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RESEARCH ARTICLE

# Influence of nitrogen and silicon on the growth and yield of black scented rice cultivar 'Chakhao Poireiton'

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## Abstract

Lodging is a common issue in the black rice cultivar Chakhao Poreiton due to height. So, the interactive effects of nitrogen(N) and silicon on black scented rice cultivars remain inadequately studied. Therefore, a field experiment was conducted during kharif season of 2024 at the School of Agriculture, Lovely Professional University, Jalandhar, to study the influence of N and silicon (Si) on the growthand yield of the black scented rice cultivar 'Chakhao Poireiton'. The experiment was laid out in a split-plot design consisting of four N levels, viz., 75, 100, 125 and 150 % of the recommended dose of nitrogen (RDN) as the main factor and four Si levels, viz., 0, 0.5, 1 and 1.5 % as sub-factors, replicated thrice, resulting in 16 treatment combinations. The results showed that highest N level (150 % RDN) and Si (1.5 % Si) produced the best results individually and in combination where the combined application of 150 % RDN + 1.5 % Si recorded significantly highest in plant height (PH) (174.01 cm), number of tillers (NT) (11.61), dry matter (DM) accumulation (56.77), growth rates, maximum grain yield (GY) (32.22 q $ha^{-1}$), straw yield (SY) (36.21 q $ha^{-1}$) and harvest index (HI) (47.01 %) than other treatments. Quality traits, such as grain protein (13.02 %) and carbohydrate (74.65 %) content were also significantly improved with higher N-Si levels. In comparison, anthocyanin content showed a slight but non-significant increase at 150 % RDN + 1.5 % Si (81.65 mg 100 $g^{-1}$). These findings highlight a synergistic effect, where N enhanced biomass and yield, while Si improved structural strength, stress tolerance and nutrient use efficiency. Thus, the combined application of 150 % RDN and 1.5 % Si proved to be an effective strategy for optimising the growth, yield and quality of black scented rice.

**Keywords:** black scented rice; growth; nitrogen; silicon; treatment; yield

## Introduction

Rice (*Oryza sativa* L.) is a semi-aquatic perennial crop that belongs to the Poaceae family and the species within the genus '*Oryza*' are about 20. As one of the world's main staple foods, it contributes 35–60 % of global caloric intake, providing both substantial carbohydrates and a good source of protein. More than 65 % of the population in every country consumes rice in considerable amounts almost daily, making it one of the top three crops globally in high demand (1–3). With the fast-growing population, rice production needs to be significantly upscaled, as demand is expected to reach 496 million tons (mt) in 2020, 553 mt in 2035 and 623 mt in 2050, compared with 439 mt in 2010 (4, 5).

Black rice, locally known as "Chakhao," is a pigmented variety of *O. sativa* characterised by its deep black color, due to its high anthocyanin content. It is glutinous, rich in protein, vitamins, minerals namely iron (Fe), zinc (Zn), manganese (Mn) and phosphorus (P) and antioxidants and has a nutty, slightly sweet flavor. Black rice is predominantly produced in Asian regions, specifically in India's Manipur state. The widespread recognition of black rice's health and nutritional benefits has led to its growing availability in recent years as public health consciousness continues to intensify. So, access to black rice would help promote good health and achieve health-related goals, such as reducing the risk of heart disease and chronic illnesses (6–8).

