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SILICON ENHANCES PHOTOSYNTHETIC PIGMENT ACCUMULATION AND ANTIOXIDANT DEFENCE IN NASTURTIUM UNDER SHADE AND SEMI-SHADE CONDITIONS

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Abstract

Silicon (Si) is recognized for enhancing plant stress tolerance, its physiological role in alleviating low-light stress in ornamental species remains poorly understood. This study evaluated the effects of foliar-applied Si (0, 50, and 100 µM) on growth, photosynthetic pigments, antioxidant metabolism, osmolyte accumulation, and flowering of nasturtium grown under shade and semi-shade conditions. Silicon application significantly increased plant biomass, leaf production, flower size, flower fresh weight, and floral yield, particularly at 100 µM. These improvements were associated with enhanced chlorophyll accumulation, increased activities of superoxide dismutase, peroxidase, and catalase, elevated ascorbic acid and total phenolic contents, and greater accumulation of proline and glycine betaine. Hence, Si enhances low-light tolerance by improving photosynthetic capacity, antioxidant defense, and osmotic adjustment, thereby promoting vegetative growth and floral productivity.

Key words: Antioxidants, Defense system, Light conditions, Physiological indices, Signaling molecules

Introduction

Nasturtium (*Tropaeolum majus* L.) is a water-loving plant well known for aesthetic and medicinal uses (Melo *et al*., 2018). Nasturtium contains a diversity of flower colors, including orange, yellow, and red. Nasturtium originated in Peru and Mexico, and can bloom with excellent adaptability (Koike *et al*., 2015). Previous work on nasturtium's phytochemicals has discovered that its leaves contain benzyl thiocyanate, linoleic and oleic acids, and the flavonoids isoquercitrin and kaempferol glycoside (Junior *et al*., 2011). Nasturtium is also taken as a tea to cure many diseases such as asthma, constipation, infection of the bladder, and cardiovascular disorders (Fernández-Pintor *et al*., 2025). Flowers contain a vital place in religion, and health. Edible flowers have become more trendy due to an increase in cookbooks, magazine articles, and nutrition (Pires *et al*., 2019). Edible flowers are more susceptible to damage compared to ornamental flowers because their stems are heavily trimmed and they are kept in dry conditions during storage (Seleiman *et al*., 2021; Waleed *et al*., 2025; Njiru *et al*., 2026).

Each crop has its requirement for sunshine (Ahmad *et al*., 2023). However, nasturtium undergoes different categories of sunlight (Xu *et al*., 2025). Shade-loving plants do not thrive under direct sunshine. However, sun-loving plants bloom very well in direct sunlight (Palmitessa *et al*., 2024). Nasturtium can be categorized into different groups based on the requirement of sunlight. Nasturtium is a shade-loving plant, and exposure to sunshine causes negative effects such as photoinhibition, oxidative stress, and high rates of perspiration (Wang *et al*., 2023). However, shading can reduce the absorption of necessary light energy, which reduces photosynthesis and various developmental processes in plants. So, it is necessary to balance between the two extremes for optimum plant health and development (Wang *et al*., 2020). Silicon is considered a beneficial element that improves plant growth and development and stress tolerance (Muhammad *et al*., 2022). Si is effective in helping plants become more resilient against harsh climatic conditions. The adverse effects of light can be eliminated by the Si, which improves the plant's defense mechanisms and lowers oxidative damage (Mushtaq *et al*., 2024; Maryam *et al*., 2026).

Different management practices mitigate the adverse effects of cliamtic conditions in plants (Makumi *et al*., 2025; Shabbir *et al*., 2026). Silicon (Si) supplements make the nasturtium plant go through various physiological developments. It enhances plant defense mechanisms against light stress (Rivera *et al*., 2025). Si enhances the activity of carbon fixation enzymes that help in photosynthesis. It is helpful against drought stress as it

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boosts water use efficiency and reduces transpiration rates in shaded environments (Ashfaq *et al*., 2024). Si supplementation produces lush foliage in floral crops (Fernández-Pintor *et al*., 2025). It is helpful in the production of structural substances like lignin and cellulose that encourage the rigidity and thickness of leaves (Ahmad *et al*., 2025). These modifications help plants to absorb and use optimum light conditions (Rastogi *et al*., 2021). Si encourages the synthesis of secondary metabolites such as flavonoids and phenolic compounds that are necessary for the coloration of leaves and plant growth (Semenova *et al*., 2021).

The impact of Si under reduced light conditions (shade and semi-shade) is still scarce in floral crops. There is limited information on whether exogenous Si can support vegetative growth, maintain floral yield, and stabilize photosynthetic pigments under reduced light conditions. The interface between Si and light intensity has not been scientifically explored. To overcome these challenges, current research aimed to determine the beneficial role of Si supplementation on nasturtium plants in terms of growth, floral yield, and biochemical indices subjected to shade and semi-shade conditions. It has been hypothesized that Si spray may improve tolerance to reduced light conditions by boosting photosynthetic pigments, biomass accumulation, and floral yield.

Materials and Methods

Nasturtium plantation details: Different levels of Si were sprayed on plants after 30 days of germination. Seeds were sown on 11 October 2022. Si spray continues till the final harvesting of plants after 15 days of interval. During crop maintenance, urea fertilizer of about 3 g was applied. However, insecticides were not applied because no insect attack was recorded. However, weeds were discarded manually from the pots. Each pot (45 × 30 cm) contained 4 kg of well-drained soils with silt loam texture, 30% saturation, pH 8, 0.42% organic matter, 1.78 $mScm^{-1}$ EC, 4.02 mg kg^{-1} available phosphorus, and 120 mg kg^{-1} available potassium.

Plants were subjected to shade conditions using a shade net during the day (PPFD 80-110 μMm^{-2} s^{-1} and DLI 3.1-5 Mm^{-2} d^{-1}). However, plants were subjected to semi-shade conditions by covering the plants with shade net for half of the day (PPFD 160-210 μMm^{-2} s^{-1}; DLI 6-8 Mm^{-2} d^{-1}). Under shade, mean temperature and humidity were 18-20ºC and 70-80%, respectively. Moreover, under semi-shade conditions, mean temperature and humidity were 20-22ºC and 60-70%, respectively.

Experimental details: Nasturtium plants were placed in shade and semi-shade, via Si spray at 50 and 100 µM, along with a control. The experiment was grouped according to a completely randomized design (CRD) under a two-way factorial with three replicates. Fifteen plants were tagged for data collection from each treatment. The source of Si was potassium meta-silicate ($K_2SiO_3 \cdot xH_2O$; Sigma-Aldrich, St. Louis, MO, USA). For the preparation of the stock solution, 15.43 g L^{-1} of potassium meta-silicate was dissolved in deionized water by regulating the pH at 6.5 with hydrochloric acid (HCl). After this, working solutions (50 and 100 µM) were prepared from the stock solution. The volume of spray was about 20 mL on each plant using a hand sprayer.

Measurements of growth attributes and flowering yield: A digital vernier caliper was used for plant height, flower length, and flower width data estimation. Plant fresh and dry biomass and flower fresh weight were recorded via digital weighing balance. The number of nasturtium plant leaves was also counted from the tagged plants.

