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SILICON FERTILIZATION AND ITS IMPACTS ON PHOTOSYNTHESIS AND PRODUCTIVITY OF RICE CULTIVARS

A FERTILIZAÇÃO COM SILÍCIO E SEUS IMPACTOS NA FOTOSSÍNTESE E NA PRODUTIVIDADE DE CULTIVARES DE ARROZ

LA FERTILIZACIÓN CON SILICIO Y SUS EFECTOS SOBRE LA FOTOSÍNTESIS Y LA PRODUCTIVIDAD DE LOS CULTIVARES DE ARROZ

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ABSTRACT

Oryza sativa (rice) is one of the most important crops in the global agricultural sector. For rice cultivars, the mineral element silicon (Si) has been the focus of investigation due to its positive impacts on physiological, molecular, and productivity aspects. In this sense, the objective of this study was to verify the potential of Si on the productivity of rice cultivars with different morphophysiological characteristics. The methodology used consisted of evaluating three rice cultivars: IRGA-409, IRGA-423, and EPAGRI-109, which were subjected to fertilization with or without silicon, at a concentration of 2 mM, in the form of silicon dioxide (SiO_2), under rainfed cultivation conditions. Leaf gas exchange, chlorophyll a fluorescence, growth, and productivity were evaluated. Si impacted panicle emergence uniformity and grain maturation in the rice cultivars. For the dry mass of vegetative organs (leaves, roots, and stems), no statistical differences were observed between plants with and without Si in the different cultivars. However, in terms of productivity, an increase in the number and biomass of filled grains was observed in the different cultivars treated with Si, these aspects being associated with an increase in the photosynthetic rate, without, however, altering the chlorophyll a fluorescence parameters. Thus, the use of Si in rice cultivars favors increased productivity and may constitute a viable alternative for field application.

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Keywords: Carbon Balance. *Oryza sativa*. Production. Silicate Fertilization.

RESUMO

Oryza sativa (arroz) é uma das culturas mais importantes no setor agrícola global. Para cultivares de arroz, o elemento mineral silício (Si) tem sido foco de pesquisa devido aos seus impactos positivos em aspectos fisiológicos, moleculares e de produtividade. Nesse sentido, o objetivo deste estudo foi verificar o potencial do Si na produtividade de cultivares de arroz com diferentes características morfofisiológicas. A metodologia utilizada consistiu na avaliação de três cultivares de arroz: IRGA-409, IRGA-423 e EPAGRI-109, que foram submetidas à fertilização com ou sem silício, na concentração de 2 mM, na forma de dióxido de silício (SiO_2), em condições de cultivo de sequeiro. Foram avaliadas as trocas gasosas foliares, a fluorescência da clorofila a o crescimento e a produtividade. O Si impactou a uniformidade de emergência da panícula e a maturação dos grãos nas cultivares de arroz. Para a massa seca dos órgãos vegetativos (folhas, raízes e caules), não foram observadas diferenças estatísticas entre as plantas com e sem Si nas diferentes cultivares. Contudo, em termos de produtividade, observou-se um aumento no número e na biomassa de grãos cheios nas diferentes cultivares tratadas com Si, sendo esses aspectos associados a um aumento na taxa fotossintética, sem, porém, alterar os parâmetros de fluorescência da clorofila a. Assim, o uso de Si em cultivares de arroz favorece o aumento da produtividade e pode constituir uma alternativa viável para aplicações em campo.

Palavras-chave: Balanço de Carbono. *Oryza sativa*. Produção. Adubação com Silicato.

RESUMEN

Oryza sativa (arroz) es uno de los cultivos más importantes del sector agrícola mundial. En los cultivares de arroz, el elemento mineral silicio (Si) ha sido objeto de investigación debido a sus efectos positivos en aspectos fisiológicos, moleculares y de productividad. En este sentido, el objetivo de este estudio fue verificar el potencial del Si en la productividad de cultivares de arroz con diferentes características morfofisiológicas. La metodología empleada consistió en evaluar tres cultivares de arroz: IRGA-409, IRGA-423 y EPAGRI-109, los cuales fueron sometidos a fertilización con o sin silicio, a una concentración de 2 mM, en forma de dióxido de silicio (SiO_2), bajo condiciones de cultivo de secano. Se evaluaron el intercambio gaseoso foliar, la fluorescencia de la clorofila a, el crecimiento y la productividad. El Si influyó en la uniformidad de la emergencia de la panícula y la maduración del grano en los cultivares de arroz. En cuanto a la masa seca de los órganos vegetativos (hojas, raíces y tallos), no se observaron diferencias estadísticamente significativas entre las plantas con y sin Si en los diferentes cultivares. Sin embargo, en términos de productividad, se observó un incremento en el número y la biomasa de granos llenos en los diferentes cultivares tratados con Si. Estos aspectos se asociaron con un aumento en la tasa fotosintética, sin alterar, no obstante, los parámetros de fluorescencia de la clorofila a. Por lo tanto, el uso de Si en cultivares de arroz favorece una mayor productividad y puede constituir una alternativa viable para su aplicación en campo.