Nitrogen (N) is the most essential nutrient for rice crop growth and yield, requiring higher application rates than other elements (9). It plays a pivotal role in helping the rice plant synthesise proteins and chlorophyll. It supports photosynthesis, increases the number of effective tillers, spikelets and promotes biomass accumulation. Nitrogen fertilisers also yield good returns, increasing crop yield and quality (9, 10). Nonetheless, overuse or misuse is harmful to the environment. It can make soil acidic and hard, pollute water and reduce crop photosynthesis capabilities (11). So, applying the appropriate amount of N helps ensure increased N use efficiency (NUE), crop productivity and quality while minimising environmental damage. On the other hand, Si is the second most prevalent element in the Earth's crust. In rice, its uptake is greater than that of any other nutrient except for N, P and potassium (K). Silicon application also enhances leaf firmness and relieves biotic and abiotic stress (e.g., lodging, drought, insect pest infestation, freezing). Fertilisation with Si also exhibits positive effects on rice, as it is highly absorbent of Si. The application of Si therefore, enhances crop growth and yield. In addition, the integrated use of both N and Si in sufficient proportions supports optimal nutrition of rice plants throughout their growth and development (12–15). However, despite recognition of their individual roles, limited research has addressed the combined effects of N and Si on black scented rice, thereby limiting region-specific nutrient management recommendations or strategies to optimise both productivity and nutritional quality. Therefore, the present study was undertaken to assess the impact of N and Si on the growth and yield of the black scented rice cultivar 'Chakhao Poireiton' under the agro-climatic conditions of Punjab.

## Materials and Methods

The field trial was established during kharif season of 2024 at the Agronomy Research Farm of Lovely Professional University, Punjab. Coordinates of the experimental sites were 31. 242˚N and 75. 701˚E. The experimental field had sandy loam soil as its textured base, having a pH value of 8.13 (alkaline), low organic carbon (0.40 %) and available nutrient levels of 219.57 kg N $ha^{-1}$, 19.15 kg P $ha^{-1}$ and 178 kg K $ha^{-1}$. The experiment was laid out in split-plot design consisting four N levels, viz. 75, 100, 125 and 150 % of the recommended dose of nitrogen (RDN) as the main factor and four Si levels, viz., 0 , 0.5 , 1 and 1.5 % as sub-factors and replicated thrice. The details of the experiment consisted of sixteen treatment combination, as follows:

| | | |
|---|---|---|
| T1 | : | 75 % RDN + Control |
| T2 | : | 75 % RDN + 0.5 % Si |
| T3 | : | 75 % RDN + 1 % Si |
| T4 | : | 75 % RDN + 1.5 % Si |
| T5 | : | 100 % RDN + Control |
| T6 | : | 100 % RDN + 0.5 % Si |
| T7 | : | 100 % RDN + 1 % Si |
| T8 | : | 100 % RDN + 1.5 % Si |
| T9 | : | 125 % RDN + Control |
| T10 | : | 125 % RDN + 0.5 % Si |
| T11 | : | 125 % RDN + 1 % Si |
| T12 | : | 125 % RDN + 1.5 % Si |
| T13 | : | 150 % RDN + Control |
| T14 | : | 150 % RDN + 0.5 % Si |
| T15 | : | 150 % RDN + 1 % Si |
| T16 | : | 150 % RDN + 1.5 % Si |

The black rice nursery seedlings (29 days old) were transplanted at a spacing of 20 cm × 15 cm. Fertilisers were applied at the recommended rate of 42 kg N, 12 kg phosphate ($P_2O_5$) and 12 kg potash ($K_2O$) $acre^{-1}$. The entire doses of P and K were applied basally at transplanting, while N was administered in three split doses. Potassium silicate was foliar-sprayed to supply Si at the tillering and panicle initiation stages. During the experiment, growth parameters, including plant height (PH) (cm), number of tillers (NT) $hill^{-1}$ and dry matter (DM) accumulation were recorded at harvest, while crop growth rate (CGR) and relative growth rate (RGR) were measured from 90 days after transplanting (DAT) to harvest. Similarly, yield parameters such as grain yield (GY) (q $ha^{-1}$), straw yield (SY) (q $ha^{-1}$) and harvest index (HI) (%) were also measured to evaluate the effects of the treatments on overall plant growth and productivity. Additionally, quality parameters, including protein, carbohydrate and anthocyanin content were assessed. All these parameters (HI, CGR, RGR) and quality traits were determined using standard formulae.

