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Effects of Degree of Milling on Nutritional and Edible Quality of High-Resistant Starch Rice

Jianjiang Bai[1], Jianhao Tang[1], Qi Zhao[1], Ying Yan[1], Ruoyu Xiong[1] & Ruifang Yang[1]

[1] Ministry of Agriculture and Rural Affairs, Crop Breeding and Cultivation Research Institute, Shanghai Academy of Agricultural Sciences, Shanghai, China

Correspondence: Ruifang Yang, Key Laboratory of Germplasm Innovation and Genetic Improvement of Grain and Oil Crops (Co-Construction by Ministry and Province), Ministry of Agriculture and Rural Affairs, Crop Breeding and Cultivation Research Institute, Shanghai Academy of Agricultural Sciences, Shanghai 201403, China. Tel: 86-021-62204273. E-mail: yangruifang1982@163.com

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Abstract

The aim of this study was to investigate the effects of milling degree on nutrient content, especially resistant starch (RS), and edible quality of starch rice variety Youtangdao3 (YTD3) with high RS. High RS rice variety YTD3 was processed with different milling times (0, 10, 20, 30, and 40s) to evaluate the effects on nutritional components, mineral content, vitamins, pasting properties, and cooking/eating quality. With the increase in milling time, the average milling reduction rate increased from 0 to 8.54, 11.81, 13.27, and 16%, which correlated with a decrease in the yield of head rice, crude fat, crude protein, and ash content. Minerals and vitamins, especially vitamin E and B vitamins, decreased significantly with increasing milling time. Sensory analysis revealed a decrease in rice hardness and an increase in viscosity with longer milling, suggesting improved palatability. However, excessive milling reduced the nutritional value of the rice. The study highlights the need for an optimal balance between the degree of milling (DOM) and the preservation of nutritional value to improve the overall quality of rice products. The results are important for guiding rice processing practices to maintain the health benefits of RS while preserving the sensory appeal of rice.

Keywords: rice, degree of milling (DOM), resistant starch, nutrient content

1. Introduction

Rice (*Oryza sativa* L.), a staple food that feeds more than half of the world's population, serves as a critical dietary source of carbohydrates, protein, and essential nutrients. Rice is frequently consumed in the form of milled white rice (Li et al., 2021). Whole brown rice is the unpolished whole grain, despite its rich endowment of fiber, vitamins, minerals, and other nutrients, is often less favored due to its shorter shelf life, darker color, and chewier texture post-cooking. To enhance its sensory attributes, brown rice undergoes milling to produce white rice, a process that significantly alters its nutritional content and digestibility (Saleh et al., 2019).

The Degree of Milling (DOM) emerges as a pivotal parameter in rice processing, dictating the extent of bran removal and directly influencing the resultant nutritional profile and sensory attributes of rice (Liu et al., 2015). An increased DOM results in rice with a more desirable white color and smoother texture, yet this enhancement comes at the expense of nutritional content, leading to a notable reduction in proteins, fiber, and ash, and a proportional increase in carbohydrates (Liu et al., 2015; Sandhu et al., 2018). Recent research has focused on understanding how DOM affects the phytochemical content and the physicochemical and functional properties of rice (Zhou et al., 2023). For instance, Shobana et al. (2011) evaluated the influence of DOM on phytochemical content, including dietary fiber, γ-oryzanol, vitamin E, and total phenolics in Indian rice varieties (Shobana et al., 2011). Another recent investigation has delved into how DOM influences the levels of total phenolics, flavonoids, anthocyanins, and pro-anthocyanidins in pigmented rice across a spectrum of milling intensities (Ma et al., 2020).

