

Effect of Nitrogen Application Rates on the Nitrogen Utilization, Yield and Quality of Rice

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Abstract

Research on the effect of the nitrogen application rate on the balance of the nitrogen utilization, yield and quality of rice is common in South China but is relatively lacking in Northeast China, especially in the Liaohe Delta. In this study, Yanfeng 47 rice was planted in Panjin city, China, to explore the effect of six nitrogen rates (0, 160, 210, 260, 315 and 420 kg N/ha) on the nitrogen use efficiency, rice quality and grain yield of rice plants. The results showed that the application of an appropriate nitrogen rate (210 - 260 kg N/ha) remarkably increased the nitrogen use efficiency of rice plants, grain yield, rice milling quality and nutritional quality and resulted in a moderate rice eating quality. Although low nitrogen rates (160 kg N/ha) maintained a high rice eating quality, they decreased grain yield and other rice qualities, and excessive nitrogen (315 kg N/ha) increased rice appearance quality but significantly reduced the nitrogen use efficiency ($p < 0.05$), yield and eating quality of rice. Therefore, to produce rice in the Liaohe Delta by an environmentally friendly method and guarantee rice with high quality and yield, the recommended nitrogen application rate is 210 kg N/ha.

Keywords

Nitrogen Fertilizer, Grain Yield, Rice Quality, Chalkiness, Eating Quality

1. Introduction

Rice is one of the main grain crops in the world and constitutes a substantial proportion of the consumption and production of cereal. Currently, the climate for rice production is dramatically changed by artificial or natural factors, such as unreasonable cultivation and global warming, bringing severe challenges to the safety of rice production [1] [2] [3]. It is important to guarantee a stable rice yield in real-time environmental conditions for the food security of humanity.

Simultaneously, with the development of economics and trade and the improvement of quality of life, the demand for higher quality rice is rapidly increasing. Therefore, it is quite important to sustainably cultivate rice with high yield and quality to meet the demands of society.

There are many factors affecting rice yield and quality, such as variety, accumulation temperature during the growth period, and relatively minor factors such as cultivation techniques (fertilizer rates, fertilization period, water management, etc.) [4] [5] [6] [7]. Due to the effect of increased yield brought by the application of nitrogen fertilizer, an increasing number of nitrogen fertilizers have been applied in rice production. However, recent results have shown that excessive long-term application of nitrogen fertilizers has not resulted in a significant increase in rice yield but a significant decrease in fertilizer utilization rate [8] [9], causing a series of problems, such as deterioration of soil properties, serious environmental pollution, and declined rice quality [10]. Therefore, an understanding of the interaction between the different nitrogen rates and nitrogen utilization rates and the quality and yield of rice is not only essential for optimizing rice production by the application of nitrogen but also important for protecting the environment.

In the past two decades, several studies have investigated the effect of nitrogen application rates on rice quality and yield, and it is generally considered that nitrogen application rates are positively related to grain yield [11], and rice milling quality and nutritional quality [12] and have negative effects on rice eating quality [10]. For the appearance quality, previous results varied due to different experimental locations and rice varieties [5] [13]. Although there has been a marked improvement in rice quality and yield in South China [10], little progress has been made in Northeast China, especially for japonica rice, which is widely planted in North China. In addition, previous research focuses vary among disciplines; for example, experts in agronomy have mostly studied the effects of different cultivation conditions on grain yield and limited quality indicators of rice [5], while experts in the food industry have focused on changes in quality indicators during postharvest rice storage [14]. However, the quality and storage performance of rice is closely associated with prenatal factors, so it is necessary to analyze rice quality in terms of both prenatal and postnatal factors. The qualities of rice are mainly divided into milling quality, appearance quality, cooking and eating quality and nutritional quality. Merchants mainly focus on the first two qualities, and consumers pay more attention to the latter two qualities. In fact, improvement in the quality of rice is a shared goal. Therefore, in this study, we conducted a detailed and comprehensive investigation of rice quality indicators in terms of a combination of preharvest fertilizer application rates and postharvest yield and quality of rice in northeast China.

