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Research Article

Synergistic Effect of Silica and NPK Fertilizer on Nutrient Status, Chlorophyll Content, and Rice Yield (*Oryza sativa* L.)

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Silica

Abstract: Rice productivity must be increased to meet the high food needs. One of them is by fulfilling nutrients through fertilization. This study aims to evaluate the use of Silica fertilizer on the effectiveness of NPK fertilizer on nutrient status, chlorophyll content, and rice yield. The experimental method with a Complete Randomized Block Design consisting of 9 treatments, namely A = control, B = recommended NPK, C = ¼ NPK + 2.6 kg ha^{-1} SiO_2, D = ½ NPK + 2.6 kg ha^{-1} SiO_2, E = ¾ NPK + 2.6 kg ha^{-1} SiO_2, F = 1 NPK + 2.6 kg ha^{-1} SiO_2, G = ¾ NPK + 0.65 kg ha^{-1} SiO_2, H = ¾ NPK + 1.3 kg ha^{-1} SiO_2, I = ¾ NPK + 1.95 kg ha^{-1} SiO_2. The fertilizers used were Urea, SP-36, KCl, and liquid K_2SiO_3. The study results showed that adding silica fertilizer could improve the effectiveness of NPK fertilizer in rice cultivation. The use of various doses of Si (¼ to 1 dose) and ¾ dose of NPK can increase the effectiveness of NPK fertilizer use, thereby reducing its use. The dose has also been proven to support producing better nutrient status values, chlorophyll levels content and rice yields than recommended NPK.

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1. Introduction

Rice is a staple food for most of the world's population including Indonesia, which ranks fourth after China, India, and Bangladesh (Shahbandeh, 2024). However, Indonesia's rice production in 2023 decreased by 767.98 thousand tons or 1.40% compared to 2022 (Statistic Indonesia, 2024), so several efforts are needed to increase rice productivity. Rice productivity in Indonesia in 2022 was 5.19 tons/ha (PBS, 22) lower than Vietnam at 5.89 tons ha^{-1} (FAO, 2023). However, Indonesia still imported rice reaching 3.48 million tons in 2024 (BPS 2024). Therefore, rice production must continue to be increased through several methods such as the use of superior varieties, pest, disease and weed control, application of cultivation methods and increased use of fertilizers (Jiraporncharoen, 1993).

One of the factors that supports the achievement of high productivity is the availability of nutrients; as stated by Bertham et al. (2022), the need for rice for the N element is 139.17 kg ha^{-1}. The need for phosphorus nutrients is 27 kg ha^{-1} (Jiang et al., 2021), and potassium nutrients are 29.1 – 386.7 kg ha^{-1} (Amin et al., 2019). Since the introduction of synthetic fertilizers, farmers have started using them as a source of NPK and there has been a tendency for the dosage to continue to increase, causing land degradation (Syamsiyah et al., 2023). This condition ultimately causes nutrient imbalances, one of which is in the Si element (Husnain et al., 2016).

The Si element is very abundant in the soil, but most of it is in the form of soil minerals such as feldspar, mica, quartz, and SiO_2, which are not available to plants (Hayati and Astuti, 2015; Amin et al., 2021). This makes using Si fertilizer very important, so it needs to be added. Based on the statement by Jayawardana et al. (2014), potassium silicate fertilizer can source highly soluble Si and K nutrients. The research results by Mini et al. (2023) stated that using of Si fertilizer is still limited and the results are varied. The use of 0.5% Si and NPK gave higher grain yields compared to the results of recommended NPK fertilization. In comparison, according to Shah (2022), the combination of NPK fertilizer and 1% silica increased plant height by 126.4 cm and the number of productive tillers was 185.5 tillers per m^2.