Palabras clave: Balance de Carbono. *Oryza sativa*. Producción. Fertilización con Silicatos.

1 INTRODUCTION

Rice (*Oryza sativa*) is the second most consumed food crop worldwide, serving as a major source of energy due to its high carbohydrate content, mainly starch (~75–80% of the grain), and because it contains vitamins and minerals such as iron, zinc, and potassium (Majumder et al., 2019; Zafar and Jianlong, 2023; Zhao et al., 2025). In addition, rice is an extremely versatile agricultural crop that adapts to different soil and climatic conditions, thus presenting high potential to combat world hunger, which has led to important initiatives such as “Golden Rice” (Nadir et al., 2017; Arvas et al., 2025). Furthermore, because it is an important agricultural species and a silicon (Si) accumulating plant, numerous studies have sought to understand the effects of this mineral element on physiology, metabolism, and productivity under biotic and abiotic stress conditions (Verma et al., 2021).

With a relative abundance of 27.70% in the lithosphere and 0.03% in the biosphere, silicon (Si) is considered the second most abundant element in the Earth’s crust (Exley, 1998). In plants, it is present in the tissues of all organs; however, its content varies according to the species, ranging from 0.1 to 10% of dry biomass (Ma and Takahashi, 2002; Guerreiro et al., 2016). The highest absorption rates and contents have been observed in the Poales and Cyperales groups, with particular emphasis in the Poales group on sugarcane (Saccharum officinarum), rice (O. sativa), and wheat (Triticum spp.) (Guerreiro et al., 2016).

In O. sativa cultivars, the benefits generated by the high absorption and incorporation of Si into leaves and stems are evidenced by increased resistance to pathogen attack (Rodrigues et al., 2004; Ahmad et al., 2023), as well as increases in grain yield and nitrogen use efficiency (Detmann et al., 2012; Jiang et al., 2024). In addition, several studies have reported the mitigating effects of Si on different abiotic stress factors such as salinity (Alam et al., 2025), drought (Du et al., 2026), and toxic metals (Khan et al., 2018; Hosain et al., 2026). Regarding productivity, the positive effects observed in different genotypes, both under stress conditions (Dos Santos, 2019) and under optimal cultivation conditions (Detmann et al., 2012; Lavinsky et al., 2016), were associated with increased photosynthetic rate (A), coupled with increases in stomatal conductance (gs) and mesophyll conductance (gm), which favor the biochemical capacity for CO2 fixation. Associated with these photosynthetic modifications, the positive regulation of

Lsi6 gene expression, as verified by the authors, promoted higher Si content in developing panicles, suggesting that Si levels in panicles play an important role in increasing grain production and grain filling through mechanisms that remain unknown (Detmann et al., 2012; Lavinsky et al., 2016). These changes promoted higher Si content in developing panicles, suggesting that Si levels in panicles play an important role in increasing grain production and grain filling through mechanisms that are still unknown. Thus, although the effects of Si are satisfactory in physiological and productivity terms for these genotypes, there is still no substantial evidence as to whether national cultivars, which exhibit distinct morphophysiological characteristics (e.g., plant height, number of tillers, leaves, and filled grains), may respond positively to Si application.

In Brazil, the Southern region is responsible for approximately 88.2% of total rice production (Embrapa Rice and Beans, 2017), and there are numerous flooded-rice cultivars with excellent harvest indices developed by the Rio Grande do Sul Rice Institute (IRGA) and the Agricultural Research and Rural Extension Company of Santa Catarina (EPAGRI). However, no studies have investigated whether these indices can be enhanced through Si application. In general, Si nutrition has emerged as a promising alternative for rice management in terms of protection against environmental stress, as well as productivity enhancement. Overall, it remains unclear whether cultivars developed by Brazilian institutions such as EPAGRI and IRGA are responsive to silicon under non-stress conditions. In light of the above, it is hypothesized that silicon fertilization enhances the productivity of rice cultivars by increasing the number of panicles and grains per panicle. Therefore, the present study aimed to address the following questions: (i) can Si fertilization increase productivity regardless of the cultivar? and (ii) would the impact of Si on productivity be evidenced by increases in photosynthetic rate and biomass accumulation?

2 METHODOLOGY

2.1 CULTIVATION CONDITIONS, SEED ACQUISITION, AND TREATMENT APPLICATION

The experiment was conducted at State University of Santa Cruz, located in Ilhéus (39°13'59'' W; 14°45'15'' S). Seeds were obtained from the Rio Grande do Sul Rice Institute and the Santa Catarina Agricultural Research and Rural Extension Company, using the following cultivars: IRGA-409, IRGA-423, and EPAGRI-109. The seeds were sterilized by immersion in a 0.5% sodium hypochlorite solution for 10 min and subsequently rinsed with distilled water. Following germination and seedling emergence, 42 seedlings were transferred to 3-L pots containing previously analyzed soil under rainfed conditions, totaling 14 plants per cultivar.

