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Modulation of growth and photosynthetic efficiency in common buckwheat through combined seed priming and foliar application of silicon under drought

M.R.H. RAIHAN* , F. AHMED** , and A. RASTOGI*⁺

*Department of Bioclimatology, Faculty of Environmental and Mechanical Engineering, Poznań University of Life Sciences, Piątkowska 94, Poznań 60-649, Poland**

*Department of Vegetable and Mushroom Growing, Institute of Horticultural Sciences, Hungarian University of Agriculture and Life Sciences, Villányi út 29-43, 1118 Budapest, Hungary***

Abstract

This study aimed to evaluate the effectiveness of silicon (0.5 and 1.0 mM), applied through seed priming, foliar spray, and their combined application, in enhancing drought tolerance in buckwheat under 30% field water capacity by modulating key physiological mechanisms. Drought markedly reduced growth attributes and impaired PSII efficiency and gas exchange. Under drought conditions, the combined 1.0 mM Si treatment increased fresh and dry biomass by 54 and 96%, respectively, and enhanced leaf thickness by 39% compared with untreated plants. The photosynthetic rate increased from -0.22 to $1.87 \mu\text{mol}(\text{CO}_2) \text{ m}^{-2} \text{ s}^{-1}$, stomatal conductance and transpiration rose nearly 13-fold, intercellular CO_2 concentration decreased by 32%, and key PSII parameters improved markedly, with the effective quantum yield of PSII increasing by 112% and the performance index by 2.65-fold. Overall, the results demonstrate that combining Si-seed priming with foliar application effectively enhanced plant drought resilience.

Keywords: chlorophyll *a* fluorescence; minor cereal; photosynthesis; silicon; water deficit.

Highlights

- Combined silicon seed priming and foliar spray improves buckwheat drought tolerance
- Silicon enhanced biomass, water status, and photosynthetic efficiency
- Si treatment improved PSII efficiency and stabilized electron transport in drought

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*Corresponding author

e-mail: anshu.rastogi@up.poznan.pl

Abbreviations: ABS/RC – absorption flux per one active RC; DAS – days after sowing; dH_2O – distilled water; DI_0/RC – dissipated energy flux by one active RC at $t = 0$; DM – dry mass; EL – electrolyte leakage; ET_0/RC – rate of electron transport by one active RC at $t = 0$; FM – fresh mass; F_m – maximal fluorescence when all PSII RCs are closed; F_i – fluorescence signal; F_i/F_0 – normalized fluorescence intensity; F_v – maximal variable fluorescence; FWC – field water capacity; M_0 – approximated initial slope of the fluorescence transient; OJIP curve – fast chlorophyll *a* fluorescence induction curve; PI_{ABS} – performance index; q_L – photochemical quenching of variable fluorescence; RC – photochemically active reaction center of PSII that is able to reduce Q_A ; S_m – normalized total area above the OJIP curve; SPAD – soil plant analysis development; TR_0/RC – energy flux trapped by one active RC at $t = 0$; TM – turgid mass; V_i – relative variable fluorescence in step I; V_j – relative variable fluorescence in step J; Φ_{DO} – quantum yield of energy dissipation (at $t = 0$); Φ_{EO} – quantum yield of electron transport (at $t = 0$); Ψ_0 – probability (at $t = 0$) of electron transport outside Q_A^- .

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Data availability: The raw data related to the article is deposited in the Open Data Repository RepOD (<https://reprod.icm.edu.pl/>) – the PULS institutional repository and the dataset is publicly available at: <https://doi.org/10.18150/GPZ8XS>.