Providing Si to plants also increases chlorophyll content support photosynthesis efficiency thus resulting in the formation of energy as ATP (Silva et al., 2014). Rice is a high silicon accumulating plant, reaching 10% of the dry weight of the plant (Ma and Yamaji, 2006). The research results show that rice plants produce 5.0 tons ha^{-1} of grain, where the rice plants absorb 230 - 470 kg Si ha^{-1} from the soil (Rodrigues and Datnoff, 2005). According to Amrullah et al. (2014) Rice plants absorb Si approximately 10 times N, 20 times P, 6 times K and 30 times Ca. The critical level of Si in soil is 40 mg kg^{-1} and in rice (leaves and straw) 5% (Nagula, et al, 2015).

Silica although not an essential nutrient, is vital for rice plants (Patil et al., 2018), which are required in high amounts of 230–470 kg ha^{-1} (Sabatini et al., 2017). In plants, Si increases rice resistance to biotic and abiotic stresses (Hastuti et al., 2016), increasing N uptake, improving efficiency, and increasing crop yields (Mabagala et al., 2020). The provision of Si accompanied by P fertilization can increase the efficiency of P fertilizer (Singh et al., 2005; Wang et al., 2020) and increase K uptake by rice by 87.32% compared to the control (Nagula et al., 2018). This study aims to evaluate the use of Si fertilizer on the effectiveness of NPK fertilizer on nutrient status, chlorophyll content, and rice plant yields.

2. Material and Methods

2.1. Research site

Field research was conducted in April 2023 - July 2023 in Plupuh, Sragen Regency, Central Java, Indonesia, which is geographically located at 7°28’41.40” S and 110°53’15.08” E with an altitude of 100 m asl, average rainfall in one year 220 mm $month^{-1}$ (Statistic Indonesia, 2023). Laboratory analysis was conducted at the Soil Chemistry and Fertility Laboratory, Universitas Sebelas Maret. The type of soil includes Vertisols with characteristics pH H_2O 7.34, C-organic 1.71%, cation exchange capacity (CEC) 68.27 me 100 g^{-1}, total N 0.25%, available P 3.08 ppm, and available K 0.23 me 100 g^{-1}. Overall, the soil at the research location has a relatively low level of soil fertility (Soil Research Center Indonesia, 1995).

2.2. Sampling techniques

Experimental research with a completely randomized block design consisted of 9 treatments with three replications. Each plot was 3 m x 4 m in size, with a distance between blocks of 60 cm and a distance between plots in each block of 40 cm. The rice variety used was Inpari 32 with characteristics including having a plant age of approximately 120 days, plant height of 97 cm, having moderate resistance to brown stem leafhoppers biotypes 1, 2, and 3, resistant to leaf blight and blast, suitable for planting in lowland rice field up to an altitude of 600 masl (IAARD, 2019). This crop was planted 20 days after sowing with 25 cm x 25 cm distance, and 2 seedlings in each planting hole. Treatments include A = no fertilizer (control), B = recommended NPK (same doses as 1 NPK), C = ¼ NPK + 2.6 kg ha^{-1} SiO_2, D = ½ NPK + 2.6 kg ha^{-1} SiO_2, E = ¾ NPK + 2.6 kg ha^{-1} SiO_2, F = 1 NPK + 2.6 kg ha^{-1} SiO_2, G = ¾ NPK + 0.65 kg ha^{-1} SiO_2, H = ¾ NPK + 1.3 kg ha^{-1} SiO_2, I = ¾ NPK + 1.95 kg ha^{-1} SiO_2, this treatment is in accordance with Minister of Agriculture Regulation no. 13 of 2022. The NPK fertilizer used is Urea 350 kg ha^{-1}, SP-36 50 kg ha^{-1}, KCl 50 kg ha^{-1}, and liquid K_2SiO_3 (K_2O 20.13% and SiO_2 13.80%). The NPK sources were Urea, SP-36, and KCl because these fertilizers are most commonly used by local farmers. Urea fertilizer was applied thrice at 0, 14, and 28 Days After Planting (DAP), while SP-36 and KCl fertilizers were applied once at 0 DAP. Silica fertilizer used is liquid and applied twice at 14 and 28 DAP by spraying it onto the soil. Plant care was carried out according to local farmers' habits.

