 5).

3.5 Nitrogen effect on starch pasting properties

With the increase in nitrogen topdressing levels, the peak viscosity, final viscosity, hot paste viscosity, and breakdown value of all varieties exhibited a decreasing trend, where the reduction in N9 was less pronounced than that in N8. Conversely, the setback value demonstrated an increasing trend, although the increment in N9 was smaller than that in N8 (Table 6).

3.6 Nitrogen effect on grain filling parameters

The application of additional nitrogen as panicle fertilizer significantly reduced Tmax, GRmax, and GRmean, and significantly prolonged D, but the extent of response varied among cultivars (Table 7). Compared to the N0 treatment, under N60, N120, and N180 treatments, the Tmax of N9 decreased by 2.7%, 4.1%, and 12.6% respectively, while that of N8 decreased by 11.8%, 14.3%, and 26.3% respectively. Compared to the N0 treatment, the GRmax of N9 under N60, N120, and N180 treatments decreased by 3.7%, 9.7%, and 20.5% respectively, while that of N8 decreased by 13.0%, 23.7%, and 37.8% respectively. Compared to the N0 treatment, the GRmean of N9 under N60, N120, and N180 treatments decreased by 7.3%, 17.1%, and 28.7% respectively, while that of N8 decreased by 17.5%, 39.6%, and 42.1% respectively. Compared to the N0 treatment, the D of N9 under N60, N120, and N180 treatments was prolonged by 8.6%, 16.6%, and 23.7% respectively, while that of N8 was prolonged by 15.7%, 32.6%, and 47.4% respectively.

3.7 Relationship between rice grain qualities and grain filling parameters

Correlation analysis indicated that GRmax, GRmean, and D were significantly negatively correlated with the chalky grain rate

TABLE 4 Effects of panicle nitrogen levels on nutritional quality of early-maturing late-japonica rice with different grain filling rate.

V	E	N	Protein content	Amylose content
			%	%
N9	Lishui	N0	7.6 C	10.6 B
		N60	8.2 B	11.3 A
		N120	8.7 A	11.6 A
		N180	8.8 A	11.3 A
		CV	2.9	1.6
	JiangYan	N0	8.3 C	13.1 B
		N60	8.8 B	13.7 A
		N120	9.4 A	14.0 A
		NN180	9.0 AB	13.8 A
		CV	2.6	1.3
N8	Lishui	N0	8.6 B	12.5 B
		N60	8.6 B	13.5 A
		N120	9.6 A	13.7 A
		NN180	9.9 A	12.7 B
		CV	3.3	1.7
	JiangYan	N0	7.4 C	13.1 A
		N60	8.1 B	11.6 C
		N120	8.5 A	12.7 B
		NN180	8.5 A	12.0 B
		CV	3.2	2.6

V, E and N means variety, environment and panicle nitrogen level, respectively. N0, N60, N120 and N180 means 0, 60, 120, 180 kg N ha^{-1}, respectively. Different uppercase letters in the same column indicate statistical significance at the 0.05 level among different nitrogen levels. CV means the coefficient of variation.

and chalkiness degree (Table 8). Tmax was significantly negatively correlated with protein content, while D was significantly positively correlated with protein content. GRmax and GRmean were significantly positively correlated with Appearance, Stickiness, Springiness, Taste, PV (Peak Viscosity), HV (Hot Paste Viscosity), FV (Final Viscosity), and BD (Breakdown), but significantly negatively correlated with Hardness.