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Introduction

As the world continues to face the major threat of climate change, an increasing number of abiotic stress factors are emerging to challenge agricultural production globally. Drought is a prevalent abiotic stressor that adversely impacts both the development and productivity of crops (Du *et al.* 2020), as it influences various plant traits, including morphology, physiology, and molecular aspects (Salehi-Lisar and Bakhshayeshan-Agdam 2016). The Palmer Drought Severity Index indicates that the frequency of drought conditions is projected to rise over the next 30 to 90 years due to lower precipitation and higher evaporation rates in many areas, including Europe (Dai 2013). Under drought conditions, the imbalance of water in plants adversely affects protoplasts, resulting in the leakage of ions and amino acids from membranes, which then leads to the accumulation of harmful reactive oxygen species (ROS), negatively impacts photosynthesis, triggers a swift rise in abscisic acid contents, causes stomatal closure, and ultimately reduces or halts plant growth (Gao *et al.* 2022).

Silicon (Si) is the eighth most abundant element in the universe, though it is rarely found in its pure form. Instead, it commonly occurs as silicates and silica, which together make up more than 90% of the Earth's crust, making Si the second most abundant element after oxygen. In plants, Si content ranges from 0.1 to 10% of their dry mass (Ma and Yamaji 2015). Silicon alleviates various abiotic and biotic stresses, including drought, low temperatures, salinity, heavy metal toxicity, plant diseases, and insect infestations (Hurtado *et al.* 2019, Yin *et al.* 2019). In recent years, interest in using Si as a plant biostimulant has grown, particularly for mitigating the adverse effects of abiotic stresses such as drought (Zahedi *et al.* 2023, Ashfaq *et al.* 2025, Raihan *et al.* 2026). Under drought conditions, Si enhances water-use efficiency by promoting root growth and regulating transpiration, allowing plants to maintain physiological activity despite limited water availability (Wang *et al.* 2021).

Seed priming is an effective and simple strategy to improve plant tolerance to various abiotic stresses. It enhances germination efficiency and seedling establishment under both optimal and stressful conditions, while supporting subsequent growth and stress resilience (Alinia *et al.* 2024). The method involves controlled hydration, during which seeds are soaked in a low osmotic potential solution for a defined period and then re-dried to their initial moisture content (Ceritoglu *et al.* 2024). When combined with mineral nutrients or bioregulators, seed priming modulates key physiological and biochemical processes at both metabolic and whole-plant levels, thereby strengthening innate stress defenses (Zhu *et al.* 2020). For example, priming improves drought tolerance in maize by enhancing enzymatic activities and increasing physiological growth and biomass accumulation (Parveen *et al.* 2019).

Silicon further contributes to stress tolerance by regulating secondary metabolism (Ahanger *et al.* 2020).

Growing evidence demonstrates that Si enhances germination, growth, photosynthetic performance, and yield in differently stressed crops such as wheat (Gheisary *et al.* 2025), black gram (Ahmad *et al.* 2024), buckwheat (Raihan *et al.* 2026), and maize (Sabir *et al.* 2024). Physiologically, Si mitigates drought stress through multiple mechanisms, including regulation of antioxidant systems, improvement of photochemical efficiency, increased biomass production, chlorophyll preservation, and reduced pigment degradation (Simko *et al.* 2025). Additionally, Si supplementation supports nutrient homeostasis, modifies gas-exchange characteristics, enhances osmotic adjustment, regulates compatible-solute synthesis, and stimulates antioxidant enzyme activity and related gene expression (Bhardwaj *et al.* 2023).

Common buckwheat (*Fagopyrum esculentum* Moench) is a flowering plant belonging to the knotweed family Polygonaceae, cultivated for its seed-like grains. The seeds contain substantial amounts of starch, minerals, vitamins, rutin, antioxidants, and dietary fiber, along with a unique amino acid profile (notably high in lysine and arginine), and they are naturally gluten-free (Płazek *et al.* 2023, Hossain *et al.* 2024). Despite these advantages and its potential for developing gluten-free products, this crop remains considerably less studied compared to major cereals. This gap is particularly evident regarding the effects of stress factors such as drought, the overall impact on crop development, and effective mitigation strategies. Furthermore, although numerous studies have independently examined the effects of seed priming with Si and foliar Si application on various crops, there is a lack of research integrating both approaches, especially in buckwheat. Seed priming and foliar silicon supplementation may offer complementary benefits, yet this potential synergy remains unexplored in this species. Therefore, this research aims to investigate the individual effects of seed priming and foliar application of Si on buckwheat, as well as their combined influence under drought conditions, to evaluate their potential synergistic role in enhancing drought tolerance.

