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ORIGINAL PAPER

Does Foliar Application of Silicon under Natural Water Stress Conditions Increase Rice Yield in Subtropical Dry Regions?

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Abstract

Silicon, although not an essential element for plant, when it is absorbed can alter cells flexibility, and then may affect plant architecture; reduce leaf senescence and deleterious effects caused by abiotic stresses. Rice is a Si accumulator, surpassing even nitrogen and potassium accumulation when compared. Thus, we evaluate the effect of foliar application of Si on the development and grain yield of upland rice. We used a randomized block design consisting of foliar application of the following five doses of Si: 0; 126.0; 252.0; 378.0; and 504.0 g ha^{-1} of Si applied as potassium and sodium silicate, with five replications. We balanced potassium concentrations in the solutions applied to all treatments. We divided foliar fertilization into three applications, at 30, 60, and 90 days after emergence (DAE). We evaluated foliar contents of Si and N, relative chlorophyll content (RCC), and grain yield. Si application increased silicon contents linearly, which reached 8.34 and 12.17 g kg^{-1} when evaluated at 60 and 90 DAE, respectively, with a dose of 504.0 g ha^{-1} of Si. Positive gradient of Si doses absorption represented increased grain yield by 252.0 g ha^{-1} of Si, and after this grain yield decreased. However, foliar silicon application up to the dose of 252.0 g ha^{-1} under water stress increased the grain yield of rice grown in rainfed system in approximately 9%. The application of 252.0 g of Si ha^{-1} promotes a grain yield (5778 kg ha^{-1}) and also a higher differential revenue (the US $ 129.49 per hectare). The economic analysis is determined by the spraying costs.

Keywords *Oryza sativa* · Water stress · Productive efficiency · Cerrado · Beneficial element

1 Introduction

One of the most widespread planting methods in Brazilian *Cerrado* is the upland rice crop production without irrigation, due to its characteristics [1]. This crop was massive as a production when the frontiers of Central-West Zone in Brazil was fostered by regional development policies, and the high climatic compatibility and agricultural aptitude of the region. In the decade from 1975 to 1985, rice was considered the main crop in the region, reaching an area of 4.5 million hectares with average grain yield of 1.0 t ha^{-1} [2, 3].

Rice is a strategic crop production in Brazil because it makes part of the food priority as source of consumption [4]. So, it is essential to dedicate studies on rice yield and the best way to produce, especially because the Brazilian as time passed upland agroecosystem has shown low yield near to 1.8 t ha^{-1} [5]. These areas of low yield there are irregularity and heterogeneity of rainfall, and this climatic variation may cause countless physiological and metabolic stress in plants [6], among them rice, besides affecting its nitrogen (N) balance [7].

Some studies are indicated that Si reduces the effects of abiotic stress, including the one caused by dry [8–11]. It is also known that there is a strong association between N and Si for yield responses in different crops [12]. From the physiological and metabolic point of view, these both nutrients can increase protein content and grain yield with nutritional quality [13]. Some studies of rice crop production in a controlled

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situation evaluated N and Si interactions. They observed a direct effect between Si inputs on rising NO_3^- content in roots, leaves' chlorophyll, and rice panicles per plant [14, 15]. Other studies are reported that Si helps in the retention of photosynthetic pigments and carotenoids. Then, when plants are in stress conditions (nutritional, phytosanitary, or water) Si can work to relieve the stress in chloroplasts [16, 17].

Despite all studies dedicated to rice in tropical regions, there is still no consensus about how Si can improve productivity in a dry situation. In this way, to achieve maximum yield, it is essential to indicate the most appropriate Si-dose, according to nutritional requirements from the perspective of use. Moreover, it is also important to indicate this dose keeping attention to economic balance [18] to ensure the sustainability of the agroecosystem.

There are studies which demonstrated rice as Si accumulator been noticed uptake up to 8.4% of Si in its dry matter [19]. In this way, taking this information apart it is possible to decide the use of Si as an agronomic strategy to reduce damage by dry, such as decreased grain yield, as noticed before [20]. The application of Si can be made by soil or leaves [21], and this decision is based on the kind of source.

In soil application the option has been calcium and/or potassium silicates because they have low solubility and decreasing of inhibitor that hamper Si uptake by plant [22]. On the other hand, incorporation with low solubility may elevate the costs, and beyond that it is required a large amount to fit the rice crop nutritional exigence. In this case, foliar application has been an alternative economically viable, and fewer quantity [23].

This study was stated that Si can be used to improve rice production, even with hydric stress. Then this study had the intention to demonstrate the effect of foliar silicon application on rice crop development and yield, take into account the differential revenue in these upland agroecosystems of *Cerrado* Biome.