Plants were fertilized from the end of the Vn phenological stage (completion of flag leaf formation) to the beginning of the R0 stage, corresponding to panicle initiation (EMBRAPA, 2000). Treatments consisted of seven plants supplied with silicon (+Si) and seven plants without silicon (−Si), totaling 14 plants per cultivar. Silicon was applied at a concentration of 2 mM in the form of silicon dioxide (SiO_2), obtained by diluting 98% SiO_2 in water. Silicon was applied via foliar spraying using a manual sprayer, with 1.282 g of SiO_2 diluted in 10 L of water, until grain maturation.

2.2 LEAF GAS EXCHANGE AND CHLOROPHYLL A FLUORESCENCE

Net photosynthetic rate (A) and leaf transpiration rate (E) were measured using a portable photosynthesis system, model LI-6400 (Li-Cor, USA), equipped with a 6400-02B RedBlue artificial light source programmed to provide 1000 μmol photons m^{-2} s^{-1}, at a temperature of 28°C, relative humidity between 60 and 65%, and ambient CO_2 concentration (± 400 ppm). Intercellular CO_2 concentration (Ci) and stomatal conductance to water vapor (gs) were calculated by the instrument based on A and E values (Von Caemmerer and Farquhar, 1981). Measurements were performed between 08:00 and 12:00 h on one flag leaf per plant. From the values of A, gs, E, and Ci, the instantaneous carboxylation efficiency (A/Ci) was calculated.

The photochemical efficiency of photosystem II (ϕPSII) was measured using a portable fluorometer, Pocket PEA (Hansatech Instruments, UK). A clip was attached to the leaf to maintain it in darkness for 20 min, ensuring complete oxidation of the photosynthetic electron transport system. After this period, the leaves were exposed to a saturating light pulse (3500 μmol photons m^{-2} s^{-1}, wavelength of 650 nm, for 1 s), and fluorescence emission signals were recorded using the Pocket PEA data acquisition system and specific software. Among the obtained parameters, the maximum quantum yield of photosystem II (Fv/Fm) and the performance index (PIabs) were selected (Strasser and Strasser, 1995).

2.3 BIOMASS AND YIELD ANALYSIS

Leaf area was determined using an electronic leaf area meter LI-3100 (Li-Cor Inc., Lincoln, Nebraska, USA). Biomass analyses were performed at the end of the experiment, including plant height measurement, counting the number of tillers and flag leaves, total tillers and total panicles per plant, and leaf area (LA) determination. Stem, leaf, and root tissues were separated, placed in paper bags, and dried in an oven at 60°C. Based on dry mass data (stem dry mass [SDM], leaf dry mass [LDM], and root dry mass [RDM]) and leaf area (LA), the following ratios were calculated: root mass ratio (RMR = RDM/TDM), stem mass ratio (SMR = SDM/TDM), and leaf mass ratio (LMR = LDM/TDM).

In addition to the analyzed variables, yield parameters were assessed through grain counting and weighing, including: 1000-grain weight (filled grains), percentage of filled grains, harvest index, and number of grains per plant (filled and empty).

2.4 STATISTICAL ANALYSIS

The experiment was conducted in a completely randomized design arranged in a 2 × 3 factorial scheme, consisting of two silicon concentrations (0 and 2 mM) and three rice cultivars, with two replicates per treatment, totaling 42 plants distributed across seven replicates. Prior to analysis, assumptions of error normality (Shapiro–Wilk test) and homogeneity of variances (Levene's test) were verified. Data meeting these assumptions were subjected to analysis of variance (ANOVA), and means were compared using Tukey's test at a 5% probability level. All statistical analyses were performed using the R statistical software.

3 RESULTS

The silicon content, leaf gas exchange, biomass accumulation, and yield differed significantly among the three cultivars, whereas Si effects were observed only for some photosynthesis, growth, and yield variables (Table 1). Silicon (Si) application significantly affected leaf gas exchange (A and gs), the photochemical performance index (PIABS), the number of filled grains, and the number of unfilled grains per plant (Table 1). In general, the absence of a statistically significant interaction (C × Si) indicated that the response to Si fertilization occurred independently of the cultivar (C), acting through photosynthetic adjustments that affect yield in terms of grain formation and grain filling (Table 1).