Materials and methods

Plant materials, growth conditions, and treatments:

A greenhouse experiment was conducted with common buckwheat (*F. esculentum* cv. Smuga) at the Faculty of Environmental and Mechanical Engineering, Poznań University of Life Sciences, Poznań, Poland, from 27 May to 15 July 2024. This cultivar was selected because it is the most recently released Polish variety. Achenes were obtained from *Logistic sp. z o.o.*, Góra, Poland. Daily photosynthetic photon flux density and temperature during the experiment are provided in Fig. 1S (Supplement). Uniform, mature achenes were manually sorted and surface-sterilized in 70% ethanol, followed by repeated rinsing with distilled water (dH₂O). Seed priming and foliar spraying were carried out using metasilicate nonahydrate (Na₂SiO₃·9H₂O) at 0.5 mM (pH 11.02) and 1.0 mM (pH 11.30) as the Si source. For seed priming, 15 g of achenes were soaked in 200 mL of the respective Si

solutions for 6 h and subsequently air-dried. For uniformity, the control and the “foliar-only” seeds were soaked in dH₂O and air-dried following the same procedure. Four seeds were sown per plastic pot (8 cm height × 7 cm diameter) filled with 100 g of fresh deacidified peat (pH 6.5). Germination started at 3 d after sowing (DAS). At 7 DAS, one healthy, uniform seedling was retained per pot. Seedlings were irrigated to 80% field water capacity (FWC) until the onset of water-stress treatment at 21 DAS. Plants were then separated into two distinct groups for two irrigation regimes (80% or 30% FWC) based on the effective quantum yield of PSII (Φ_{PSII}) measured from the top of the plant.

The fresh peat contained 74.1% dry matter (*i.e.*, 100 g fresh substrate = 74.1 g dry matter). At 100% saturation, the same 100 g portion weighed 200.22 g; thus, 80% FWC corresponded to a substrate mass of 178.65 g and 30% FWC to 115.57 g. Pots were weighed, including the pot mass (9.58 g), to achieve the target FWC levels. Irrigation regimes were maintained for 4 weeks (until 49 DAS). Pots were weighed every other day, and water was added as required. Foliar spraying with 0.5 or 1.0 mM Si was applied twice (21 and 28 DAS) at a dose equivalent to 400 L ha⁻¹, assuming a planting density of 150 plants per square meter. Fourteen treatment combinations were established:

Treatment combinations

1	80% FWC, no Si (control)
2	80% FWC + 0.5 mM seed priming
3	80% FWC + 1.0 mM seed priming
4	80% FWC + 0.5 mM foliar spray
5	80% FWC + 1.0 mM foliar spray
6	80% FWC + 0.5 mM seed priming + 0.5 mM foliar spray
7	80% FWC + 1.0 mM seed priming + 1.0 mM foliar spray
8	30% FWC, no Si (drought)
9	30% FWC + 0.5 mM seed priming
10	30% FWC + 1.0 mM seed priming
11	30% FWC + 0.5 mM foliar spray
12	30% FWC + 1.0 mM foliar spray
13	30% FWC + 0.5 mM seed priming + 0.5 mM foliar spray
14	30% FWC + 1.0 mM seed priming + 1.0 mM foliar spray

The experiment followed a completely randomized design. Morphological, physiological, and photosynthetic traits were assessed at 49 DAS using five biological replicates per treatment ($n = 5$).