2 Material and Methods

2.1 Plant Material and Experimental Conditions

The study was performed in the experiment field at the School of Agronomy. Federal University of Goiás (UFG) (16° 35' S, 49° 17' W, 730 m altitude), Brazil, in the 2018/2019 crop season, with rice (cultivar BRSGO Serra Dourada). According to Köppen classification, climate is Aw type (megathermal), or tropical savanna, dry winters, rainy summers, and average of annual precipitation near to 1600 mm. During the study, climate conditions were monitored by a meteorological station located at the School of Agronomy, UFG, with the results in Fig. 1.

The soil of the study was classified as Distroferric Red Latosol according to the Brazilian Soil Classification System (SiBCS) [24]. The material was subjected to previous chemical and granulometric analysis, as proposed by Silva [25], at depth of 0.00–0.20 m, and the following results were obtained: clay (350 g kg^{-1}), silt (60 g kg^{-1}), sand (590 g kg^{-1}), carbon (15.7 g kg^{-1}), organic matter (27 g kg^{-1}), pH at $CaCl_2$ (5.0) pH at H_2O (5.2), pH at KCl (4.8), Ca (2.7 $cmol_c$ kg^{-1}), Mg (1.5 $cmol_c$ kg^{-1}), K (0.37 $cmol_c$ kg^{-1}), Zn (1.9 $cmol_c$ kg^{-1}), sum of bases (4.6 $cmol_c$ kg^{-1}), Al (0.0 $cmol_c$ kg^{-1}), H + Al (2.2 $cmol_c$ kg^{-1}), Cation Exchange Capacity (CEC) (6.77 $cmol_c$ kg^{-1}), base saturation (67.5%), and P (36.4 mg dm^{-3}). Si in the soil was quantified by sulfuric extraction as proposed by Embrapa, with 10.25% of SiO_2 [26].

The experiment was set up in a randomized block design consisting of five doses of silicon (0; 126.0; 252.0; 378.0; and 504.0 g ha^{-1}) of Si applied as potassium and sodium silicate stabilized with sorbitol solution in 10% (124 g Si L^{-1}; 42 g K_2O L^{-1}; 31 g Na_2O L^{-1}; d = 1.15 g L^{-1}; pH = 12.0; and soluble in water) [23], which were applied to the leaves. Each treatment had five replications, totaling 25 experimental units. Experimental units consisted of 3.0 m long rows spaced 0.45 m between them (6.75 m^2 per plot). The experiment was performed and evaluated during the rainy season, as shown in Fig. 1, although with a drought period in January 2019, with only 25.0, 6.0, and 7.0 mm of rain in the days 5, 13, and 19, respectively, with remaining days without precipitation.

2.2 Silicon Application

The Si solution was divided into three equal parts, where each third of volume was applied at 30, 60, and 90 days after emergence (DAE), respectively. The pattern fertilization was performed with application of 20 kg N ha^{-1} (urea), 100 kg P_2O_5 ha^{-1} (simple superphosphate) and 60 kg K_2O ha^{-1} (potassium chloride), as stated by Sousa and Lobato [27]. Topdressing consisted of 60 kg N ha^{-1} in the form of urea divided into two applications, the first in the tillering phase (30 days after sowing) and the second in the floral primordium. In each treatment, the solutions were made balancing potassium content to isolate the silicon effect, by KCl as K source.

2.3 Data Collection

One week after foliar application of each dose of Si, relative chlorophyll content (RCC) was evaluated with the aid of a chlorophyll meter (FALKER®, model ClorofilLOG – CFL1030). To evaluate plant nutritional status, nitrogen and silicon foliar contents were evaluated. For this purpose, 30 diagnostic leaves (flag leaf, with the first collar visible) were collected randomly in each experimental unit at 60 and 90 DAE, according to recommendation by Flores et al. [23]. The material was washed with distilled and deionized water, dried in a forced air circulation oven at