Starch, a principal component of rice, plays a critical role in human health due to its digestion rate and absorption site within the gastrointestinal tract (Li et al., 2021). Li et al. (2021) demonstrated that DOM significantly affects the digestibility of starch in cooked rice during in vitro small intestine digestion, emphasizing the importance of rice processing on its nutritional impact (Li et al., 2021). This is especially pertinent for functional rice varieties like high-resistant starch (RS) rice, which possess elevated RS content, conferring enhanced health benefits. RS, a carbohydrate that bypasses small intestine digestion and ferments in the large intestine, is associated with improved glycemic control, better colon health, and a reduced risk of diseases such as colorectal cancer and heart disease (Bello-Perez et al., 2020; Shen et al., 2022). RS exists in various forms, categorized as RS1 through RS5, each with distinct origins and physiological effects. RS1 is derived from intact starch granules in raw or undercooked foods, RS2 is a natural raw starch granule that resists digestion due to its crystalline structure, RS3 is retrograded starch formed by cooling cooked starch, RS4 is chemically modified starches that resist digestion, and RS5 is a complex of amylose and lipid (Shen et al., 2022; Wang et al., 2023). Among these, RS2 has been widely found in high-amylose plants such as raw potatoes, green bananas and high-amylose maize starch (Hughes et al., 2021). The research and development of RS in the food industry are burgeoning fields, driven by the potential of high-RS rice to combat chronic diseases like diabetes, obesity, hypertension, and hyperlipidemia (Wang et al., 2023; Yang et al., 2023; Baptista et al., 2024; Li et al., 2024). Understanding the genetic and molecular mechanisms of RS formation and the cultivation strategies to increase RS content in rice are active areas of study (Baysal et al., 2020; Shen et al., 2022).

‘Youtang’ rice, as a high-RS rice variety, has received widespread attention due to its low Glycemic Index (GI). Our previous research determined that the GI value of ‘Youtang’ rice is 48.53, which belongs to low GI foods ($GI \leq 55$) (Shi et al., 2014; Frendy Ahmad et al., 2021). Low GI foods significantly benefit blood sugar control, particularly for individuals with type II diabetes, because they help moderate postprandial blood sugar levels (Thomas & Elliott, 2010). Numerous studies have demonstrated that patients with type II diabetes who consume high-RS rice experience less fluctuation in blood sugar levels 30 and 60 minutes after meals, significantly reducing blood sugar changes compared to traditional rice (Yuhi et al., 2020; Tan et al., 2022). Innovations in rice processing, particularly post-harvest techniques, are crucial for preserving phytochemicals and improving the nutritional profile of rice. Given the focus of our study on RS2 in high-RS rice, understanding its response to DOM is crucial for optimizing the health benefits of rice.

The current study extends existing research by looking at the subtleties of DOM on the nutritional profile of high-RS rice Youtangdao. Through a careful analysis of the effects of different milling durations on key nutritional components, particularly RS, this study aims to establish processing guidelines that can optimize the health benefits of high-RS rice while preserving its sensory appeal. As part of a comprehensive approach, the study also evaluates mineral content, vitamins and pasting properties to provide a holistic understanding of how DOM affects the nutritional and culinary qualities of high-RS rice.

2. Method

2.1 Experiment Materials

The high-RS rice variety Youtangdao 3 (YTD3), bred by the Shanghai Academy of Agricultural Sciences (SAAS), China, is distinguished by its exceptionally high content of RS2 type with an RS content of up to ~13 %. YTD3 received the Shanghai Crop Variety Approval Committee certification (2020012) in 2020. The RS content of YTD3 was about 20-fold higher than that of typical rice varieties. This significant increase was primarily attributed to a specific mutation in the gene OsSBEIIb, which led to reduced functionality of the enzyme responsible for starch branching in rice (Yang et al., 2012, 2016). YTD 3 were planted in the field during the 2023 growing season in Shanghai, China.

2.2 Different Processing Precision Rice Preparation

The rice sample passed through the rice huller twice (JlGJ-45, Taizhou, Zhejaing, China) to obtain brown rice, and impurities were removed. The resultant brown rice then passed through the rice polisher (JNM-III, Grain Reserves Corporation, Beijing, China) to obtain milled rice. The milling quantity is 200 g per time, milled for 10, 20, 30, and 40 s respectively to obtain different milling reduction rates. The Milling reduction rate actually refers to the rice milling rate, which is the percentage decrease in volume and weight of brown rice during the milling process. The higher the milling reduction rate, the greater the processing precision of the rice. Different processing precision rice samples are taken for high-speed crushing into a powdery state, followed by sieving through a 100-mesh sieve for later use.

$$\text{Milling reduction rate} = (\text{Mass of brown rice} - \text{Mass of rice after milling})/(\text{Mass of brown rice}) \times 100\% \qquad (1)$$