### Crop growth rate

It is the DM accumulation per unit crop area during a period, expressed in g $m^{-2}$ $day^{-1}$ (16). Plants' dry weight (DW) measurements from 90 DAT to harvest intervals were used to determine CGR.

$$CGR = \frac{W_2 - W_1 \ (g\ m^{-2}\ day^{-1})}{(t_2 - t_1)\ S} \qquad \text{(Eqn. 1)}$$

Where, $W_1$: Dry weight of plant (g) at $t_1$; $W_2$: Dry weight of plant (g) at $t_2$; $t_1$: Initial time; $t_2$: Final time; S: Land area ($m^2$)

### Relative growth rate

It refers to the increment in DW per unit of DM during any defined period for which the measurement is expressed as g $g^{-1}$ $day^{-1}$ (17).

$$RGR = \frac{\log_e W2 - \log_e W1}{t_2 - t_1}\ (g\ g^{-1}\ day^{-1}) \qquad \text{(Eqn. 2)}$$

Where, $W_1$: Dry weight of plant (g) at $t_1$; $W_2$: Final DW of plant (g) at $t_2$; $t_1$: Initial time; $t_2$: Final time

### Harvest index

Harvest index was calculated for each plot by dividing the economic yield (EY) by the biological yield (BY) and expressed as a percentage (18).

$$\text{Harvest index (\%)} = \frac{EY\ (q\ ha^{-1})}{BY\ (q\ ha^{-1})} \times 100 \qquad \text{(Eqn. 3)}$$

### Crude protein content

The required formula used for the estimation of crude protein in rice grain is as follows:

Protein (%) = Total nitrogen (%) × 5.95 (rice conversion factor)

(Eqn. 4)

### Carbohydrate content in rice grain

The evaluation of carbohydrates in grain depends on the determination of moisture (%) by oven drying, fat (%) by the solvent extraction method, ash (%) by incineration and protein (%) by the Kjeldahl method of nitrogen analysis. The initial four values allow the calculation of the total carbohydrate percentage according to the following equation:

Carbohydrates (%) = 100 – [Moisture (%) + Fat (%) + Ash (%) + Protein (%)]

(Eqn. 5)

### Anthocyanin

Anthocyanin content was estimated using ethanol-HCl extraction and the optical density (OD) of the solution measured at 535 nm (19).

$$\text{Total absorbance value for the sample (per 100 mg)} = \frac{e \times b \times c}{d \times a} \times 100 \qquad \text{(Eqn. 6)}$$

$$\text{Total anthocyanin content (mg 100 g}^{-1}) = \frac{\text{Total absorbance for the sample}}{98.2} \qquad \text{(Eqn. 7)}$$

Where, a: Weight of sample; b: Volume made for colour measurement; c: Total volume made; d: Volume of aliquot taken for estimation; e: Specific OD value at 535 nm wavelength.

All collected data were tabulated and analysed using Fisher's analysis of variance (ANOVA) (20). The critical difference (CD) values at the 5 % significance level were provided wherever the *F*-test was significant. Data analysis and figures were prepared using Microsoft Excel.