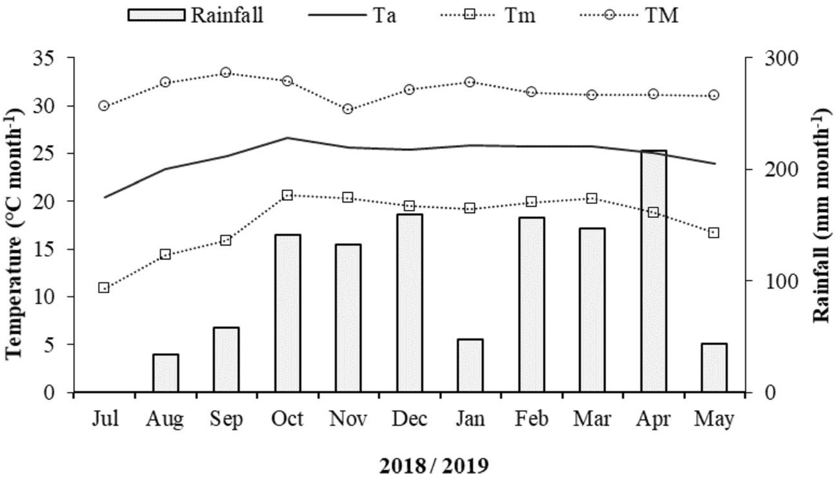

Fig. 1 Air temperature maximum (TM), minimum (Tm) and average (Ta), and rainfall per month, from July/2018 to May/2019, in the College of Agronomy, Federal University of Goiás, Goiânia, GO, Brazil

65 °C for 72 h and grounded in a Willey mill. Afterwards, nitrogen contents in the plant tissues (shoot) were determined according to methodology by Silva [25], and silicon contents were determined according to methodology by Konrdörfer, Pereira, and Nolla [28].

Grain yield was obtained after manual harvesting of rice (after physiological maturation) by harvesting two meters linearly in the two central rows of each plot. Plants were threshed and dry grain were weighed, with data being converted to kg ha^{-1} (13% wet basis moisture). In order to obtain yield benefit, 100 g of the harvested rice was removed and husked and de-husked grains weighted.

Economic analysis was performed using the partial budget technique, according to Noronha [29]. The method calculates the effects of additional costs and revenues in relation to a baseline, providing differential profits as an economic indicator, using the following equation:

$$\mathrm{Dp} = \mathrm{Dr}–\mathrm{Dc} \tag{1}$$

Where:

Dr. (US$ ha^{-1}) = Differential revenue, calculated from the variation of the yield obtained in each treatment in relation to the control, considered as baseline, multiplied by the historical record of the average price of rice with pell (Dr = differential yield x product price). The historical record of rice prices was obtained from prices observed in Brazil in the last 11 years (2009–2019), which were deflated to the real values in 2020 and converted into dollars, at the rate of US$ = R$ 5.08 (12/12/2020). Prices were obtained from the Municipal Agricultural Survey [30].

Dc (US$ ha^{-1}) = Differential cost was calculated directly from the price of the concentration of the product used in each treatment, as these were already differential in relation to the control. Analyses were performed in relation to the input price, resulting in the differential cost of the input and the cost of the product added to the operational cost of application, which subsequently resulted in the differential cost of operation. The operational cost of application was obtained from Róman et al. [31], who evaluated the operational efficiency of application for different spray volumes. This study allowed to calculate the updated value (US$ - 2020) of US$ 46.55 for three applications at spray volume of 100 L ha^{-1}. Thus, it was possible to calculate from Eq.1 the differential profit (Dp) for each treatment in relation to the control, which was subdivided into Dpi = Differential profit of input and Dpo = Differential profit of operation.

2.4 Statistics

Data were subjected to analysis of variance by F test and, when significant, to polynomial regression analysis, with selection of significant models by F test at 5% probability and by selecting models with the highest value of coefficient of determination. In order to demonstrate the effect of correlation within and between treatments, dissimilarity measures between parameters of nutritional and physiological responses were used through correlation networks. Variables were analyzed and treated using a multidimensional scale of absolute values of correlations. Correlation between two variables was presented by vectors, in which green and red represented positive and negative correlations. The narrow and intensity of the vector indicated the weight and intensity of correlation, respectively.

3 Results

The results showed that doses of silicon influenced Si accumulation in leaves (Fig. 2). Accumulation was enhanced over time from 378.0 g ha^{-1} of Si. At 60 days after germination, the proposed model responded to 91% of the effect of the doses on Si accumulation in the plant, while at 90 days we observed a decreased response (86%). However, the results showed a

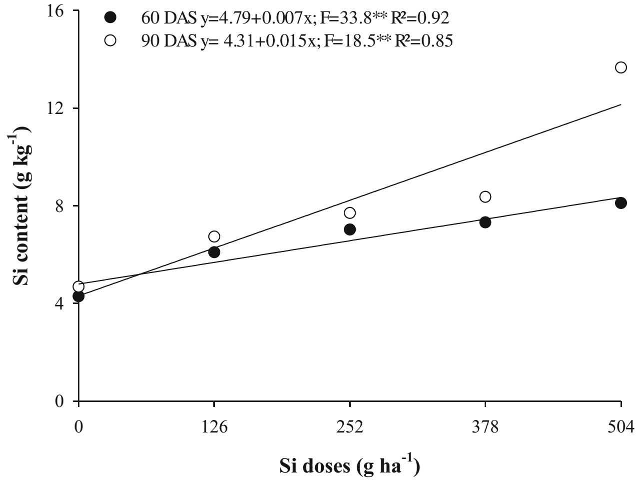

Fig. 2 Relationship with Si content (g kg^{-1}) and Si doses (g L^{-1}) in 60 and 90 days after emergecing (DAE). ** – statistical significant by F-test at 1% probability

trend to accumulate Si in a similar range between doses of 126.0 and 378.0 g ha^{-1}.