Determination of photosynthetic pigments in nasturtium plants: Chlorophyll 'a', chlorophyll 'b', and total chlorophyll were measured from the leaf powder of 0.5 g. Samples were homogenized in 80% acetone and centrifuged for the removal of debris from samples. The supernatant was collected, and optical readings were noted via spectrophotometer using earlier procedures of Arnon (1949). Pure acetone of 3 mL was used as a blank to subtract the acetone value from the nasturtium leaf samples during the determination of photosynthetic pigments.

Evaluation of enzymatic activities in nasturtium plants: Superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT) were determined to measure the activation level of antioxidants in the nasturtium leaves as per earlier described protocols. Nasturtium leaf samples of 0.5 g were finely ground in phosphate buffer (50 mM, 2 mL) at pH 7.0. Supernatant was collected in a new tube after centrifugation (12000 × g).

For the SOD estimation, the reaction mixture about 3 mL, PPB of 50 mM, methionine (13 mM), riboflavin (2 µM), EDTA (0.1 mM), and enzyme extract (100 µL). The homogenized solution was centrifuged (12000 × g), and the supernatant was removed and collected for SOD estimation at a wavelength 560 nm by a spectrophotometer (MBS, Hitachi Instruments, Japan) (Mishra *et al*., 2023).

For the POD estimation, a guaiacol oxidation method was successfully employed. The reaction mixture (3 mL) PPB (50 mM) with pH 7.6, guaiacol (20 mM), hydrogen peroxide (H_2O_2) (40 mM), and enzyme extract (100 µL) was homogenized, and the solution was centrifuged at 12000 × g. The increment in absorbance reading was monitored for 3 min at 470 nm by a spectrophotometer (Cakmak *et al*., 1991).

For the CAT approximation, the reaction mixture (3 mL), phosphate buffer (50 mM) (pH 7.0), H_2O_2 (15 mM), and enzyme extract (100 µL). These reagents were homogenized and centrifuged at 12000 × g. The decline in absorbance was monitored for 2 min. The decomposition of H_2O_2 was monitored at 240 nm for CAT estimation. However, the decline in absorbance was noted for 2 min, and H_2O_2 was used as the coefficient because the enzyme decomposition was 1 µmol of H_2O_2 per minute (Maqsood *et al*., 2026).

Ascorbic acid and total phenolics estimation: Ascorbic acid was determined according to a protocol of Ruck (1963) a titration procedure. About 0.5 g of leaf powder was mixed and homogenized with 0.4% (5 mL) oxalic acid. After this, the solution was filtered through Whatman No. 1 filter paper. Oxalic acid was also to prepare as a standard curve. The leaf samples were titrated against 2,6-dichlorophenolindophenol dye till color appearance (light pink).

Total phenolics were determined through the Folin-Ciocalteu procedure as per the previously described protocol Nakano and Asada *et al*., (1981). Leaf samples (0.5 g) were ground in methanol (80%) using mortar and pestle. After this, the solution was centrifuged at 12000 × g, and the supernatant was collected. Supernatant (100 µL) was homogenized with Folin-Ciocalteu reagent (10%, 500 µL), sodium carbonate (7.5%, 400 µL), and homogenized in the reagent. After this, reading was noted at the spectrophotometer on a specific wavelength of 765 nm.

Accumulation of proline and GB in nasturtium plants: Nasturtium fresh-harvested leaves were ground in liquid nitrogen to stop enzymatic activity. About 0.5 g of leaf powder was mixed in the appropriate buffer for extraction of proline and GB. Proline and GB values were noted at specific wavelengths via a spectrophotometer. A well-known protocol was followed for the determination of proline and GB (Souri *et al*., 2021).

Statistical analysis

Nasturtium data were analyzed by the analysis of variance technique through Statistix 8.1 software. Treatment means were separated using the LSD test at a probability ($p<0.05$). Principal Component Analysis (PCA) was developed to determine the variation among the applied treatments Rstudio (https://CRAN.R-project.org/package=pheatmap).

Results

Si improves nasturtium lush foliage: The longer plant height (15.83 cm) was recorded under shade as compared to semi-shade conditions (12.18 cm). Among Si levels, 100 µM showed taller plant height (16.70 µM), while control (0 µM) exhibited smaller plant height (11.32 µM). The maximum plant fresh biomass (13.33 g) was recorded in semi-shade plants, while the minimum plant fresh biomass (10.84 g) was determined in shaded plants. Si at 100 µM had the maximum plant fresh biomass (15.48 g), while control had the minimum plant fresh biomass (9.54 g). The greater plant dry biomass (3.54 g) was measured in semi-shade plants, while the minimum plant dry biomass (2.32 g) was estimated in shaded plants. Si at 100 µM provided greater plant dry biomass (3.70 g), while control had lower plant dry biomass (2.48 g). Higher number of leaves were counted in semi-shade plants (14.28) than in shaded plants (10.76). Si of 100 µM showed higher number of leaves (15.22 g), while control had lower number of leaves (9.52 g) (Table 1).

The interaction of reduced light conditions and exogenous Si spray, plant height was taller under shade × Si (100 µM), while plant height was smaller under semi-shade × control conditions (Fig. 1A). Plant fresh biomass was greater under semi-shade × Si (100 µM), followed by shade × Si (100 µM), while plant fresh biomass was lower under shade × control (Fig. 1B). Plant dry biomass was higher under semi-shade × Si (100 µM), while plant dry biomass was lower under shade × control (Fig. 1C). Number of leaves was greater under semi-shade × Si (100 µM), while number of leaves was lower under shade × control (Fig. 1D).