4 Discussion

4.1 Nitrogen regulation of appearance quality in varieties with different grain-filling rates

Appearance quality is one of the most commercially valuable traits in rice and a critical factor influencing consumer purchasing decisions. Chalky grain rate and chalkiness degree are the two most important indicators affecting appearance quality. Research on nitrogen's impact on rice appearance quality has yielded varied results. Most studies suggest that moderate nitrogen application enhances rice population vigor and individual plant development, prolongs the grain-filling period, improves starch granule and protein body packing density, reduces interstitial spaces, and thus mitigates chalkiness (Qiao et al., 2011; Zhou et al., 2015; Zhang Q. et al., 2021; Guo et al., 2022). However, Zhu et al. (2017a) observed that excessive nitrogen fertilizer increased chalkiness in soft-japonica rice. Our study similarly found that GRmax, GRmean and D showed a highly significant negative correlation with the chalky grain rate and chalkiness degree, and that two early-maturing late-japonica cultivars exhibited significantly higher chalkiness degree and chalky grain rate under high nitrogen topdressing levels. Notably, compared to slow-grain-filling varieties, fast-grain-filling varieties showed greater increments. Nitrogen-induced chalkiness may arise from reduced protein abundance related to respiratory and energy metabolism, disrupting endosperm starch biosynthesis and accumulation. Additionally, nitrogen metabolic disorders during the grain-filling stage and upregulated expression of storage proteins (Xi et al., 2021), as well as elevated activities of glutamine synthetase, glutamate synthase, glutamic-oxaloacetic transaminase, and glutamic-pyruvic transaminase at 15 days post-anthesis (Xi et al., 2020), contribute to this phenomenon.

TABLE 5 Effects of panicle nitrogen levels on eating quality of early-maturing late-japonica rice with different grain filling rate.

V	E	N	Appearance	Hardness	Stickiness	Springiness	Taste
N9	Lishui	N0	8.90 A	5.55 B	9.40 A	9.10 A	87.00 A
		N60	8.95 A	5.65 B	9.55 A	9.10 A	87.20 A
		N120	8.30 B	5.95 A	8.85 B	8.50 B	82.20 B
		N180	8.20 B	5.95 A	8.75 B	8.35 B	81.55 B
		CV	4.6	3.6	4.3	4.5	3.6
	JiangYan	N0	8.00 A	6.30 B	8.45 A	7.95 A	79.05 A
		N60	6.90 B	6.70 B	7.25 B	6.70 B	71.10 B
		N120	5.40 C	7.25 A	5.95 C	5.40 C	62.75 C
		N180	5.15 C	7.45 A	5.40 C	4.95 D	59.95 C
		CV	21.0	7.6	20.2	21.7	12.7
N8	Lishui	N0	8.35 A	6.00 B	8.95 A	8.55 A	82.90 A
		N60	7.70 A	6.35 B	8.45 A	7.85 B	78.05 B
		N120	6.60 B	6.75 A	7.25 B	6.60 C	70.40 C
		N180	6.35 B	6.90 A	6.90 B	6.35 C	68.45 C
		CV	12.9	6.3	12.3	14.2	9.0
	JiangYan	N0	8.25 A	6.10 B	8.40 A	8.10 A	79.75 A
		N60	6.40 B	6.90 AB	6.55 B	6.20 B	67.60 B
		N120	5.50 C	7.30 A	5.40 B	5.10 B	60.95 C
		N180	5.35 C	7.35 A	5.00 B	5.05 B	53.35 C
		CV	31.2	13.8	29.7	31.2	22.3

V, E and N means variety, environment and panicle nitrogen level, respectively. N0, N60, N120 and N180 means 0, 60, 120, 180 kg N ha^{-1}, respectively. Different uppercase letters in the same column indicate statistical significance at the 0.05 level among different nitrogen levels. CV means the coefficient of variation.

4.2 Nitrogen regulation of processing quality in varieties with different grain-filling rates

Numerous studies indicate that nitrogen application improves brown rice rate, milled rice rate, and head rice rate, primarily due to increased protein content (especially gliadin) and grain hardness, which enhance milling resistance and elevate head rice rate (Ma et al., 2009). However, outcomes vary depending on cultivar type and environmental conditions. For example, Wang et al. (2012) reported that modern indica cultivars showed smaller increases in head rice rate compared to traditional indica cultivars, and that excessive nitrogen even reduced this trait. Tao et al. (2016) observed inconsistent responses across growth stages in medium-indica rice, with modern cultivars exhibiting smaller declines under high nitrogen. In our study, environment–cultivar interactions were evident: at the Lishui site, moderate nitrogen topdressing significantly improved processing quality in both early-maturing late-japonica cultivars, with faster-grain-filling varieties showing greater gains. Conversely, at the Jiangyan site, processing quality decreased—albeit less so in fast-grain-filling cultivars. These differences may relate to soil fertility: nitrogen reduction in high-fertility soils and supplementation in low-fertility soils could optimize processing quality (Zhang et al., 2011; Jiang et al., 2016). Additionally, divergent heading and maturity dates across environments (earlier at Lishui, later at Jiangyan) influenced outcomes, as delayed nitrogen application under prolonged grain-filling phases might compromise grain plumpness. This study found no significant correlation between grain filling rate and processing quality, which may be attributed to the fact that the head rice rate of the studied varieties was predominantly governed by their genetic background rather than the grain filling rate. Additionally, the rice at the test site in 2022 encountered persistent high temperatures in August coinciding with the booting stage. The varying tolerance of different varieties to such high temperatures might have altered the inherent simple correlation between grain filling rate and processing quality.