Morphological attributes: The height was measured from the base to the apex of the plants using a scale, and the recorded values were then averaged to obtain the final height. The stem diameter was measured from three different segments of each plant (base, middle, and top) using slide calipers. The measurements taken from these three segments were averaged to determine the stem diameter of each plant, after which the values from all the plants were averaged to obtain the final stem diameter. The number of leaves was counted from each plant in

each treatment, and the average of all measurements was taken to determine the number of leaves per plant. The leaf thickness of 4th, 5th, and 6th node leaves was measured from the same plant using slide calipers; the thickness values of these three leaves were averaged to obtain the leaf thickness of each plant, and then the values from five plants were averaged to obtain the final leaf thickness. Five plants from each treatment were harvested from the base of the plant, and immediately after harvesting, the fresh mass (FM) of each plant was recorded separately, after which the values were averaged. For dry mass (DM), the plants were first air-dried to reduce the initial moisture and then oven-dried at 70°C for three days before weighing, and the values were averaged.

Relative water content: Three fully expanded leaves were collected from each plant and weighed immediately to record the FM. The leaves were then immersed in dH₂O for 24 h, blotted away excess moisture, and weighed again to obtain the turgid mass (TM). Afterward, they were dried in an oven at 70°C for 72 h to determine the DM. Relative water content (RWC) was calculated according to [Barrs and Weatherley \(1962\)](#) using the following equation: $RWC [\%] = [(FM - DM)/(TM - DM)] \times 100$.

Electrolyte leakage: To assess electrolyte leakage (EL), 0.5 g of fresh leaf tissue was placed in 15 mL of dH₂O and incubated at 40°C for 1 h. After incubation, the electrical conductivity of the solution (EC₁) was measured using a *CPC-411 pH/Conductivity Meter* (Zabrze, Poland). The same samples were then heated at 100°C for 40 min to release all electrolytes, and the final conductivity (EC₂) was recorded. Electrolyte leakage was expressed following [Dionisio-Sese and Tobita \(1998\)](#) as: $EL [\%] = (EC_1/EC_2) \times 100$.

Chlorophyll fluorescence parameters: Chlorophyll (Chl) fluorescence was measured using a *FluorPen FP 110/D* (Photon System Instruments, Drásov, Czech Republic) equipped with detachable dark-adaptation clips. After 30 min of dark adaptation, the leaves were exposed to continuous illumination consisting of 30% flash pulse, 80% super pulse, and 60% actinic pulse intensities, provided by a 455-nm light source to induce a rapid Chl fluorescence transient. The fluorescence signal (F_t) and the normalized fluorescence intensity (F_t/F_0 , where F_0 represents the minimal fluorescence) were plotted against the logarithm of the measurement time. Five biological replicates were analyzed for each treatment. The parameters and corresponding equations used to derive data from the Chl *a* fluorescence transient followed the methodology described by [Strasser *et al.* \(2004\)](#) and [Kalaji *et al.* \(2017\)](#).

Gas exchange and photosynthetic parameters: Gas-exchange parameters of differently treated plants were measured using a *GFS-3000* portable gas exchange fluorescence system (*Heinz Walz GmbH*, Effeltrich, Germany) between 9:30 and 15:30 h. Measurements were conducted on a standardized leaf area of 8 cm². During the measurements, the chamber air temperature was

maintained at 23°C, the CO₂ concentration was set to 400 ppm, and the photosynthetic photon flux density (PPFD) in the reference chamber was 1,000 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Gas-exchange parameters, including the net photosynthetic rate (P_N), stomatal conductance (g_s), transpiration rate (E), and intercellular CO₂ concentration (C_i), were recorded simultaneously from five biological replicates per treatment.