2.3 Determination of Resistant Starch Content

The method used to determine the RS content in rice was the AOAC method 2002.02, using the RS analysis kit from Megazyme (K-RSTAR 08/11, Wicklow, Ireland) (Yang et al., 2023). Briefly, 0.1 g of rice flour was incubated with amylase and starch glucosidase at 37 °C for 16 hours to digest digestible starch in the rice into glucose, leaving behind the RS. The RS was precipitated by adding an equal volume of ethanol, followed by centrifugation and washing with 50% ethanol. The RS was then dissolved in 2 M KOH and neutralized with acetate buffer. Starch glycosidase was added to hydrolyze the RS to glucose. Finally, the glucose oxidase/peroxidase (GOPOD) reagent was added to the sample for color development, and the absorbance of each solution was measured at 510 nm using a spectrophotometer. The glucose concentration was then converted to RS content.

2.4 Determination of Total Starch Content

Total starch concentrations were determined with a Megazyme starch assay kit (Megazyme, Wicklow, Ireland) based on the use of thermostable α-amylase and amyloglucosidase (Sardari et al., 2019). Three repeats were carried out for each sample.

2.5 Determination of Nutritional Composition

Physical and chemical indexes were detected according to the National Standards of China. The ash, protein, crude fat, and dietary fiber content are determined concerning GB 5009.4-2016, GB 5009.5-2016, GB 5009.6-2016, and GB 5009.88-2014 (Xie et al., 2022).

2.6 Determination of Mineral Element Contents

The mineral element contents of rice samples were obtained based on the standard of the 'National Food Safety Standard, Determination of Multi-Elements in Food (GB 5009.268-2016)' regulated by China (Chen et al., 2022).

2.7 Determination of Vitamin

Vitamins B were analyzed using Ultra-High-Performance Liquid Chromatography and High-Resolution Mass Spectrometry and Tandem Mass Spectrometry (UHPLC-MS/MS). B vitamins include thiamine (Vitamin B1), riboflavin (Vitamin B2), niacin (Vitamin B3) and pyridoxine (Vitamin B6). Vitamin E (α-, β-, γ-, δ-tocopherol; Tc) content was determined by GC/FID chromatography (Nawrocka et al., 2017).

2.8 Determination of Cooking/Eating Quality

The flavor value of rice grains was evaluated using the Satake Rice Flavor Analyzer (Satake, Hiroshima, Japan). The taste value is a comprehensive evaluation of cooked rice, including appearance, hardness, stickiness, balance degree, and elasticity. The specific experimental methods refer to Zhang et al. (2022). Take 30 g of each type of abrasive grain sample, place it in a stainless steel tank, rinse it with flowing pure water for 30 s, drain it, and redissolve it with pure water to obtain a rice-to-water ratio of 1:1.7. The sample was then soaked for 30 min in the tank, covered with a filter paper, and sealed with a rubber ring. The stainless-steel tank was placed into an electric rice cooker (JT783, Midea, Shunde, China), covered, steamed for 30 min, and kept warm for 10 min. The tank was taken out from the rice cooker, while gently stirring and turning over the steamed rice. Then, the tank was covered with a filter paper again and cooled for 20 min using a supporting air-cooling device. Afterward, the filter paper was replaced with the supporting steel cover to seal and cool the steamed rice at room temperature (25 °C) for 90 min. An 8 g sample of steamed rice was placed into a stainless-steel ring (30 mm diameter and 9 mm height) and then pressed the rice into a cake. The rice cake was placed in a measuring tank, and the rice taste analyzer was inserted to measure the appearance and taste value of the steamed rice sample. Six rice cakes were measured for each steamed rice sample.

2.9 Determination of Water Absorption Ratio

Water absorption was expressed as the percent increase in the weight of cooked rice to the uncooked rice weight. The water absorption ratio (WAR) was calculated by dividing the weight of cooked rice by the weight of raw rice (Wahid et al., 2022).