4.3 Nitrogen regulation of eating quality in varieties with different grain-filling rates

The eating quality of rice has increasingly attracted attention from researchers and consumers. Previous studies have generally shown that increasing nitrogen topdressing reduces eating quality (Chen et al., 2012; Meng et al., 2022). However, our research reveals that grain-filling rate showed a highly significant correlation with

TABLE 6 Effects of panicle nitrogen levels on pasting characteristics of early-maturing late-japonica rice with different grain filling rate.

V	E	N	PV (cP)	HV (cP)	BD (cP)	FV (cP)	SB (cP)
N9	Lishui	N0	3126 A	2214 A	912 A	2743 A	-383 C
		N60	3116 A	2131 B	985 A	2781 A	-335 B
		N120	3103 A	2169 B	934 A	2783 A	-320 A
		N180	3106 A	2155 B	951 A	2803 A	-303 A
		CV	1.9	5.1	12.0	4.0	25.2
	JiangYan	N0	2219 A	1471 A	748 A	2107 A	-112 C
		N60	2146 B	1365 B	781 A	2055 A	-91 B
		N120	2132 B	1450 A	682 B	2117 A	-15 A
		N180	2033 C	1405 A	628 C	1992 B	-41 A
		CV	4.2	10.7	8.1	6.7	37.3
N8	Lishui	N0	2893 A	1966 A	927 A	2728 A	-165 C
		N60	2820 A	1956 A	864 B	2707 A	-113 B
		N120	2772 B	1938 A	834 B	2710 A	-62 A
		N180	2663 C	1887 B	776 C	2609 B	-54 A
		CV	10.1	7.1	18.6	9.8	73.5
	JiangYan	N0	2240 A	1450 A	790 A	2003 A	-237 D
		N60	2024 B	1244 B	780 A	1828 B	-196 C
		N120	1933 C	1257 C	676 B	1796 B	-137 B
		N180	1800 D	1183 C	617 C	1705 C	-75 A
		CV	12.3	20.9	10.7	19.6	67.0

V, E and N means variety, environment and panicle nitrogen level, respectively. N0, N60, N120 and N180 means 0, 60, 120, 180 kg N ha$^{-1,}$ respectively. Different uppercase letters in the same column indicate statistical significance at the 0.05 level among different nitrogen levels. CV means the coefficient of variation.

TABLE 7 Effects of panicle nitrogen levels on grain filling parameters of early-maturing late-japonica rice with different grain filling rate.

V	E	N	Tmax (d)	GRmax (mg·grain^{-1}·d^{-1})	GRmean (mg·grain^{-1}·d^{-1})	D (d)
N9	Lishui	N0	20.5 A	1.68 A	1.07 A	32.8 C
		N60	19.7 B	1.65 A	1.03 A	35.1 B
		N120	19.3 B	1.55 B	0.94 B	38.4 AB
		N180	17.9 C	1.36 C	0.79 C	40.3 A
		CV	4.9	9	12.9	9.1
	JiangYan	N0	23.3 A	1.61 A	0.93 A	34.3 D
		N60	20.7 B	1.50 B	0.81 B	40.5 C
		N120	19.9 BC	1.32 C	0.67 C	44.8 B
		N180	17.8 C	1.07 D	0.59 D	49.5 A
		CV	11.1	17.2	20.1	15.3
N8	Lishui	N0	21.2 A	1.79 A	1.18 A	34.1 D
		N60	20.9 A	1.69 B	1.05 B	37.6 C

