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Research Article

Silicon priming enhances growth and photosynthetic pigments in rice plants under drought stress

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ABSTRACT

Rice (Oryza sativa L.) variety 'Inpari 24 Gabusan' offers high nutritional value and a short growth cycle that is ideal for further development. This study aimed to assess the effect of silicon priming on the growth and photosynthetic pigments of rice 'Inpari 24 Gabusan' during the vegetative stage under drought conditions. A completely randomized design (CRD) was used with two factors: sodium metasilicate (Na_2SiO_3) concentrations (0 mM, 20 mM, 40 mM, and 60 mM) and field water capacity (100, 75, and 50%). Germination parameters (percentage and rate of germination, and seed vigor index) and vegetative parameters (plant height, leaf number, root length, biomass) were measured. Leaf chlorophyll and carotenoid content were also assessed. Results showed that silicon priming increased the germination rate from 57.17% at 0 mM to 63.83% at 60 mM. Seed vigor index significantly improved at 60 mM. However, sodium metasilicate concentration had no significant effect on the percentage of germination. Priming at 40 mM and 60 mM significantly enhanced growth and chlorophyll content, particularly at 100% and 75% field capacity. Under 50% field capacity, growth improvements were more limited due to water deficit. Higher sodium metasilicate concentrations also enhanced chlorophyll content, improved photosynthetic efficiency and drought tolerance.

Keywords: carotenoid; chlorophyll; field capacity; germination; sodium metasilicate

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INTRODUCTION

Rice (*Oryza sativa* L.) is a staple food source for the majority of the Indonesian population. 'Inpari 24 Gabusan' is a local red rice variety from the Special Region of Yogyakarta (DIY), it has superior character, e.g., soft rice texture, and has essential nutrients of anthocyanins, amylose, and vitamin B1 (Romdon et al., 2014). Furthermore, the variety is resistant to several diseases, such as bacterial leaf blight pathotypes III and IV (DPKP DIY, 2012). However, its sensitivity to drought remains a problem in cultivation, particularly in areas with limited water availability.

The problem of water availability escalates due to the negative impact of climate change, in which frequent drought, extreme temperatures, and extreme weather affect the growth and development of rice. Purwono et al. (2021) note that rice genotypes determine the response to incidents of climate change. It has been known that long-term drought conditions can reduce seed vigor, decrease tolerance to environmental stresses, and ultimately diminish crop productivity.

Drought is a condition in which plants experience a water deficit due to limited water availability from growing media (Dewi et al., 2019), and it is one of the most damaging abiotic stresses for plants, particularly for rice, which requires a constant water supply. Drought induces morphological and physiological changes in plants, including reduced plant height, stomatal conductance, leaf elongation, lower dry biomass, and increased leaf senescence (Ali et al., 2021). In rice, drought is characterized by decreased grain size and weight, disrupted floret initiation, increased spikelet sterility, and reduced productivity. Additionally, drought also disrupted enzymes' activity involved in starch synthesis and assimilate partitioning (Dar et al., 2020). Furthermore, drought stress leads to a decline in chlorophyll a, b, and total chlorophyll due to the accumulation of H_2O_2 in the stroma, causing impaired growth of shoots and roots, reduced biomass production, and potentially resulting in plant death (Miftahudin et al., 2020; Ulfianida & Rachmawati, 2024).