In this paper, based on the local farmers' traditional fertilization rates, we systematically studied the effect of nitrogen fertilizer application rates on rice quality and yield from the perspective of a combination of nitrogen application rates and nitrogen utilization of rice and recommended the nitrogen rate for local rice

cultivation, providing a theoretical basis for rice cultivation aimed at improving rice quality in Northeastern China and providing a direction for breeding in Northern China.

2. Materials and Methods

2.1. Plant Materials and Experimental Design

The experiment was conducted at Liaohe Delta, Panjin city, China (122°14'17"N, 41°9'31"E), from 2017 to 2018. The climate belongs to temperate semi humid monsoon climate type, with annual rainfall of 650 mm, annual average temperature of 8°C - 9°C, frost free period of 165 - 170 days. The soil is saline alkaline paddy soil with a pH of 8.2 and OM 22.6 g/kg. The rice variety was Yanfeng 47, which is one of the main local varieties, this rice variety has compact plant type, strong stem, better resistances to fertilizer and lodging. The six nitrogen treatments had application rates of 0, 160, 210, 260, 315, and 420 kg N/ha based on the local farmer's traditional nitrogen application rate (260 kg N/ha). Seeds were transplanted on May 25 and harvested on October 8. The size of each subplot was 50 m². The transplanting density was 30 cm × 18.2 cm with three seedlings in each hill. The experiment was conducted in three replicates.

In all treatments, nitrogen fertilizer was large granular urea, phosphate fertilizer was diammonium phosphate and superphosphate, and potassium fertilizer was chlorine sulfuric acid. Sixty percent of nitrogen was applied during the transplanting period, 30% of nitrogen was used as tilling fertilizer, and 10% of nitrogen was used as panicle fertilizer. Phosphorus (90 kg P₂O₅/ha) and potassium (90 kg K₂O/ha) were applied during the transplanting period. Other practices conformed to local recommendations.

2.2. Determination of the Grain Yield and Nitrogen Use Efficiency of Rice

Grain yield was determined by a harvest area of 1 m², three hills of rice plants were randomly selected from each treatment, and each hill was used to determine the nitrogen content of rice shoots and grains by the Kjeldahl method. The calculation formulas are as follows:

$$\text{NAG (kg/ha)} = \left(\text{grains yield} \left(\left(\text{kg/ha} \right) \times \text{NG} \right) / 100 \right) \quad (1)$$

$$\text{NAS (kg/ha)} = \left(\text{shoots yield} \left(\text{kg/ha} \right) \times \text{NS} \right) / 100 \quad (2)$$

$$\text{NAP (kg/ha)} = \text{NAG} + \text{NAS} \quad (3)$$

$$\text{NUC (\%)} = (\text{NAPT} - \text{NAPC}) \times 100 / \text{Nitrogen application rates} \quad (4)$$

where NG is the nitrogen content of 100 kg grains, NS is the nitrogen content of 100 kg shoots, NAG is nitrogen accumulation in grains, NAS is nitrogen accumulation in shoots, NAP is nitrogen accumulation in plants (including rice shoots and grains in a hill rice), NAST is nitrogen accumulation in plants treated with nitrogen fertilizer, NAPC is nitrogen accumulation in plants treated with-

out nitrogen fertilizer, and NUC is nitrogen use efficiency.

2.3. Determination of Rice Quality Traits

Harvested grains were dried under natural air until the moisture content was 14% for the next determination.

2.3.1. Milling Quality

The brown rice rate (BRR) and milled rice rate (MRR) were determined according to GB/T 21499-2008 [15]. A total of 150 g of paddy was crushed to obtain brown rice by a ridge mill (FC2K, Yamamoto, Japan), and then, the brown rice was milled by a milling machine (VP-32T, Yamamoto, Japan). Each treatment was repeated three times.