2.3. Measurement of variables

Soil plant samples were taken at 50 DAP. Soil samples were taken in the area around the roots at a depth of 0-20 cm from the surface, while plant samples used for analysis used leaf tissue. harvesting was done at 93 DAP by cutting the base of the stem and threshing the grain using a thresher machine. The soil parameters observed included total N using the Kjeldahl method (Syamsiyah et al., 2023), available P using the $NaHCO_3$ (Olsen) extraction method (Tang et al., 2014), available K using the ammonium acetate ($NH_4CH_3CO_2$) extraction method (Zhang and Kong, 2014), and available Si using the $CaCl_2$ extraction method (Liang et al., 2015). Plant parameters included tissue N content using the Kjeldahl method (Oksana et al., 2012), tissue P and tissue K using the HNO_3 and $HClO_4$ wet ashing methods (Hazra et al., 2019), tissue Si using the colorimetric method (Pati et al., 2016), and chlorophyll content using the Arnon method (Rajalakshmi and Banu, 2015). Yield components included the number of productive tillers (Saragih and Wirnas, 2019), the weight of 1000 seeds with a water content of 14% (Herve et al., 2017), and the weight of grain at harvest.

2.4. Statistical analysis

Data were analyzed using Analysis of Variance (ANOVA) followed by Duncan's Multiple Range Test (DMRT) with a 95% confidence level to see the difference in influence between treatments, Pearson correlation to see the closeness of the relationship between treatments and the parameters tested, and linear regression to measure the influence of treatments on the parameters tested.

3. Results and Discussion

3.1 NPK and Si content in soil

Table 1. shows that the fertilizer addition treatment significantly affects total N. The addition of Si fertilizer with NPK showed a higher total N than the recommended NPK, although not statistically significant. This result aligns with Samaddar et al. (2019) that the NPK + Si treatment showed a total N that was not significantly different from without Si, but the total N value increased by around 28%. The provision of silica fertilizer with as much as one dose with ¼ to ½ NPK showed an increase in total soil N compared to the recommended NPK, but the results would be higher when given ¾ to 1 dose of NPK. The application of fertilizers such as Urea containing N will cause an increase in nutrients in the soil (Swify et al., 2023) thus creating optimal cultivation practices (Maulana et al., 2024). Silica plays a role in maintaining nutrient availability by reducing the leaching rate (Bocharnikova and Matichenkov, 2010) and increasing the soil exchange capacity so that N is weakly adsorbed on the Si surface and remains in a form available to plants (Matichenkov and Bocharnikova, 2001).

Table 1. Nitrogen, phosphorus, potassium, and silica content in soil

Code	Total N (%)	Available P (ppm)	Available K (me 100 g^{-1})	Available Si (ppm)
A	0.21±0.04 a	3.24±0.01 a	0.25±0.03 a	211.97±7.40 a
B	0.29±0.01 b	3.30±0.03 ab	0.26±0.03 ab	234.08±6.70 bc
C	0.30±0.04 bc	3.44±0.03 b	0.30±0.01 abc	252.62±6.85 e
D	0.30±0.04 bc	3.54±0.07 c	0.27±0.02 ab	228.18±4.05 b
E	0.35±0.02 cde	3.69±0.01 d	0.37±0.00 de	247.92±6.46 de
F	0.39±0.03 e	3.70±0.04 d	0.39±0.04 e	254.02±2.41 e
G	0.36±0.01 de	3.69±0.11 d	0.36±0.06 cde	251.87±2.18 e
H	0.33±0.03 bcd	3.57±0.01 c	0.32±0.03 bcd	224.94±3.43 b
1	0.30±0.03 bc	3.59±0.05 c	0.34±0.04 cde	240.10±5.82 cd

Note: Numbers followed by the same letter in the column show no significant difference at the 5% level.