(Continued)

TABLE 7 Continued

V	E	N	Tmax (d)	GRmax (mg·grain^{-1}·d^{-1})	GRmean (mg·grain^{-1}·d^{-1})	D (d)
		N120	20.7 A	1.58 C	0.92 C	39.7 B
		N180	18.5 B	1.40 D	0.81 D	42.5 A
		CV	6.1	10.3	16.2	9.2
	JiangYan	N0	25.5 A	1.77 A	0.99 A	33.6 D
		N60	22.3 B	1.43 B	0.77 B	38.1 C
		N120	21.9 B	1.25 C	0.58 C	45.2 B
		N180	18.1 C	1.03 D	0.52 C	50.6 A
		CV	13.8	22.8	29.6	17.9

V, E and N means variety, environment and panicle nitrogen level, respectively. N0, N60, N120 and N180 means 0, 60, 120, 180 kg N ha$^{-1,}$ respectively. Tmax, GRmax, GRmean and D means the time reaching the maximum grain filling rate, the maximum grain filling rate, the average grain filling rate, the active grain filling period. Different uppercase letters in the same column indicate statistical significance at the 0.05 level among different nitrogen levels. CV means the coefficient of variation.

eating quality. Different japonica rice varieties with varying grain-filling rates respond distinctively to nitrogen topdressing: slow-grain-filling varieties exhibit greater sensitivity to nitrogen fertilizer, particularly under medium-to-high nitrogen levels, resulting in more significant declines in eating quality values. This difference may be attributed to the significantly reduced grain-filling rate observed in the slow-grain-filling variety N8 with the application of additional nitrogen panicle fertilizer. Studies have indicated that

TABLE 8 Correlation of rice grain-filling parameters with grain quality.

	Tmax	GRmax	GRmean	D
GL	0.04	0.32	0.38	-0.51*
GW	0.55*	-0.22	-0.39	0.25
L/W	-0.36	0.29	0.44	-0.40
CR	0.05	-0.55*	-0.63**	0.64**
CD	-0.07	-0.65**	-0.71**	0.70**
BR	0.34	-0.40	-0.56*	0.41
MR	0.06	0.35	0.38	-0.28
HR	0.17	0.09	0.03	-0.05
Protein content	-0.58*	-0.38	-0.33	0.52*
Amylose content	0.17	-0.13	-0.23	0.33
Appearance	0.29	0.83**	0.88**	-0.89**
Hardness	-0.21	-0.80**	-0.85**	0.86**
Stickiness	0.23	0.85**	0.91**	-0.89**
Springness	0.23	0.83**	0.89**	-0.88**
Taste	0.26	0.85**	0.90**	-0.90**
PV	-0.22	0.60*	0.74**	-0.59*
HV	-0.28	0.54*	0.69**	-0.52
BD	0.01	0.73**	0.81**	-0.75**
FV	-0.28	0.57*	0.71**	-0.51*
SB	-0.10	-0.46	-0.51*	0.62

Tmax, GRmax, GRmean and D means the time reaching the maximum grain filling rate, the maximum grain filling rate, the average grain filling rate and the active grain filling period, respectively. GW, L/W, CR and CD means grain length, grain width, length/width, Chalky grain rate and chalkiness degree, respectively. BR, MR and HR means brown rice rate, milled rice rate and head rice rate, respectively. PV, HV, FV, BD and SB means peak viscosity, hot viscosity, final viscosity, breakdown and setback.

excessive topdressing of nitrogen fertilizer can delay the grain-filling process, leading to inadequate grain plumpness and negatively impacting eating quality (Zhao et al., 2022). This also indicates that the sensitivity of eating quality to nitrogen fertilizer varies by cultivar (Gao et al., 2010). While some studies suggest that differences in grain protein content in response to nitrogen could explain variations in eating quality (Gu et al., 2015; Yang et al., 2024), our experiment shows that both fast- and slow-grain-filling varieties exhibit increased protein content with higher nitrogen application rates, with similar magnitudes of increase. Additionally, amylose content responds to nitrogen depending on environmental conditions. Therefore, eating quality cannot be simply evaluated based on low amylose or high protein content—it may also relate to starch structure, protein composition and ratios, and even fat content (Zhu et al., 2017b; Cao et al., 2018; Shi et al., 2019; Zhou et al., 2020; Jiang et al., 2022).

