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Application of silicon improved rice productivity and reduced chalky rice

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Abstract

Chalkiness, together with head rice, is an important indicator of rice appearance quality. Chalky grains are more brittle than translucent grains and tend to break easily during milling. Silicon (Si) is recognized as a beneficial element that supports plant growth and enhances crop performance, particularly in rice. This study investigated the effect of Si application on rice yield, yield components and grain quality, including chalkiness. The available Si content in soil was also quantified. A pot experiment was conducted under a net-house from 2017 to 2018 across two planting cycles using Malaysian rice varieties, MR 263 and MR 297 (officially declared as MARDI Siraj 297). Five Si application rates, which were 0 (Si0), 100 (Si100), 200 (Si200), 300 (Si300), 400 (Si400) kg/ha, were arranged in a randomized complete block design (RCBD) with three replications. Results indicated that Si application significantly increased available Si in the soil, with Si300 and Si400 increased by up to 79.8% compared to the baseline. Yield components, including the number of panicles and percentage of filled grains, increased significantly, resulting in higher rice yield. The optimum Si rate for maximum rice yield (9.10 t/ha) was estimated at 247 kg/ha. Furthermore, Si application increased head rice yield, reduced the percentage of broken rice and chalkiness, and improved grain whiteness. Regardless of variety, chalkiness and broken rice decreased by 55% and 19%, respectively, from Si0 to Si400. In conclusion, Si fertilization effectively improved rice productivity and grain quality, particularly by reducing the percentages of chalkiness and broken rice.

Keywords: Silicon, Rice yield, Milling quality, Chalkiness, Cooking and eating quality

1. Introduction

Rice is a globally important staple food crop as it is critical to the daily survival of billions of people. It is cultivated worldwide and has been considered the second most important cereal grain after wheat [1]. Globally, annual rice production (based on milled rice) was approximately 495.78 million metric tons and is projected to increase by 114 million tons by 2035 [2]. In Malaysia, the total rice planted area was 0.64 million hectares, with an annual production of 2.20 million metric tons, and the average yield was 3.5 t/ha in 2022/2023 [3]. The demand for high-quality rice is continuously growing in parallel with economic evolution. Each year, a new rice variety with a higher yield and improved resistance to abiotic and biotic stresses is developed and released, but the grain quality is sometimes overlooked.

Rice quality is a multifaceted trait that impacts crop value, including milling quality, grain appearance, and cooking and eating quality. Although preferences for some quality characteristics are subjective and vary, most people prefer rice with a uniform shape and translucent appearance. Most rice is consumed as polished white grain, despite brown rice having a higher nutritional value. The fact that rice in the market is sold in milled form signifies the importance of the grain's appearance. Rice grains are chalky when they are not fully translucent. Such grains are more brittle than non-chalky grains and therefore prone to breakage during milling. Chalkiness appears most commonly at the center of the grain and can occupy more than half of the grain area, thus increasing its susceptibility to breakage. When the proportion of chalky grains exceeds 15%, the eating quality decreases [4]. Chalkiness decreases the value of rice in most world markets, and certain markets will not accept rice with more than 2% chalky grains [5]. For Malaysian rice, the permissible percentage of chalkiness ranges from 3% to 10%, depending on the rice grade. This range is generally acceptable for standard, premium and super rice grades. Chalkiness is one of the key determinants in grading Malaysian rice, with specifications outlined in MS 225:1997 and the Rice (Grade and Price Control) (Amendment) 2008.

The occurrence of a chalky grain develops when starch and protein particles are not tightly packed and become loose or incompletely filled within the endosperm during the grain filling and maturation stages. Grain filling is a process of starch accumulation and a significant phase in yield formation [6]. The traits and parameters used to evaluate grain quality are generally grouped into four major indicators, i.e. appearance quality (grain length, grain width, length/width ratio, and chalky grain), milling quality (milled rice recovery, head rice yield and broken rice), cooking and eating quality (amylose content, gel consistency and gelatinization temperature), and nutritional quality (protein, starch and amino acid).

Silicon (Si) is the second most abundant element in the earth's crust, after oxygen. Si combines strongly with oxygen to make highly polymeric solid structures called silicates, also known as silicon dioxide (SiO_2). Plants mostly obtain Si from the soil; however, this does not mean that Si is readily available to the plant. It is taken up by plant roots as silicic acid and transported to stems and leaves through the xylem. Si uptake and deposition increase the strength and hardness of rice tissues, acting as a physical barrier to prevent the damage caused by abiotic stress and function as plant regulators to increase rice yield and tolerance [7].

In the past 20 years, Si fertilization has become a common agronomic practice in many agricultural lands worldwide. Si is beneficial when added to the soil in which rice and several other plants are cultivated. The scientific documentation on the benefits of Si to crops began in the early 1900s when Si was identified as one of the 15 essential elements required for plant life [8]. Although it is still not recognized as an essential element for plants, Si is widely recognized as a beneficial factor for plant growth and development. In 2012 and 2015, the Association of American Plant Food Control Officials (AAPFCO) and the International Plant Nutrition Institute (IPNI) designated Si as a "beneficial substance" [9,10]. To date, Si can also be referred to as a plant nutrient [11].

Rice crops can absorb large amounts of Si, thereby contributing to their mechanical and chemical strength. Si is widely reported to increase both rice yield and grain quality. Depending on the species, Si content within plants ranges from as low as 0.1% to as high as 10% of shoot dry weight. Rice is recognized as a typical Si-accumulating plant that derives substantial agronomic and physiological benefits from Si nutrition. The ability of plants to accumulate Si is strongly influenced by factors such as soil Si availability, plant genotype, cultivar-specific uptake efficiency, and plant transpiration dynamics [11]. However, in highly weathered Oxisols, most of the total Si is present in insoluble forms and the level of plant-available Si is often very low. This limitation restricts Si uptake by rice, thereby constraining the expression of its full yield potential and increasing the risk of quality losses, such as chalkiness. Under such conditions, exogenous Si supplementation is necessary to overcome soil constraints and sustain rice productivity.

Rice varieties are known to differ in grain quality traits depending on their genotypes. These genotypic differences highlight the importance of integrating Si management with varietal selection in efforts to improve grain quality. In this study, two high-yielding Malaysian rice varieties, MR 263 and MARDI Siraj 297, were selected due to their contrasting agronomic characteristics and grain quality attributes, making them ideal for comparative analysis. MR 263 generally exhibits a higher degree of chalkiness than MARDI Siraj 297. Beyond genetic control, these varietal differences also extend to their respective requirements and responses to Si. For example, MR 263 may rely more on Si to sustain grain quality, whereas MARDI Siraj 297 tends to maintain superior grain quality with relatively lower Si dependence, or vice versa, depending on their inherent genotypic response to Si.