## Results

### Influence of different nitrogen and silicon levels on black rice growth attributes

The application of different nitrogen (RDN) and Si levels significantly affected the rice growth attributes, including PH (cm), NT hill$^{-1}$, DM production (g hill$^{-1}$), CGR (g m$^{-2}$ day$^{-1}$), RGR (g g$^{-1}$ day$^{-1}$) at 90 DAT and at harvest (Table 1 and 2). Application of 150 % RDN produced significantly higher PH (165.90 cm), NT hill$^{-1}$ (11 no.), plant DW (53.43 g hill$^{-1}$), CGR (5.72 g m-$^{2}$ day$^{-1}$) and RGR (0.044 g g$^{-1}$ day$^{-1}$), while the lowest was obtained with 75 % RDN. Regarding Si, significantly higher PH (158.74 cm) and the NT hill$^{-1}$ (10.29) were recorded with the application of 1.5 % Si compared to 0.5 % , but were at par with 1.0 % Si. The lowest values for PH (151.69 cm) and NT hill$^{-1}$ (9.71) were observed from control. The plant DW (48.28 g hill$^{-1}$), CGR (5.21 g m$^{-2}$ day$^{-1}$) and RGR (0.042 g g$^{-1}$ day$^{-1}$) were significantly higher with the application of 1.5 % Si than with other treatments. The interaction between 150 % RDN + 1.5 % Si was found to be significantly higher in PH (174.01 cm), plant DW (56.77 g hill$^{-1}$), CGR (6.38 g m$^{-2}$ day$^{-1}$) and RGR (0.046 g g$^{-1}$ day$^{-1}$) than the other combinations. Conversely, the treatment combination 75 % RDN + 0 % Si recorded the lowest PH (139.23 cm), NT hill$^{-1}$ (9.16), plant DW (38.03 g hill$^{-1}$), CGR (3.81 g m$^{-2}$ day$^{-1}$) and RGR (0.035 g g$^{-1}$ day$^{-1}$) respectively.

### Influence of different nitrogen and silicon levels on black rice yield attributes

Yield attributes showed a significant response to varying levels of N and Si application (Table 1 and 2). For the main effects of N, 150 % RDN recorded the highest GY (28.62 q ha$^{-1}$), SY (36.18 q ha$^{-1}$) and HI (44.04 %). The treatment 150 % RDN was statistically on par with the 125 % RDN for GY (22.94 q ha$^{-1}$), SY (35.63 q ha$^{-1}$) and HI (39.16 %), followed by 100 % RDN and 75 % RDN for all three yield parameters, while 75 % RDN resulted in the lowest value of GY (16.14 q ha$^{-1}$), SY (31.98 q ha$^{-1}$) and HI (33.45 %). For Si, 1.5 % Si gave the highest GY (23.46 q ha$^{-1}$), but was on par with 1 % Si (22.48 q ha$^{-1}$). The higher SY (35.09 q ha$^{-1}$) was also observed under the 1.5 % Si treatment, which was comparable to both the 1 % Si (34.86 q ha$^{-1}$) and 0.5 % Si (34.65 q ha$^{-1}$). Harvest index, which was highest at 1.5 % Si (39.45 %) was on par with 1 % Si (38.80 %), followed by 0.5 % Si (38.36 %), whereas control (0 % Si) recorded the lowest GY (19.20 q ha$^{-1}$), SY (33.56 q ha$^{-1}$) and HI (36.06 %). The interaction effect of the treatment combination 150 % RDN + 1.5 % Si produced the highest SY (36.21 q ha$^{-1}$), surpassing all other treatment combinations. Furthermore, 150 % RDN + 1.5 % Si produced higher GY (32.22 q ha$^{-1}$) and HI (47.01 %) and was statistically on par with 150 % RDN + 1 % Si. In contrast, the lowest GY (14.25 q ha$^{-1}$), SY (29.07 q ha$^{-1}$) and HI (32.85 %) were recorded at 75 % RDN + 0 % Si, respectively.

### Influence of different nitrogen and silicon levels on black rice quality parameters

Protein and carbohydrate contents are significantly enhanced with increases at each level of RDN and Si, both individually and interactively, as shown in Table 3 and 4. The highest protein content (11.94 %) was recorded at 150 % RDN, while the lowest (9.47 %) was recorded at 75 % RDN. Similarly, highest carbohydrates content at 150 % RDN (73.18 %) was statistically on par with 125 % RDN (72.45 %), followed by 100 % RDN (71.46 %), while 75 % RDN (70.72 %) recorded the lowest carbohydrate content. Among the different Si levels, 1.5 % Si produced the highest protein (11.20 %) and carbohydrate (72.54 %) levels, while the control (0 % Si) had the lowest protein (10.27 %) and carbohydrate (71.62 %) levels. Furthermore, the interaction effect between N levels (RDN) and Si levels was significant, where 150 % RDN + 1.5 % Si recorded the highest protein (13.02 %) and carbohydrate (74.65 %) content, while the lowest protein (9.16 %) and carbohydrate (70.60 %) content was recorded in 75 % RDN + 0 % Si. Although, anthocyanin content (mg 100 g$^{-1}$) was not statistically affected by N, Si or their interaction, the highest anthocyanin was recorded at 150 % RDN