Photosynthetic parameters based on Chl fluorescence were assessed using a *MultispeQ V2.0* device (*PhotosynQ Inc.*, East Lansing, MI, USA) linked to the *PhotosynQ* online platform (<http://www.photosynq.org>). The instrument provided measurements of the effective quantum yield of PSII (Φ_{PSII}), the quantum yield of regulated nonphotochemical energy dissipation (Φ_{NPQ}), the quantum yield of nonregulated energy dissipation (Φ_{NO}), and the photochemical quenching coefficient (q_L) (*Gupta et al.* 2024). Data were collected from five biological replicates for each treatment. The equations used to calculate Φ_{PSII} , Φ_{NO} , Φ_{NPQ} , and q_L are as follows:

$$\Phi_{\text{PSII}} = (F_m' - F_s)/F_m'$$

$$\Phi_{\text{NO}} = F_s/F_m'$$

$$\Phi_{\text{NPQ}} = 1 - (\Phi_{\text{PSII}} + \Phi_{\text{NO}})$$

$$q_L = \left(\frac{F_m' - F_s}{F_m' - F_o'} \right) \times \left(\frac{F_o'}{F_s} \right)$$

The SPAD values were also obtained using the *MultispeQ V2.0* device. For each treatment, five independent measurements were taken and averaged to obtain the final SPAD value.

Statistical analysis: Data visualization was performed using *Microsoft Excel* (*Microsoft Corporation*, Redmond, WA, USA). All results are presented as the mean $\pm$ standard deviation (SD) based on five biological replicates ($n = 5$). Data were tested for normality and homogeneity of variances using the *Shapiro–Wilk* and *Levene's* tests, respectively. When these assumptions were met, the variables were analyzed using a one-way analysis of variance (*ANOVA*), followed by *Tukey's* honestly significant difference (HSD) test for post hoc multiple comparisons at a significance level of $p \leq 0.05$. All statistical procedures were conducted in *RStudio* (version 4.5.1, *RStudio Inc.*, Boston, MA, USA).

Results

Plant growth, biomass, and SPAD value: Under control conditions (80% FWC, no Si), the average plant height was 105 cm, whereas drought stress (30% FWC, no Si) reduced it to 35 cm (67% reduction). The combined application of seed priming and foliar Si (0.5 mM) under well-watered conditions increased plant height to 123.5 cm (18% higher than the control). However, under drought stress, neither individual nor combined Si applications significantly affected plant height (Table 1). The stem diameter in control plants was 6.94 mm, which declined to 4.6 mm

Table 1. Effect of seed priming and foliar silicon (Si) supplementation on the plant height, stem diameter, number of leaves per plant, leaf thickness, fresh mass, dry mass, and SPAD value of common buckwheat under control (80% FWC) and drought (30% FWC) conditions. *Different letters indicate significant differences between treatments, $p \leq 0.05$.*