2.3.2. Nutritional Components

Brown rice was used to measure the total protein content (TPC) and amylose content (AC) by a near-infrared grating nutrient analyzer (DA7200, Pertem, Sweden). The fat content (FC) was determined according to the Soxhlet extraction method described in GB5009.6-2016 [16].

2.3.3. Appearance Quality

The chalky rice rate (CRR), chalkiness (C) and head rice rate (HRR) were measured by an appearance quality analyzer (ES-1000, Shizuoka, Japan) according to GB/T 1354-2009 [17].

2.3.4. Eating and Cooking Quality

The hardness score (HS), viscosity score (VS) and taste score (TS) of the cooked rice were measured according to Champagne [18] by a rice taste analyzer (STA1B, Satake, Japan), which used optical principles to determine sensory characteristics such as the appearance, hardness, viscosity and balance and taste value of cooked rice. The full scores for the hardness and viscosity of the cooked rice were all 10, and the full score for taste value was 100. In detail, 30 g of milled rice was cooked according to GB/T 15682-2008 [19], and then 8 g of cooked rice was pressed into rice cakes and measured with a rice taste analyzer.

2.3.5. Pasting Properties

The pasting property parameters of rice flour, such as peak viscosity (PV), trough viscosity (TV), final viscosity (FV), breakdown (BD), setback (SB), peak time (PET) and pasting temperature (PAT), were determined by a rapid viscosity analyzer (RVA-4, Newport Scientific, Australia).

2.4. Data Statistics and Analysis

All data were first processed using Excel 2003 and then analyzed for significance using SPSS 22 software by the Duncan method with a significance standard of 0.05. All tables were generated with Word 2003; graphs were plotted with Origin 8.5.

3. Results

3.1. Effect of Nitrogen Fertilizer on the Grain Yield and Nitrogen Use Efficiency of Rice

According to **Figure 1**, a relatively high yield of grain was achieved at nitrogen application rates of 210, 260 and 315 kg/ha, and the difference between the three nitrogen rates was not significant. Nitrogen deficiency (160 kg N/ha) and excess nitrogen (420 kg N/ha) resulted in a significant decrease in grain yield. For nitrogen use efficiency, with the increase in nitrogen application rates, the nitrogen use efficiency first increased and then decreased, and the highest value (42%) was reached at 210 kg N/ha. High nitrogen application rates (greater than 315 kg N/ha) reduced both the grain yield and nitrogen use efficiency of rice. Therefore, 210 kg N/ha was recommended for the relatively better positive effects on guaranteeing a high grain yield, saving nitrogen resources and having less negative influences on the environment.

Different letters indicate the least significant differences within each column ($p < 0.05$).

3.2. Effect of Nitrogen Fertilizer on Rice Quality

3.2.1. Milling Quality

Milling quality traits include the BRR, MRR and HRR. Compared with the no nitrogen application treatment, nitrogen application significantly increased the BRR (**Figure 2**) of rice and had little influence on the MRR. Both nitrogen deficiency and excess nitrogen significantly reduced the HRR, and only the appropriate nitrogen application rate (210 - 260 kg N/ha) maintained a superior HRR. The BRR, MRR and HRR first increased and then decreased with increasing nitrogen rates, and the highest values were all reached at 260 kg N/ha. The difference in milling quality traits between treatments with different nitrogen rates was not significant at nitrogen rates between 210 kg N/ha and 260 kg N/ha. Therefore, 210 kg N/ha was recommended to obtain high milling quality for rice cultivation.

Vertical error bars represent the standard deviation of the mean, and different letters indicate the least significant differences within each column ($p < 0.05$).

3.2.2. Nutritional Components

TPC, AC and FC are considered to contribute much to the formation of rice quality. The differences in the nutritional components of rice treated with different nitrogen rates are shown in **Figure 3**. With the increase in nitrogen rates, the TPC increased significantly, AC decreased, and FC had little change. Only high nitrogen rates (more than 315 kg N/ha) decreased the AC significantly, and low nitrogen rates (160 kg N/ha) increased the FC.