Various techniques have been developed to enhance plant tolerance to unfavorable environmental conditions, such as priming. Priming is a technique that controls seed hydration by stimulating pre-germination metabolic processes, such as increased water imbibition and activation of hydrolytic enzymes to accelerate germination and develop vigorous seedlings. Priming enhances the antioxidant system, minimizes abiotic stress, and speeds up the germination phase by increasing the activity of protease, lipase, and amylase enzymes to support embryonic growth (Ali et al., 2021). Priming can also shorten the growth phase, reduce water requirements, and decrease the costs of seed and fertilizer purchases. Seed priming controls hydration, initiating normal metabolic processes during early germination before radicle protrusion (Johnson & Puthur, 2021; Lutts et al., 2016). It enhances rice seed tolerance during germination and growth by increasing α-amylase activity and soluble sugar content (Nie et al., 2022), accelerating germination and seedling emergence even under extreme climatic conditions and problematic soils (Devika et al., 2021). Additionally, priming stimulates protein synthesis by increasing rRNA production and improving ribosome integrity, while also promoting antioxidant enzyme activity, including superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), to maintain a balance between ROS generation and elimination under stress conditions (Farooq et al., 2017; Wojtyla et al., 2016). Seed priming enhances the speed and uniformity of germination, leading to improved seedling emergence and establishment, which is crucial for crops under stress conditions as rapid establishment increases survival rates (Farooq et al., 2019). By accelerating germination and ensuring uniform seedling growth, priming reduces the need for reseeding and excessive fertilizer use, minimizing seed wastage and lowering production costs. Additionally, primed seeds develop better root systems, allowing for more efficient nutrient uptake, which can improve crop yields with reduced fertilizer inputs (Devika et al., 2021). Primed plants exhibit greater resilience to abiotic stresses such as drought and salinity, as well as biotic stresses like pests, reducing the risk of crop failure and making seed priming a valuable agricultural strategy (Devika et al., 2021; Habibi et al., 2023; Nile et al., 2022). Furthermore, priming helps maintain seed vigor and viability, which influences the success of germination and plant development under various environmental conditions (Finch-Savage & Bassel, 2016; Mangena, 2020).

Silicon, as a functional nutrient, has been shown to enhance plant resistance to both biotic and abiotic stresses, including drought (Koentjoro et al., 2022). Previous research indicates that silicon strengthens plant cell walls (Khan & Gupta, 2018), improves antioxidant capacity (Wicaksono et al., 2017), and helps plants regulate water use efficiently during drought periods (Pereira et al., 2021). In addition to stimulating the production of antioxidant compounds, silicon can enhance nutrient absorption, which may reduce oxidative damage to plants (Ali et al., 2021). Therefore, the application of silicon priming is expected to improve rice tolerance to drought and optimize its growth.

This study aimed to assess the effect of silicon priming on the growth and photosynthetic pigments of rice 'Inpari 24 Gabusan' during the vegetative stage under drought conditions. The findings of this research might contribute to enhancing rice productivity, particularly for the rice 'Inpari 24 Gabusan', through the development of adaptive methods that support plant resilience to drought.

MATERIALS AND METHODS

Research site

The research was conducted in July 2024 at the Plant Physiology Laboratory, Faculty of Biology, Universitas Gadjah Mada, DI Yogyakarta, Indonesia. Rice seeds (Inpari 24 Gabusan) were obtained from the Ngudi Makmur II Farmers Group in Yogyakarta. Sodium metasilicate (Na_2SiO_3) (Sigma Aldrich) was used as the priming agent containing silicon (Si).

Treatment procedure

The experiment was arranged using a completely randomized design with two factors: Na_2SiO_3 concentrations (0, 20, 40, and 60 mM) and drought as represented by field capacity levels (100%, 75%, and 50%). Each treatment combination was replicated three times. Field capacity refers to the amount of maximum water retention by soil after excess water has drained away due to gravity (Cahyanti et al., 2023). Field capacity was calculated using two methods: Air-Dry Moisture Content (ADMC) and Field Capacity Moisture Content (FCMC). FCMC was determined by oven-drying a soil sample to obtain its dry weight (A), while ADMC was obtained by rewetting an air-dried soil sample and then oven-drying it again (B). The amount of water required to achieve 100% field capacity was calculated using the formula 100% = B-A. Based on this calculation, the water volume required for 100%, 75%, and 50% field capacities were determined as 800 mL, 600 mL, and 400 mL, respectively.

Germination experiment

Na_2SiO_3 was diluted using double-distilled and deionized water (ddH_2O) according to concentration treatment. A hundred rice seeds were soaked in a beaker glass containing 100 mL Na_2SiO_3 solution for eight hours at room temperature (27 °C). The beaker glass was covered with a thin paper to prevent contamination. After soaking, the seeds were air-dried for 24 hours before measurement.

The seeds were weighed to evaluate the amount of water absorption. Then, it was germinated in petri dishes with Whatman No. 1 paper and water. Each treatment of Na_2SiO_3 was replicated four times, with 25 rice seeds in each replication.