**Table 1.** Influence of different nitrogen and silicon levels on black rice growth and yield attributes

| Treatments | Growth attributes | | | | | Yield attributes | | |
|---|---|---|---|---|---|---|---|---|
| | PH (cm) | NT hill$^{-1}$ | PDW (g hill$^{-1}$) | CGR (g m$^{-2}$ day$^{-1}$) | RGR (g g$^{-1}$ day$^{-1}$) | GY (q ha$^{-1}$) | SY (q ha$^{-1}$) | HI (% ) |
| **Nitrogen** | | | | | | | | |
| $N_1$: 75 % RDN | 146.21 | 9.36 | 39.76 | 4.04 | 0.0370 | 16.14 | 31.98 | 33.45 |
| $N_2$:100 % RDN | 152.41 | 9.67 | 43.85 | 4.75 | 0.0404 | 19.38 | 34.37 | 36.02 |
| $N_3$:125 % RDN | 156.52 | 10.07 | 47.83 | 5.18 | 0.0423 | 22.94 | 35.63 | 39.16 |
| $N_4$:150 % RDN | 165.9 | 11.00 | 53.43 | 5.72 | 0.0443 | 28.62 | 36.18 | 44.04 |
| SEd (±) | 2.7 | 0.14 | 0.49 | 0.17 | 0.0007 | 7.56 | 2.64 | 6.45 |
| C.D ($p$=0.05) | 6.62 | 0.35 | 1.21 | 0.42 | 0.0016 | 18.49 | 6.47 | 15.78 |
| **Silicon** | | | | | | | | |
| $S_1$: Control (0 % Si) | 151.69 | 9.71 | 44.30 | 4.72 | 0.0401 | 19.20 | 33.56 | 36.06 |
| $S_2$: 0.5 % Si | 154.29 | 9.89 | 45.45 | 4.80 | 0.0405 | 21.93 | 34.65 | 38.36 |
| $S_3$: 1 % Si | 156.32 | 10.20 | 46.85 | 4.97 | 0.0413 | 22.48 | 34.86 | 38.80 |
| $S_4$: 1.5 % Si | 158.74 | 10.29 | 48.28 | 5.21 | 0.0422 | 23.46 | 35.09 | 39.45 |
| SEd (±) | 1.35 | 0.13 | 0.26 | 0.06 | 0.0002 | 0.73 | 0.62 | 0.74 |
| CD ($p$ = 0.05) | 2.8 | 0.26 | 0.54 | 0.11 | 0.0005 | 1.51 | 1.29 | 1.53 |
| **Interaction (N×S)** | | | | | | | | |
| SEd (±) | 2.71 | 0.25 | 0.53 | 0.11 | 0.0005 | 1.46 | 1.25 | 1.48 |
| CD ($p$ = 0.05) | 5.59 | 0.52 | 1.09 | 0.23 | 0.0010 | 3.02 | 2.58 | 3.05 |

PH: Plant height; NT: Number of tillers per hill; PDW: Plant dry weight; CGR: Crop growth rate; RGR: Relative growth rate; GY: Grain yield; SY: Straw yield; HI: Harvest index; CD: Critical difference; RDN: Recommended dose of nitrogen; Si: Silicon.