2.10 Pasting Properties of Starch Analysis

A Rapid Visco Analyzer (RVA) (Techmaster, Newport Scientific, Warriewood, Australia) was used to assess the pasting properties of rice starch, as described previously (Zhang et al., 2017). Add 3 g of sample (based on 14% humidity) to 25 g of deionized water in an aluminum cup. Samples were dispersed in water using an RVA paddle before testing. A constant shear temperature profile of 160 rpm was applied, starting at 50 °C for 60 s, then heating to 95 °C at a heating rate of 0.2 °C/s, holding this temperature for 162 s and heating to 200 rpm. Driving at high speed. Cool to 50 °C at 0.2 °C/s and hold the final temperature for 120 s. Parameters analyzed include peak vi The RVA parameters were extracted from the viscosity curve and included the peak time (PT), peak viscosity (PKV), cool paste viscosity (CPV), hot paste viscosity (HPV), breakdown viscosity (BDV, PKV-HPV), and setback viscosity (SBV, CPV-PKV) (Yun et al., 2016).

2.11 Statistical Analyses

Experimental data were analyzed using analysis of variance (One-way ANOVA), expressed as the mean value±standard deviation of at least three replicates, and significant differences among means were determined by Duncan's test. All analyses were performed using the SPSS Statistics software (Version 25, SPSS Inc. Chicago, IL, USA). The significance level in all cases was set at $p < 0.05$.

3. Results

3.1 Effect of Processing Precision on Nutritional Components of High-Resistant Rice YTD3

The DOM increases with the extension of the whitening time, since rice is easily broken during milling, leading to a decrease in the head rice yield from 100% at 0 s to 58.38% at 40 s (Table1). The crude fat content, crude protein content, and ash content show varying degrees of decrease, while the RS content and total starch content show an increasing trend. The ratio of RS to total starch also shows an increasing trend (Table 1). This is consistent with the findings of Zhang et al (Zhang et al., 2023).The results indicate that processing time has a significant impact on the processing and nutritional quality of functional rice. Previous studies have shown that the microstructure and digestibility of rice powder were significantly changed by increasing the DOM (Li et al., 2021; Zhang et al., 2023). The extension of processing time could potentially augment the RS content within the rice grains. However, this increase in RS content must be weighed against the possible reduction in particle size that may accompany extended milling, which could, in turn, affect the rice's resistance to digestion when cooked. In light of this, it is important to consider the balance between the integrity and quality of the rice grains and the nutritional quality. Extending the processing time may affect the whole grain milled rice rate and the content of some nutrients. Therefore, in actual processing, it is crucial to choose the appropriate processing time to balance the product's quality and nutritional quality according to demand and market requirements.

Table 1. Effect of processing precision on nutritional components

Processing time (s)	Head rice Yield (%)	Milling reduction rate (%)	Crude fat content (%)	Crude protein content (g/kg)	Ash content (g/100 g)	Resistant starch content (%)	Total starch content (%)	RS/total starch (%)
0s	100	0	4.56±0.11a	6.91±0.14 a	1.51±0.04 a	9.59±0.53c	58.08±0.94c	16.51
10s	87.05	8.54	1.89±0.04b	6.12±0.03b	0.90±0.00 b	10.52±0.75c	67.26±0.07b	15.63
20s	80.99	11.81	1.06±0.01b	6.05±0.03 b	0.61±0.00c	11.76±0.44b	66.85±1.07b	17.59
30s	71.91	13.27	0.76±0.04c	6.04±0.09 b	0.61±0.01c	12.86±0.55a	68.68±1.40b	18.72
40s	58.38	16.12	0.84±0.03c	5.94±0.03c	0.56±0.01d	13.38±0.94a	71.45± 1.45a	18.72

Note. Results were expressed as means±standard deviation ($n = 3$). Different lowercase letters in the same column represent statistically significant differences at the $p < 0.05$ level.

3.2 Effect of Processing Precision on Mineral Element Contents of High-Resistant Rice YTD3

Minerals are important for maintaining human health (Tarasov et al., 2021). We observed significant differences in the content of elements such as sodium (Na), magnesium (Mg), aluminum (Al), phosphorus (p), potassium (K), calcium (Ca), manganese (Mn), iron (Fe), copper (Cu), and zinc (Zn) under different processing times. Initially, at 0s processing time, all nutrients were present in relatively high amounts. However, as the processing time increased, there was a gradual decrease in the levels of most nutrients. For example, Mg, Al, P, K, Ca, Mn, Fe, and Zn all showed a significant decrease in their concentrations as processing time increased. On the other hand, some nutrients like Na and Zn remained relatively stable throughout the processing time. Our research results are consistent with previous studies that have shown the distribution pattern of most trace elements in rice as follows: rice bran > bran > brown rice > polished rice (Zhang et al., 2022).