Available P in the soil is significantly affected by the provision of Si with NPK fertilizer. In general, the availability of P increases along with the increasing dose of NPK fertilizer and the application of several doses of silica fertilizer (0.65 to 2.6 kg ha^{-1}). The increase in available P is due to the provision of SP-36 fertilizer containing P and Si which can mobilize P from the unavailable phase (Schaller et al., 2019). Monosilicic acid ($H_3SiO_4^-$) formed from the provision of silicate fertilizer will compete with $H_2PO_4^-$ in the absorption site, where $H_3SiO_4^-$ can replace $H_2PO_4^-$ so that it can be available to plants (Agostinho et al., 2017). The provision of Si and NPK fertilizers can increase available P by up to 12% compared to fertilization without Si. These results align with Greger et al. (2018), which concluded that Si fertilizer can increase P availability by up to 50%.

Table 1. shows that NPK + Si fertilization significantly increases soil available K. The provision of ¾ doses of NPK fertilizer with various doses of silica fertilizer showed significant and higher available K results compared to the control and recommended NPK. The increase in available K occurs due to the addition of KCl fertilizer and the effect of Si fertilizer on available K. According to Rao et al. (2019) and Al-Shahmani and Al-Juthery (2021), silica will push potassium from the exchange site to the soil solution. The added Si element synergizes with K to replace K from the exchange site to the soil solution (Savant et al., 1996). The highest potassium availability was obtained from the treatment of 1 NPK + 2.6 kg ha^{-1} SiO_2, which resulted in a 50% increase in available K compared to fertilization without silica.

The availability of Si in this study was significantly influenced by NPK and silica fertilization. Table 1. shows that the highest available Si was obtained from 1 NPK + 2.6 kg ha^{-1} SiO_2 treatment. This treatment showed an increase of 19.84% compared to the control and 8.52% compared to the recommended NPK. Increasing the NPK dose from ¼ to 1 total dose with one dose of Si fertilizer (2.6 kg ha^{-1}) showed an increase in the level of available Si, while increasing the dose of silica fertilizer from 0.65 to 2.6 kg ha^{-1} at the same NPK level, namely ¾ dose, resulted in varying levels of available Si. Silica fertilization causes an increase in the concentration of H_4SiO_4 in the soil solution (Tubaῆa and Heckman, 2015). A similar thing was also stated by Schaller et al. (2021) and Rupashinge et al. (2022) that adding Si fertilizer could increase the levels of available Si in the soil.

3.2 Uptake of NPK and Si

Fertilization of Si with NPK resulted in a significant increase in uptake of NPK and Si compared to the control and recommended NPK ($P<0.05$). This is related to the presence of Si, which improves the root system, thus stimulating higher nutrient uptake (Pati et al., 2016). Increased N uptake in rice is due to increased N availability by Si and NPK fertilizers (r=0.712**). Makka et al. (2015) stated that uptake of nitrogen is related to the total N content in the soil. Plants fertilized with Si and N fertilizers cause plant stems to be straighter and receive better sunlight, thus increasing photosynthesis activity (Siam et al., 2018).

Figure 1. shows an increase in P uptake due to adding silica fertilizer, although some Si and NPK + Si fertilization treatments are not significantly different from NPK treatment alone. This increase is related to the increase in available P (r=0.643**) caused by Si, which can help increase soil P availability (Greger et al., 2018). The results also align with research by Schaller et al. (2022) that the addition of Si causes an increase in the concentration of available P to exceed the critical limit of P availability for rice cultivation, which is around 3.5 mg kg^{-1} P.

Potassium uptake is determined by the concentration of K in the soil (r = 0.619**); the higher the concentration, the higher the uptake (Chatterjee et al., 2014). According to Hafez et al. (2021) using additional fertilizer in the form of potassium silicate will increase the source of highly soluble K nutrients; in addition, available K also comes from the KCl fertilizer given. This is in line with the results of research from Nagula et al. (2018) showing that the combination treatment of NPK and spraying potassium silicate can increase K absorption by 87.32% compared to the control.