Chalkiness remains a challenge in rice improvement due to its complex genetics and environmental sensitivity. While breeding alone has achieved limited success, Si offers a complementary approach by enhancing rice productivity and grain quality, suggesting that integration of genetic improvement with Si management could more effectively reduce chalkiness. Although rice genotypes differ in their Si uptake efficiency and response, the present study did not specifically address these genotypic mechanisms. Instead, the objective was to evaluate the effect of Si in improving rice yield and grain quality, particularly in minimizing chalkiness, through Si application during planting of MR 263 and MARDI Siraj 297. Specifically, the study examined the effects of different Si application rates on yield performance, milling quality, and the cooking and eating quality of rice. We hypothesized that Si application at the panicle initiation stage would increase rice yield and grain quality in both rice varieties grown on Oxisols.

2. Materials and methods

2.1 Plant materials and soil properties

The seeds of two rice varieties, MR 263 and MARDI Siraj 297, were obtained from the Malaysian Agricultural Research and Development Institute (MARDI), Malaysia. These two rice varieties were popular and well-grown among farmers in many granary areas in Malaysia in 2016/2017. The comparison of agronomic traits between MR 263 and MARDI Siraj 297 is shown in Table 1. The soil used for planting purposes was collected from Tanjong Karang, Selangor, Malaysia. According to USDA Soil Taxonomy, the soil is classified as Oxisols, a highly weathered tropical soil with low natural fertility. Prior to planting, soil samples were collected from each replication for the analysis of soil properties (Table 2). The results indicated that the soil texture is generally clay loam, based on the proportions of sand, silt, and clay percentages. The soil pH ranged between 6.2 and 6.3, indicating a slightly acidic condition characteristic of Oxisols, which are commonly observed in rice-growing soils in Malaysia.

Table 1 Comparison of MR 263 and MARDI Siraj 297 on agronomic traits and yield-related components.

Characteristic	MR 263	MARDI Siraj 297
Maturity period (day)	105 – 110	110 – 115
Culm length (cm)	63.0 – 70.0	64.4 – 70.0
Panicle length (cm)	21.5 – 24.6	21.0 – 27.0
Panicle/m^2	421	523
Filled grain (%)	59.8 – 66.6	77.10 – 86.2
Number of grains/panicle	104 – 136	86 – 106
1,000-grain weight (g)	24.9 – 25.1	27.8 – 29.2

Table 2 Physicochemical properties of the soil used for rice planting.

Planting cycle	Soil order (USDA)	Texture	pH	CEC (meq/100 g)	Total Si (g/kg)	Total N (g/kg)	Total P (g/kg)	Total K (g/kg)
Cycle 1	Oxisols	Clay loam	6.2	9.92	266	2.5	0.9	1.8
Cycle 2			6.3	10.45	270	2.9	0.7	1.9

CEC = cation exchange capacity, meq = milliequivalents

2.2 Experimental setup and treatments

The experiments were conducted under a net-house at MARDI Serdang, Selangor (2°59′32.9″ N, 101°41′57.5″ E), during the rice growing seasons of 2017 (planting cycle 1) and 2018 (planting cycle 2). The seedling was prepared by soaking the seeds for 24 h and then pre-germinating them for one day before sowing. The sprouted seeds were sown in moist soil in trays. A thin layer of rice straw was used to cover the seeds. The trays were watered regularly to keep the soil moist but not flooded. In this pot experiment, the 14-day-old seedlings were transplanted into plastic containers (60 x 40 x 30 cm) containing 40 kg of soil. The seedlings were arranged at a spacing of 20 x 20 cm, with three seedlings per hill and each pot contained four hills. The pots were flooded, and a 2.5 cm water depth was maintained throughout the growing period until 2-3 weeks before harvest.

Si fertilizer in the form of calcium silicate powder (containing 60–80% Si) was obtained from a commercial brand (HmbG Chemicals). Four levels of Si rate were applied: Si100, Si200, Si300 and Si400, corresponding to 100, 200, 300 and 400 kg/ha of Si (pure Si), respectively. A treatment without Si fertilizer served as the control (Si0). These rates were equivalent to 0, 4, 8, 12 and 16 g Si per pot, calculated using the following formula:

$$\text{Required amount (g)} = \frac{Target\ rate\ (kg/ha)}{Purity\ fraction}\ x\ 1{,}000 \tag{1}$$

The Si application rates in this study were applied based on a previous researcher who evaluated Si fertilizer levels from 0 to 400 kg/ha SiO_2 and reported that 329 kg/ha SiO_2 (equivalent to 154 kg/ha of Si) was the optimum rate for achieving higher rice yield [12]. The experiment was conducted using a randomized complete block design (RCBD) with two rice varieties, MR 263 and MARDI Siraj 297, and five levels of Si application rates (0, 100, 200, 300, and 400 kg/ha Si). Each experimental unit comprised four hills arranged uniformly to ensure consistent growth conditions, with treatments randomly assigned within each block to minimize environmental variability.

The crop management and fertilization practices followed the guidelines outlined in the Manual Teknologi Penanaman Padi Lestari, MARDI [13]. Seven days after transplanting, the first fertilization was applied at a rate of 23.8 kg/ha N, 28 kg/ha P_2O_5 and 14 kg/ha K_2O. The second fertilization was applied three weeks after transplanting at a rate of 36.80 kg/ha N. The third fertilization was administered 40 days after transplanting, consisting of 34 kg/ha N, 23 kg/ha P_2O_5, and 35 kg/ha K_2O. Si was applied 41 days after transplanting (55 days after sowing), coinciding with the panicle initiation stage of both varieties. The fourth fertilization was carried out 65 days after transplanting with 8.5 kg/ha N, 1.5 kg/ha P_2O_5, and 12.5 kg/ha K_2O. Weeds were managed manually, while pests and diseases were controlled using chemicals when necessary. The water level in each pot was maintained at approximately 10–15 cm throughout the growing period and was drained out two weeks before harvest. All recommended agronomic practices were applied throughout the growing season.

2.3 Available silicon content in soil determination

The available Si content in the soil, both before planting and after harvest, was determined using the acetic acid extraction method followed by the colourimetric molybdenum blue assay, as described by Korndörfer et al. [14]. Briefly, 1 g of air-dried soil was placed into a centrifuge tube and extracted with 10 mL of 0.5 M acetic acid. The mixture was shaken at high speed for 1 h using a reciprocal shaker and then filtered through filter paper. A 0.5 mL aliquot of the filtrate was transferred into a volumetric flask containing 10 mL of dH_2O. Subsequently, 0.5 mL of 0.25 N HCl and 1 mL of 10% ammonium molybdate (pH 7.0–7.5) were added. After 5 min, 1 mL of 20% tartaric acid was added and left for 2 min, then 1 mL of the reducing agent was added. The reducing agent was prepared by mixing Solution A (2 g of Na_2SO_3 and 0.4 g of 1-amino-2-naphthol-4-sulfonic acid in 25 mL of dH_2O) with Solution B (25 g of $NaHSO_3$ in 200 mL of dH_2O), and adjusting to 250 mL with dH_2O. The mixture was then adjusted with dH_2O to a final volume of 25 mL, mixed thoroughly and left to stand for 30 min before measuring the absorbance at 630 nm. The Si concentration was quantified based on a standard calibration curve prepared from a Si standard solution.