**Table 2**. Interaction effect of different nitrogen and silicon levels on black rice growth and yield attributes

| Treatments | | Growth attributes | | | | | Yield attributes | | |
|---|---|---|---|---|---|---|---|---|---|
| | | PH (cm) | NT hill$^{-1}$ | PDW (g hill$^{-1}$) | CGR (g m$^{-2}$ day$^{-1}$) | RGR (g g$^{-1}$ day$^{-1}$) | GY (q ha$^{-1}$) | SY (q ha$^{-1}$) | HI (%) |
| $N_1$: 75 % RDN | $S_1$: Control (0 % Si) | 139.23 | 9.16 | 38.03 | 3.81 | 0.0358 | 14.25 | 29.07 | 32.85 |
| | $S_2$: 0.5 % Si | 146.58 | 9.30 | 38.97 | 3.87 | 0.0361 | 16.23 | 32.50 | 33.28 |
| | $S_3$: 1 % Si | 148.81 | 9.43 | 40.66 | 4.19 | 0.0378 | 16.96 | 33.13 | 33.85 |
| | $S_4$: 1.5 % Si | 150.24 | 9.53 | 41.40 | 4.30 | 0.0383 | 17.12 | 33.20 | 33.81 |
| $N_2$: 100 % RDN | $S_1$: Control (0 % Si) | 151.73 | 9.57 | 42.57 | 4.61 | 0.0398 | 17.55 | 33.90 | 34.06 |
| | $S_2$: 0.5 % Si | 152.29 | 9.62 | 43.31 | 4.74 | 0.0404 | 19.86 | 34.30 | 36.63 |
| | $S_3$: 1 % Si | 152.34 | 9.68 | 44.19 | 4.79 | 0.0406 | 19.90 | 34.45 | 36.66 |
| | $S_4$: 1.5 % Si | 153.26 | 9.81 | 45.32 | 4.87 | 0.0410 | 20.22 | 34.83 | 36.74 |
| $N_3$: 125 % RDN | $S_1$: Control (0 % Si) | 155.35 | 9.88 | 46.08 | 5.04 | 0.0417 | 20.63 | 35.10 | 37.06 |
| | $S_2$: 0.5 % Si | 156.32 | 10.03 | 47.13 | 5.14 | 0.0422 | 23.42 | 35.63 | 39.66 |
| | $S_3$: 1 % Si | 156.98 | 10.16 | 48.51 | 5.23 | 0.0425 | 23.44 | 35.67 | 39.70 |
| | $S_4$: 1.5 % Si | 157.44 | 10.20 | 49.62 | 5.30 | 0.0428 | 24.27 | 36.10 | 40.22 |
| $N_4$: 150 % RDN | $S_1$: Control (0 % Si) | 160.46 | 10.25 | 50.51 | 5.41 | 0.0432 | 24.37 | 36.17 | 40.27 |
| | $S_2$: 0.5 % Si | 161.99 | 10.63 | 52.40 | 5.43 | 0.0433 | 28.23 | 36.18 | 43.87 |
| | $S_3$: 1 % Si | 167.16 | 11.51 | 54.06 | 5.66 | 0.0441 | 29.64 | 36.19 | 45.01 |
| | $S_4$: 1.5 % Si | 174.01 | 11.61 | 56.77 | 6.38 | 0.0465 | 32.22 | 36.21 | 47.01 |
| S at the same level of N | SE d (±) | 2.71 | 0.25 | 0.53 | 0.11 | 0.0005 | 0.85 | 0.62 | 0.95 |
| | CD ($p$ = 0.05) | 5.59 | 0.52 | 1.09 | 0.23 | 0.0010 | 1.76 | 1.28 | 1.96 |
| N at the same or different levels of S | SE d (±) | 3.58 | 0.26 | 0.67 | 0.20 | 0.0008 | 1.26 | 0.89 | 1.49 |
| | CD ($p$ = 0.05) | 7.39 | 0.54 | 1.39 | 0.41 | 0.0016 | 2.60 | 1.84 | 3.07 |

PH: Plant height; NT: Number of tillers per hill; PDW: Plant dry weight; CGR: Crop growth rate; RGR: Relative growth rate; GY: Grain yield; SY: Straw yield; HI: Harvest index; CD: Critical difference; RDN: Recommended dose of nitrogen; Si: Silicon.