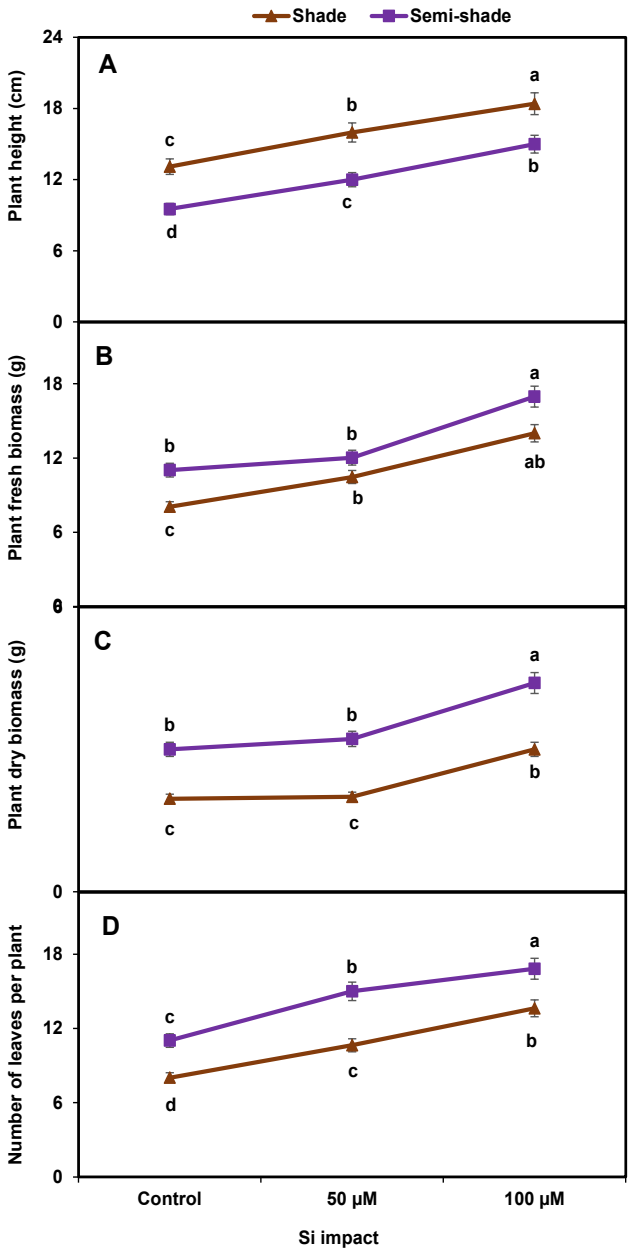


Fig. 1. Displays the shade and semi-shade effects on nasturtium growth under different silicon concentrations. Plants under shade show taller plant height (A), reduced fresh biomass (B), low dry biomass (C) and poor number of leaves (D) compared to semi-shade conditions. Silicon supplementation (control, 50, and 100 µM) improves overall growth traits under shade and semi-shade conditions.

Si enhanced floral yield: Flower length was found to be larger in plants growing under semi-shade (14.67 mm) as compared to shaded (11.23 mm) nasturtium plants. Si (100 µM) had the potential to enhance flower length (17.00 mm) as compared to the control (10.35 mm) and 50 µM Si (11.50 mm). Flower width was the maximum (19.4 mm) in plants growing under semi-shade as compared to shade nasturtium plants (15.0 mm). Si supplementation had the potential to enhance the flower width (21.00 mm) as compared to control (13.60 mm). Flowers' fresh weight per plant was significantly higher in semi-shade plants (0.38 g) as compared to shade plants (0.30 g). Si application (100 µM) resulted in a higher fresh weight of flowers per plant (0.47 g) as compared to non-treated Si plants (0.23 g) and 50 µM Si (0.33 g) (Table 1).

The combination of reduced light conditions and Si spray illustrated that flower length was longer under semi-shade × Si (100 µM), followed by shade × Si (100 µM), while flower length was smaller under shade × control, followed by shade × 50 µM (Fig. 2A). Flower width was longer under semi-shade × Si (100 µM), while flower diameter was smaller under shade × control, followed by shade × Si (100 µM) and semi-shade × control (Fig. 2B). Flower fresh weight was higher under semi-shade × Si (100 µM), while flower fresh weight was lower under shade and semi-shade × control (100 µM) (Fig. 2C).

Si regulates photosynthetic pigments: Photosynthetic pigments i.e., chlorophyll a, chlorophyll b, and total chlorophyll were significantly influenced from light reduced conditions and Si concentrations. Semi-shaded plants attained the maximum chlorophyll a (24.00 µg 100 g^{-1}), chlorophyll b (28.67 µg 100 g^{-1}), and total chlorophyll (52.67 µg 100 g^{-1}), while the minimum chlorophyll a (19.67 µg 100 g^{-1}), chlorophyll b (23.00 µg 100 g^{-1}), and total chlorophyll (42.66 µg 100 g^{-1}) were recorded in shaded plants. Si of 100 µM treated plants showed higher chlorophyll a (25.00 µg 100 g^{-1}), chlorophyll b (30.00 µg 100 g^{-1}), and total chlorophyll (55.00 µg 100 g^{-1}), while lower chlorophyll a (18.50 µg 100 g^{-1}), chlorophyll b (21.00 µg 100 g^{-1}), and total chlorophyll (39.50 µg 100 g^{-1}) were recorded in control (Table 2).

The cumulative effect of reduced light conditions and Si exhibited that chlorophyll a was higher under semi-shade × Si (100 µM), followed by shade × Si (100 µM), semi-shade × Si (50 µM), and shade × control. However, chlorophyll a was lower under shade × control (Fig. 3A). Chlorophyll b was greater under semi-shade × Si (100 µM), while chlorophyll b was lesser under shade × control (Fig. 3B). Total chlorophyll was greater under semi-shade × Si (100 µM). Meanwhile, total chlorophyll was lower under shade and semi-shade × control (100 µM) (Fig. 3C).

Si boosts enzymatic activities in nasturtium plants: SOD activity was recorded to be higher in semi-shade plants (4.37 U mg^{-1} Protein) than in shaded plants (3.86 U mg^{-1} Protein). Silicon at 100 µM increased SOD activity in semi-shade plants (5.30 U mg^{-1}) more than in control (3.25 U mg^{-1}) and Si of 50 µM treated plants (3.80 U mg^{-1}). The maximum CAT activity was recorded in semi-shade plants (4.00 U mg^{-1} Protein) as compared to shaded plants (3.43 U mg^{-1} Protein). CAT activity was higher in Si (100 µM) treated plants (4.95 U mg^{-1} Protein), while it was lower (2.85 U mg^{-1} Protein) in control (2.85 U mg^{-1} Protein) (Table 3). POD activity was the maximum in Si (100 µM) treated plants (6.75 U mg^{-1} Protein), while it was lower (4.70 U mg^{-1} Protein) in control (2.85 U mg^{-1} Protein) (Table 3). The joint effects of shade, semi-shade, and silicon spray exposed that SOD, POD, and CAT were higher under semi-shade and shade conditions × Si (100 µM). However, SOD, POD, and CAT were lower under shade × control (Fig. 4A-C).

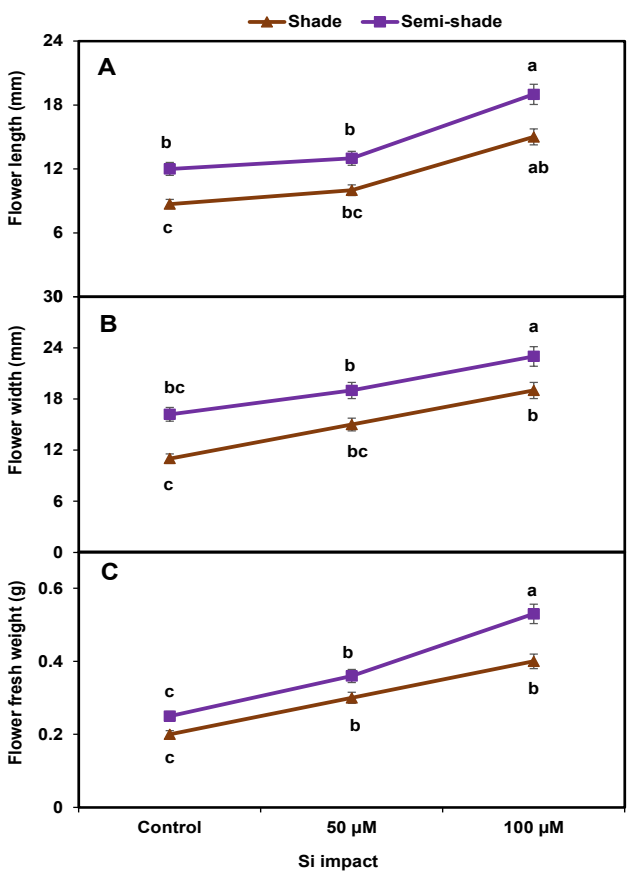


Fig. 2. Illustrates the shade and semi-shade effects on floral yield of nasturtium plants under different silicon concentrations. Plants under semi-shade conditions showed greater flower length (A), flower width (B), and flower fresh weight (C) compared to shade conditions. Silicon supplementation (control, 50, and 100 µM) also boosts floral traits under shade and semi-shade conditions.