2.4 Growth, yield components, rice yield and harvest index determination

Plant growth parameters (plant height, panicle length, leaf width and leaf length) were measured from four plants per pot two weeks before harvest. Plant height was measured from the soil surface to the highest point of the plant. The panicle length was measured from the base to the tip of the panicle. Leaf length was taken from the base of the leaf blade to the tip, while the leaf width was measured at the widest part of the third fully expanded leaf, which served as the target leaf.

Aboveground biomass from four plants per pot was sampled at 96 days after transplanting to determine the yield components for both varieties. The measurement included the number of panicles per hill, total number of grains per panicle, percentage of filled grains and 1,000-grain weight. The number of panicles in each hill was counted manually. The number of grains per panicle was counted from the total number of spikelets (filled and unfilled), while the percentage of filled grains was calculated as the total number of filled grains relative to the total number of spikelets. The 1,000-grain weight was determined from filled spikelets dried to 14% moisture content and calculated using the following formula:

$$\text{1,000 grain weight (g)} = \frac{(100-MC)}{86}\ x\ 1{,}000\ grain\ weight\ (g) \qquad (2)$$

Where MC is the rice moisture content (%) and 86 represents the reference MC for standard adjustment (14%).

The rice yield was calculated based on the weight of filled grains harvested per unit area, adjusted to a standard moisture content of 14%, using the following formula:

$$\text{Rice yield (t/ha)} = \frac{Plot\ Gy}{1{,}000}\ x\ \frac{(100-MC)}{86}\ x\ \frac{10{,}000}{A} \qquad (3)$$

Where Plot Gy is filled grains from four plants (g), MC is the rice moisture content (%), A is the harvested area (m^2), 1,000 is the conversion factor from g to kg, 10,000 is the conversion factor from m^2 to ha, and 86 is the reference MC for standard adjustment (14%).

At harvest, the remaining straw (including grains, leaves, stems and panicles) was collected and dried to determine the harvest index, calculated as the ratio of economic yield (rice yield) to biological yield (rice yield + straw yield).

2.5 Milling quality determination

The milling quality of rice, which included milled rice recovery, head rice yield, broken rice, chalkiness and whiteness, was determined. Three replicates of each 200 g of cleaned paddy grains were dehulled in a Satake

THU35B rice huller. The resulting brown rice was weighed and polished for 60 s using a Satake TM05C polisher to obtain white rice. The milled rice was weighed. The milled rice recovery was calculated by dividing the weight of the milled rice by the weight of the paddy. Head rice and broken rice were separated from the total milled rice using a Satake TRG05B rice grading machine, and the amount of head rice yield and broken rice was calculated per total milled rice. For each sample, chalky grains from milled rice, obtained from 200 g of paddy, were manually inspected using the Standard Evaluation System (SES) for Rice developed by IRRI [15]. Grains with a white opaque area that covers 20% or more of the kernel area were considered a chalky grain, whereas grains with a chalky area of 20% or less were considered a non-chalky grain. The percentage of chalkiness was calculated by dividing chalky grain weight by milled rice weight and multiplying by 100. The whiteness of milled rice was measured using a milling meter (MM1D, Satake, Japan).

2.6 Cooking and eating quality (CEQ) determination

The amylose content (AC) was analyzed using the starch-iodine colorimetric method as described by Juliano [16]. Finely ground rice (0.1 g) was placed in a 100 mL volumetric flask. Then, 1 mL of 95% ethanol was added and slightly shaken to wet the entire sample. Next, 9 mL of 1 M NaOH was added and mixed thoroughly. The sample was heated for 20 min in a boiling bath to dissolve the starch, and it was allowed to cool prior to the final addition of dH_2O. The amylose assay was prepared by adding 0.1 mL acetic acid to 5 mL of dH_2O, followed by the sample aliquot (0.5 mL). Then, iodine solution (0.2 mL) was added before adding dH_2O to the final volume of 10 mL. The mixture was mixed well, and the absorbance was measured at 720 nm against a blank solution. A calibration curve was plotted for amylose from potatoes containing 0, 8, 16, 24, 32 and 40% amylose.

For gel consistency (GC) determination, finely ground rice (0.1 g) was placed in a test tube and wetted with 0.2 mL of 95% ethanol containing 0.025% thymol blue. The samples were digested in 2 mL of 0.2 M KOH in a boiling water bath for 8 min and placed at room temperature for 5 min. After cooling, the tubes were placed in cold water for 20 min before being positioned horizontally on a flat surface for 1 h. Finally, the length of the gel was measured as the GC value [17]. Gelatinization temperature (GT) was estimated as the alkali spreading value (ASV) determined by the degree of dispersal of whole-milled rice grain in an alkali solution. Grains were soaked in 1.7% KOH and incubated at room temperature for 23 h. The degree of spreading of individual grains was evaluated based on a 7-point numerical scale [18].

2.7 Statistical analysis

Data were analyzed using analysis of variance (ANOVA) with Statistical Analysis System (SAS) software, version 9.4. Analysis of combined experiments was applied, where planting cycle was the random effect, while Si treatment and variety were the fixed effects, following the approach outlined by Moore and Dixon [19], allowing for integrated interpretation of treatment effects and varietal responses under varying Si levels. Treatment means were then separated using the Least Significant Difference test at the $p \leq 0.05$ significance level.

3. Results and discussion

3.1 Available silicon content in the soil

The available Si contents in the soil initially ranged from 15.23 to 16.39 mg/kg, with a mean of 15.79 mg/kg. After harvest, they increased to a range of 16.81 to 28.40 mg/kg (Table 3). As the determination of the available Si content in soil was conducted before planting activity and Si application, no significant effects of variety or Si application rate were observed at that stage. However, the available Si content increased significantly following Si application, reaching the highest values at Si300 (28.40 mg/kg) and Si400 (28.37 mg/kg), corresponding to a 79.8% increase over the baseline value (15.79 mg/kg).

The available Si contents and its availability in soil depend largely on soil formation processes and soil type. The soil used in this experiment was collected from a farmer's farm field and considered cultivated soil. The Si content was influenced by agricultural practices, which can alter soil properties and often result in low Si availability. Since the response to Si fertilization depends on the inherent soil Si levels, source and application rate, the initial available Si contents were measured before the experiment commenced and compared with the values obtained after harvest.