The observation included germination percentage, germination rate, and seed vigor index. Germination percentage (%) was calculated using the formula of Tefa (2017). Germination percentage (GP) was calculated as:

$GP = \frac{\sum NS}{\sum total\ seeds} \times 100\%$; GP: germination percentage, NS: normal seedling

The germination percentage was observed when the control treatment reached 75%–100% germination. Thus, germination observations were carried out for three days.

Germination rate (%/etmal) was calculated daily for 3 days on normal germinated seeds using the formula of Tefa (2017). Normal seedling was determined as germinated seed with complete structures of plumula, coleoptile, mesocotyl, and radicle. Germination rate (Kct) was calculated as:

$$Kct = \sum_{0}^{tn} N/t$$

Description:

t = Observation time/counting day (i)

N = Germination percentage (%) per day

tn = Final observation time (day 3)

1 *etmal* = 1 day

Seeds Vigor index (%) was calculated based on the number of normal seedlings in the first count using the formula of Tefa (2017). Vigor index (VI) was calculated as:

$$VI\ (\%) \frac{\sum normal\ seedlings\ on\ first\ count\ (day\ 2)}{\sum total\ seeds} \times 100\%$$

Drought treatment

Primed rice seeds according to treatments were sown and maintained in seedling tray for one week. The normal seedlings were than transplanted into a growing media consisting 5 kg of loam soils in polybags. Drought treatments according to field capacities of 100%, 75%, and 50% were applied starting at 7 days after transplanting until 42 days after treatment. Each treatment combination used 10 polybags and was repeated three times, thus in total 360 polybags were used.

Plant growth was evaluated weekly for plant height and leaf number, while the other variables were evaluated at 42 days after priming (DAT) or 28 days after priming for root length, fresh weight, and dry weight of roots and shoots, chlorophyll, and carotenoid contents. Chlorophyll and carotenoid content (mg g^{-1} fresh weight) were determined using a colorimetric method with a spectrophotometer at wavelengths of 470 nm, 645 nm, and 664 nm (Yoshida et al., 1976).

Data analysis

Data analysis was performed using ANOVA (analysis of variance) at α = 5%. For any significant differences of variables by treatments, Duncan's Multiple Range Test (DMRT) was conducted at α = 5% significance level.

RESULTS AND DISCUSSION

Germination

The germination percentage of control seeds was 90%, while seeds treated with 60 mM sodium metasilicate reached 100% germination within three days (Figure 1). This result emphasized the potential of silicon priming to accelerate the germination process under optimal conditions. All germinated seeds displayed normal development, as indicated by the presence of well-formed plumula and radicles, which meet the criteria for normal seedlings (Figure 2). Based on the observations on day 3, the seedlings up to the transplanting stage exhibited normal characteristics. This implies that the root system functioned properly, facilitating the nutrient absorption necessary for vegetative growth (Ouji et al., 2015).

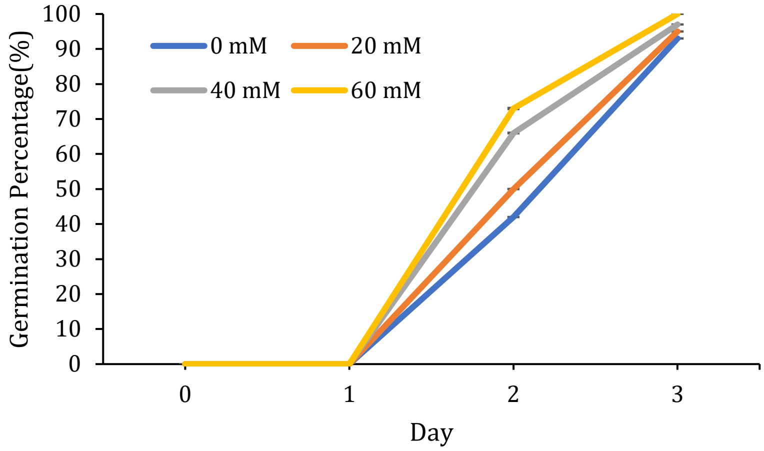

Figure 1. Germination percentage of 'Inpari 24 Gabusan' rice seeds after sodium metasilicate priming treatment.