Table 1

Results of the ANOVA (ns = not significant; $P < 0.05$; $P < 0.01$; $P < 0.001$) for the effects of silicon (Si), cultivar (Ct), and their interaction

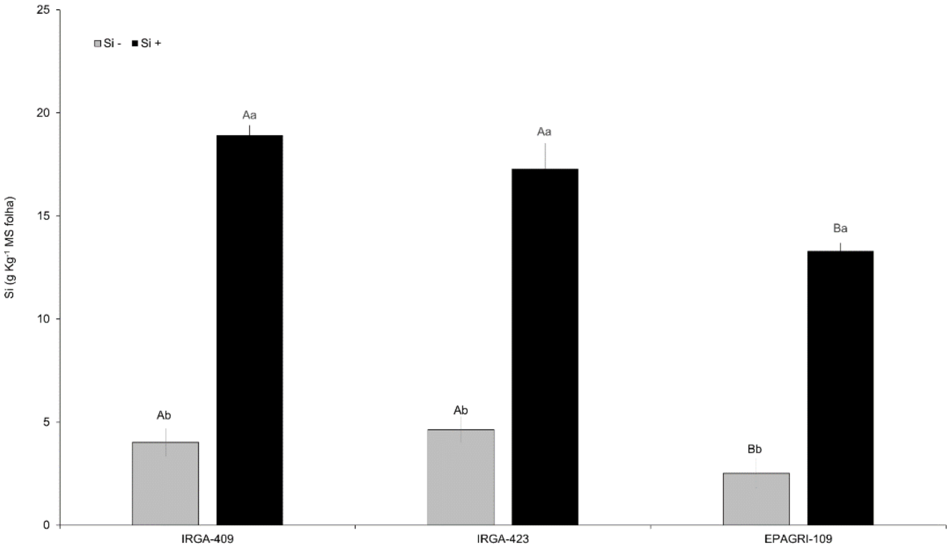
Variables	**C**	**Si**	**C x Si**
Si	**	**	*
A	ns	**	ns

gs	*	**	ns
E	***	ns	ns
Ci	***	ns	ns
Fv/Fm	ns	ns	ns
PIABS	***	*	ns
Height (cm)	***	ns	ns
Number of Flag Sheets	*	ns	ns
Profile Number	***	ns	ns
Number of Panicles	**	ns	ns
AF (m^2)	***	ns	ns
Leaf biomass (g)	***	ns	ns
Culm biomass (g)	ns	ns	ns
Root biomass (g)	***	ns	ns
Total biomass (g)	***	ns	ns
Grain biomass (g)	***	ns	ns
1000 grains weight (g)	***	ns	ns
Grains number of full plant^{-1}	***	*	ns
Grains number of empty plant^{-1}	***	***	ns
Grains number plant^{-1}	ns	ns	ns
Number of grains Panicle^{-1}	***	ns	ns

Silicon (Si) application promoted an increase in silicon content in the leaves of all cultivars compared with the −Si plants, with the highest values observed for IRGA-409 and IRGA-423. The IRGA cultivars exhibited mean silicon contents 1.4-fold higher than those of the EPAGRI cultivars.

Figure 1

Leaf Si content in the cultivars IRGA-409, IRGA-423, and EPAGRI-109 with silicon supplementation (Si+) and without silicon supplementation (Si−). Bars represent the mean ± standard error. Uppercase letters compare cultivars within the same treatment, and lowercase letters compare treatments within each cultivar, according to Tukey's test (p ≤ 0.05)