The earth's crust is predominantly composed of Si; however, the abundance of Si in soils does not mean that sufficient amounts of soluble Si are available for plant uptake. Therefore, quantifying the available Si content, which is important for plant growth, is crucial in understanding the Si-mass balance for a particular soil. The contents of available Si in the soil are dynamic as the rate of Si dissolution and the stability of dissolved Si are influenced by the form of Si and environmental factors. The total soil's Si content may have little relationship to the amount of available Si. Since Oxisols are very highly weathered soils with low levels of plant nutrients and available Si, the exogenous application of Si could improve rice productivity [20]. Furthermore, in soils that have been continuously cultivated with rice for a long period, depletion of plant-available Si is commonly observed. Thus, the practice of Si fertilization is already common in many rice-growing areas.

Table 3 Available Si content in the soil before and after planting.

Factors	Initial Si content in the soil (mg/kg)	Si content in soil after harvesting (mg/kg)
Planting cycle (C)		
Cycle 1	15.28^{b} ± 0.25	22.92^{b} ± 0.88
Cycle 2	16.30^{a} ± 0.31	24.38^{a} ± 0.98
Variety (V)		
MR 263	15.57^{a} ± 0.31	24.34^{a} ± 0.94
MARDI Siraj 297	16.01^{a} ± 0.28	22.96^{b} ± 0.93
Si rate (T)		
0	15.23^{a} ± 0.28	16.81^{d} ± 0.17
100	15.30^{a} ± 0.45	21.12^{c} ± 0.69
200	16.39^{a} ± 0.58	23.54^{b} ± 0.74
300	16.05^{a} ± 0.37	28.40^{a} ± 0.81
400	15.98^{a} ± 0.56	28.37^{a} ± 1.05
C x V	ns	ns
C x T	ns	ns
V x T	ns	ns
C x V x T	ns	ns

Means (± SE, n = 3) followed by the same letter within a column and for each factor are not significantly different at $p \leq 0.05$ according to the LSD test. ns = non-significant.

A previous study reported that the median of the total Si content of 180 soil samples was 291 g/kg; the relative ratios of available Si contents to the total Si content were calculated to be 0.017 to 0.027%, thus suggesting extremely low ratios of the available Si fraction to the total Si [21]. In fact, estimating the content of Si available to plants is difficult. Numerous approaches have been developed to determine the available Si in soil [22], but none is currently recognized as a standard method. The present work used a classical acetic acid (0.5 M) extraction procedure to determine available Si content. The findings revealed that Si application to the soil during planting strongly influenced the availability of Si in the soil, thus increasing Si accumulation in ice plants.

3.2 Response of growth to silicon application

The Si application had no significant effect on any of the growth parameters measured in this study. Regardless of the Si application rate, plant height, panicle length, leaf length and leaf width remained unaffected. However, significant differences between rice varieties were observed for panicle length and leaf width (Table 4).

Table 4 Effects of Si application rates on plant height, panicle length, leaf width and leaf length.

Factors	Plant height (cm)	Panicle length (cm)	Leaf length (cm)	Leaf width (cm)
Planting cycle (C)				
Cycle 1	89.85^{a} ± 0.30	26.21^{b} ± 0.12	34.30^{b} ± 0.31	1.25^{b} ± 0.02
Cycle 2	97.40^{b} ± 0.35	27.53^{a} ± 0.19	40.08^{a} ± 0.51	1.30^{a} ± 0.01
Variety (V)				
MR 263	93.38^{a} ± 0.82	26.42^{b} ± 0.16	36.67^{a} ± 0.77	1.31^{a} ± 0.01
MARDI Siraj 297	93.88^{a} ± 0.72	27.32^{a} ± 0.20	37.71^{a} ± 0.57	1.23^{b} ± 0.01
Si rate (T)				
0	93.15^{a} ± 1.35	26.88^{a} ± 0.33	36.88^{a} ± 0.96	1.25^{a} ± 0.03
100	94.45^{a} ± 1.16	26.96^{a} ± 0.29	37.13^{a} ± 1.12	1.28^{a} ± 0.02
200	92.99^{a} ± 1.25	26.44^{a} ± 0.26	37.20^{a} ± 1.44	1.27^{a} ± 0.03
300	93.26^{a} ± 1.31	27.15^{a} ± 0.35	37.30^{a} ± 0.85	1.27^{a} ± 0.02
400	94.28^{a} ± 1.13	26.93^{a} ± 0.37	37.44^{a} ± 1.06	1.29^{a} ± 0.01
C x V	ns	ns	ns	ns
C x T	ns	ns	ns	ns
V x T	ns	ns	ns	ns
C x V x T	ns	ns	ns	ns

Means (± SE, n = 3) followed by the same letter within a column and for each factor are not significantly different at $p \leq 0.05$ according to the LSD test. ns = non-significant.

Different rates of Si application had no significant effect on plant heights. This may be attributed to the relatively low level of Si used in the present study (0–400 kg/ha), which might have been insufficient to induce height increment. A previous study reported that the Si application rate at 600 kg/ha significantly increased plant heights, suggesting that a higher Si rate is required to stimulate such growth [23]. In rice, Si deposition in cell walls has been associated with increased plant height by strengthening the stem and leaves, making them more erect. This reduces mutual shading and improves light interception, thereby increasing the photosynthetic rate [24]. Plant height has a direct influence on crop yields; therefore, increasing height can be advantageous for improving productivity. However, excessive plant height is undesirable, as taller plants are more susceptible to lodging, which can lead to yield reduction. Some researchers have reported that Si fertilizer does not necessarily affect plant growth parameters but increases crop yield and harvest index [25], probably due to increased stress tolerance and higher chlorophyll content [26].

The panicle length was also not affected by Si application; however, MR 263 exhibited a longer panicle length than MARDI Siraj 297. This result aligns with a previous study that reported no significant differences in panicle length of rice crops following Si application [27]. In contrast, other researchers observed that Si application increased panicle length compared to the control [28]. A longer panicle is generally associated with a higher number of grains per panicle, as it allows more space for spikelet development, which could improve rice yield. In the present work, the Si application was ineffective in increasing the number of grains per panicle, likely because it did not significantly influence panicle length.

Since the Si application did not influence the development of leaf length and width in rice plants, the leaf area also remained unchanged. Leaf area (cm^2) can be calculated by K x length (cm) x width (cm). K is the correction factor (0.75) [24, 29]. The leaf area increases as the plant's height gradually increases and leaves emerge regularly during the vegetative stage [24]. In the present work, plant height did not increase following Si treatment; therefore, the leaf area remained unchanged. Moreover, because Si was applied after the vegetative stage, this likely explains why Si fertilization had no significant effect on leaf length, width, or area.