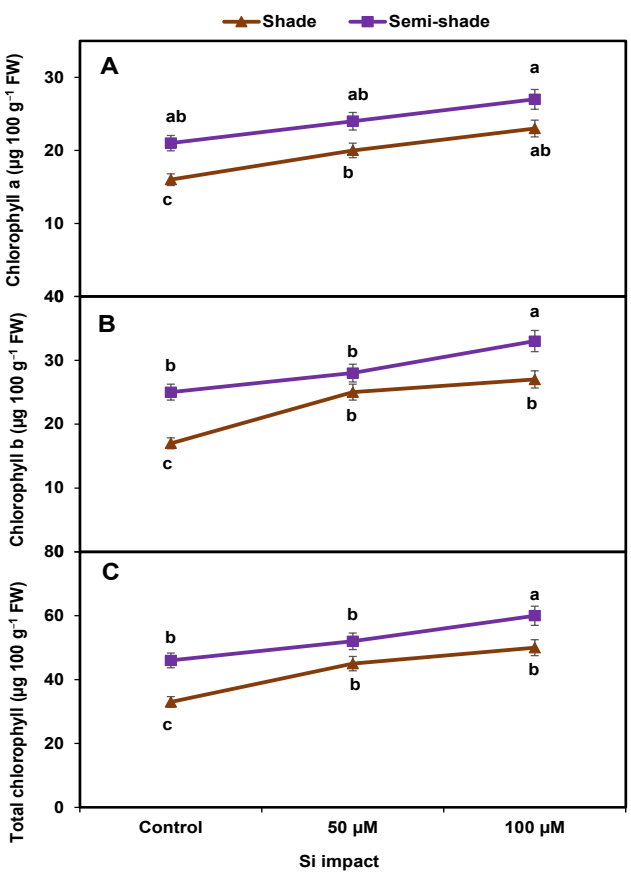


Fig. 3. Demonstrates the shade and semi-shade effects on photosynthetic pigments of nasturtium plants under different silicon concentrations. Plants under semi-shade conditions showed greater chlorophyll a (A), chlorophyll b (B), and total chlorophyll (C) compared to shade conditions. Silicon supplementation (control, 50, and 100 µM) also boosts photosynthetic pigments under shade and semi-shade conditions.

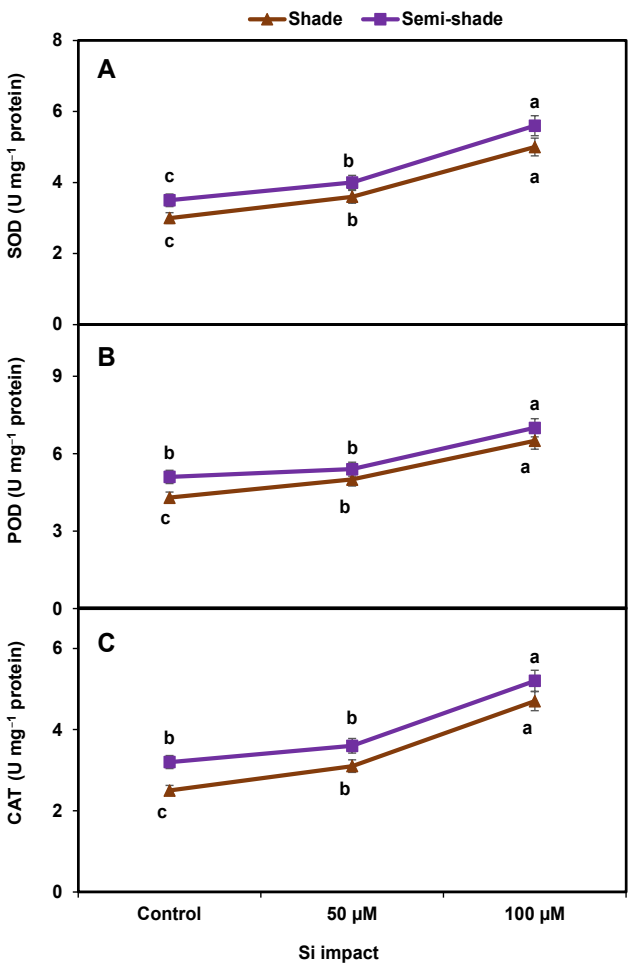


Fig. 4. Exhibits silicon impact on enzymatic activities in nasturtium growing under shade and semi-shade conditions. Plants under semi-shade conditions exposed slightly higher enzymatic activities SOD (A), POD (B), and CAT (C) compared to shade conditions. Silicon supplementation (control, 50, and 100 µM) also boosts enzymatic activities under shade and semi-shade conditions.

Si boosts non-enzymatic activities in nasturtium plants: Ascorbic acid content was recorded to be higher in semi-shade plants (84.01 mg 100 g^{-1}) than in shaded plants (65.33 mg 100 g^{-1}). Si spray of 100 µM revealed greater ascorbic acid in semi-shade plants (92.0 mg 100 g^{-1}), while lower ascorbic acid was recorded in shaded plants (60.00 mg 100 g^{-1}). Total phenolics were recorded to be higher in semi-shade plants (96.67 mg 100 g^{-1}) and lower in shaded plants (72.50 mg 100 g^{-1}). Si (100 µM) spray showed higher phenolic levels in semi-shade plants (96.60 mg 100 g^{-1}), while it was lower in control (72.5 mg 100 g^{-1}). Si spray slightly improved proline (3.50 U mg^{-1} Protein) and glycine betaine (2.55 U mg^{-1} Protein) as compared to other treatments (Table 4). The interaction of reduced light conditions and Si levels, ascorbic acid, and total phenolics were higher under semi-shade × Si of 100 µM. However, ascorbic acid and total phenolics were lower in control × shade conditions (Fig 5AB). Proline and glycine betaine were greater under semi-shade × Si of 100 µM. However, proline and glycine betaine were lower in control × shade conditions (Fig 6AB). Si supplementation shows a feasible method to control levels of physiological and chemical changes so plants may bloom in different levels of light (Fig. 7).