Figure 1 shows that the germination percentage increased with the addition of Na_2SiO_3 priming concentration from day 0 to day 3 of observation. The germination percentage reached over 75% on day 3, with the highest germination percentage observed at Na_2SiO_3 priming concentrations of 60 mM, which was 100%.

Application of Na_2SiO_3 priming from 0 to 60 mM did not affect the germination percentage in rice 'Inpari 24 Gabusan' (Table 1). The germination rate increased by increasing Na_2SiO_3 concentration from 0 to 60 mM. The germination rate at 0 mM was significantly lower compared to 40 and 60 mM, indicating that higher concentrations of Na_2SiO_3 stimulated seedling growth. However, no significant differences were observed between the 40 mM and 60 mM concentrations. These findings suggest that silicon plays a role in enhancing germination capacity, such ability may be related to higher water absorption as stated by Amin et al. (2023).

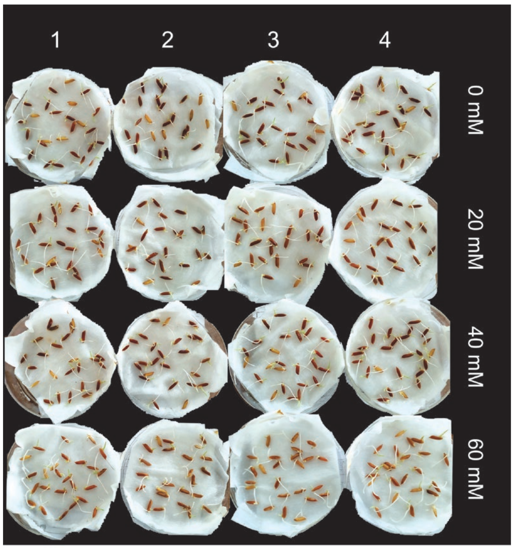

Figure 2. Rice seed germination at 3 days after imbibition from different Na_2SiO_3 priming concentrations.

Table 1. Germination characteristics of 'Inpari 24 Gabusan' rice seeds from different Na_2SiO_3 priming concentrations.

Variable	Na_2SiO_3 priming concentration				Sig.
	0 mM	20 mM	40 mM	60 mM	
Germination percentage (%)	93.00 ±1.26b	95.00±0.96ab	97.00±0.96ab	100.00±0.00ab	ns
Germination rate (%/day)	52.00±0.03c	56.67±0.04bc	65.33±0.06ab	69.83±0.10a	*
Seed vigor index (%)	42.00±0.05c	50.00±0.07bc	66.00±0.12ab	73.00±0.20a	*

Note: Values in the same row followed by the same letter are not significantly different based on the DMRT test α = 5%; *: significant at α = 5% level, ns: not significant.

Priming with Na_2SiO_3 significantly improved the germination rate and seed vigor index (Table 1); the improvement is likely due to the role of silicon in enhancing cell membrane integrity (Koentjoro et al., 2022) and reducing water loss (Ahmed et al., 2013). Priming also might stimulate physiological processes during germination, resulting in a more even germination rate. Although all priming concentrations provided a very high germination percentage (93.00%-100.00%), no significant differences were found among treatments, indicating that Na_2SiO_3 priming did not directly affect the seed germination percentage. Moreover, the vigor index significantly increased with rising sodium metasilicate concentrations from 42.00% at 0 mM to 73.00% at 60 mM. These results indicated that silicon plays a role in improving plant water status and nutrient absorption (Parveen et al., 2019), which in turn strengthens seed vigor.

Growth responses

The growth of 'Inpari 24 Gabusan' rice plants significantly declined as field capacity decreased, while priming treatments with sodium metasilicate could enhance plant growth. The dynamics of plant height growth are one indicator of drought occurrence in rice plants. Drought, due to decreased water availability, results in a decrease in photosynthesis and plant growth, leading to suboptimal growth (Miftahudin et al. 2020).

Table 2 shows that plant height tended to decrease by decreasing field capacity. A field capacity of 50% exerts greater water stress, resulting in stomatal closure and reduced plant height (Anggraini et al., 2016). Priming enhances plant height, especially at a concentration of 60 mM, resulting in greater plant height irrespective of field capacity. Silicon allows plants to adapt to abiotic stresses such as drought by strengthening cell walls, reducing transpiration, and enhancing water absorption (Chen et al., 2011; Ahmed et al., 2013). Additionally, silicon maintains chloroplast structure and mitigates the negative effects of oxidative stress (Wang et al., 2019).