Contrary to the Si accumulation capacity of plants, relative chlorophyll content (RCC) did not show specific responses to Si application between 30 and 60 days after germination (Fig. 3). Although tenuous, considering the doses of this study, RCC showed a reduced qualitative trend of inflection in the dose of 378.0 g ha^{-1} of Si up to 60 DAE. Although RCC reduced over time, at 90 DAE this parameter showed a similar behavior to Si accumulation by the plant (Fig. 2). Figure 3 demonstrates this behavior for RCC at a 97% significance probability model. As a further matter, it is essential to inform that N does not change along with this experiment, from germination until the senescence stage (N content at 60 days: 37.16 g kg^{-1}; F = 0.17^{ns}; p = 0.95; N content at 90 days: 30.45 g kg^{-1}; F = 0.04^{ns}; p = 0.99). It is one of the possible explanations which also RCC has not been changed on this present study.

When measuring 100-grain weight (Fig. 4), we have not observed effect of doses on the weight variation of husked grains. As expected, the weight of shelled rice was heavier than that of peeled rice, although showing that there is a trend of accumulating mass in the rice grain that goes beyond our data, being observed in the control and silicon application treatments regardless of dose. The model explained approximately 75% of the increase in Si accumulation in the rice grain. Therefore, these data highlight the possibility of Si accumulation in peeled grains.

In addition, we highlight that the response to rice yield was related to the variation of doses of Si proposed by our study. Figure 5 shows the productive performance of rice with significant difference between treatments and with a model that responds to 80% of the effect of doses on grain yield. The intermediate dose (252.0 g Si ha^{-1}) showed the highest yield, 9% above the control, with approximately 6000 kg ha^{-1}. From this dose, grain yield decreased, indicating phytotoxic effect caused by the high concentrations of Si applied.

Figure 6 shows some correlations among all parameters by treatment applied to the rice crop without distinction of temporal effect, in order to group variables that could respond better to each other. The control treatment (Fig. 6a), i.e., without Si application, demonstrated that the Si naturally present in the system, regardless of evaluation period (60 or 90 DAE), was positively correlated with rice grain yield. Another important parameter for yield was RCC and N content evaluated at 90 and 60 DAE, respectively. Correlation analysis confirmed, when considering the entire data set, that there is little variation between weights of husked and de-husked rice, with

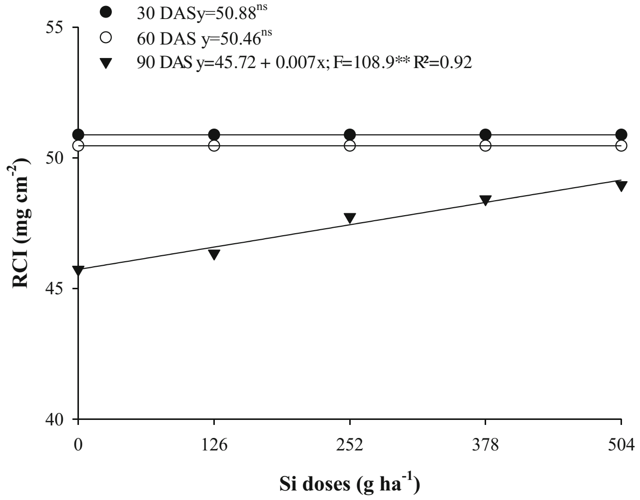

Fig. 3 Relationship with Si doses (g ha^{-1}) and Relative Chlorophyll Content (RCC - μg cm^{-2}) in 30, 60 and 90 days after emergence (DAE). ** and ^{ns} – statistical significant and non-significant by F-test at 1% and 5% probability, respectively