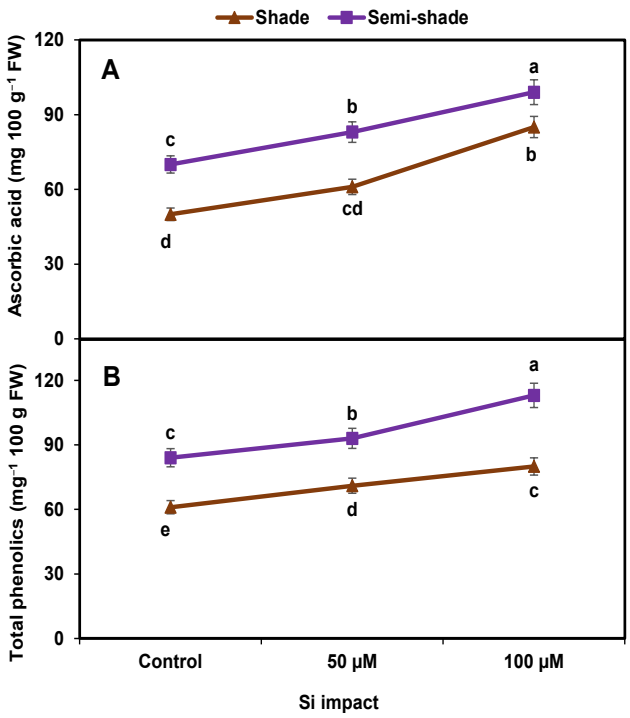


Fig. 5. Exposed silicon impact on non-enzymatic activities in nasturtium plants growing under shade and semi-shade conditions Ascorbic acid (A) and total phenolics (B). Plants under semi-shade conditions exhibited slightly higher enzymatic activities ascorbic acid (A) and total phenolics content (B) compared to shade conditions. Silicon supplementation (control, 50, and 100 µM) also boosts non-enzymatic activities under shade and semi-shade conditions.

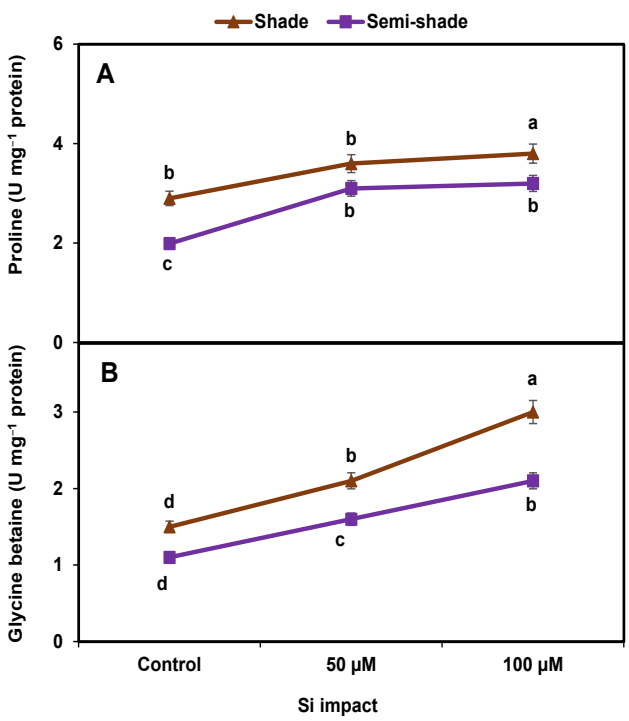


Fig. 6. Illustrates silicon impact on signaling molecules in nasturtium plants growing under shade and semi-shade conditions. Plants under semi-shade conditions exposed slightly higher signaling molecules comprising proline (A) and glycine betaine (B) compared to shade conditions. Silicon supplementation (control, 50, and 100 µM) also boosts signaling molecules under shade and semi-shade conditions.

Table 1 Mean of nasturtium growth and floral yield as affected by shade, semi-shade, and silicon supplementation.

Light conditions	Plant height (cm)	Plant fresh biomass (g)	Plant dry biomass (g)	Number of leaves per plant	Flower length (mm)	Flower width (mm)	Flower fresh weight (g)
Shade	15.83 a	10.84 b	2.32 b	10.76 b	11.23 b	15.0 b	0.30 b
Semi-shade	12.18 b	13.33 a	3.54 a	14.28 a	14.67 a	19.4 a	0.38 a
Silicon spray	-	-		-	-	-	-
Control	11.32 c	9.54 c	2.48 b	9.52 c	10.35 b	13.60 c	0.23 b
50 µM	13.99 b	11.24 b	2.61 b	12.82 b	11.50 b	17.00 b	0.33 b
100 µM	16.70 a	15.48 a	3.70 a	15.22 a	17.00 a	21.00 a	0.47 a

Table 2 Mean of photosynthetic pigments of nasturtium plants subjected to shade, semi-shade, and silicon supplementation.

Light conditions	Chlorophyll a (µg 100 g^{-1} FW)	Chlorophyll b (µg 100 g^{-1} FW)	Total chlorophyll (µg 100 g^{-1} FW)
Shade	19.67 b	23.00 b	42.66 b
Semi-shade	24.00 a	28.67 a	52.67 a
Silicon spray	-	-	-
Control	18.5 c	21.0 c	39.5 c
50 µM	22.0 b	26.5 b	48.5 b
100 µM	25.0 a	30.0 a	55.0 a

Table 3. Mean of enzymatic activities of nasturtium plants modulate under shade, semi-shade, and silicon supplementation.

Light conditions	Superoxide dismutase (SOD) (U mg^{-1} protein)	Peroxidase dismutase (POD) (U mg^{-1} protein)	Catalase (CAT) (U mg^{-1} protein)
Shade	3.86 b	5.27 a	3.43 b
Semi-shade	4.37 a	5.83 a	4.00 a
Silicon spray	-	-	-
Control	3.25 b	4.70 c	2.85 c
50 µM	3.80 b	5.20 b	3.35 b
100 µM	5.30 a	6.75 a	4.95 a

Table 4 Mean of non-enzymatic activities and signaling molecules of nasturtium plants moderate under shade, semi-shade, and silicon supplementation.

Light conditions	Ascorbic acid (mg 100 g^{-1} FW)	Total phenolics (mg^{-1} 100 g FW)	Proline (U mg^{-1} protein)	Glycine betaine (U mg^{-1} protein)
Shade	65.33 b	70.66 b	3.43 a	2.2 a
Semi-shade	84.01 a	96.67 a	2.76 a	1.6 a
Silicon spray	-	-	-	-
Control	60.0 c	72.5 c	2.45 b	1.30 b
50 µM	72.0 b	82.0 b	3.35 a	1.85 b
100 µM	92.0 a	96.6 a	3.50 a	2.55 a

Table 5. Impact of silicon on treatment by trait association of nasturtium crop growing under shade and semi-shade conditions.