3.2.3. Appearance Quality

CR and C were negatively related to the appearance quality of rice, and only excess nitrogen application significantly improved the appearance quality of rice

(Figure 4). Compared with no nitrogen, CR slightly increased at low nitrogen application rates (less than 260 kg N/ha) but significantly decreased under high nitrogen application rates (more than 260 kg N/ha). C significantly increased at low nitrogen application rates and significantly decreased under 420 kg N/ha compared to without nitrogen application. Under different nitrogen application conditions, the change trend of rice C was consistent with the CR. Only 420 kg N/ha significantly reduced the CR and C compared with other nitrogen application rates, but further discussion combined with other quality traits is needed to recommend this as the local application rate because it is fast higher than the traditional application rate.

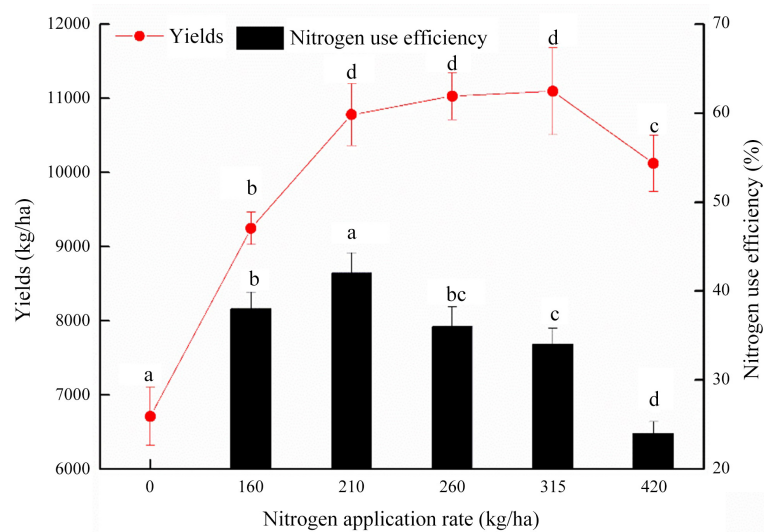


Figure 1. Effect of nitrogen application rates on the yields and nitrogen use efficiency of rice.

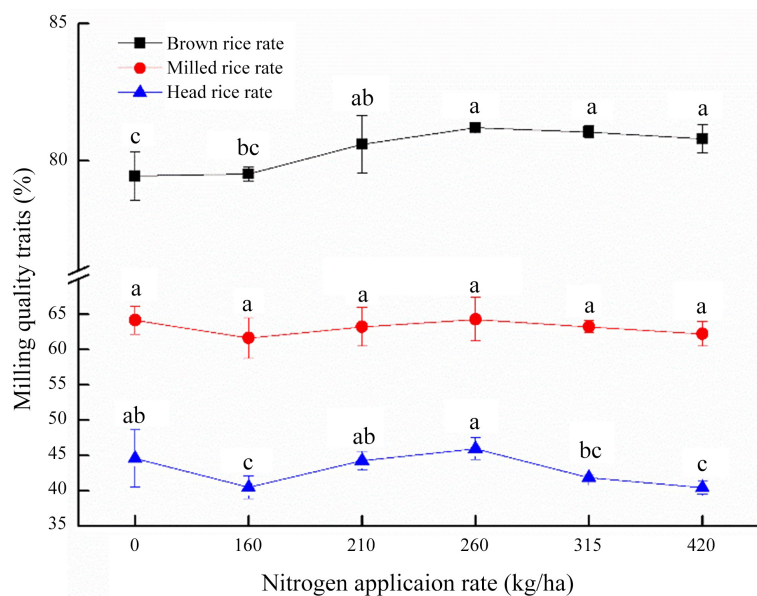


Figure 2. Effect of nitrogen application rates on rice milling quality.