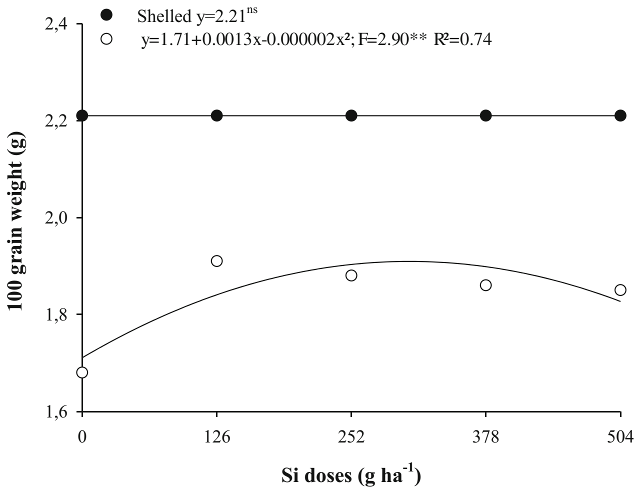

Fig. 4 Relationship with Si doses (g ha^{-1}) and 100-grain weight of shelled rice and peeled rice in grain (g). ** and ^{ns} – statistical significant and non-significant by F-test at 1% and 5% probability, respectively

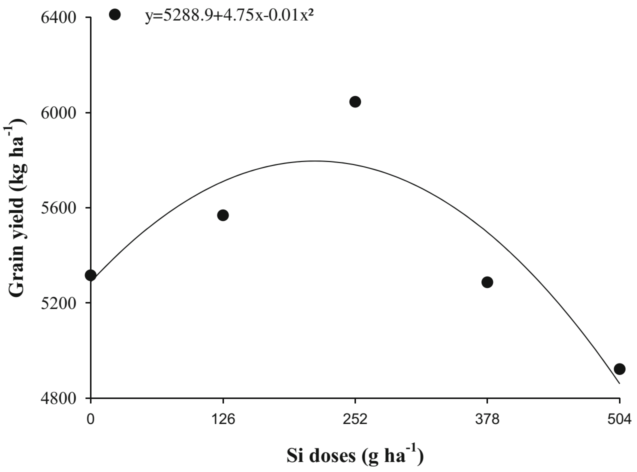

Fig. 5 Relationship with Si doses (g ha^{-1}) and rice yield (kg ha^{-1}). * – statistical significant by F-test at 5% probability

strong correlation between them. In general, there is balance between interactions in the control conditions.

We have not observed the same balance after application of the first dose of Si (126.0 g ha^{-1} of Si) (Fig. 6b). In this treatment, the results were negatively correlated with high intensity (color red and narrow), showing reduced dependence of most variables on yield. Although yield was strongly correlated with relative chlorophyll content at 90 days, it showed proportional negative correlation with nitrogen also evaluated at 90 days. Thus, our results indicate that rice performance at the lowest dose of silicon is associated with other factors that were not evaluated in this study that had greater influence on RCC, which in turn contributed to increase yield in detriment of the control treatment.

As we already observed for the lowest dose treatment, the dose 2 (252.0 g ha^{-1} of Si) was positively correlated with grain yield and RCC at 90 days of evaluation, which is positively correlated with the evaluation of N content at 90 days (Fig. 6c). In addition, we can state that Si content at 90 days was directly affected by Si application at 60 days, suggesting accumulation, as aforementioned. N content at 60 days was also positively correlated with yield, which coincides with the physiological phase of the plant of accumulation of energy reserves for grain filling. Moreover, the results were consistent with what we previously observed, especially regarding yield (Fig. 5), which allows us to state that Si application and RCC directly affected rice grain yield.