Table 2. Plant height and leaf number of rice 'Inpari 24 Gabusan' from different Na_2SiO_3 priming concentrations and field capacities at 42 days after treatment.

Field capacity	Na_2SiO_3 priming concentrations			
	0 mM	20 mM	40 mM	60 mM
	Plant height (cm)			
100%	73.33±0.72e	78.67±0.76b	79.83±0.76b	82.50±0.50a
75%	67.83±0.76h	72.67±1.53e	74.67±0.76d	77.00±0.50c
50%	65.83±0.76i	70.00±0.50g	71.00±0.50fg	72.00±0.50ef
	Leaf number			
100%	10.0±1.0def	10.7±0.6cde	13.0±1.7ab	13.3±0.6a
75%	8.0±1.0f	9.0±1.0ef	12.7±1.2abc	13.3±2.1a
50%	6.0±1.0g	9.0±1.0ef	11.0±1.0bcde	11.7±1.2abcd

Note: Values in the same variable followed by the same letter are not significantly different based on the DMRT test α = 5%.

The interaction between field capacity and Na_2SiO_3 concentration indicates that at 100% field capacity, the application of Na_2SiO_3 from 0 mM to 60 mM gradually increased plant height. However, at 50% field capacity, although plants from treatment 60 mM Na_2SiO_3 still had the tallest canopy, the differences between 40 mM and 20 mM concentrations were not significant. This is due to the severe drought conditions that alter cell membrane permeability, which in turn affects metabolic processes and cell growth, including cell division and elongation (Salsinha et al., 2020).

Field capacity and Na_2SiO_3 concentration significantly influence the number of leaves (Table 2). Table 2 shows that the highest number of leaves was achieved at 100% field capacity with 60 mM Si concentration (13.3 leaves), while the lowest number of leaves was at 50% field capacity with 0 mM Si concentration (6.0 leaves). The reduction in leaf number occurs at lower field capacities, particularly with low Si concentrations, as optimal water availability supports leaf growth (Jafar et al., 2013; Ihsan et al., 2024). Water plays a crucial role in dissolving nutrients and supporting photosynthesis, which impacts leaf growth (Buntoro et al., 2014; Ihsan et al., 2024). However, at 50% field capacity, the increase in Si from 40 mM to 60 mM did not significantly enhance leaf number; it is probable that 50% field capacity has over drought limits for rice growth (Chen et al., 2018; Salsinha et al., 2020).

Overall, field capacity and Na_2SiO_3 concentration enhance the number of leaves, particularly at higher field capacities (Table 2). The increase in Si priming concentration from 0 mM to 60 mM supported leaf growth at all field capacity levels, except at 50% field capacity, where concentration of 40 mM to 60 mM did not improve leaf number. Statistically, similar trends were observed at both 75% and 100% field capacity, with no significant differences between the 40 mM and 60 mM concentrations. However, at 100% field capacity, the 60 mM concentration exhibited the greatest effect on leaf growth. This positive effect is attributed to the role of Si in maintaining cell membrane integrity, increasing membrane fluidity, lowering transpiration, and stimulating leaf cell division and elongation processes (Zainul et al., 2022).

Root length is one of the key parameters in evaluating a plant's ability to absorb water and nutrients from the soil. Different concentrations of silicon priming had significant effects on root length (Table 3 and Figure 3). Silicon functions as an important element that serves as a protective agent for plants against various abiotic stresses, including drought, salinity, and pathogen attack (Zainul et al., 2022).

The interaction between field capacity and Si concentration showed a synergistic effect, where without silicon (0 mM) rice root was shorter compared to silicon treatments (Table 3). At 50% field capacity and 60 mM, root length reached 32.50 cm, demonstrating that silicon helps plants cope with water stress (Siregar & Yusuf, 2020). Silicon also improves root morphology, increases root surface area, and enhances nutrient uptake efficiency, which is crucial for plant adaptation to soil stress conditions (Etesami & Jeong, 2018; Gao et al., 2005). Overall, silicon plays a key role in supporting root growth and enhancing the plant's ability to withstand environmental stresses (Parveen et al., 2019).