Table 2. Effect of processing precision on nutritional components

Processing time (s)	Na (g/Kg)	Mg (g/Kg)	Al (g/Kg)	P (g/Kg)	K (g/Kg)	Ca (g/Kg)	Mn (g/Kg)	Fe (g/Kg)	Cu (g/Kg)	Zn (g/Kg)
0 s	0.01±0.00a	1.79±0.46a	0.32±0.014a	3.38±0.28a	2.33±0.45a	0.16±0.02a	0.05±0.01a	0.09±0.02a	0.00±0.00	0.02±0.00a
10 s	0.00±0.00b	0.97±0.20b	0.33±0.022a	2.15±0.17b	1.54±0.20b	0.13±0.01b	0.03±0.00b	0.05±0.00b	0.00±0.00	0.02±0.00a
20 s	0.00±0.00b	0.64±.141c	0.30±0.035a	1.60±0.22c	1.19±0.09c	0.11±0.00c	0.02±0.00c	0.04±0.01bc	0.00±0.00	0.02±0.00a
30 s	0.00±0.00b	0.45±0.18d	0.22±0.17b	1.23±0.18d	1.02±0.14d	0.10±0.01d	0.01±0.01cd	0.02±0.01d	0.00±0.00	0.01±0.00ab
40 s	0.00±0.00b	0.30±0.00e	0.23±0.00b	0.93±0.00e	0.88±0.00e	0.09±0.00e	0.00±0.00d	0.02±0.00d	0.00±0.00	0.01±0.00b

Note. Results were expressed as means±standard deviation (n = 3). Different lowercase letters in the same column represent statistically significant differences at the $p < 0.05$ level.

3.3 *Effect of Processing Precision on The Vitamin of High-Resistant Rice YTD3*

Rice contains more B (B1, B2, B3, and B6) vitamins, vitamin E (VE). VE comprises four tocopherols (TPs) and four tocotrienols; both groups have α-, β-, γ-, δ-isomers (Kim et al., 2015; Odai et al., 2019). It can be observed that with the increase of processing time, the contents of different forms of vitamins change. The vitamin content of brown rice (0 s) is higher than that of white rice and rice with different degrees of milling. At 0 s, the vitamin content in brown rice is the highest, but with the increase of processing time, some vitamin contents gradually decrease or even disappear. Specifically, α-VE, γ-VE, and β-VE completely disappear after 20 s. The contents of VB1, VB3, VB6, and VB2 also decrease gradually. These results suggest that vitamin content is influenced by the processing time in this specific processing procedure. This is because the outer layers of the rice grain, which are rich in nutrients, are removed during the milling process (Tie et al., 2023). Another possible reason includes the sensitivity of vitamins to factors such as temperature and oxygen exposure during processing (Radeka et al., 2022). Therefore, when conducting food processing, it is important to consider how to maximize the retention of vitamin content in food to ensure the nutritional value of the final products.

Table 3. Effect of processing precision on nutritional components

Processing time (s)	δ-VE (ug/100 mg)	γ-VE (ug/100 mg)	β-VE (ug/100 mg)	α-VE (ug/100 mg)	VB1 (ng/100 mg)	VB3 (ng/100 mg)	VB6 (ng/100 mg)	VB2 (ng/100 mg)
0 s	0.31±0.01a	0.04±0.00a	0.06±0.00a	0.13±0.01a	107.56±3，17a	16.53±0.10a	108.51±0.07a	59.94±2.21a
10 s	0.30±0.01a	0.00±0.00b	0.00±0.00b	0.06±0.00b	77.84±4.87b	10.82±0.17b	95.43±1.60b	29.13±0.62b
20 s	0.29±0.01a	0.00±0.00b	0.00±0.00b	0.00±0.00c	58.19±0.16c	8.43±0.23c	78.85±1.38c	21.32±0.54c
30 s	0.26±0.01b	0.00±0.00b	0.00±0.00b	0.00±0.00c	43.97±2.83d	6.80±0.12d	77.30±0.57c	20.11±0.54c
40 s	0.23±0.01b	0.00±0.00b	0.00±0.00b	0.00±0.00c	31.41±1.1e	6.39±0.39e	70.85±1.13e	11.21±0.53d

Note. Results were expressed as means±standard deviation (n = 3). Different lowercase letters in the same column represent statistically significant differences at the $p < 0.05$ level.