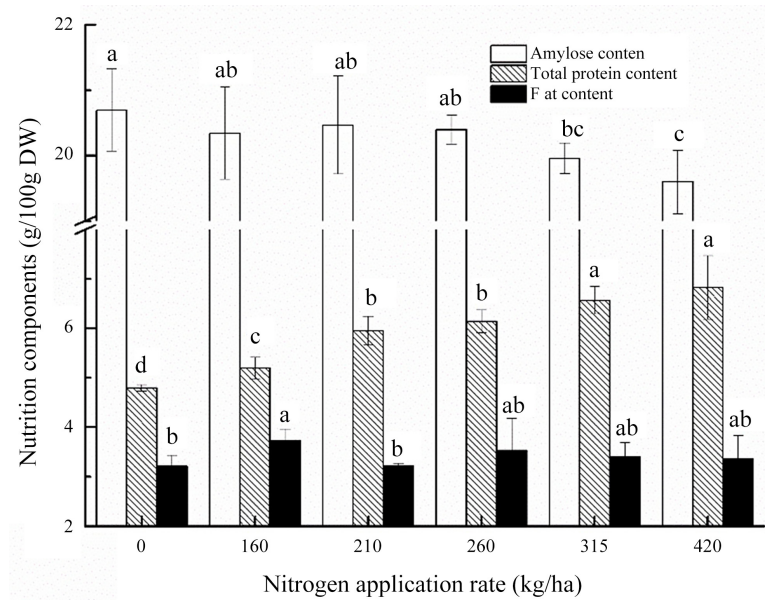


Figure 3. Effect of nitrogen application rates on rice nutrition components. Vertical error bars represent the standard deviation of the mean, and different letters indicate the least significant differences within each column ($p < 0.05$).

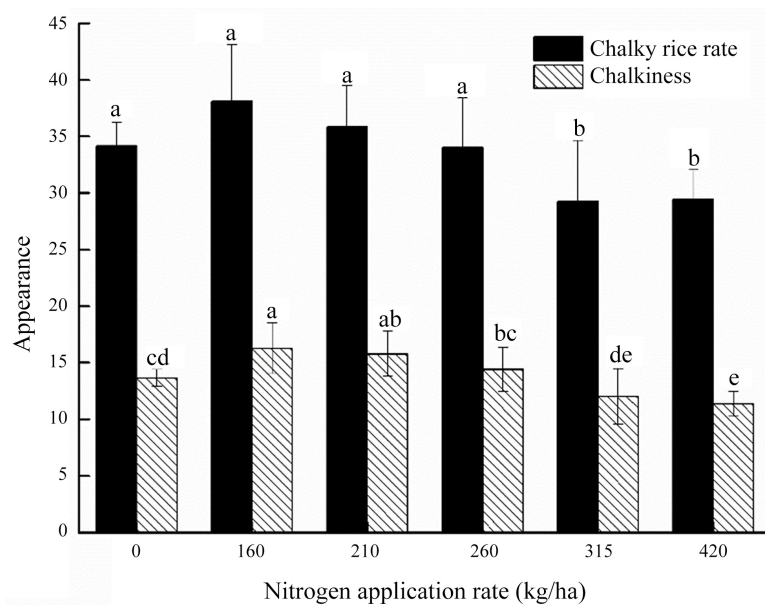


Figure 4. Effect of nitrogen application rates on rice appearance quality.

Vertical error bars represent the standard deviation of the mean, and different letters indicate the least significant differences within each column ($p < 0.05$).

3.2.4. Eating and Cooking Quality

As shown in **Figure 5**, only 160 kg N/ha had no impact on the eating quality of rice, and other nitrogen levels significantly reduced the VS and increased the HS, resulting in a reduced TS.