**Table 3.** Influence of different nitrogen and silicon levels on black rice quality parameters

| Treatments | Quality parameters | | |
|---|---|---|---|
| | Protein (%) | Carbohydrates (%) | Anthocyanin (mg 100 g$^{-1}$) |
| Nitrogen | | | |
| $N_1$: 75 % RDN | 9.47 | 70.72 | 74.60 |
| $N_2$:100 % RDN | 10.27 | 71.46 | 77.85 |
| $N_3$:125 % RDN | 10.98 | 72.45 | 79.53 |
| $N_4$:150 % RDN | 11.94 | 73.18 | 81.13 |
| SE d (±) | 0.29 | 0.33 | 1.83 |
| CD ($p$ = 0.05) | 0.70 | 0.81 | NS |
| Silicon (Si) | | | |
| $S_1$: Control (0 % Si) | 10.27 | 71.62 | 77.01 |
| $S_2$: 0.5 % Si | 10.46 | 71.68 | 78.15 |
| $S_3$: 1 % Si | 10.73 | 71.98 | 78.86 |
| $S_4$: 1.5 % Si | 11.20 | 72.54 | 79.09 |
| SEd (±) | 0.13 | 0.22 | 0.77 |
| CD ($p$ = 0.05) | 0.27 | 0.45 | NS |
| Interaction (N×S) | | | |
| SEd (±) | 0.27 | 0.43 | 1.54 |
| CD ($p$ = 0.05) | 0.55 | 0.89 | NS |

**Table 4.** Interaction effect of different nitrogen and silicon levels on black rice quality parameters

| Treatments | | Quality parameters | |
|---|---|---|---|
| | | Protein (%) | Carbohydrates (%) |
| $N_1$: 75 % RDN | $S_1$: Control (0 % Si) | 9.16 | 70.60 |
| | $S_2$: 0.5 % Si | 9.32 | 70.62 |
| | $S_3$: 1 % Si | 9.38 | 70.79 |
| | $S_4$: 1.5 % Si | 10.01 | 70.88 |
| $N_2$: 100 % RDN | $S_1$: Control (0 % Si) | 10.08 | 70.90 |
| | $S_2$: 0.5 % Si | 10.10 | 70.98 |
| | $S_3$: 1 % Si | 10.45 | 71.88 |
| | $S_4$: 1.5 % Si | 10.48 | 72.08 |
| $N_3$: 125 % RDN | $S_1$: Control (0 % Si) | 10.50 | 72.39 |
| | $S_2$: 0.5 % Si | 11.01 | 72.40 |
| | $S_3$: 1 % Si | 11.12 | 72.47 |
| | $S_4$: 1.5 % Si | 11.30 | 72.54 |
| $N_4$: 150 % RDN | $S_1$: Control (0 % Si) | 11.33 | 72.58 |
| | $S_2$: 0.5 % Si | 11.42 | 72.71 |
| | $S_3$: 1 % Si | 11.97 | 72.77 |
| | $S_4$: 1.5 % Si | 13.02 | 74.65 |
| S at the same level of N | SEd (±) | 0.27 | 0.43 |
| | CD ($p$ = 0.05) | 0.55 | 0.89 |
| N at the same or different levels of S | SEd (±) | 0.37 | 0.50 |
| | CD ($p$ = 0.05) | 0.76 | 1.03 |

(81.13 mg 100 $g^{-1}$) and 1.5 % Si (79.09 mg 100 $g^{-1}$), while the lowest at 75 % RDN (74.60 mg 100$g^{-1}$) and (77.01 mg 100 $g^{-1}$) under the control (0 % Si), respectively.