Traits	PLH	PFB	PDB	NOL	FLS	FFW	TCH	SOD	POD	CAT	ASA	TPH	GB	PRO
PLH	**1**	**	**	**	**	**	*	**	**	**	**	**	*	*
PFB	**0.98**	**1**	*	**	**	**	**	**	**	**	**	*	**	**
PDB	**0.95**	**0.91**	**1**	**	**	*	*	*	*	ns	**	**	ns	ns
NOL	**0.98**	**0.99**	**0.92**	**1**	**	**	**	**	**	**	**	*	ns	**
FLS	**0.99**	**0.99**	**0.95**	**0.98**	**1**	**	*	**	ns	ns	**	*	*	*
FFW	**0.96**	**0.95**	**0.85**	**0.94**	**0.95**	**1**	*	ns	**	**	*	*	ns	*
TCH	**0.90**	**0.92**	**0.82**	**0.95**	**0.89**	**0.89**	**1**	*	*	*	**	*	**	**
SOD	**0.95**	**0.97**	**0.84**	**0.95**	**0.96**	0.56	**0.84**	**1**	**	**	**	ns	*	*
POD	**0.95**	**0.98**	**0.85**	**0.96**	**0.97**	0.36	**0.84**	**0.99**	**1**	**	**	ns	**	*
CAT	**0.95**	**0.98**	**0.55**	**0.96**	0.57	**0.94**	**0.84**	**0.99**	**0.99**	**1**	**	ns	*	**
ASA	**0.98**	**0.99**	**0.93**	**0.99**	**0.97**	**0.92**	**0.93**	**0.93**	**0.94**	**0.94**	**1**	**	**	**
TPH	**0.93**	**0.89**	**0.95**	**0.92**	**0.91**	**0.88**	**0.91**	0.78	0.79	0.79	**0.92**	**1**	ns	ns
GB	**-0.89**	**-0.95**	-0.77	-0.53	**-0.90**	-0.29	**-0.96**	**-0.91**	**-0.92**	**-0.91**	**-0.93**	**-0.80**	**1**	**
PRO	**-0.88**	**-0.93**	-0.73	**-0.94**	**-0.88**	**-0.90**	**-0.96**	**-0.90**	**-0.90**	**-0.90**	**-0.92**	**-0.80**	**0.99**	**1**

ns = Non-significant; * = p≤0.05; ** = p≤0.01; *** = p≤0.001. The upper right half part of the table presents the significance, while the lower left half of the Table presents the values of the correlation. The numbers in bold represent significance at p≤0.05. PLH = Plant height, PFB = Plant fresh biomass, PDB = Plant dry biomass, NOL = Number of leaves, FLS = Flower size, FFW = Flower fresh weight, TCH = Total chlorophyll, SOD = Superoxide dismutase, POD = Peroxidase, CAT = Catalase, ASA = Ascorbic acid, TPH = Total phenolics, GB = Glycine betaine, and PRO = Proline

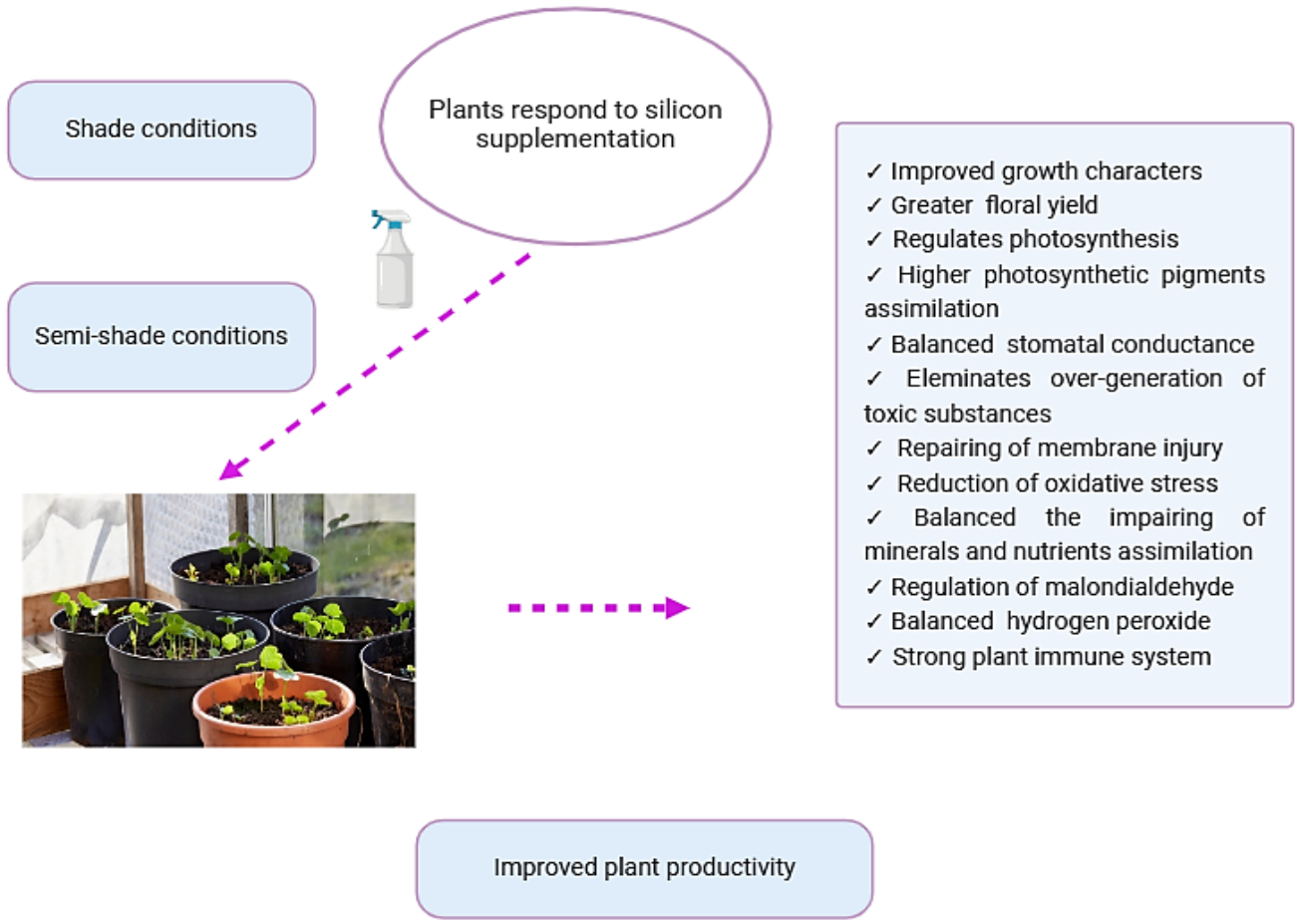


Fig. 7. Impact of silicon spray on plant growth, yield, physiological and biochemical activities growing under shade and semi-shade conditions.