3.3 Effect of silicon on yield components, rice yield and harvest index

The application of Si had a significant impact on most yield components, rice yield and harvest index (Table 5). The number of panicles, percentage of filled grains, and rice yield were significantly affected by different Si application rates. Meanwhile, the number of grains per panicle and 1,000-grain weight were not significantly affected. The ANOVA results also revealed significant varietal effects on all yield components, rice yield and harvest index, with MARDI Siraj 297 recording the highest values for all parameters compared to MR 263, except for the number of grains per panicle. MR 263 produced more grains than MARDI Siraj 297.

The number of panicles increased following Si application; however, no significant differences were observed between Si100 and Si400. Although Si300 produced the highest number of grains per panicle, the differences among treatments were not statistically significant. Meanwhile, the percentage of filled grains was found to be highest at Si200 (85.10%), but the differences among Si100, Si200, Si300, and Si400 were not statistically significant.

Table 5 Effects of Si application rates on yield components, rice yield and harvest index.

Factors	No. of panicle	No. of grains per panicle	Filled grain (%)	1,000-grain weight (g)	Rice yield (t/ha)	Harvest index
Planting cycle (C)						
Cycle 1	$13^{a} \pm 0.19$	$196^{b} \pm 4.67$	$80.94^{b} \pm 1.20$	$26.38^{a} \pm 0.42$	$8.29^{b} \pm 0.16$	$0.47^{b} \pm 0.003$
Cycle 2	$12^{a} \pm 0.16$	$210^{a} \pm 1.18$	$84.00^{a} \pm 1.21$	$26.32^{a} \pm 0.37$	$8.84^{a} \pm 0.17$	$0.48^{a} \pm 0.003$
Variety (V)						
MR 263	$12^{a} \pm 0.15$	$220^{a} \pm 3.03$	$79.14^{b} \pm 1.15$	$24.32^{b} \pm 0.11$	$8.09^{b} \pm 0.13$	$0.47^{b} \pm 0.003$
MARDI Siraj 297	$13^{a} \pm 0.19$	$186^{b} \pm 3.58$	$85.80^{a} \pm 0.99$	$28.38^{a} \pm 0.13$	$9.04^{a} \pm 0.16$	$0.48^{a} \pm 0.003$
Si rate (T)						
0	$11^{b} \pm 0.20$	$199^{a} \pm 7.76$	$80.45^{b} \pm 2.17$	$26.12^{a} \pm 0.71$	$7.64^{c} \pm 0.16$	$0.45^{d} \pm 0.003$
100	$12^{a} \pm 0.20$	$198^{a} \pm 8.00$	$84.55^{ab} \pm 2.14$	$26.47^{a} \pm 0.64$	$8.52^{b} \pm 0.24$	$0.47^{c} \pm 0.004$
200	$13^{a} \pm 0.13$	$205^{a} \pm 6.49$	$85.10^{a} \pm 1.22$	$26.43^{a} \pm 0.64$	$9.27^{a} \pm 0.19$	$0.49^{a} \pm 0.005$
300	$13^{a} \pm 0.30$	$207^{a} \pm 6.55$	$81.07^{ab} \pm 1.57$	$26.49^{a} \pm 0.63$	$8.78^{ab} \pm 0.26$	$0.49^{a} \pm 0.004$
400	$13^{a} \pm 0.33$	$204^{a} \pm 8.06$	$81.17^{ab} \pm 2.28$	$26.24^{a} \pm 0.58$	$8.61^{b} \pm 0.27$	$0.48^{b} \pm 0.003$
C x V	ns	ns	ns	ns	ns	ns
C x T	ns	ns	ns	ns	ns	ns
V x T	ns	ns	ns	ns	ns	ns
C x V x T	ns	ns	ns	ns	ns	**

Means (± SE, $n = 3$) followed by the same letter within a column and for each factor are not significantly different at $p \leq 0.05$ according to the LSD test. ns = non-significant; ** = significant at $p \leq 0.01$.

The present work showed that Si application at the panicle initiation stage slightly increased the number of panicles, proving that Si is vital in the reproductive development of rice. When Si was applied during the vegetative stage, its effect was minimal or absent until supplementation occurred at the reproductive stage [30]. Several studies have documented that Si application at the panicle initiation stage significantly increased the number of panicles [12, 31], suggesting that Si alone is insufficient to improve the panicle development during the vegetative stage. In rice, the transition from the vegetative to the reproductive phase typically occurs around 50–60 days after planting, which coincides with the panicle initiation stage. The present study suggests that applying Si at 55 days after planting can promote panicle formation, thereby contributing to higher rice yield. Rice yield is determined by tillering capacity, which is closely associated with the number of panicles [32].

In the present study, different Si application rates did not significantly affect the number of grains per panicle. This finding is in line with several previous reports, which reported no significant impact of Si fertilizer on this trait [31]. Similarly, the 1,000-grain weight did not differ significantly among treatments, suggesting that Si has little influence on rice hull size. A previous study has reported that the 1,000-grain weight was a constant characteristic and the grain size was controlled by the hull size [33]. Consequently, the grains cannot grow larger than the hull despite excellent weather and adequate nutrient supply to the plant. The most important factors contributing to the higher rice yield are the percentage of filled grain and 1,000-grain weight. This likely explains the higher rice yield observed in MARDI Siraj 297 compared to MR 263, indicating that MARDI Siraj 297 is a superior genotype.

The present study revealed that the Si application helps to improve the harvest index of rice. The result for the harvest index as a function of the planting cycle-variety-Si rate interaction is presented in Figure 1. During the planting cycle 1, the highest harvest index for MR 263 (0.477) was achieved at an Si application rate of 200 kg/ha, while MARDI Siraj 297 recorded the highest harvest index (0.483) at 300 kg/ha. In the second planting, the optimal Si rate for maximizing harvest index in both varieties was 200 kg/ha, with MR 263 achieving values of 0.494 and 0.505, respectively. These findings indicate that Si application enhances the harvest index, with 200 and 300 kg/ha being the most effective rates across both planting cycles and varieties. This finding is similar to the previous report, which documented that rice Si-treated plants produced a higher harvest index than untreated control plants [25]. This improvement may be attributed to the effect of Si in enhancing root growth and increasing phosphorus (P) availability, as well as increasing photosynthetic efficiency, resulting in increased growth and yield-related attributes [34]. Si fertilization has also been shown to improve P uptake, resulting in increased plant growth and rice yield [35].