Table 3. Root length of rice 'Inpari 24 Gabusan' from different Na_2SiO_3 priming concentrations and field capacities at 42 days after treatment.

Field capacity	Root length (cm)			
	0 mM	20 mM	40 mM	60 mM
100%	14.00±1.00h	21.83±0.29f	27.93±0.40d	30.50±0.50b
75%	18.83±0.29g	22.67±0.15e	28.40±0.36cd	31.17±0.29b
50%	21.17±0.29f	23.07±0.12e	29.03±0.15c	32.50±0.50a

Note: Values followed by the same letter are not significantly different based on the DMRT test α = 5%.

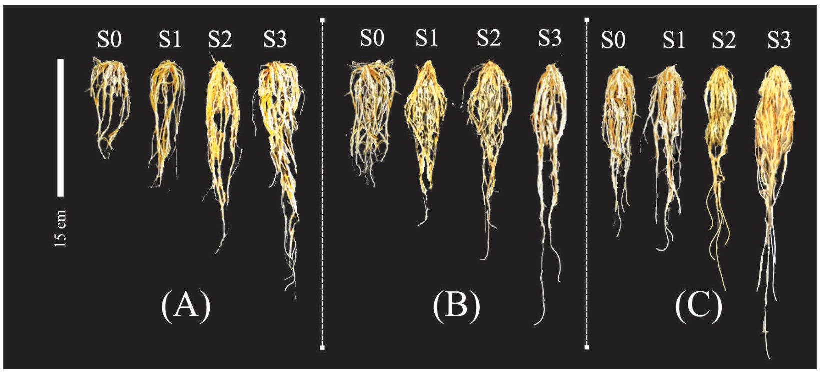

Figure 3. Root morphology of 'Inpari 24 Gabusan' rice from different Na_2SiO_3 priming concentrations and field capacities at 42 days after treatment; (A) 100% field capacity, (B) 75% field capacity, (C) 50% field capacity; S0= 0 mM, S1 = 20 mM, S2 = 40 mM, S3 = 60 mM Na_2SiO_3. Bar = 15 cm.

Increasing silicon priming concentration improved the dry weight of shoots and roots (Table 4). It seems that silicon supports root growth, especially in plants experiencing drought, by enabling the roots to reach deeper soil layers to obtain water. With sufficient water availability, the growth rate of plants increases, primarily through optimal photosynthesis, as indicated by the increased dry weight of both shoots and roots, even under drought conditions (Bijanzadeh et al., 2019; Wang et al., 2021).

Low water availability negatively affects the fresh weight of shoots and roots (Table 4). A shortage of water might limit nutrient absorption and inhibit photosynthesis, resulting in decreased plant growth. This leads to a reduction in biomass, including fresh weight of shoots and roots (Aslanpour et al., 2019; Seleiman et al., 2021). Silicon protects photosynthetic pigments, improves membrane stability, and enhances the photosynthesis rate, leading to higher biomass accumulation, as seen in the increased fresh weight of shoots and roots (Ebeed et al., 2023).

The reduction in photosynthates due to water shortage also causes a decrease in the dry weight of roots and shoots, as the limited photosynthates restrict the formation of plant biomass (Melandri et al., 2021). Increasing silicon priming concentration can mitigate this condition by facilitating deeper root growth to absorb water, thereby increasing the dry weight of roots and shoots, even under drought conditions (Bijanzadeh et al., 2019; Wang et al., 2021).

Table 4. Fresh and dry weight of shoot and roots of rice 'Inpari 24 Gabusan' from different Na_2SiO_3 priming concentrations and field capacities at 42 days after treatment.