3.4 *Effect of Processing Precision on the Taste Value of High-Resistant Rice YTD3*

The eating quality of rice is assessed through a comprehensive set of criteria that encompasses various post-cooking quality sensory attributes, such as aroma, visual appeal, texture, flavor, stickiness, firmness, and other perceptible indicators (Chen et al., 2022). From the data (Table 4), it can be observed that as the processing time increases, the hardness of the rice tends to decrease. At 0 s, the hardness is 14.28±0.84, and by the time it reaches 40 s, the hardness has dropped to 5.99±0.38. The viscosity data indicates that after 10 s of processing time, the viscosity of the rice begins to appear and gradually increases with time, resulting in a better taste. The data indicates a significant improvement in the balance degree at 10 s of processing time (0.07±0.03), which is notably higher than the unprocessed state (0 s). This suggests that an initial period of processing can enhance the balance degree of Youtang rice. However, as processing time extends beyond 10 s, the data does not show a substantial increase in balance degree. This could imply that the optimal balance is achieved relatively early in the processing stage, and further processing does not contribute significantly to the balance degree. The elasticity data shows a slight decrease as processing time increases from 10 to 30 s, but the trend is not marked. There is a slight recovery at 40 s (0.65±0.03), yet overall, the changes in elasticity across the different processing times are not pronounced. The data provided indicates a notable increase in water absorption of Youtang rice from 0 to 40 s of processing time. Specifically, the water absorption values rise significantly from 1.09±0.01 at 10 s to 2.83±0.19 at 40 s. Higher water absorption rates can impact the cooking properties of rice. Grains that absorb more water may cook faster and result in a softer texture. This could be advantageous for certain culinary applications where a softer rice is desired.

Table 4. Effect of processing precision on taste traits of YTD3

Processing time (s)	Hardness	Viscosity	Balance degree	Elasticity	Water Absorption
0 s	14.28±0.84a	0.00±0.00b	0.00±0.00b	0.77±0.03a	1.09±0.01b
10 s	7.83±0.86b	0.07± 0.03a	0.01± 0.01a	0.68±0.03b	2.58±0.06a
20 s	6.10±0.49c	0.07±0.01a	0.01±0.01a	0.57±0.24bc	2.85±0.26a
30 s	5.99±0.36c	0.07± 0.02a	0.01±0.01a	0.66±0.02b	2.78±0.12a
40 s	5.99±0.38c	0.08±0.02a	0.01±0.01a	0.65±0.03b	2.83±0.19a

Note. Results were expressed as means±standard deviation (n = 6). Different lowercase letters in the same column represent statistically significant differences at the $p < 0.05$ level.

3.5 Effect of Processing Precision on Pasting Properties of High-Resistant Rice YTD3

The gelatinization of starch plays a pivotal role in influencing the taste and texture of rice upon cooking (Wang et al., 2022). RVA is a set of indicators used to measure starch gelatinization characteristics (Shi et al., 2021). These parameters are closely related to rice cooking and eating quality and serve as valuable tools for evaluating the quality of rice grains. The RVA resulting data and profile of different rice starch are shown in Figure1 and Table 5. Peak viscosity (PKV) reflects the water absorption and swelling capacity of starch (Wang et al., 2022), which shows a significant increase with extended milling times. Notably, the rice milled for 30 s has the highest PKV, indicating that longer milling times may lead to a more pronounced thickening effect during cooking.