(A) (B)

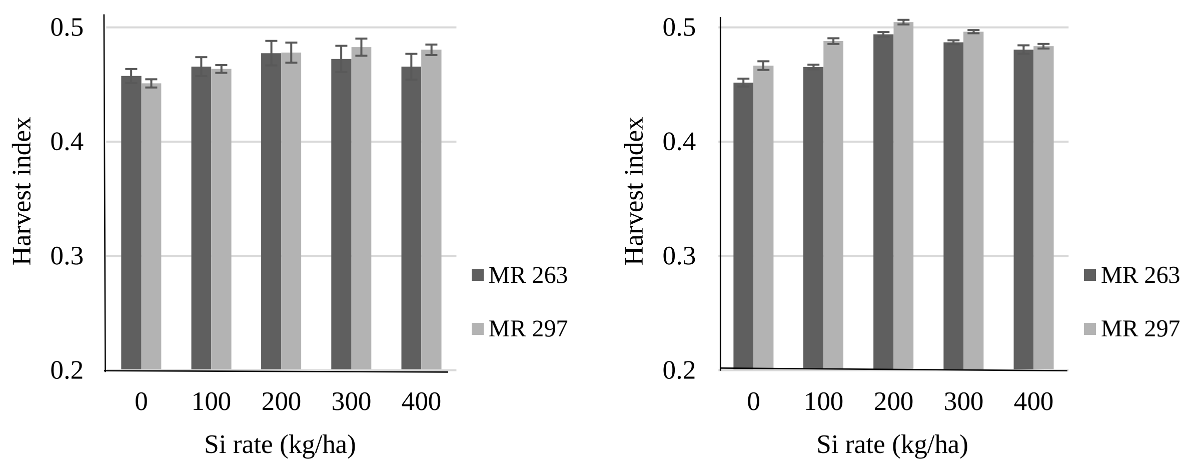

Figure 1 Effect of planting cycle-variety-Si rate interaction on harvest index of rice during (A) planting cycle 1, and (B) planting cycle 2. MR 297 = MARDI Siraj 297.

The rice yield of both varieties significantly increased after Si application. MARDI Siraj 297 recorded about 9.04 t/ha of yield, higher by 11.7% than MR 263 (8.09 t/ha). The lowest rice yield was recorded in Si0 (7.64 t/ha) (Table 5). Rice yield was significantly influenced by the Si rate and fitted well to a quadratic regression model (Table 6). The relationship was described by the equation $y = -0.000024x^2 + 0.0117x + 7.6507$ ($R^2 = 0.91$). Based on this model, the optimum Si application rate was estimated at 247 kg/ha, giving a maximum rice yield of 9.10 t/ha (Figure 2). Beyond this rate, further increases in Si application resulted in yield reduction. Compared to the control, the optimum Si application increased rice yield by approximately 18.98%.

Table 6 Analysis of orthogonal contrast on rice yield.

Contrast	DF	Contrast SS	Mean square	F Value	Pr > F
Linear	1	5.80800000	5.80800000	14.19	0.0005
Quadratic	1	9.44777143	9.44777143	23.08	<.0001
Cubic	1	0.24300000	0.24300000	0.59	0.4448
Quartic	1	1.24201190	1.24201190	3.03	0.0880
Error	48	19.6507133	0.40938986		
Corrected total	59				

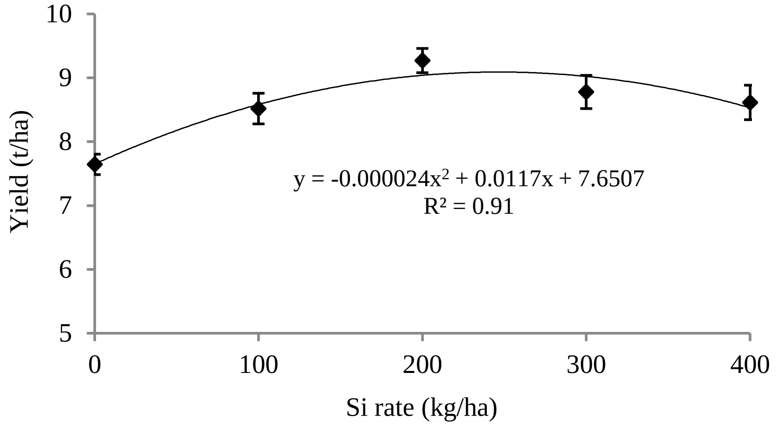

Figure 2 Rice yield as a function of increasing Si application rates.

Si application during planting at the panicle initiation stage could significantly boost rice yield, as demonstrated by several studies. Understanding the rice growth stages is therefore crucial for effective crop management. The panicle initiation stage is the first stage in the reproductive phase, which indicates the start of panicle formation, followed by the heading and flowering stages. Applying the Si at the panicle initiation stage is beneficial since some research has shown that Si deficiency can reduce rice yield by limiting the spikelet formation, fertilization and grain-filling process [36]. Grain filling is the key stage in rice growth that determines the final weight of the rice grains. A previous study reported that grain filling is typically a process of starch build-up and a significant phase for yield formation [6]. Thus, increasing rice yield can be accomplished by optimizing grain filling. In the present study, Si application improved specific yield components differently in each variety. It increased panicle number, filled grains, and 1,000-grain weight, contributing to higher rice yield. However, the magnitude of these improvements varied between MR 263 and MARDI Siraj 297, highlighting genotype-specific responses to Si fertilization and the importance of aligning nutrient management with varietal characteristics.

The present study demonstrated an increasing trend in rice yield with higher Si application rates up to the optimum level of 247 kg/ha was reached. Previous studies have shown that rice yield increases with the application of various Si, ranging from 10 to 30% [37]. The others reported a 23% increase in rice yield when the Si level increased from 100 to 400 kg/ha of SiO_2 [12]. They also reported a significant quadratic regression equation with the optimum Si fertilizer at the rate of 329 kg/ha. Other researchers also reported that using Si at 200 kg/ha along with a recommended dose of fertilizers resulted in the significantly highest rice yield of rice [38]. They suggested that adding Si to the soil in which rice crops are grown is crucial in improving rice yield. Si depletion and unpromising rice yield are common in rice-growing areas due to intensive farming without adding Si, particularly when rice straw is not integrated into the soil.

3.4 Effect of silicon on rice milling quality

Different Si application rates significantly affected the percentage of head rice yield, broken rice, chalkiness and whiteness (Table 7). However, milled rice recovery, which is the percentage of milled rice obtained from a dehulled paddy, was not affected by different rates of Si. There were significant differences between rice varieties in all the parameters evaluated, with MARDI Siraj 297 exhibiting superior characteristics compared to MR 263. Specifically, MARDI Siraj 297 exhibited higher milled rice recovery and lower broken rice and chalkiness.