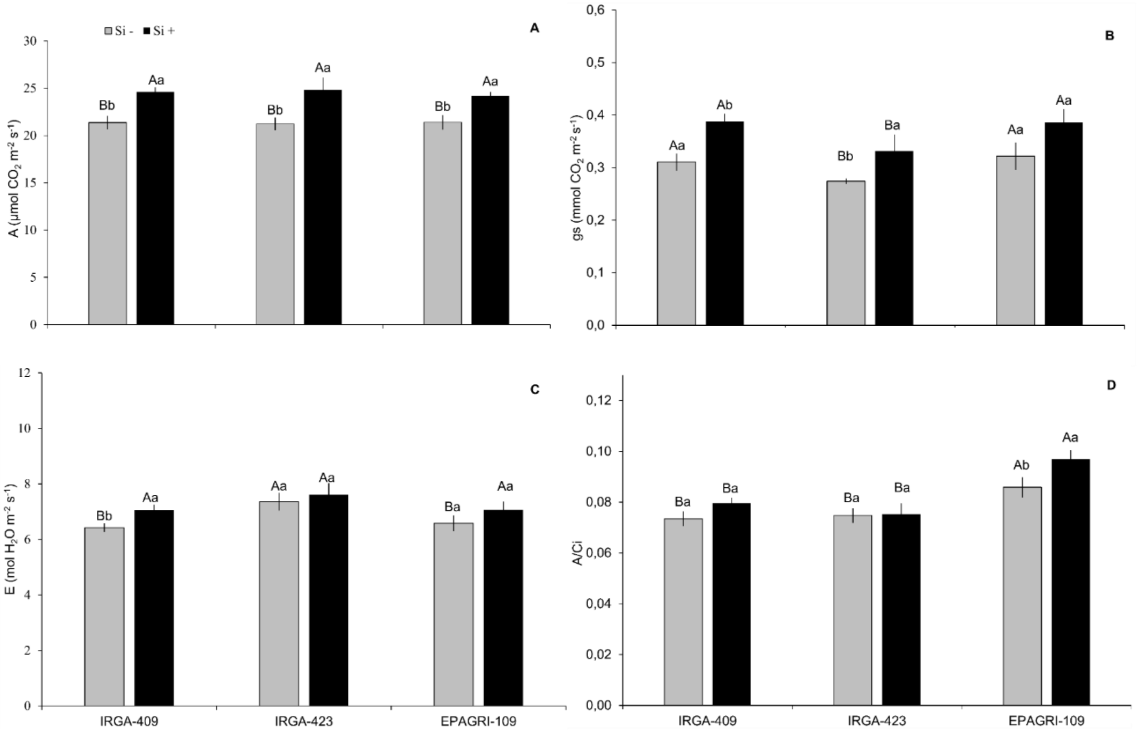


Silicon fertilization promoted an increase in photosynthesis (A) in all cultivars compared with plants grown without Si (Si−). Increases in +Si plants were 15%, 17%, and 13% for the cultivars IRGA-409, IRGA-423, and EPAGRI-109, respectively, with no differences observed among cultivars regardless of treatment (Figure 1A). Under the

−Si treatment, no differences were observed among cultivars. Stomatal conductance (gs) also responded positively to Si application, with increases of 22% and 26% for EPAGRI-109 and IRGA-409, respectively, whereas IRGA-423 showed an increase of 22% (Figure 1B). Transpiration (E) showed a similar, although less pronounced, trend, with a significant increase in E observed for IRGA-409 and EPAGRI-109, while IRGA-423 showed no differences between treatments (Figure 1C). Carboxylation efficiency (A/Ci) was mainly affected in the cultivar EPAGRI-109, which increased by 11% under silicon fertilization. For IRGA-409 and IRGA-423, the increase was 29% in +Si plants compared with −Si plants, regardless of cultivar (Figure 1D).

Figure 2

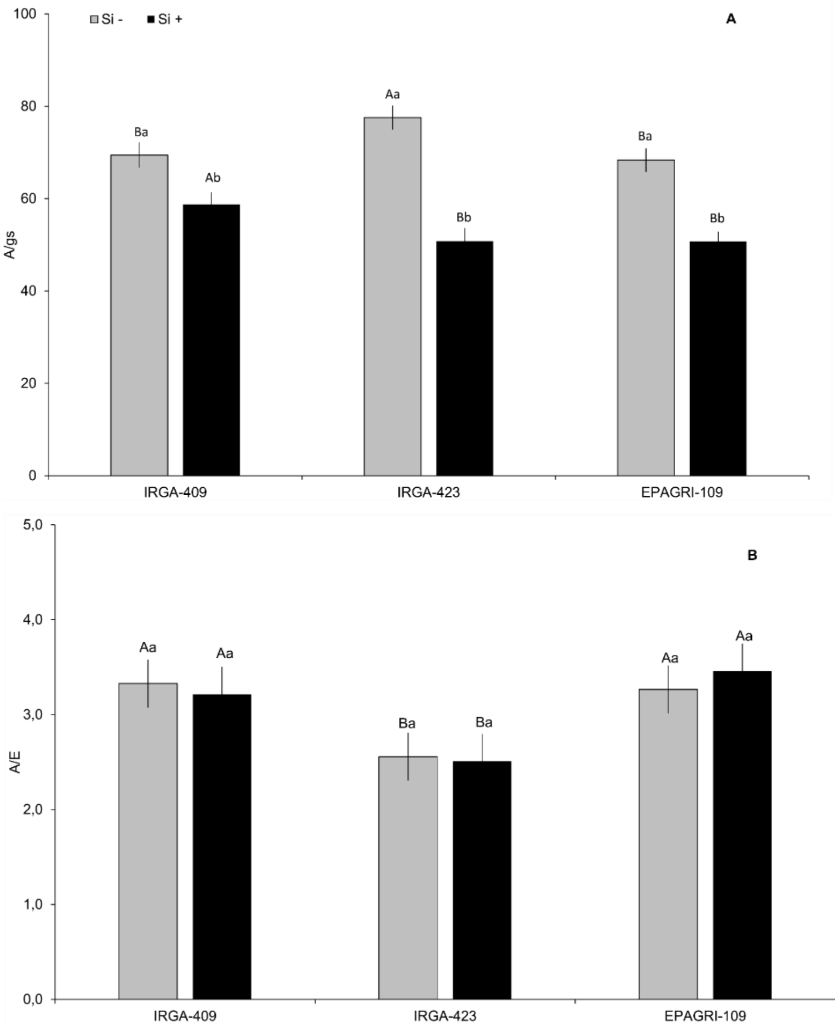
(A) CO_2 assimilation rate (A), (B) stomatal conductance (gs), (C) transpiration rate (E), and (D) instantaneous water use efficiency (A/Ci) in rice cultivars (IRGA-409, IRGA-423, and EPAGRI-109) grown without silicon supplementation (Si−) and with silicon supplementation (Si+). Bars represent the mean ± standard error. Uppercase letters compare cultivars within the same treatment, and lowercase letters compare treatments within each cultivar, according to Tukey's test (p ≤ 0.05)