Field capacity	Na_2SiO_3 priming concentration			
	0 mM	20 mM	40 mM	60 mM
	Shoot fresh weight (g)			
100%	6.46±0.06e	6.82±0.06d	7.26±0.04c	7.71±0.08a
75%	5.06±0.04h	5.51±0.04g	5.73±0.07f	7.38±0.07b
50%	3.30±0.04j	4.43±0.06i	4.49±0.07i	5.65±0.04f
	Shoot dry weight (g)			
100%	2.33±0.27ef	2.95±0.26cd	3.35±0.07abc	3.72±0.39a
75%	1.98±0.23fg	2.76±0.17de	3.19±0.31bcd	3.48±0.29ab
50%	1.61±0.33g	1.95±0.08fg	2.99±0.30bcd	3.39±0.26abc
	Root fresh weight (g)			
100%	0.81±0.01k	2.23±0.03h	3.03±0.03g	5.53±0.03c
75%	1.53±0.03j	3.03±0.03g	4.53±0.03e	6.53±0.03b
50%	2.03±0.03i	4.03±0.03f	5.03±0.03d	7.03±0.03a
	Root dry weight (g)			
100%	0.19±0.01g	0.18±0.04g	0.45±0.00d	0.43±0.02d
75%	0.19±0.00g	0.24±0.01f	0.51±0.04c	0.47±0.02cd
50%	0.26±0.01f	0.35±0.02e	0.58±0.01b	0.67±0.05a

Note: Values in the same variable followed by the same letter are not significantly different based on the DMRT test α = 5%.

Chlorophyll and carotenoids

The chlorophyll a, b, and total content, and carotenoid content increased with higher silicon priming concentrations, especially at higher field capacities (100% and 75%) (Table 5). However, the 20 mM concentration did not result in a significant enhancement at 50% field capacity. The significant increase in chlorophyll content at higher concentrations indicates that silicate provides adaptive benefits to rice plants under low soil moisture conditions.

Table 5. Chlorophyll and carotenoid contents in leaves of rice 'Inpari 24 Gabusan' from different Na_2SiO_3 priming concentrations and field capacities at 42 days after treatment.

Field capacity	Na_2SiO_3 priming concentration			
	0 mM	20 mM	40 mM	60 mM
	Chlorophyll a (mg g^{-1})			
100%	1.55±0.01f	1.89±0.05d	2.29±0.05b	2.39±0.02a
75%	1.45±0.01g	1.73±0.01e	1.85±0.01d	1.96±0.02c
50%	1.38±0.02h	1.12±0.00i	1.85±0.06d	1.87±0.04d
	Chlorophyll b (mg g^{-1})			
100%	0.41±0.01fg	0.48±0.04de	0.64±0.05b	0.97±0.01a
75%	0.30±0.01h	0.49±0.04cde	0.37±0.03gh	0.45±0.04ef
50%	0.31±0.01h	0.94±0.04a	0.55±0.02c	0.52±0.06cd
	Total chlorophyll (mg g^{-1})			
100%	1.95±0.01f	2.36±0.03c	2.92±0.05b	3.36±0.00a
75%	1.74±0.02g	2.22±0.03d	2.39±0.03d	2.40±0.04c
50%	1.68±0.03h	2.05±0.04e	2.24±0.04c	2.38±0.03c
	Carotenoids (mg g^{-1})			
100%	0.51±0.00e	0.61±0.02c	0.75±0.04a	0.61±0.01c
75%	0.47±0.02f	0.56±0.01d	0.63±0.02c	0.69±0.02b
50%	0.45±0.00f	0.45±0.02d	0.57±0.00d	0.55±0.04d

Note: Values in the same variable followed by the same letter are not significantly different based on the DMRT test α = 5%.

Chlorophyll a is generally increases with higher field capacity (Table 5). However, at 20 mM in 50% field capacity, chlorophyll b is significantly increased and decreased at 40 and 60 mM. This anomaly is still unclear. It might indicate a temporary adaptive response, where the plant stimulates chlorophyll b synthesis to optimize light absorption under water stress conditions. High silicon concentration might alter chlorophyll biosynthesis; unfortunately, silicon level in leaves was not evaluated. Silicon helps maintain chlorophyll content even under stress, improves photosynthetic efficiency, and protects pigments from oxidative damage (Nurjanaty et al., 2019; Utami et al., 2020). Moreover, silicon is known to increase plant resistance to abiotic stress by enhancing the synthesis of photosynthetic pigments, including chlorophyll and carotenoids (Utami et al., 2020).

Silicon might enhance activity of enzymes involved in the synthesis of photosynthetic pigments, as indicated by increasing carotenoids from Na_2SiO_3 treatments (Table 5). This includes increasing carotenoid levels, which protect chlorophyll from damage caused by UV radiation and reactive oxygen species (Putri et al., 2017; Tampoma et al., 2017). The increase in carotenoid levels in response to silicon application indicates that silicon may be involved in water stress mechanism in rice.