Similar to PKV, hot paste viscosity (HPV), which measures the consistency of the rice paste at high temperatures, also increases with milling time. This suggests that more extensively milled rice may result in a paste with a higher viscosity, potentially affecting the rice’s mouthfeel. The breakdown viscosity (BDV), or the decrease in viscosity during the holding period at 95 °C, is indicative of the stability of the rice paste. The data shows that longer milling times result in a larger decrease in viscosity, which could imply a less stable paste and a softer rice texture. The final viscosity, measured after cooling, is another key parameter influencing the rice’s texture. The highest final viscosity is observed in rice milled for 30 s, suggesting that this milling duration may produce rice with a more cohesive and less sticky texture upon cooling. The setback viscosity (SBV), which is the difference between final and peak viscosity, is a measure of the retrogradation or starch recrystallization. The data indicates that there is a significant increase in the setback with extended milling times, particularly at 40 s, which could lead to a firmer texture in the cooked rice. The peak time, or the time taken to reach peak viscosity, is relatively consistent across different milling times, suggesting that the rate of gelatinization may not be significantly affected by milling precision. The generalization temperature, which reflects the overall temperature change during the RVA profile, shows a slight decrease with increased milling time. This could indicate that more milled rice may require less energy to cook, potentially affecting cooking times and energy efficiency.

The results indicate that milling time has a complex relationship with the pasting properties of high-RS rice. Longer processing times can increase peak viscosity, hot paste viscosity and final viscosity, but can also lead to an increase in degradation and rebound values. While longer milling can improve the mouthfeel and viscosity of the rice, it also carries the risk of increasing nutrient degradation. This underlines the importance of achieving an optimal balance between the milling process and the preservation of the nutrient content. A balance between milling time and nutrient retention is therefore essential for optimizing the quality of high-RS rice.

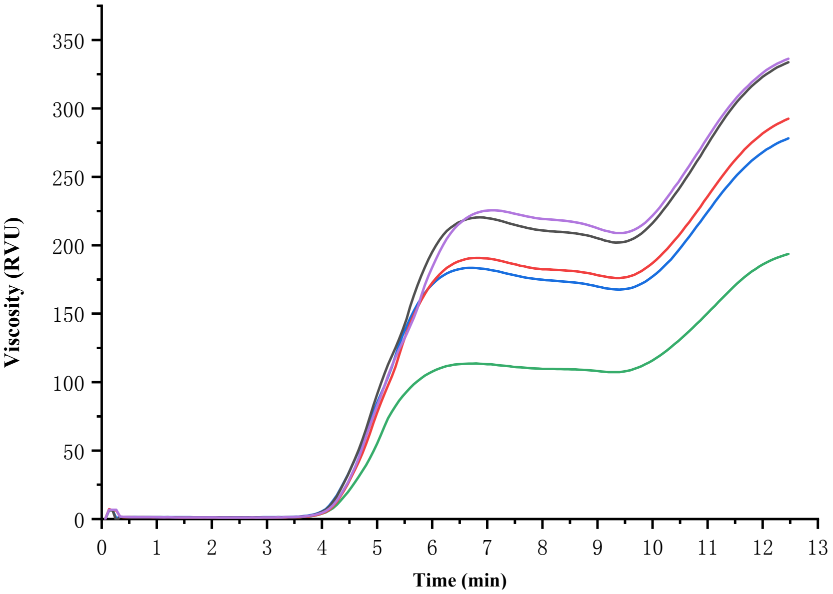

Figure 1. Rapid Visco Analyzer (RVA) patterns of different processing time samples

Note. Milling 0 s sample (green line); Milling 10 s sample (blue line); Milling 20 s sample (red line); Milling30 s sample (black line); Milling 40 s sample (purple line).

Table 5. Effect of processing precision on pasting properties of YTD3

Processing time (s)	Peak viscosity	Hot paste viscosity	Breakdown	Final viscosity	Setback	Peak time	Generalization temperature
0 s	117.42±4.71c	110.17±3.82c	7.25±0.88c	202.92±3.13c	85.50±8.42c	6.60±0.14a	88.60±0.04 a
10 s	186.84±3.08b	170.38±11.61b	16.46±1.47ab	287.46±5.49b	100.63±2.41b	6.63± 0.05a	87.13±0.53b
20 s	200.00±7.24b	184.29±6.42b	15.71±0.83b	303.46±9.91b	103.46± 12.67b	6.84± 0.14a	87.48±0.07b
30 s	225.55±3.65a	206.46±4.36a	19.09±0.71a	347.84± 2.47a	122.29±6.13a	6.77± 0.14a	87.10±0.56b
40 s	222.84±5.30a	205.84±4.12a	17.00±1.17ab	338.17± 13.08a	115.34±7.77ab	6.90± 0.28a	88.25±0.07a

Note. Results were expressed as means±standard deviation (n = 3). Different lowercase letters in the same column represent statistically significant differences at the $p < 0.05$ level.