This study, based on comparative trials of two japonica rice varieties with significantly different grain-filling characteristics under two ecological sites in the same year, preliminarily revealed the differential impact mechanisms of nitrogen topdressing on rice grain quality. However, due to limitations of the single-year, two-site experimental design, further validation is required. Future research should focus on the following priorities: (1) Multi-year and multi-ecological zone experiments: Systematically establish nitrogen gradient trials covering early-, medium-, and late-maturing varieties with varying grain-filling rates to elucidate the dynamic responses of grain filling and quality formation. (2) Integrated predictive modeling: Incorporate multidimensional data (environmental factors, nitrogen management practices, and variety traits) to develop quantitative prediction models linking grain-filling dynamics to quality indicators (e.g., amylose content, gel consistency, and aromatic compounds). (3) Optimized nitrogen management strategies: Formulate nitrogen application plans tailored to varietal grain-filling characteristics based on model simulations, providing theoretical support for precision fertilization in rice production across diverse ecological zones.

5 Conclusions

With increased nitrogen topdressing, varieties with slow grain-filling exhibit smaller changes in appearance quality, while those with rapid grain-filling show relatively greater increases. Under low soil fertility conditions, the processing quality of fast-grain-filling varieties significantly improves, whereas slow-grain-filling varieties show smaller enhancements. In contrast, under high soil fertility conditions, the processing quality of slow grain-filling varieties decreases more substantially compared to rapid grain-filling ones. The eating quality of rice exhibits a gradual decline, with slow grain-filling varieties showing a greater response to nitrogen topdressing and larger reductions in taste value.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

CD: Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. XL: Data curation, Software, Writing – review & editing. ZW: Funding acquisition, Investigation, Resources, Writing – review & editing. LW: Validation, Writing – review & editing. JZ: Investigation, Writing – review & editing. LX: Project administration, Writing – review & editing. TJ: Supervision, Writing – review & editing. YG: Supervision, Validation, Writing – review & editing. WL: Funding acquisition, Project administration, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Cao, X., Sun, H., Wang, C., Ren, X., Liu, H., and Zhang, Z. (2018). Effects of late-stage nitrogen fertilizer application on the starch structure and cooking quality of rice. *J. Sci. Food Agric.* 98, 2332–2340. doi: 10.1002/jsfa.8723

Chen, Y., Liu, K., Zhang, H. L., Li, S. Y., Zhang, Y. J., Wei, J. L., et al. (2021). Effects of machine transplanting density and panicle nitrogen fertilizer reduction on grains starch synthesis in good taste rice cultivars. *Acta Agron. Sin.* 47, 1540–1550. doi: 10.3724/SP.J.1006.2021.02069

Chen, Y. Y., Hu, X. X., Chen, J. D., Yang, X., Ma, Q., Chen, Q., et al. (2012). Effect of nitrogen fertilizer application on eating quality of early-maturing late japonica rice in Jiangsu and its difference among varieties. *Acta Agron. Sin.* 38, 2086–2092. doi: 10.3724/SP.J.1006.2012.02086

Gao, H., Ma, Q., Li, G. Y., Yang, X., Li, X. Q., Yin, C. Y., et al. (2010). Effect of nitrogen application rate on cooking and eating qualities of different growth-development types of japonica rice. *Scientia Agric. Sin.* 43, 4543–4552. doi: 10.3864/j.issn.0578-1752.2010.21.026

Gu, J., Chen, J., Chen, L., Wang, Z., Zhang, H., and Yang, J. (2015). Grain quality changes and responses to nitrogen fertilizer of japonica rice cultivars released in the Yangtze River Basin from the 1950s to 2000s. *Crop J.* 3, 285–297. doi: 10.1016/j.cj.2015.03.007

Gu, X., Wang, P., Huang, J. Y., Chen, S. Q., Li, D. D., Pu, S. H., et al. (2024). Structural and physicochemical properties of rice starch from a variety with high resistant starch and low amylose content. *Front. Nutr.* 11, 1413923. doi: 10.3389/fnut.2024.1413923