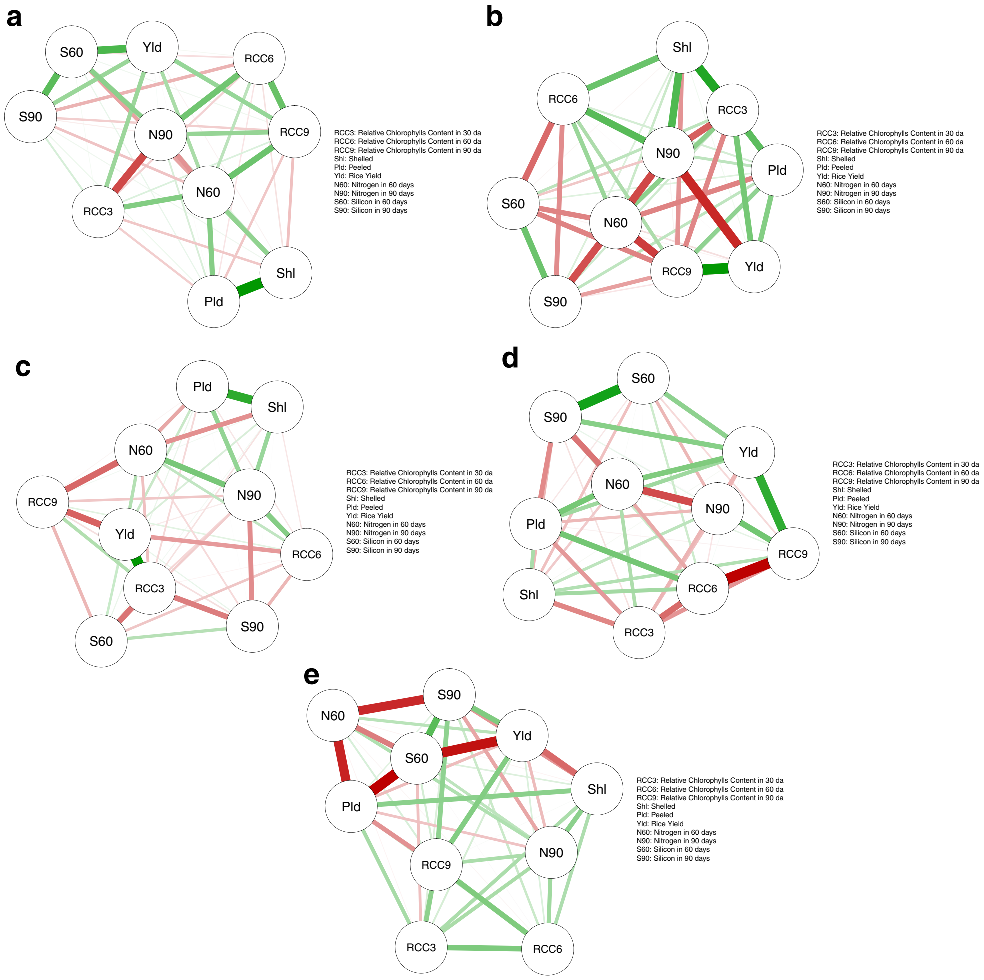

Fig. 6 Correlation-based network analysis (CNA) by (dis)similarity measures that correlate different components to each other and the magnitude of the co-linear relationship of the components. **a** dose 0 (0 g ha^{-1}), **b** dose 1 (126.0 g ha^{-1}), **c** dose 2 (252.0 g ha^{-1}), **d** dose 3 (378 g ha^{-1}), **e** dose 4 (504.0 g ha^{-1}). "Rice Yield" is literal meaning; RCC (Relative Chlorophylls Content) at 30, 60 and 90 days; N means nitrogen at 60 and 90 days; Si means silicon at 60 and 90 days, and "Shelled" means shelled rice and "Peeled" means peeled rice. As much the line is narrow, much more is the statistical deviation

Figure 6d shows correlations between factors in the application of 378.0 g ha^{-1} of Si (dose 3) in the rice production system. When comparing correlations of dose 3 with the control treatment (without addition of Si), there is a clear increase of negative correlations between factors. The only different factor among treatments was silicon application, which leads us to state that doses of 378.0 g ha^{-1} of Si can negatively affect rice grain yield; again, specifically in this treatment. So, the evaluation of N at 90 days showed direct effects on rice grains, although not showing evidence of this nutrient on crop yield. Yield was highly correlated with RCC at 30 days, suggesting that N and Si, focuses of our study, may have a secondary role in some physiological mechanism of the plant. The negative correlation is the evidence that it has some dose limit, which should be useful in agricultural practice to take the right decisions about silicon application.

The results also showed that the treatment with application of 378.0 g ha^{-1} of Si was positively correlated with several parameters, such as Si at 60 and 90 days and RCC at 90 days. However, we highlight that although positively correlated, it has showed little difference from other treatments of our study. It is important to point in the case of negative correlations among N and Si at 90 days, does not mean negative interaction. Nitrogen is mobile in the phloem, and near to 90 days a considerable part of this nutrient is piped to grains in protein form, and therefore N in leaves get fewer. This kind of effect happens mainly after 50 days of germination at the pod formation and graining phase [32].

Figure 7 shows the results of differential profits of inputs and operation in relation to Si application in the rice crop. We note that only the 252.0 g ha^{-1} dose of Si showed positive differential profit, with return of US $ 82.90 ha^{-1}, considering three sprays. If we suppress the cost of operation, there are increases of US $ 46.45 ha^{-1} in the differential profit, providing the dose of 126.0 g Si ha^{-1} with positive differential profit of US $ 41.60 ha^{-1}, while the dose of 252.0 g Si L^{-1} has a differential profit of US $ 129.46 ha^{-1}.