Vertical error bars represent the standard deviation of the mean, and different letters indicate the least significant differences within each column ($p < 0.05$).

3.2.5. Pasting Properties

The parameters of the RVA profiles of rice flour are often regarded as characteristics of rice eating and cooking quality. The pasting properties of rice flour are displayed in **Table 1**. Nitrogen deficiency (160 kg N/ha) slightly increased the PV, TV, and FV, while the other nitrogen application rates decreased them; in particular, excess nitrogen (420 kg N/ha) significantly reduced them, indicating that the viscosity of rice was reduced by nitrogen application, which was consistent with the result of VS (**Figure 4**). The residue parameters of RVA were slightly influenced by nitrogen application, indicating that nitrogen rates showed no impact on the cooking quality of rice, which was similar to our cooking time results (not displayed here).

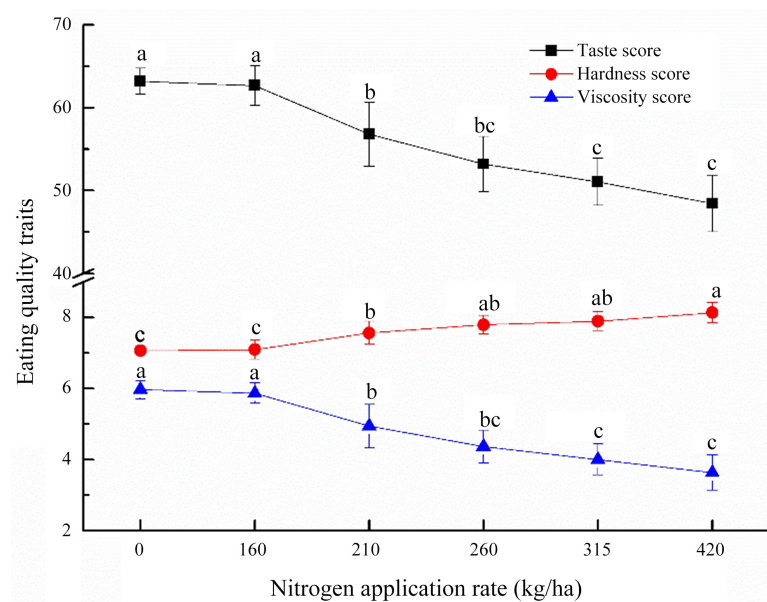


Figure 5. Effect of nitrogen application rates on rice eating quality.

Table 1. Effect of nitrogen application rate on RVA traits of rice flour^a.

Treatment (kg N/ha)	Peak viscosity (RVU)	Trough viscosity (RVU)	Final viscosity (RVU)	Breakdown (RVU)	Setback (RVU)	Peak time (min)	Pasting temperature (°C)
0	2878 ab	1977 a	2897 a	900	19	6.4	72.9
160	3003 a	1954 a	2920 a	1048	-83	6.3	72.7
210	2855 ab	1887 ab	2830 ab	973	-25	6.3	73.2
260	2816 ab	1882 ab	2808 ab	928	-7.66	6.3	72.7
315	2727 ab	1826 ab	2765 ab	901	38	6.3	73.5
420	2600 b	1683 b	2612 b	917	11.33	6.3	73.3

^aNote: Difference letters represent significant differences at the <0.05 level.

4. Discussion

To achieve sustainable development of rice with high quality and yield, this study researched the effect of nitrogen application rates on rice production from the perspective of rice plant nitrogen use efficiency, rice quality and grain yield; recommended optimal nitrogen application rates; analyzed the obstacle factors for cultivating high quality and yield rice, such as rice appearance quality and eating quality; and suggested that it is urgent for experts from different fields to struggle for more reasonable rice production together, such as breeding and agronomy and food science.