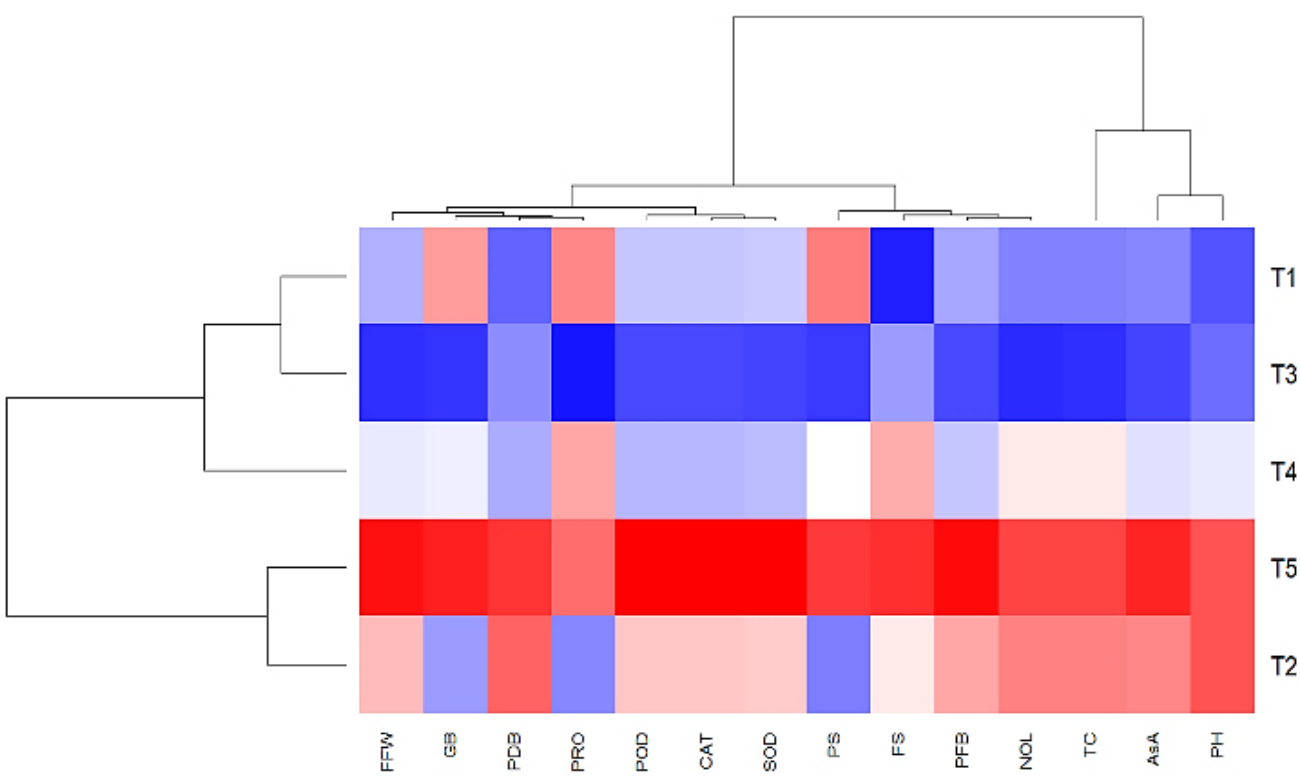


Fig. 8. Heat-map analysis of plant growth, floral yield, physiological indices, and biochemical activities. T_1 = shade, T_2 = semi-shade, T_3 = Si (0 µM), T_4 = Si (50 µM), T_5 = Si (100 µM). Plant height (PH), plant fresh biomass (PFB), plant dry biomass (PDB), number of leaves (NOL), flower size (FS), flower fresh weight (FFW), total chlorophyll (TC), superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), ascorbic acid (AsA), total phenolics (PS), glycine betaine (GB), and proline (PRO).

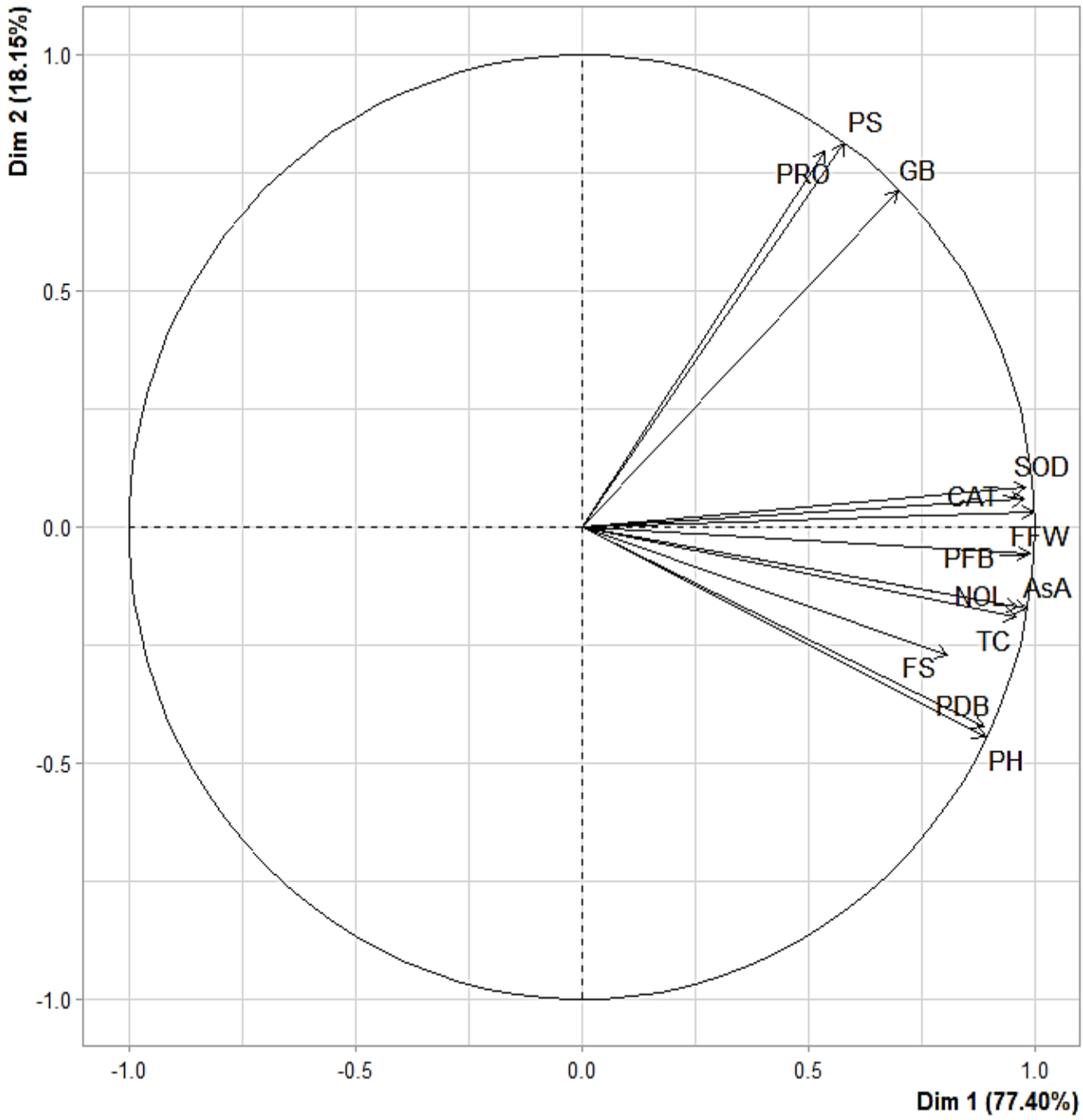


Fig. 9. Variable plot of plant growth, floral yield, physiological indices, and biochemical activities as affected by silicon under shade and semi-shade conditions. Plant height (PH), plant fresh biomass (PFB), plant dry biomass (PDB), number of leaves (NOL), flower size (FS), flower fresh weight (FFW), total chlorophyll (TC), superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), ascorbic acid (AsA), total phenolics (PS), glycine betaine (GB), and proline (PRO).