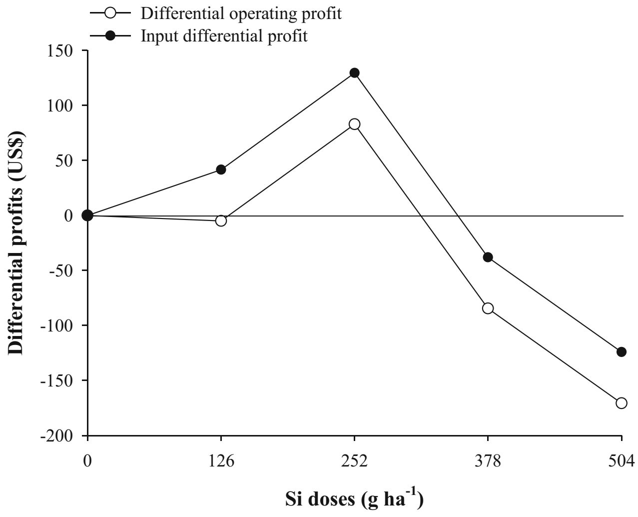

Fig. 7 Demonstration of the rice production system by economic balance bias in function of Si doses (g ha^{-1}) and the maximum yield according nutritional requirements

4 Discussion

In general, silicon is an element with maximum expression when the plant is under some conditions of biotic and/or abiotic stress [33, 34], as proposed by our study. According to Fig. 2, the capacity of concentrating Si in rice leaves gradually increases along with foliar application of doses of silicon.

High accumulation of silicon is a phenomenon widely discussed for rice [33, 35] and is explained by the gene expression of root cells [33], which are involved with the silicon efflux transporter via apoplast [33, 36, 37]. High accumulation has recently been identified by imaging techniques, proving that Si tends to accumulate in leaves [38], as reinforced by our study.

Most studies demonstrated metabolic behavior and high accumulation of silicon by mechanisms developed from the roots [39]. However, our study proved that there may be different mechanisms for high accumulation of silicon in rice. On the other hand, some physiological aspects that can affect plant development are recurrent, as identified by Chen et al. [40], who proved that foliar absorption of silicon can limit photosynthesis rates through some stomatal mechanism.

We have not identified problems of this nature in this study. Furthermore, our results proved that relative chlorophyll content (RCC) increased when compared to the control group if examining only the 90 days of evaluation (Fig. 3). This variable considers the relationship between *chlorophyll a* and *b*, which reveal the stress level of the plant under adverse conditions [41]. Some studies proved the direct relationship between increasing silicon and *chlorophyll a* content in the plant [42] and *chlorophyll a* production over time [43].

Therefore, the results of our study raise the hypothesis that high accumulation of silicon in rice can stimulate *chlorophyll a* production during plant development, possibly improving physiological longevity of rice. This hypothesis has been confirmed for other plant groups [40, 42, 44].

There is evidence that chlorophyll content is related with foliar nitrogen (N) concentration [45], as each chlorophyll molecule requires four N atoms and some studies proved that Si contributes to increased N absorption by plants [14], besides being associated with increased chlorophyll content, as reported by Al-Aghabary et al. [46]. This behavior may be associated with the fact that Si accumulates in the epidermal cells of the shoot, improving leaf opening angle and making them more erect, reducing self-shading and favoring better light capture [19]. Thus, there is consensus that Si is beneficial to the photosynthetic apparatus [47].

However, in our study Si application did not affect plant N content, with average content of 37.1 g kg^{-1} of N in the leaf tissues regardless of the Si dose applied. This contradiction was also confirmed by Mauad et al. [15] and Ávila et al. [14] in rice plants, especially with N application [15, 48]. We highlight that approximately between 50 and 70% of total foliar N are part of enzymes that are associated with chloroplasts [14]. Thus, there is correlation between chlorophyll and N content in tissues [41], although not all N content analyzed is metabolically active, which may be accumulated in vacuoles in the form of N-NO_3^- [49].

There is also extensive discussion on how moisture can affect N-Si interactions [50]. In cases of water deficiency, these interactions tend to be impaired, as stated by Silva et al. [51]. Our study demonstrated that there is positive interaction between Si and N only in the control treatment, and we believe that save relations with natural Si content (10.5 mg dm^{-3}) in the soil system. Contrary for all other conditions, we observed negative correlations between these nutrients (Fig. 5). Another hypothesis raised in our study is that although Si content positively affected *chlorophyll a* and rice senescence, it can also be restrictive for the uptake of both N and Si, to the point of establishing negative interaction. Mauad et al. [15] reported the possibility of occurrence of competitive inhibition between anions $H_3SiO_4^-$ and NO_3^- by the absorption sites of the plant. In addition, Si has specific proteins in its absorption process [39], which could explain their negative interaction.

Our results on senescence with application of doses of Si affected the 100-grain weight of husked rice (Fig. 4), which responded to 75% probability in a quadratic function. As leaves remain for longer performing photosynthesis, it results in more photoassimilates for production of carbohydrates [15, 52–54], increasing grain weight compared to the control. Similar inferences were made by other studies on rice [15, 53].