4.1. Recommended Reasonable Nitrogen Application Rate

With the development of society, Chinese agriculture has been considered to have sustainable rice production, which affects not only grain yields but also rice quality and environmentally friendly cultivation. In this study, with the increase in the nitrogen application rate, the milling quality, appearance quality, yield and nitrogen use efficiency of rice first increased and then decreased; the protein content increased; and the eating quality and AC decreased. These results, except for nitrogen use efficiency and appearance quality, were all consistent with a previous study [20] [21] [22] [23].

Our results for nitrogen use efficiency were not the same as those of Zhu, which showed that nitrogen use efficiency decreased with increasing nitrogen application rate [5], possibly because of the difference in soil properties and basic fertility between Panjin and Yangzhou [24]. For appearance quality, the difference between our results and Zhu's study will be analyzed in the subsequent sections.

These results revealed that it is impossible to control the application of nitrogen fertilizer to reach the best levels for the quality, yield and nitrogen use efficiency of rice. In addition, moderate nitrogen rates (210 - 260 kg N/ha) had a relatively high nitrogen use efficiency, rice yield, milling quality and nutritional quality. The parameters of rice treated with 210 kg N/ha were not significantly different from those of rice treated with 260 kg N/ha. Therefore, we recommended a nitrogen application rate of 210 kg N/ha, which was 20 - 60 kg N/ha lower than that in a previous study [5] [25]. Zhu planted Nanjing 9108 and Nanjing 5055 in Yangzhou city (119°42'E, 32°39'N) and recommended a nitrogen application of 270 kg N/ha for optimal rice quality and grain yield of super rice [5]. Qiao recommended a nitrogen rate of 232 - 257 kg N/ha for superior levels of nitrogen utilization and grain yield [25] after performing experiments in Yixing city (119°8' - 121°5'E, 30°5' - 32°8'N). Our study was carried out in Panjin city (41°9'E, 122°14'N), so this reduction may be explained by the different varieties of rice in southern and northeastern China responding differently to nitrogen, owing to the dramatic difference in temperature and light between the two sites.

However, in our study, rice was treated with 210 kg N/ha in Panjin, and the

rice eating quality and appearance quality were inevitably reduced. Therefore, improving the quality of rice under appropriate nitrogen rates should be the next focus of agronomy, food and breeding experts.

4.2. Negative Effect of Nitrogen on Rice Eating Quality

Eating quality is one of the main qualities focused on by consumers. It is well known that nitrogen application had a negative effect on rice eating quality owing to the increased hardness and decreased viscosity of cooked rice [5] [26] [27], which were also observed in our study, but the minimum nitrogen application rate that could significantly reduce rice eating quality was different from that in a previous study [5].

Our results showed that the application of nitrogen rates over 160 kg N/ha significantly reduced the eating quality of rice. Zhu suggested that rice eating quality decreases faster when the nitrogen application rate exceeds 262.5 kg N/ha [5]. The difference may be related to different rice varieties and growth areas. Yangzhou (119°42'E, 32°39'N) had a higher average temperature in the rice growth period than Panjin (122°14'N, 41°9'E), causing higher nitrogen loss and lower nitrogen absorption for rice, which was consistent with Li's results for maize. He reported that high temperature had a negative effect on nitrogen use efficiency [28], resulting in a higher nitrogen application rate for a significant change in rice eating quality.

To relieve the adverse impact of nitrogen on rice eating quality, intensive studies have been undertaken to reveal the relationship between nitrogen and key factors of rice eating quality, which are generally acknowledged as the hardness and viscosity of cooked rice. It has been reported that nitrogen application increased rice protein content, especially for gluten; decreased AC, leading to an increase in the hardness of rice [29] [30] [31] [32]; and simultaneously decreased the leach amylopectin content, causing a decrease in the viscosity of rice [33] and ultimately resulting in a decline in the eating quality of rice. A similar trend in protein content and AC was found in this study. Therefore, to improve eating quality under nitrogen application, it is necessary to breed rice with a low protein content and high amylopectin content in the future.