Results showed that the lowest amount of broken rice was recorded in Si400, with a reduction of approximately 19% from Si0. MARDI Siraj 297 yielded the lowest broken rice (11.69%) as compared to MR 263 (12.88%). The lowest amount of broken rice was recorded in Si400 (11.22%) as compared to Si0 (13.79%). The highest whiteness was obtained in Si300 (40.20%), but did not differ from Si200 (40.18%). MR 263 performed higher whiteness (40.30%) than that of MARDI Siraj 297 (38.83%).

The results for head rice yield as a function of planting cycle-variety-Si rate interaction are presented in Figure 3. The highest head rice yield for MR 263 was observed at Si application rates of 400 kg/ha and 200 kg/ha during planting cycles 1 and 2, with values of 84.0% and 84.6%, respectively. Meanwhile, MARDI Siraj 297 recorded the highest head rice yield for both seasons at a Si rate of 400 kg/ha, with 86.0% and 89.2%, respectively. MARDI Siraj 297 exhibited a higher head rice yield, along with lower chalkiness than MR 263, which may be attributed to its superior characteristics and better responsiveness to Si fertilization. It was observed that the amount of available Si remaining in the soil after harvest was lower in the pot planted with MARDI Siraj 297 than in those with MR 263 (Table 3), indicating higher Si uptake capacity by MARDI Siraj 297, which may enhance its ability to accumulate Si in plant tissue. Conversely, the lower Si absorption by MR 263 may reflect genotypic limitations in Si transport or uptake efficiency. The enhanced responsiveness to Si aligns with previous reports of varietal differences in Si efficiency and yield performance among rice genotypes [12, 24, 39–41].

Table 7 Effects of Si application rates on milling quality of rice.

Factor	Milled rice recovery (%)	Head rice yield (%)	Broken rice (%)	Chalkiness (%)	Whiteness (%)
Planting cycle (C)					
Cycle 1	68.71^b ± 0.22	81.71^b ± 0.67	12.58^a ± 0.27	5.71^a ± 0.51	39.32^b ± 0.23
Cycle 2	69.61^a ± 0.23	84.40^a ± 0.70	11.99^b ± 0.44	3.61^b ± 0.36	40.01^a ± 0.22
Variety (V)					
MR 263	68.50^b ± 0.17	80.77^b ± 0.66	12.88^a ± 0.37	6.35^a ± 0.43	40.37^a ± 0.23
MARDI Siraj 297	69.82^a ± 0.23	85.33^a ± 0.51	11.69^b ± 0.34	2.98^b ± 0.30	38.97^b ± 0.15
Si rate (T)					
0 (control)	68.43^a ± 0.43	79.41^d ± 1.01	13.79^a ± 0.47	6.80^a ± 0.72	39.05^b ± 0.34
100	69.16^a ± 0.38	81.86^c ± 0.94	12.60^b ± 0.48	5.54^b ± 0.77	39.69^{ab} ± 0.31
200	69.45^a ± 0.31	83.96^b ± 1.06	12.14^b ± 0.54	3.90^c ± 0.69	40.18^a ± 0.33
300	69.27^a ± 0.33	84.28^b ± 1.07	11.67^{cd} ± 0.65	4.05^c ± 0.70	40.20^a ± 0.45
400	69.49^a ± 0.39	85.75^a ± 0.77	11.22^d ± 0.53	3.03^d ± 0.44	39.21^b ± 0.31
C x V	ns	ns	ns	ns	ns
C x T	ns	ns	ns	ns	ns
V x T	ns	ns	ns	ns	ns
C x V x T	ns	*	ns	ns	ns

Means (± SE, n = 3) followed by the same letter within a column and for each factor are not significantly different at $p \leq 0.05$ according to the LSD test. ns = non-significant; * = significant at $p \leq 0.05$.

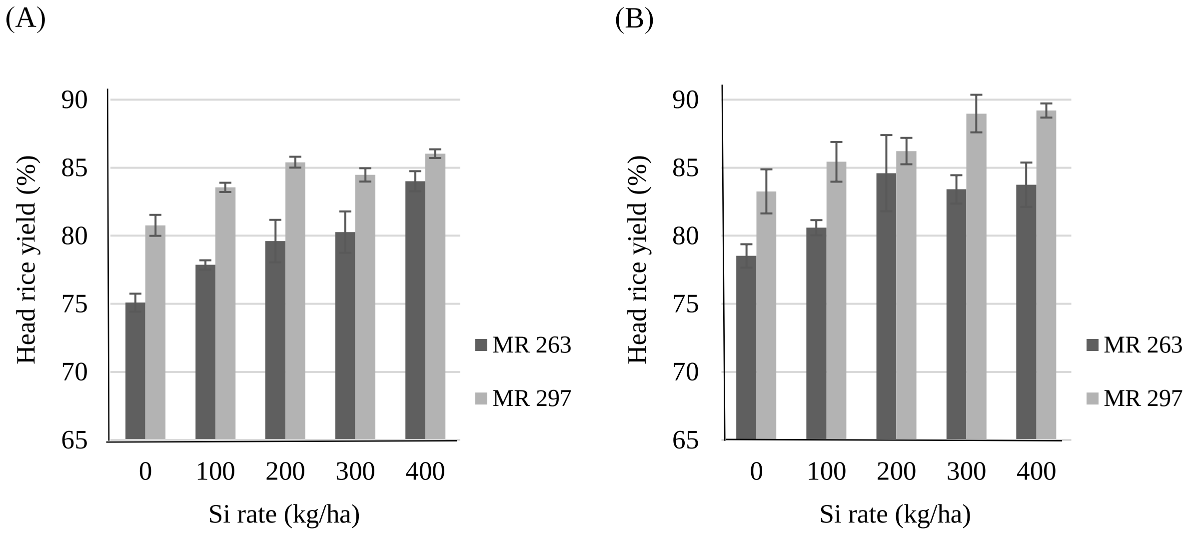

Figure 3 Effect of planting cycle-variety-Si rate interaction on head rice yield during (A) planting cycle 1, and (B) planting cycle 2. MR 297 = MARDI Siraj 297.

The present study showed that the percentage of chalky grains was found to be lowest under Si400 compared to the control, with approximately a 55% reduction observed from Si0 to Si400, regardless of varieties. Among the two, MARDI Siraj 297 consistently exhibited a lower proportion of chalky grains than MR 263. Although the

Si application improved grain quality traits, the extent of improvement varied between varieties. The genetic factors not only shape inherent traits like chalkiness but also influence how each variety responds to Si fertilization. Recognizing these genotype-specific responses is therefore crucial when aligning Si management with varietal selection to optimize rice yield and grain quality.