Intrinsic water use efficiency (A/gs) was reduced in all cultivars following Si application (Figure 3A) compared with the absence of Si. In plants treated with Si, reductions of 15%, 35%, and 26% were observed for the cultivars IRGA-409, IRGA-423, and EPAGRI-109, respectively. For instantaneous water use efficiency (A/E), only genotype effects were observed, with no influence of Si application. The cultivar IRGA-423 showed an average reduction of 24% compared with the other cultivars, regardless of Si fertilization.

Figure 3

(A) Intrinsic water use efficiency (A/gs) and (B) instantaneous water use efficiency (A/E) in rice cultivars (IRGA-409, IRGA-423, and EPAGRI-109) under the absence (Si−) and presence of silicon (Si+). Bars represent the mean ± standard error. Uppercase letters compare cultivars within the same treatment, whereas lowercase letters compare treatments within each cultivar, according to Tukey's test (p ≤ 0.05).

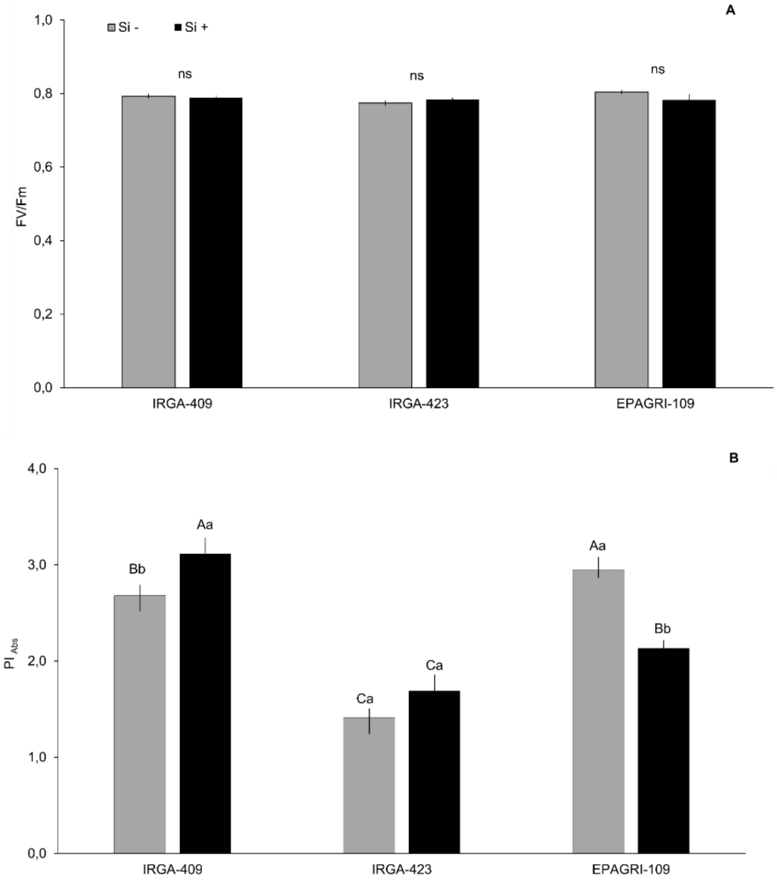


Although the effects on gas exchange were positive, no changes were observed in the maximum quantum efficiency ratio of chlorophyll a (Fv/Fm), regardless of cultivar or Si application. However, a significant effect was observed for the isolated factors (Cv × Si) on PIABS (Figure 3). The cultivars IRGA-409 and EPAGRI-109 showed contrasting responses to Si application. IRGA-409 exhibited a 16% increase under +Si conditions, whereas EPAGRI-109 showed a 28% reduction in +Si plants. No difference was observed between

Si treatments for IRGA-423, which also presented the lowest photochemical performance index among the cultivars (Figure 3B).

Figure 4

(A) Maximum quantum yield of photosystem II (Fv/Fm) and (B) performance index (PIABS) in rice cultivars (IRGA-409, IRGA-423, and EPAGRI-109) under the absence (Si−) and presence of silicon (Si+). Bars represent the mean ± standard error. Uppercase letters compare cultivars within the same treatment, whereas lowercase letters compare treatments within each cultivar, according to Tukey's test (p ≤ 0.05)



Growth and yield parameters showed significant differences among cultivars and in response to Si application (Table 1). EPAGRI-109 exhibited greater vegetative biomass production in +Si plants compared with plants grown without Si, in addition to presenting higher vegetative biomass than the other two cultivars. In contrast, IRGA-409 showed the highest grain yield when compared with the others (Table 2). Silicon affected only the number of filled and unfilled grains and the biomass of unfilled grains, with no significant response observed for the cultivar × silicon interaction (Tables 1 and 2).