These results are also consistent with Fig. 5, which confirmed the dose of 252.0 g ha^{-1} of Si as the best regarding rice grain yield. Zanetti et al. [42] found results awfully close to this concentration for cocoa under water stress, suggesting that excess Si, even if decreasing plant senescence, impacts yield.

We compared the performance of variables in correlation networks and confirmed the results and hypotheses (Fig. 6). Silicon improves plant yield, which is causally related with N and Si application and RCC, especially for the dose of 252.0 g ha^{-1} of Si.

Finally, our study proves that rice plants under water stress conditions that receive Si supply up to 252.0 g ha^{-1} of Si reduce deleterious effects, such as reducing production of reactive oxygen species (ROS), besides increasing rice grain yield. Moraes et al. [55] studied foliar silicon application in tomato crops with and without water stress and observed that Si improved gas exchanges, especially when subjected to a soil water potential equal to −60 KPa. The effect was attributed to polymerization after Si absorption and deposition on cell walls, forming silica-cuticle double layers, reducing transpiratory rates, and regulating the stomatal conductance of plants [9, 39].

Flores et al. [23] studied sunflower crops and observed linear increases in biomass production up to the dose of 504.0 g ha^{-1} of Si, i.e., increasing 27% in relation to the treatment without addition of Si. According to Peixoto et al. [56], application of up to 252.0 g ha^{-1} of Si increased sunflower biomass yield in approximately 37%, even in non-stressed plants. Flores et al. [57] studied sorghum crops and observed improved gas exchanges with application of up to 252.0 g ha^{-1} of Si, increasing biomass yield up to 30% in relation to the control treatment, without addition of Si. Couto et al. [58] studied rice crop under controlled conditions and observed that the foliar silicon application foliar did not increase biomass production. However, doses higher than 252.0 g ha^{-1} of Si reduced biomass in 6% with application of 504.0 g ha^{-1} of Si. The doses recommended in our study corroborate the results obtained with rice crops, suggesting this as the limit dose for foliar application.

According to Felix Alvarez et al. [59] these effects may be related to the product solubility, as more soluble products tend to have better effects regarding plant physiological response, as aforementioned. Despite the scarcity of studies aimed to understand the phenomena associated with foliar silicon application in the rice crop, our study demonstrates that foliar silicon application can be a promising alternative, especially regarding crop grain yield.

When performing economic analysis in relation to Si application to the rice crop, we observed that only the dose of 252.0 g Si ha^{-1} has positive differential profit, approximately US \$ 82.90 ha^{-1}. If we consider rice production systems with high technology, foliar fertilizers are often used to increase crop yields. Studies by Oliveira et al. [12] demonstrated that it is feasible to apply potassium silicate associated with manganese (Mn) in the form of chelates (Mn-EDTA 13%), with stabilizers sorbitol, fulvic acid, and salicylic acid, both for maize and sorghum crops. Guedes et al. [60] also observed the possibility of applying potassium and sodium silicate as Si source together with zinc (Zn), in the form of chelates (Zn-EDTA 14%), with stabilizers sorbitol, fulvic acid, and salicylic acid in the sorghum crop. Therefore, we note that the Si source used in the present study can be associated with other foliar fertilizers, which can reduce the operational costs of application and make Si application economically viable for rice. This is because the cost of three sprays containing Si is US \$ 46.45 ha^{-1} and each spray suppressed saves US \$ 15.48 ha^{-1}. Thus, even if we cannot suppress all sprays, we add up to US \$ 15.48 ha^{-1} to the differential profit of Si application.

5 Conclusion

1. Rice crop production as Si accumulating plant surpassed 10 g kg^{-1} of Si at the 504.0 g ha^{-1} add. But doses superiors to 252.0 g ha^{-1} may present some deleterious effect under crop development and grain yield;
2. The addition of 252.0 g ha^{-1} of Si promotes a higher grain yield with 5778 kg ha^{-1}. This same dose pushed the high differential revenue to the US $ 129.45 per hectare. All these responses are related to the spraying costs.

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Authors' Contributions AFA and AMB led the data analysis and led the writing with input of all co-authors. RAF, KOA, GGS, MM and RMP designed the experiment and provided overall project leadership. AFA, AMB, MAPS and JPSJ grew the plants, applied the treatments and collected data. AFA, AMB, MAPS and JPSJ was responsible for the lab analysis. RAF and RMP provided all structure for the experiment.

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Data Availability Data is available upon request to the correspondence author.

Declarations

Ethics Approval All experiments were conducted ethically and no issues regarding ethical issues arouse during the experiments or the manuscript confection.

Consent to Participate All authors freely agreed and gave their consent to participate on the experiment.

Consent for Publication All authors freely agreed and gave their consent for the publication of this paper.

Conflicts of Interest/Competing Interests There is no conflict of interest.

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