The data shows that Si uptake tends to increase along with the increase in the dose of Si fertilizer (0.65 to 2.6 kg ha^{-1}) applied and increase in available Si content in the soil. This is reflected in the positive correlation between Si uptake of plants and available Si (r = 0.493**). These results align with Huang et al. (2024) that there is a significant linear correlation between available Si and Si content in plants. According to Pati et al. (2016), the addition of silica fertilizer in a readily available condition causes the nutrients to be ready for plant use.

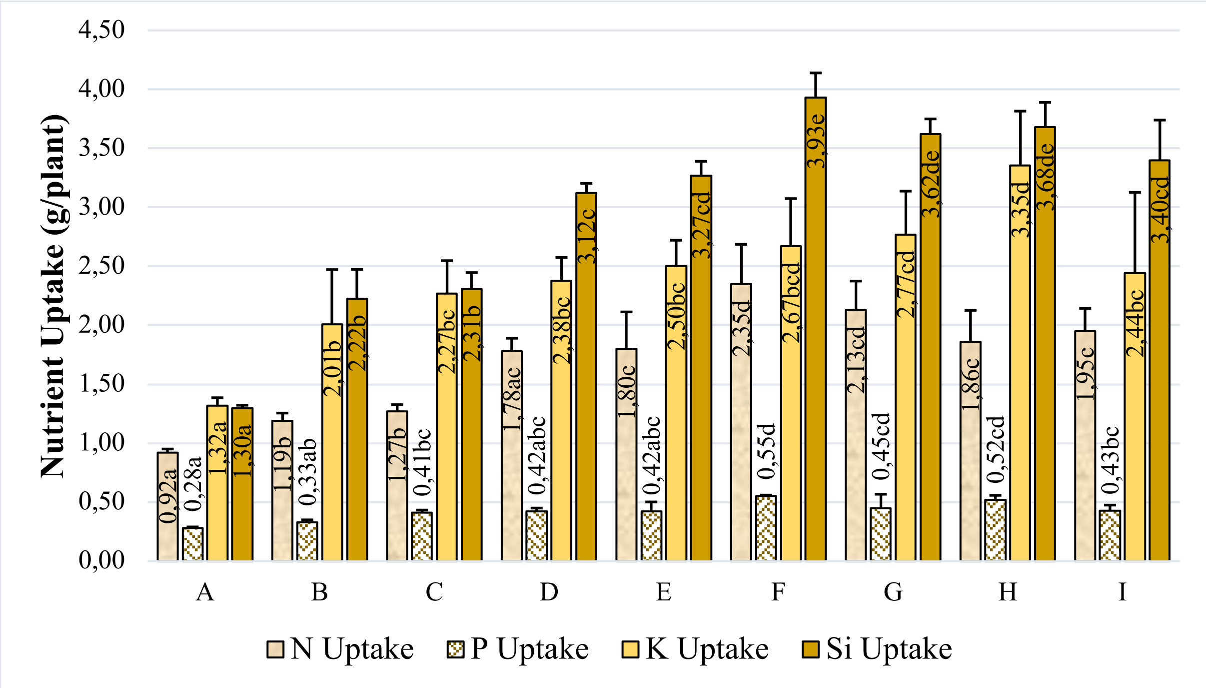

Figure 1. Effect of silica and NPK fertilization on plant nutrient uptake.

	Total N	Available P	Available K	Available Si	N Uptake	P Uptake	K Uptake	Si Uptake
Total N	-							
Available P	0.787**	-						
Available K	0.698**	0.780**	-					
Available Si	0.635**	0.628**	0.644**	-				
N Uptake	0,712**	0.773**	0.795**	0.696**	-			
P Uptake	0.700**	0.682**	0.458*	0.416*	0.703**	-		
K Uptake	0.569**	0.600**	0.619**	0.299	0.620**	0.532**	-	
Si Uptake	0.796**	0.888**	0.666**	0.493**	0.716**	0.814**	0.691**	-

Note: *Correlation is significant at the 0.05 level; **Correlation is significant at the 0.01 level

Figure 2. Relationship between nutrient content in soil and plant nutrient uptake.