4. Discussion

The DOM significantly influences the nutritional and edible quality of rice (Liu et al., 2015; Li et al., 2021; Zhou et al., 2023) Higher milling degree generally leads to a decrease in nutraceutical content and an increase in sensory attributes related to whiteness and stickiness (Kim et al., 2020). Therefore, achieving an optimal balance between milling degree and nutritional retention is crucial for enhancing the overall quality of rice products (Tie et al., 2023). Consumers and producers should consider these factors when determining the appropriate DOM for their rice products to meet specific health and sensory quality goals. Many studies on the effect of DOM on nutritional quality, eating quality, and digestive characteristics have focused on conventional traditional rice (Rodriguez-Arzuaga et al., 2016; Kim et al., 2020; Li et al., 2021; Zhang et al., 2023), while similar studies on functional rice, especially rice with high RS content such as the YTD3 variety, are relatively few and worth further investigation.

This study explored the impact of DOM on the nutritional and eating qualities of the high-RS rice varietyYTD3. High-RS content in rice can influence postprandial blood glucose levels due to its slow digestion property (Shen et al., 2022; Yang et al., 2023). The research findings indicate that as the milling intensity increases, there is a decrease in the levels of crude fat, crude protein, ash, vitamins, and mineral elements in rice, while the content of RS and total starch shows an opposite trend of increase. Moderate processing improved eating qualities, such as improved stickiness and softness. This trend suggests that moderate milling not only helps retain the nutritional components of rice but also improves its taste and appearance. To balance maintaining nutritional value and enhancing taste quality, rice processors need to control the milling process carefully. Scientific milling techniques can enhance the market quality of rice without sacrificing nutritional value, thereby meeting consumer demands for high-quality rice.

Furthermore, we must also take into account the differences between the actual form of rice consumed and the materials used in the experiments. Although rice powder was used for the evaluation in this study, consumers normally eat cooked rice. The cooking process can affect the digestibility of rice, including the rate of digestion of RS and glycemic response (Sajilata et al., 2006; Boers et al., 2015; Liu et al., 2022). Therefore, although our study results provide insights into the effects of DOM on the nutritional value and eating quality of high-RS rice powder, these results may not be fully transferable to the consumption of cooked rice. So, we recognize that future research needs to include an evaluation of the digestive properties of cooked rice to more accurately simulate the actual consumption experience of consumers.

Additionally, milling significantly alters the starch chain length distributions and the size distributions of whole starch molecules, which are crucial for determining properties such as digestibility (Enpeng et al., 2013; Zhang et al., 2023). Different milling processes, involving a variety of grinding methods and temperatures, lead to varying degrees of starch degradation and structural alteration (Jovin et al., 2013). Therefore, we intend to further explore the effects of various milling conditions and precision levels on the microstructure and digestibility of starch in both conventional rice and functional rice with high-RS. This endeavor aims to offer more guidance for the optimal processing of functional rice, ensuring that it delivers its health benefits without compromising nutritional integrity.

In conclusion, this study makes a valuable contribution to the field of food science and nutrition by elucidating the effects of milling on the nutritional and sensory qualities of high-RS rice. The findings not only inform rice processing practices but also guide future research aimed at optimizing the health benefits of RS rice for consumers.

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Authors Contributions

R.Y. and J.B. were responsible for study design and revising. Q.Z., Y.Y., and J.T. were responsible for methodology. Q.Z. was responsible for data collection. B.J. and R.X. drafted the manuscript. R.Y. was responsible for writing-review and editing. R.Y. was responsible for project administration. All authors read and approved the final manuscript.

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Competing Interests

The authors declare no conflict of interest.

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No additional data are available.

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