Guo, C. C., Yuan, X. X., Yan, F. J., Xiang, K. H., Wu, Y. X., Zhang, Q., et al. (2022). Nitrogen application rate affects the accumulation of carbohydrates in functional leaves and grains to improve grain filling and reduce the occurrence of chalkiness. *Front. Plant Sci.* 24, 921130. doi: 10.3389/fpls.2022.921130

Hu, X. Q., Zhang, W. X., Shao, Y. F., Yu, Y. H., Lu, L., and Chen, M. X. (2021). Analysis on high quality rate of rice in China during recent 20 years. *China Rice* 27, 84–87. doi: 10.3969/j.issn.1006-8082.2021.04.017

Jiang, Y., Chen, Y., Zhao, C., Liu, G., Shi, Y., Zhao, L., et al. (2022). The starch physicochemical properties between superior and inferior grains of japonica rice under panicle nitrogen fertilizer determine the difference in eating quality. *Foods* 11, 2489. doi: 10.3390/foods11162489

Jiang, Y. W., Zhao, T. T., Liu, W. W., Zhong, W. J., Zhang, L. W., Zhao, H. C., et al. (2016). Effect of reducing fertilizer nitrogen on quality of kenjing 5 in different soil fertility level. *J. Sichuan Agric. Univ.* 34, 406–413. doi: 10.16036/j.issn.1000-2650.2016.04.003

Ma, Q., Zhang, H. C., Dai, Q. G., Wei, H. Y., Huo, Z. Y., Xu, K., et al. (2009). Effects of nitrogen application rate and growth-development type on milling quality in japonica rice. *Acta Agron. Sin.* 35, 1282–1289. doi: 10.3724/SP.J.1006.2009.1282

Meng, T., Zhang, X., Chen, X., Ge, J., Zhou, G., Wei, H., et al. (2022). Trends in grain quality and responses to nitrogen application of japonica inbred rice released after the 1980s in east China. *Cereal Chem.* 99, 503–519. doi: 10.1002/cche.10512

Qiao, J., Liu, Z., Deng, S., Ning, H., Yang, X., Lin, Z., et al. (2011). Occurrence of perfect and imperfect grains of six japonica rice cultivars as affected by nitrogen fertilization. *Plant Soil* 349, 191–202. doi: 10.1007/s11104-011-0861-4

Shi, L., Zhang, X. Y., Sun, H. Y., Cao, X. M., Liu, J., and Zhang, Z. J. (2019). Relationship of grain protein content with cooking and eating quality as affected by nitrogen fertilizer at late growth stage for different types of rice varieties. *Chin. J. Rice Sci.* 33, 541–552. doi: 10.16819/j.1001-7216.2019.9022

Tao, J., Qian, X. Y., Ju, C. X., Liu, L. J., Zhang, H., Gu, J. F., et al. (2016). Grain quality and its response to nitrogen fertilizer in mid-season indica rice varieties planted in different decades from 1950s to 2010s. *Acta Agron. Sin.* 42, 1352–1362. doi: 10.3724/SP.J.1006.2016.01352

Wang, Q., Huang, J., He, F., Cui, K., Zeng, J., Nie, L., et al. (2012). Head rice yield of "super" hybrid rice Liangyoupeijiu grown under different nitrogen rates. *Field Crops Res.* 134, 71–79. doi: 10.1016/j.fcr.2012.05.001

Wang, D. Y., Xu, C. M., Chu, G., Chen, S., Liu, Y. H., Che, L. P., et al. (2021). Conflict and coordination between high yield and good quality in rice planting. *China Rice* 27, 58–62. doi: 10.3969/j.issn.1006-8082.2021.04.012

Wang, C. L., Zhang, Y. D., Zhu, Z., Chen, T., Zhao, Q. Y., Zhong, W. G., et al. (2017). Research progress on the breeding of japonica super rice varieties in Jiangsu Province, China. *J. Integr. Agric.* 16, 992–999. doi: 10.1016/S2095-3119(16)61580-0