To quantify the effect of treatment, a single effect of treatment was evaluated. Table 6 shows that all growth and pigment features were featured by the interaction of silicon concentration and field capacity levels. Increasing Na_2SiO_3 concentration increased all growth parameters, such as plant height increased by 11.84% from control to 60 mM.

Table 6. Growth characters and photosynthetic pigments of rice treated with Na_2SiO_3 and drought levels.

Source of variation	Plant height (cm)	Roots length (cm)	Shoot FW (g)	Shoot DW (g)
Na_2SiO_3(S)	*	*	*	*
0 mM	69.00d	18.00d	4.94d	1.97d
20 mM	73.78c	22.52c	5.58c	2.56c
40 mM	75.17b	28.46b	5.83b	3.18b
60 mM	77.17a	31.39a	6.91a	3.53a
Field capacity (D)	*	*	*	*
100% (full water)	78.58a	23.57c	7.06a	3.09a
75%	73.04b	25.27b	5.92b	2.86b
50%	69.71c	26.44a	4.47c	2.49c
S×D	*	*	*	ns

Source of variation	Root fresh weight (g)	Root dry weight (g)	Leaves number	Chl a (mg g^{-1})
Na_2SiO_3 (S)	*	*	*	*
0 mM	1.45d	0.21c	8.0c	1.46d
20 mM	3.09c	0.26b	9.6b	1.58c
40 mM	4.19b	0.51a	12.2a	2.00b
60 mM	6.36a	0.52a	12.8a	2.07a
Field capacity (D)	*	*	*	*
100% (full water)	2.89c	0.31c	11.8a	2.03a
75%	3.9b	0.35b	10.8b	1.75b
50%	4.53a	0.46a	9.4c	1.55c
S×D	*	*	*	*

Source of variation	Chl b (mg g^{-1})	Chl total (mg g^{-1})	Carotenoid (mg g^{-1})
Na_2SiO_3 (S)	*	*	*
0 mM	0.34d	1.79d	0.47d
20 mM	0.64c	2.21c	0.54c
40 mM	0.52b	2.52b	0.65b
60 mM	0.65a	2.71a	0.62a
Field capacity (D)	*	*	*
100% (full water)	0.63a	2.65a	0.62a
75%	0.4b	2.19b	0.59b
50%	0.58c	2.09b	0.50c
S×D	*	*	*

Note: Values in the same column and factor followed by the same letter are not significantly different based on the DMRT test α = 5%. SxD: interaction of Na_2SiO_3 and drought; *: significant at α = 5% level, ns: non-significant; FW-fresh weight, DW-dry weight

Table 6 showed total chlorophyll increased from 1.79 at 0 mM to 2.71 at 60 mM, indicating that silicon priming enhances the photosynthetic capacity of plants. A similar pattern was observed for total chlorophyll, where the highest value of 2.65 occurred at 100% field capacity and the lowest value of 2.09 occurred at 50% field capacity. Variations in field capacity showed that at 100% field capacity, plant height reached the highest value of 78.58 cm but significantly decreased to 69.71 cm under drought conditions (50% field capacity). This suggests drought reduces the ability of plants to grow and photosynthesize. The pattern of the combination treatments showed that higher Na_2SiO_3 concentrations helped plants mitigate the negative effects of drought, although not entirely eliminating them. For instance, under 50% field capacity, plant height at 60 mM Na_2SiO_3 remained higher at 74.33 cm as compared to 65.33 cm at 0 mM. Physiological parameters for total chlorophyll showed a similar pattern, with higher concentrations of Na_2SiO_3 helping to maintain better values even while the plants were under drought stress. The present study exhibited the benefit of silicon application to enhance rice seedling growth.

CONCLUSIONS

Application of sodium metasilicate priming at concentrations of 40 mM and 60 mM improved all germination parameters and rice growth parameters of plant height and leaf number, particularly at soil water capacities of 100% and 75%. All physiological indicators, including chlorophyll and carotenoid contents, were higher in primed seeds than those of non-primed ones, although the significant response was limited to 50% of field water capacity.

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