The number of panicles was 27% higher in EPAGRI-109 compared with IRGA-409 and 22% higher than in IRGA-423. However, the opposite response was observed for the number of grains per panicle, in which IRGA-409 was 25% higher than EPAGRI-109 and 10% higher than IRGA-423. These responses were reflected in grain biomass; however, while the highest filled grain biomass was observed in the cultivar IRGA-409 (11.53 g), EPAGRI-109 presented the highest unfilled grain biomass, representing an increase of 247% compared with IRGA-409 and 119% compared with IRGA-423 (Table 2), indicating differences in strategies between grain number and grain filling.

For the Si-fertilized plants, the cultivar IRGA-423 showed a 42.2% reduction in the number of empty grains, highlighting the positive effect of silicon on grain filling. These effects contributed to a 6.3% increase in grain biomass and a 4.0% increase in 1000-grain weight. However, there was a slight reduction in total biomass (-3.8%) and stem biomass (-8.6%). In Si-fertilized plants, when compared with non-fertilized plants, the higher productivity observed under Si application may also be associated with the reduction in the number of empty grains across all genotypes, particularly in IRGA-409, which exhibited a 51% reduction in empty grains plant^{-1} (Table 3). In contrast, unlike the IRGA cultivars, EPAGRI-109 treated with Si showed an 8.7% reduction in grain biomass, a 3.8% decrease in 1000-grain weight, and a 10.6% reduction in the number of grains per panicle, suggesting that the increase in vegetative growth did not translate into greater grain production. Overall, the productive response varied among genotypes, with IRGA-423 showing the best balance between vegetative growth and reproductive performance, as reflected by the simultaneous increase in grain filling, grain biomass, and 1000-grain weight.

Table 2

Mean values ± standard error of growth, yield, and biomass variables of the rice cultivars IRGA-409, IRGA-423, and EPAGRI-109 grown without (Si−) and with (Si+) silicon supplementation

	IRGA-409		**IRGA-423**		**EPAGRI-109**	
Variables	**Si-**	**Si+**	**Si-**	**Si+**	**Si-**	**Si+**
Height (cm)	83.4 ± 1.4	83.7 ± 0.8	77.3 ± 1.7	79.6 ± 0.7	78.0 ± 1.1	77.4 ± 1.0
Number of Flag Sheets	5.4 ± 0.43	4.9 ± 0.3	5.9 ± 0.5	5.6 ± 0.5	6.0 ± 0.4	7.0 ± 0.6
Profile Number	5.4 ± 0.4	4.9 ± 0.3	5.9 ± 0.5	5.6 ± 0.5	6.7 ± 0.4	7.4 ± 0.5
Number of Panicles	4.7 ± 0.3	4.4 ± 0.3	4.7 ± 0.4	4.7 ± 0.4	5.6 ± 0.4	6.0 ± 0.4
AF (m^2)	473.8 ± 33.0	498.9 ± 30.7	521.0 ± 34.2	567.1 ± 51.7	801.4 ± 65.8	877.6 ± 83.1
Leaf biomass (g)	3.5 ± 0.2	3.3 ± 0.1	2.6 ± 0.2	2.7 ± 0.2	4.9 ± 0.2	5.4 ± 0.1
Culm biomass (g)	6.1 ± 0.4	5.7 ± 0.2	5.8 ± 0.3	5.3± 0.5	5.9 ± 0.4	6.0± 0.3
Root biomass (g)	2.9 ± 0.2	2.8 ± 0.1	2.0 ± 0.3	2.0 ± 0.2	4.6 ± 0.5	4.2 ± 0.4
Total biomass (g)	12.4 ± 0.6	11.7 ± 0.4	10.5± 0.7	10.1 ± 0.9	15.4 ± 0.9	15.6 ± 0.7
Grain biomass (g)	12.1 ± 0.7	11.3 ± 0.4	9.6 ± 0.5	10.2 ± 0.5	10.4 ± 0.8	9.5 ± 0.5

4 DISCUSSION

The rice cultivars IRGA-409, IRGA-423, and EPAGRI-109 exhibit differences in vegetative and reproductive growth. The cultivar IRGA-423 has an early growth cycle (~120 days), whereas IRGA-409, due to its intermediate cycle (~135 days), shows a greater balance between vegetative biomass accumulation and grain production. In contrast, EPAGRI-109 has the longest cycle (~142 days), which favors greater vegetative growth prior to flowering and grain filling. The duration of the phenological cycle is directly related to the inherent differences among cultivars (Streck et al., 2006).