3.3 Chlorophyll content and plant yield

Figure 3. shows increased chlorophyll A, B, and total chlorophyll levels (P<0.05). This is due to increased availability and uptake of NPK as an energy source for N transport to leaves (Isnaini and Novitasari, 2020), as well as increasing the quality of chloroplasts by the element K resulting in good grana stacks and expanding the stroma in the lamella with a small amount of starch granules (Zhao et al., 2001). At the same time, Si plays a role in osmoregulation, which fulfills the essential nutrient needs that are important in chlorophyll formation (Zainul et al., 2022). The results showed a linear relationship between NPK and Si uptake with chlorophyll (Figure 4a). Chlorophyll A levels ranged from 1.09 to 1.28 µg ml^{-1}, chlorophyll B ranged from 0.57 to 0.73 µg ml^{-1}, and total chlorophyll ranged from 1.66 to 1.98 µg ml^{-1} (Table 2). These results align with Ramirez-Olvera et al. (2021) that applying Si fertilizer will increase chlorophyll levels, both chlorophyll A, B, and total chlorophyll.

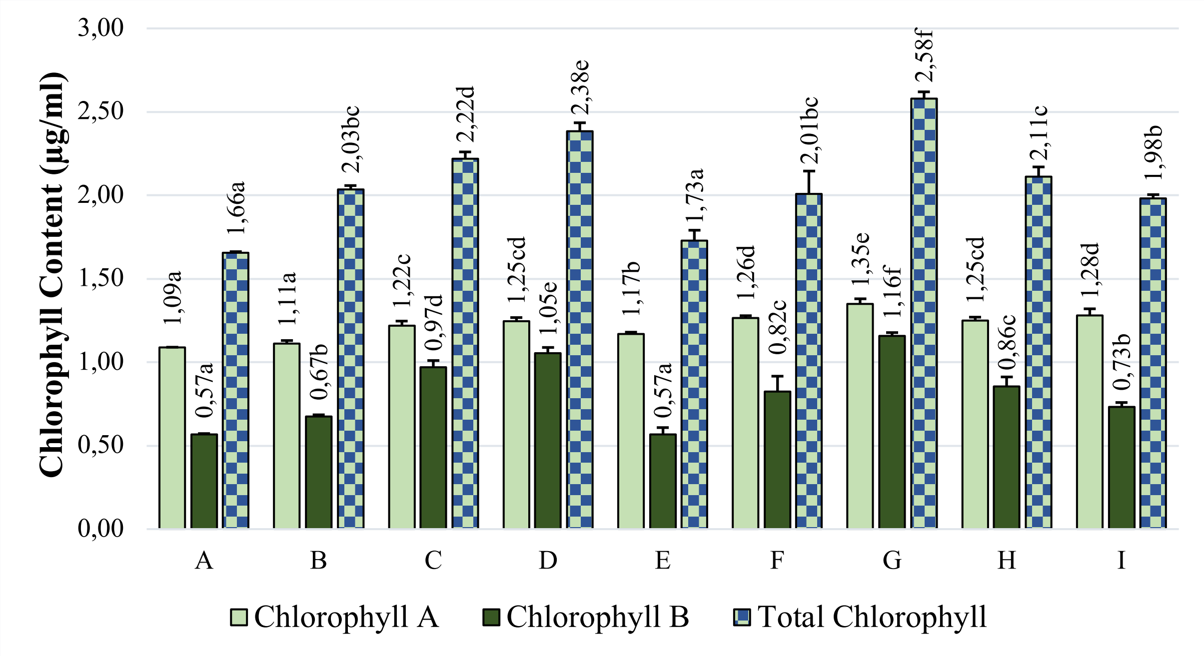

Figure 3. Chlorophyll A, B, and total chlorophyll levels in various treatments.