Trait association among the studied traits: Nasturtium plant height showed significant trait association among growth, physiological, and biochemical properties modified under Si supplementation, shade, and semi-shade conditions. Plant height revealed a significant and positive correlation was plant fresh biomass, plant dry biomass, number of leaves, flower size, flower fresh weight, total chlorophyll, SOD, POD, CAT, AsA, and total phenolics, while significant and negative correlation with glycine betaine and proline. Plant fresh biomass had significant correlation with plant dry biomass, number of leaves, flower size, flower fresh weight, total chlorophyll, SOD, POD, CAT, ascorbic acid, and total phenolics, while negative correlation with proline and glycine betaine. Plant dry biomass had a significant association with number of leaves, flower size, flower fresh weight, total chlorophyll, SOD, POD, CAT, ascorbic acid, and total phenolics. Number of leaves revealed a significant association with flower size, flower fresh weight, and total chlorophyll, while negative association with proline. However, the number of leaves had non-significant association with glycine betaine. Total chlorophyll content exhibited significant association with SOD, POD, CAT, ascorbic acid, total phenolics, glycine betaine, and proline. SOD exposed significant association with POD, CAT, and ascorbic acid, while negative association with

proline and glycine betaine. POD had a significant association with CAT, while negative relationship with proline and glycine betaine. Proline had a significant association with glycine betaine (Table 5).

Heat map and variable plot of the studied traits of nasturtium: The first two PCA illustrated 70.40 and 18.15% of the total variance. The variable plot exhibited strong treatment separation on the basis of the studied traits in terms of growth, yield, and biochemical indices, meanwhile heat map demonstrated clustering patterns dependable with the PCA consortia. Heat map illustrates the performance of the Si treatments on the studied traits of nasturtium growing under shade and semi-shade conditions. A color scale indicating that dark blue and red colors scale showed the maximum mean performance of traits under shade conditions (T_0), and shade conditions and 100 µM Si (T_5). The darker color showed the maximum mean performance of the treatments, while low color intensity exhibited the minimum mean performance of the treatments. Therefore, darker red and blue colors exhibited shade conditions, and Si-treated plants exhibited higher plant growth, floral yield, and defense system (Fig. 8). The variable plot is an effective way of graphical visualization to explore complex relationships among multiple variables. SOD, POD, and CAT were significantly correlated with each other. Variables at the right angle remained independent in the variable plot. Hence, huge data sets can be visualized using such statistical tools to determine tolerant and susceptible cultivars (Fig. 9).

Discussion

Nasturtium growth was significantly influenced from the light regime. Growth characteristics i.e., plant height, plant fresh and dry biomass, and number of leaves, were reduced under shade conditions (Table 1 and Fig. 1). The reduction in growth characteristics was due to reduced light conditions, especially under full shade. Poor formation of photosynthetic pigments was also observed in plants subjected to shade conditions. Additionally, full shade reduced carbon assimilation and hastens chlorophyll degradation in plants (Souri *et al*., 2021). Si application improves nasturtium growth traits under reduced light conditions (Table 1 and Fig. 1). Si regulates the formation of photosynthetic pigments and improves carbon assimilation, which further results in better plant growth under reduced light conditions. Exogenous Si had an excellent contribution to the improvement of plant foliage subjected to sub-optimal light conditions (Maqsood *et al*., 2026).

Si mitigates adverse effects in plants in terms of floral yield subjected to shade conditions. Flower size and fresh weight of flowers were reduced in shade conditions than semi-shade conditions. Si improves floral yield under both shade and semi-shade conditions (Table 1 and Fig. 2). The current findings are at par with earlier findings because light involved in the blooming of flowers. Si maintains the structural integrity of leaves to enhance flowering in plants. Si improves nutrient uptake and promotes photosynthesis in plants (Chen *et al*., 2024). Si spray strengthens the cell wall even in low light conditions, which protects plants from becoming elongated and weak (Xu *et al*., 2023). Si doses at growth levels improve the flowering of nasturtium plants (Rastogi *et al*., 2021; Samal *et al*., 2023). Hence, floral yield of nasturtium plants can be enhanced with silicon spray under optimal light conditions.

The reduction in photosynthetic pigments was recorded under shade as compared to semi-shade conditions. Si maintains the formation of photosynthetic pigments in nasturtium plants subjected to shade and semi-shade (Table 2 and Fig. 3). Shade has low light conditions, which affect photosynthesis and reduce chlorophyll contents. However, Si supplements improve the photosynthetic machinery, which directly improves chlorophyll content in nasturtium (Devireddy *et al*., 2018; Thakral *et al*., 2024). A current study revealed that Si supplementation acts as a vital nutrient for the plant cycle in shade and semi-shade (Ali and Singh, 2024). There is a noticeable difference in photosynthetic pigments under shade and semi-shade conditions, and the present study conforms with the earlier work (Lam *et al*., 2021; Dabravolski & Isayenkov, 2024).

Antioxidant enzymes (SOD, POD, and CAT) were slightly higher in semi-shade plants. These enzymatic activities boosted under Si supplementation (Table 3 and Fig. 4). The activation of the plant defense system depends on the activation of enzymatic activities (Ali *et al*., 2024; Khan *et al*., 2025). Enzymatic activities have greater potential to scavenge toxic superoxide free radicals H_2O_2 (Kalaji *et al*., 2018; Anjum *et al*., 2024;). Light intensity causes oxidative damage which diminishes the defense system, Si can solve this problem by promoting the activity of these enzymes (Bardhan *et al*., 2024). Therefore, Si supplements improve the plant defense system and boost blooming with better growth and development in shade and semi-shade conditions.

Si promotes the production of ascorbic acid and phenolic compounds in nasturtium plants in shade and semi-shade environments (Table 4 and Fig. 5). Si is well known for its role in secondary metabolites such as ascorbic acid and phenolics that supports plant defense mechanisms against biotic and abiotic stressors (Park *et al*., 1996; Li *et al*., 2022; Ma *et al*., 2026). Shade and semi-shade environments have a low light intensity, which alters the metabolic activities in plants. Si supplementation enhances the generation of phenolics and ascorbic acid, which support plants' resilience against stress conditions (Semenova *et al*., 2021). These substances have antioxidant properties that protect plants from oxidative injury (Palmitessa *et al*., 2024). So, these findings have revealed that Si acts as a vital agent for nasturtium plants subjected to shade and semi-shade conditions (Imtiaz *et al*., 2016; Hasddin and Ulyasniati, 2025; Zhao *et al*., 2026).

Si improves glycine betaine and proline levels in nasturtium plants subjected to reduced light conditions (Table 4 and Fig. 6). These molecules contribute to the enhancement of stress tolerance. Si increases the production of these osmolytes, which play a vital role in stress tolerance. Enzyme activity is catalyzed with Si supplements that boost up GB and proline (Etesami *et al*., 2018). Si promotes nutritional absorption and utilization that tolerates stress (Mavrič *et al*., 2021). Hence, under

shade and semi-shade, Si controls GB and proline generation that enables plants to cope with environmental challenges by sustaining their physiological activities (Ahire *et al*., 2021; Li *et al*., 2026).

Conclusion

Silicon (Si) helps nasturtium plants achieve better growth with beautiful flowering and foliage quality. Si (100 µM) modulated physiological and biochemical pathways that produce excellent growth characteristics in nasturtium plants. This modification is critical for those plants that grow under reduced light conditions. A balance can be developed for nasturtium plants to grow under these extremes. The result of the study also demonstrated that Si (100 µM) is effective in enhancing the defense of floral crops by the activation of enzymatic and non-enzymatic activities. Hence, Si supplementation can increase nasturtium growth, floral yield, and photosynthetic pigments by modulating biochemical indices.

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