To better understand how Si influences grain quality, it is important to consider the physiological processes associated with chalk formation. Chalkiness can arise from nutrient deficiencies during endosperm development, decreased ability to synthesize starch in the endosperm, or starch degradation during ripening [42]. Previous studies have reported that Si application improves several physiological characteristics, particularly during grain filling [43]. By strengthening cell walls and enhancing the movement and deposition of assimilates, primarily sucrose, from leaves to developing grains, where they are converted into starch and stored in the endosperm, Si application directly influences grain weight and yield. Furthermore, these physiological improvements facilitate more uniform starch accumulation within the endosperm, resulting in well-packed starch granules and reduced chalkiness. In the present study, the lower percentage of chalky grains observed under Si treatment, particularly in MR 263, may be attributed to this effect, highlighting the role of Si in modulating grain quality through its influence on cellular structure and assimilate partitioning during the critical grain-filling stage. Nonetheless, further research is needed to fully elucidate the relationship between Si application and starch mechanism.

3.5 Effect of silicon on cooking and eating quality of milled rice

Results presented in Table 8 showed that the Si application did not affect the cooking and eating quality (CEQ) of the rice grains. MARDI Siraj 297 recorded the highest amylose content (AC) compared to MR 263. However, the amylose value for all treatments fit into the intermediate group (20–25%), which would result in a soft texture of cooked rice. AC is widely recognized as the most important factor that determines the CEQ of milled rice. According to IRRI, rice is commercially classified into three categories according to its AC: 25–30% (high), 20–25% (intermediate), and 10–20% (low). Rice with intermediate AC is preferred in most rice-growing regions worldwide. The results of this study indicated that AC for both varieties fell within the intermediate group and was not affected by Si application.

Furthermore, the average of gel consistency (GC) values obtained supported the findings that rice with intermediate AC typically has a soft to moderate texture when cooked. GC is categorized into three groups based on the distance of the rice gel flows in a test tube after cooking and cooling: 61–100 mm (soft), 41–60 mm (intermediate), and 27–40 mm (hard) [16]. In this study, MR 263 exhibited a higher GC (88.87 mm) compared to MARDI Siraj 297 (81.67 mm). The application of Si tended to lower the GC, suggesting that a higher rate of Si might reduce rice softness. However, all treatments resulted in GC values between 61–100 mm, which was categorized as soft. Generally, rice varieties with high AC tend to have a hard GC, while those with lower AC exhibit a softer GC [44, 45].

Table 8 Effects of Si application rates on cooking and eating quality of milled rice.

Factors	Amylose content (AC)	Gel consistency (GC)	Alkali spreading value (ASV)
Planting cycle (C)			
Cycle 1	$22.11^{b} \pm 0.16$	$84.67^{a} \pm 1.09$	$5.50^{a} \pm 0.28$
Cycle 2	$24.04^{a} \pm 0.14$	$85.87^{a} \pm 1.16$	$5.37^{b} \pm 0.26$
Variety (V)			
MR 263	$22.54^{b} \pm 0.24$	$88.87^{a} \pm 0.87$	$6.87^{a} \pm 0.06$
MARDI Siraj 297	$23.61^{a} \pm 0.19$	$81.67^{b} \pm 0.95$	$4.00^{b} \pm 0.00$
Si rate (T)			
0 (control)	$23.25^{a} \pm 0.40$	$89.25^{a} \pm 1.78$	$5.50^{a} \pm 0.45$
100	$22.99^{a} \pm 0.31$	$83.17^{b} \pm 1.21$	$5.50^{a} \pm 0.45$
200	$23.14^{a} \pm 0.42$	$86.00^{b} \pm 1.41$	$5.33^{a} \pm 0.41$
300	$23.11^{a} \pm 0.36$	$83.67^{b} \pm 1.61$	$5.50^{a} \pm 0.45$
400	$22.88^{a} \pm 0.39$	$84.25^{b} \pm 2.33$	$5.33^{a} \pm 0.41$
C x V	ns	ns	ns
C x T	ns	ns	ns
V x T	ns	ns	ns
C x V x T	ns	ns	ns

Means (± SE, $n = 3$) followed by the same letter within a column and for each factor are not significantly different at $p \leq 0.05$ according to the LSD test. ns = non-significant.

The results also showed that the Si application did not affect the gelatinization temperature (GT) (Table 8). Alkali spreading value (ASV) is used as an inverse indicator of the GT of rice. The ASV could be classified into three categories: low (1–3), intermediate (4–5), or high (6–7). A low ASV corresponds to a high GT; conversely, a high ASV indicates a low GT. Rice kernels with low or intermediate GT need less cooking time, which is widely preferred since this kind of cooked rice is soft. The score indicated that MR 263 is categorized as rice with low GT, while MARDI Siraj 297 has intermediate GT.

Rice grain typically contains around 90% starch, with 6-25% of that starch made up of amylose and the remaining made up of amylopectin. All the starch-related properties like AC, GC and GT affect the CEQ of milled rice; hence, the starch properties have been used to determine the chemical quality of milled rice. The CEQ of rice is an important characteristic to look at since rice is mainly consumed in cooked form. AC strongly influences the texture, stickiness and softness of cooked rice. Cooked rice kernels with a high AC (>25%) are dry, separate, become less tender, and harden upon cooling, whereas those with low (12–20%) are glossy, soft, and sticky. In this present work, the Si application had no significant effect on the AC, GC and GT for both varieties. Although environmental factors highly influence AC, it is primarily controlled by genetics [43]. On the other hand, under stress conditions, the value of grain quality is usually reduced, and Si has been shown to improve the AC of rice exposed to water deficit conditions [46]. However, the mechanism of grain quality improvement needs further elucidation, particularly on the molecular level.

4. Conclusions

The application of Si during planting at the panicle initiation stage positively affects the yield components, rice yield, harvest index and grain quality. Based on our findings, we recommend Si fertilization at 247 kg/ha during the panicle initiation stage for improving rice yield and milling quality. The enhanced rice productivity observed in this study was attributed to the significant increase in soil-available Si following Si application. It also helped reduce chalkiness, as evidenced by less chalky grain after milling. Furthermore, Si application increased head rice yield, reduced broken rice and improved the whiteness of rice grains. This strategy aligns with sustainable intensification goals in rice production systems. However, since the present finding was generated from a pot experiment, it should be further validated under field conditions.

5. Conflict of interest

The authors have no conflict of interest to declare.

6. Acknowledgments

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7. Author contributions

Engku Hasmah, EA.: Conceptualization, Methodology, Data curation, Writing – original draft; Azizah, M.: Conceptualization, Methodology, Project administration, Resources, Funding acquisition, Writing – review & editing, Supervision; Mohd Rafii, Y.: Methodology, Resources, Supervision; Muhammad Nazmin, Y.: Methodology, Resources, Supervision; Asfaliza, R.: Methodology, Resources, Funding acquisition, Writing – review & editing, Supervision.

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