Table 2. Number of productive tillers (tillers per clump), weight of 1000 seeds (gram), and weight of grain (ton ha^{-1}) from Si and NPK fertilizer treatments

Code	Number of Productive Tillers	Weight of 1000 Seeds	Weight of Grain
A	14.87±2.01 a	21.52±0.48 a	3.42±0.45 a
B	21.80±1.83 b	23.31±1.42 b	5.28±0.91 b
C	26.60±3.42 bcd	23.83±0.72 b	5.27±0.42 b
D	23.93±3.20 bc	24.66±1.05 b	5.63±0.44 bc
E	29.53±3.52 cd	24.44±0.14 b	5.73±0.75 bc
F	31.00±3.67 d	25.03±0.65 b	6.66±0.68 c
G	30.27±2.08 cd	24.58±0.90 b	5.79±0.59 bc
H	29.60±3.14 cd	23.93±1.69 b	5.35±0.93 b
I	29.93±5.90 cd	23.71±0.46 b	5.32±0.11 b

Note: Numbers followed by the same letter in the column show no significant difference at the 5% level.

The application of Si fertilizer together with NPK fertilizer significantly increased the number of productive tillers, the weight of 1000 seeds, and the weight of grain (Table 2) compared to control. The formation of optimal productive tillers will support the seed filling process effectively, and can contribute to increasing the weight of 1000 seeds as an indicator of the quality and weight of grain. Results revealed that increasing the availability and uptake of NPK and Si elements from Si and NPK fertilizers significantly supports rice yields. Uliyah et al. (2017) states that the amount of nutrient absorption is closely related to the weight of the plants produced. This is align with Basha et al. (2013), which states that the application of silica can affect in NPK uptake, thus affecting the accumulation of protein in seeds and straw. These elements play an essential role in plant growth and production. The N element can stimulate tiller growth through the formation of hormones and enzymes (Widodo and Damanhuri, 2021), P plays a role in root formation and increasing the number of tillers (Rosalina and Nirwanto, 2021). Potassium increases productive tillers because it stimulates ATPase, an enzyme that plays a crucial role in plant growth and development (El-Mageed et al., 2023). At the same time, Si is needed in the cell division process (Hasmeda et al., 2023), thus encouraging the formation of productive tillers. The relationship between nutrients uptake and production components is presented in Figures 4b, 4c, and 4d. which show a linear relationship between uptake of nutrients and grain weight. Based on Figure 4, it is known that Si plays an important role in influencing the number of productive tillers, weight of 1000 seeds, and weight of grain, which are respectively 82.64%, 75.04%, and 71.88%. Silica application can increase productive tillers and grain yield by 28.23% compared to without Si addition (Dehaghi et al., 2018). The increased grain yield in this study is in line with research by Wissa et al. (2017) that silica plays a role in meeting rice nutrient needs and supporting productive growth, thereby maximizing grain yield.