The differential increase in silicon content among the cultivars suggests possible differences in the physiological demands and mechanisms related to the absorption, translocation, and accumulation of this element. The IRGA cultivars exhibited higher mean Si content when compared with EPAGRI-109. In fact, there is a natural variation in Si uptake among cultivars, with the highest Si values observed in IRGA-409 and the lowest in EPAGRI-109 under non-stress conditions and even under iron toxicity, both at the vegetative stage (Dos Santos et al., 2020a) and at the reproductive stage (Dos Santos et al., 2020b).

Furthermore, foliar application promoted lower Si accumulation in the leaves of the cultivars when compared with leaf Si content supplied via root application (Santos, 2017). Such differences in absorption are directly related to the organs involved (roots and leaves) and to the Si transport mechanisms and transporters involved, since the roots contain the transporters OsLsi1 and OsLsi2 (Ma et al., 2007; Ma et al., 2006), whereas the leaves contain OsLsi3 and OsLsi6 (Yamaji et al., 2015; Huang and Ma, 2024).

For chlorophyll a fluorescence, Fv/Fm showed no differences regardless of the cultivars or Si application, with values close to 0.8, suggesting the absence of photoinhibition or relevant structural damage to the reaction centers of photosystem II (Jiao and Hu, 2025), despite the differences observed in PIABS. The increase in PIABS for the cultivar IRGA-409 with Si application, the reduction in EPAGRI-409, and the absence of a Si effect for IRGA-423 further indicate a genotype-dependent effect rather than an effect of fertilization with the mineral nutrient. The differences in PIABS among the genotypes reflect the overall efficiency of photosystem II, integrating the performance of light energy capture, transport, and utilization (Strasser et al., 2004). In fact, no damage to PSII was observed, but rather a natural genotypic difference in light conversion efficiency.

The increase in net photosynthetic rate (A) in Si-fertilized plants was directly associated with the significant increase in stomatal conductance (gs). In fact, Si may directly affect photosynthesis by modulating gs (Lavinsky et al., 2016) or mesophyll conductance (gm) (Detmann et al., 2012) in rice plants during the reproductive stage under non-stress conditions, as well as under iron toxicity stress (Dos Santos et al., 2020) and arsenic stress (Sanglard et al., 2014). The higher carboxylation efficiency (A/Ci) observed in all cultivars indicates that Si enhanced CO_2 assimilation by possibly influencing the biochemical processes involved in carbon assimilation, but it also suggests that the increase in A may be more strongly associated with diffusive factors, as evidenced by the increase in gs. Although transpiration increased as a consequence of greater stomatal opening, the proportionally greater increase in A resulted in more efficient use of both CO_2 and water, particularly in the IRGA-409 and EPAGRI-109 cultivars. These responses reinforce the role of silicon in optimizing gas exchange and maintaining plant physiological balance, as previously demonstrated in rice cultivars under optimal growing conditions (Detmann et al., 2012; Lavinsky et al., 2016) or under abiotic stress conditions (Somaddar et al., 2022; Chen et al., 2024).

The increase in yield under non-stress conditions was initially demonstrated by Ma et al. (1989), who reported that Si fertilization during the reproductive stage, specifically during panicle formation, promoted an increase in the number of grains per panicle without, however, affecting thousand-grain weight. More recently, this response was associated with physiological and molecular modifications induced by Si in rice genotypes cv. ‘Oochikara’ and its low silicon 1 (Lsi1) mutant defective in Si uptake (Lavinsky et al., 2016). Detmann et al. (2012) verified that the effect of Si on yield is primarily related to an increase in net photosynthetic rate (A), accompanied by increases in leaf conductance (gs), resulting in higher grain yield in Si-supplemented plants. Similar results were observed in the present study for the cultivars IRGA-409, IRGA-423, and EPAGRI-109. However, unlike the findings reported by Lavinsky et al. (2016), who demonstrated that the increase in harvest index was associated with a greater number of grains and higher 1000-grain weight, the cultivars IRGA-409, IRGA-423, and EPAGRI-109 did not exhibit this response. These results reinforce that the effects of silicon strongly depend on genotype and on the capacity of each cultivar to utilize the physiological benefits promoted by this element.

5 CONCLUSION

Silicon application promotes important physiological and productive responses in rice cultivars with different morphophysiological characteristics, even under rainfed cultivation conditions. Although Si did not significantly alter the biomass of vegetative organs or the chlorophyll a fluorescence parameter, its supplementation favored the uniformity of panicle emergence, grain maturation, and the increase in the number and biomass of filled grains. These effects were associated with an increase in photosynthetic rate, indicating that Si acts primarily by optimizing physiological performance related to grain formation and filling. Indeed, Si represents a promising strategy for increasing rice production efficiency, contributing to greater yield stability and offering potential application in field agricultural systems, especially under cultivation conditions subject to environmental limitations.

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