In addition, a reliable method that can accurately evaluate the eating quality of rice is significant for considering the impact of nitrogen on rice eating quality. Currently, eating quality is mainly determined by the sensory characteristics of trained persons and machines [34]. Machines were divided into three categories according to their principles. First, the taste analyzer and grain analyzer displayed the results as scores obtained from rice components by the near infrared method. Second, texture profile analysis (TPA) and a rheometer were used to evaluate the texture parameters (hardness and viscosity) of cooked rice by squeezing it with a probe [35]. Third, RVA and differential scanning calorimetry (DSC) were used to assess the pasting properties of rice flour and indirectly reflect the properties of cooked rice. Due to their low cost, eating quality has

mostly been determined by machines in previous studies.

In our study, the results from the taste analyzer showed that nitrogen application increased the HS and reduced the VS, leading to poor eating quality. Similarly, for the RVA, parameters related to viscosity, such as the PV, TV and FV, decreased; however, parameters related to the palatability and texture of cooked rice, such as the BD and SB, were little affected by nitrogen rates, which contrasted with the results obtained by the taste analyzer. The difference may be caused by the difference in samples between milled rice flour and cooked rice, indicating that selecting for determining eating quality plays a pivotal role in the results and that there is a need for better machine methods.

4.3. A Low Nitrogen Application Rate Reduced Rice Appearance Quality, While a High Nitrogen Rate Improved It

C is the opaque part of rice, which is attributed to its poor appearance quality. Previous results regarding the effect of nitrogen application rates on the CR and C varied from each other due to different varieties, locations, growth environments and cultivation methods of rice. Zhu believed that the application of nitrogen fertilizer increased the CR [5], while Chen agreed that nitrogen application effectively reduced the generation of chalky rice [13]. In this study, nitrogen deficiency increased the CR and C, and excessive nitrogen (315 - 420 kg N/ha) reduced the CR significantly, which was similar to Dou (119°28'21"E, 31°54'31"N), Zhou (123°24'E, 41°48'0"N) and Brandon's results [7] [20] [36]. These diversity results revealed that the effect of nitrogen rates on rice C may be influenced by environmental factors such as temperature, light, and water [37] [38] [39], indicating that it was not reasonable to improve rice appearance quality just by controlling nitrogen application rates.

To improve rice appearance quality, the factors influencing rice C and its mechanism were explored in other studies, and the results showed that the occurrence of rice C was related to many biological metabolic pathways, such as carbon and nitrogen metabolism, scavenging of reactive oxygen species, infiltration, cell wall synthesis and mineral ion homeostasis [40] [41] [42] [43] [44]. Due to its extreme complexity, an effective method for regulating C formation has not been discovered. Therefore, the main physiological metabolic regulators of chalk formation in each metabolic pathway should be the focus of future research.

Except for environmental factors, variety was reported as a key factor for the different appearance qualities of rice [45]. Therefore, breeding rice with better appearance quality may be a more efficient method than controlling environmental factors for improving rice appearance quality. Currently, for the factors that may impact rice C, most research is considered from the perspective of preharvest factors such as environmental factors (light, temperature, water) and field management (fertilizer application rate, irrigation). The same limitation existed in this paper, but few studies have examined postharvest factors such as storage conditions (time, temperature, humidity, and package). The exploration of the impact of postharvest factors on rice C may contribute to new possibilities

in regulating rice appearance quality in the future.

5. Conclusion

The optimal level of rice quality and yield could not be achieved under the same nitrogen rate, but superior levels of nitrogen use efficiency, grain yield, milling quality and nutritional quality of rice could be achieved under 210 kg N/ha. For the best rice eating quality, the nitrogen rates must be controlled within 160 kg N/ha, and rice appearance quality only significantly improved when it exceeded 260 kg N/ha. Moreover, excessive nitrogen contemporarily reduced the nitrogen utilization, yield and quality of rice. Further considerations of breed and cultivation or postharvest factors aimed at improving eating and appearance quality are required.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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