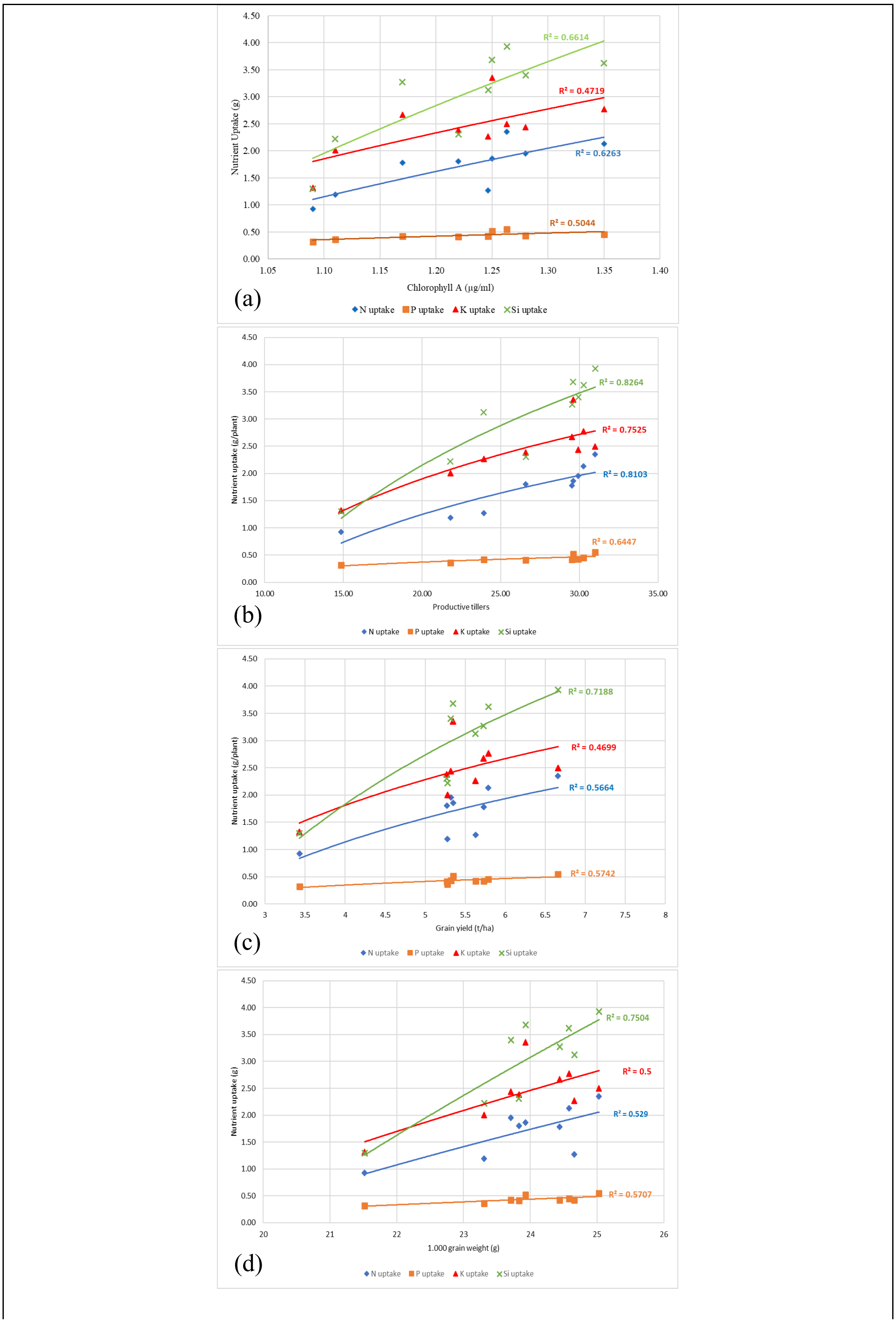

Figure 4. Regression analysis between nutrients uptake and chlorophyll content (a), productive tillers (b), grain yield (c), and 1 000 grain weight (d).

Conclusion

Adding Si fertilizer can improve the availability and uptake of nutrients, as well as crop yields. The use of various doses of Si (¼ to 1 dose) and ¾ dose of NPK can increase the effectiveness of NPK fertilizer use, thereby reducing its use. The dose has also been proven to support producing better nutrient status values, chlorophyll levels content, and rice yields than recommended NPK. To maintain the sustainability of rice productivity, Si fertilizer needs to be given continuously so that farmers can benefit from it.

Ethical Statement

Ethical approval was not required for this study as there was no specific type of research involving humans or animals.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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Author Contributions

The first and second authors as research supervisors, outlined the framework of the research task. The third and fourth authors provided input to present the findings. The fifth and sixth authors conducted the research and analyzed the data and drafted the manuscript. The seventh and eighth authors provided additional feedback and refined the manuscript.

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