Xi, M., Wu, W., Xu, Y., Zhou, Y., Chen, G., Ji, Y., et al. (2020). iTRAQ-based quantitative proteomic analysis reveals the metabolic pathways of grain chalkiness in response to nitrogen topdressing in rice. *Plant Physiol. Biochem.* 154, 622–635. doi: 10.1016/j.plaphy.2020.06.012

Xi, M., Wu, W., Xu, Y., Zhou, Y., Chen, G., Ji, Y., et al. (2021). Grain chalkiness traits is affected by the synthesis and dynamic accumulation of the storage protein in rice. *J. Sci. Food Agric.* 101, 6125–6133. doi: 10.1002/jsfa.11269

Yang, Y., Lin, G., Yu, X., Wu, Y., and Xiong, F. (2020). Rice starch accumulation at different endosperm regions and physical properties under nitrogen treatment at panicle initiation stage. *Int. J. Biol. Macromol.* 160, 328–339. doi: 10.1016/j.ijbiomac.2020.05.210

Yang, G. T., Wang, Q., Zhang, G. H., Jiang, C. Y., Ma, P., and Hu, Y. G. (2024). Effect of nitrogen and phosphorus application on starch characteristics and quality of rice with different nitrogen efficiency. *Front. Nutr.* 11, 1462689. doi: 10.3389/fnut.2024.1462689

Yin, C. Y., Wang, S. U., Liu, H. M., Xue, Y. Z., Zhang, X., Wang, H. L., et al. (2013). Effects of nitrogen fertilizer application on grain filling characteristics and rice quality of superior and inferior garins in super japonica rice Xindao18. *Chin. J. Rice Sci.* 27, 503–510. doi: 10.3969/j.issn.1001-7216.2013.05.007

Zhang, Q., Guo, B. W., Hu, Y. J., Zhang, H. C., Xu, Y. F., Xu, X. J., et al. (2021). Differences in yield and rice quality of soft japonica rice with high quality and high yield under different nitrogen levels. *Chin. J. Rice Sci.* 35, 606–616. doi: 10.16819/j.1001-7216.2021.201101

Zhang, J., Zhang, H. C., Duan, X. M., Xu, Z. J., Yang, B., Guo, B. W., et al. (2011). Effects of soil fertility and nitrogen application rates on super rice yield, quality, and nitrogen use efficiency. *Acta Agron. Sin.* 37, 2020–2029. doi: 10.3724/SP.J.1006.2011.02020

Zhang, J., Zhang, Y. Y., Song, N. Y., Chen, Q. L., Sun, H. Z., Peng, T., et al. (2021). Response of grain-filling rate and grain quality of mid-season indica rice to nitrogen application. *J. Integr. Agric.* 20, 1465–1473. doi: 10.1016/S2095-3119(20)63311-1

Zhao, C., Liu, G., Chen, Y., Jiang, Y., Shi, Y., Zhao, L., et al. (2022). Excessive nitrogen application leads to lower rice yield and grain quality by inhibiting the grain filling of inferior grains. *Agriculture* 12, 962. doi: 10.3390/agriculture12070962

Zhou, L., Liang, S., Ponce, K., Marundon, S., Ye, G., and Zhao, X. (2015). Factors affecting head rice yield and chalkiness in indica rice. *Field Crops Res.* 172, 1–10. doi: 10.1016/j.fcr.2014.12.004

Zhou, T., Zhou, Q., Li, E., Yuan, L., Wang, W., Zhang, H., et al. (2020). Effects of nitrogen fertilizer on structure and physicochemical properties of 'super' rice starch. *Carbohydr. Polym.* 239, 116237. doi: 10.1016/j.carbpol.2020.116237

Zhu, D. W., Zhang, H. C., Guo, B. W., Xu, K., Dai, Q. G., Wei, H. Y., et al. (2017a). Effects of nitrogen level on yield and quality of japonica soft super rice. *J. Integr. Agric.* 16, 1018–1027. doi: 10.1016/S2095-3119(16)61577-0

Zhu, D. W., Zhang, H. C., Guo, B. W., Xu, K., Dai, Q. G., Wei, C. X., et al. (2017b). Effects of nitrogen level on structure and physicochemical properties of rice starch. *Food Hydrocolloids* 63, 525–532. doi: 10.1016/j.foodhyd.2016.09.042