## Discussion

### Influence of different nitrogen and silicon levels on black rice growth attributes

The applied N levels had a significant influence on all growth attributes, including PH (cm), NT $hill^{-1}$, DW, CGR and RGR. Nitrogen, a key component of protoplasm and chlorophyll, stimulates cell division and elongation, enhances nutrient absorption and promotes rapid expansion of foliage and overall plant development, collectively leading to greater biomass accumulation (8, 21–23). Similarly, other studies reported that Si application enhanced the structural integrity of the plant, thereby promoting more erect leaves, increasing light interception and photosynthetic capacity, which, in turn, boost DM accumulation, tiller production and growth rates (24–28). Conversely, the combined application indicates a synergistic effect in which N enhances vegetative growth and biomass production, while Si provides a structural framework to optimise light capture and photosynthesis. Together, they also promote greater leaf area expansion, photosynthetic efficiency and increased resource allocation, thereby resulting in an increase in all growth attributes when both nutrients were supplied adequately. Thus, these results align with the findings of the previous studies (21, 29, 30).

### Influence of different nitrogen and silicon levels on black rice yield attributes

Nitrogen application significantly influenced the GY by enhancing the nutrient uptake, vegetative growth and the translocation of photosynthates from leaves to the grain (8, 31, 32). The use of Si further boosted yields by improving leaf erectness and reducing shading and lodging risk. It mitigates biotic and abiotic stresses, such as insect pest infestation and mineral toxicity and contributes to higher biomass and grain production (33–35). The combination of both N and Si resulted increase in GY, SY and HI, thereby enhancing photosynthesis, panicle formation, spikelet filling and overall biomass accumulation. A synergistic effect was also observed, leading to a more efficient conversion of overall growth into economic yield and an improved HI without compromising grain quality. These findings are consistent with previous studies (36–38).

### Influence of different nitrogen and silicon levels on black rice quality parameters

The nutritional quality of the rice grains was enhanced by the combined application of N and Si, where an increase in protein content was due to N's role in amino acid synthesis. This quality trait is also co-determined by crop variety, environmental conditions and overall crop management factors (39–41). On the other hand, Si slightly increased grain protein by enabling more efficient N translocation from leaves to the grain and by reducing amylose content, thereby facilitating better protein deposition (27, 42, 43). Similarly, both nutrients positively affected carbohydrate metabolism, where N boosted starch content by enhancing photosynthesis and carbon allocation. At the same time, Si promoted sugar phosphorylation, strengthened the cell wall and increased overall carbohydrate synthesis (44–47). Conversely, N application was negatively correlated with grain anthocyanin levels, as it tends to induce anthocyanin production more in vegetative tissues, such as shoots, than in seeds. Neither Si nor its interaction with N had a significant effect on grain anthocyanin content, due to strong genetic regulation in black rice pericarp, which limits its responsiveness to fertiliser inputs. These results align with previous findings of previous studies (48–51).

## Conclusion

The results of this research revealed that the strategic application of both N and Si had a positive impact on the productivity, nutrient efficiency and stress resilience of black rice. Among all the treatments, 150 % (RDN) + 1.5 % (Si) significantly enhanced growth parameters and yield components and improved grain quality, with increased protein and carbohydrate content. Thus, this integrated nutrient management, incorporating optimised doses of N and Si, offers a viable strategy for expanding the cultivation of the high-value black-scented rice cultivar ‘Chakhao Poireiton’ to meet food security needs beyond Manipur's regions in diverse agricultural landscapes.

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## Authors' contributions

SA conceptualised the study, conducted the field research and data collection, performed the data analysis and prepared the manuscript. KB assisted in conceptualising the study, designed the research framework, verified and analysed the data and contributed to revising the manuscript. B drafted sections of the manuscript and contributed to writing the initial version of the paper. SHR reviewed and edited the manuscript and provided critical input to finalise the paper. All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflicts of interest to declare.

**Ethical issues:** None

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