Treatments	Plant height [cm]	Stem diameter [mm]	Number of leaves per plant	Leaf thickness [mm]	Fresh mass [g per plant]	Dry mass [g per plant]	SPAD value
Control	No Si	105.00 $\pm$ 5.66 ^b	6.94 $\pm$ 0.34 ^a	25.83 $\pm$ 1.33 ^b	0.33 $\pm$ 0.02 ^{efg}	5.40 $\pm$ 0.03 ^d	35.18 $\pm$ 1.63 ^{cd}
	Seed priming	114.00 $\pm$ 7.46 ^{ab}	7.36 $\pm$ 0.45 ^a	26.17 $\pm$ 0.75 ^b	0.41 $\pm$ 0.02 ^{ab}	5.96 $\pm$ 0.41 ^{bc}	35.94 $\pm$ 2.21 ^c
	1.0 mM	110.83 $\pm$ 7.03 ^b	7.25 $\pm$ 0.48 ^a	31.50 $\pm$ 2.07 ^a	0.38 $\pm$ 0.02 ^{bed}	6.08 $\pm$ 0.34 ^{bc}	31.23 $\pm$ 1.62 ^{de}
	Foliar spray	110.33 $\pm$ 7.06 ^b	6.89 $\pm$ 0.43 ^a	27.33 $\pm$ 1.86 ^b	0.34 $\pm$ 0.01 ^{def}	5.99 $\pm$ 0.17 ^{bc}	30.72 $\pm$ 1.39 ^e
	0.5 mM	111.17 $\pm$ 8.57 ^b	7.17 $\pm$ 0.44 ^a	27.67 $\pm$ 1.37 ^b	0.35 $\pm$ 0.03 ^{cde}	5.81 $\pm$ 0.29 ^{cd}	34.44 $\pm$ 1.96 ^{cde}
	1.0 mM	123.50 $\pm$ 9.81 ^a	7.39 $\pm$ 0.25 ^a	26.83 $\pm$ 1.17 ^b	0.35 $\pm$ 0.01 ^{cde}	6.66 $\pm$ 0.34 ^a	32.98 $\pm$ 1.49 ^{cde}
Drought	Foliar spray	103.83 $\pm$ 8.50 ^b	7.06 $\pm$ 0.46 ^a	33.33 $\pm$ 2.88 ^a	0.44 $\pm$ 0.04 ^a	6.40 $\pm$ 0.34 ^{ab}	36.23 $\pm$ 2.20 ^e
	No Si	35.00 $\pm$ 2.28 ^c	4.60 $\pm$ 0.38 ^b	14.33 $\pm$ 0.52 ^d	0.29 $\pm$ 0.01 ^g	0.83 $\pm$ 0.09 ^f	47.12 $\pm$ 2.62 ^b
	Seed priming	39.83 $\pm$ 2.14 ^c	5.00 $\pm$ 0.24 ^b	17.83 $\pm$ 0.98 ^c	0.30 $\pm$ 0.01 ^{fg}	1.34 $\pm$ 0.06 ^{ef}	55.05 $\pm$ 1.36 ^a
	1.0 mM	43.00 $\pm$ 8.46 ^c	5.08 $\pm$ 0.35 ^b	17.83 $\pm$ 1.17 ^c	0.34 $\pm$ 0.02 ^{def}	1.41 $\pm$ 0.08 ^e	50.24 $\pm$ 1.54 ^b
	Foliar spray	40.67 $\pm$ 2.50 ^c	5.00 $\pm$ 0.26 ^b	15.33 $\pm$ 1.21 ^{cd}	0.33 $\pm$ 0.02 ^{d-g}	1.24 $\pm$ 0.09 ^{ef}	55.14 $\pm$ 3.52 ^a
	0.5 mM	42.83 $\pm$ 1.33 ^c	5.08 $\pm$ 0.29 ^b	17.50 $\pm$ 1.05 ^c	0.39 $\pm$ 0.03 ^{bc}	1.50 $\pm$ 0.07 ^e	57.02 $\pm$ 1.40 ^a
Seed priming + Foliar spray	0.5 mM	38.33 $\pm$ 2.25 ^c	5.11 $\pm$ 0.20 ^b	18.00 $\pm$ 1.41 ^c	0.37 $\pm$ 0.03 ^{b-c}	1.38 $\pm$ 0.06 ^{ef}	58.59 $\pm$ 2.90 ^a
	1.0 mM	40.83 $\pm$ 2.04 ^c	5.17 $\pm$ 0.21 ^b	17.66 $\pm$ 1.03 ^c	0.41 $\pm$ 0.03 ^{ab}	1.64 $\pm$ 0.05 ^e	57.84 $\pm$ 2.98 ^a

(34% reduction) under drought stress. Silicon treatments, whether applied through seed priming, foliar spray, or their combination, did not significantly influence stem diameter under either well-watered or drought conditions (Table 1). Control plants produced an average of 25.83 leaves, whereas drought stress reduced leaf number to 14.33 (45% decrease). Under well-watered conditions, the combined application of 1.0 mM Si resulted in the highest leaf number (33.33; 29% higher than control). Under drought stress, seed priming with 0.5 or 1.0 mM Si increased leaf number to 17.83 (24% higher than drought without Si). Foliar application of 1.0 mM Si also increased leaf number (17.5), while the combined application of 0.5 mM Si resulted in the highest leaf count under drought (~18; 26% higher than drought without Si) (Table 1). Leaf thickness in control plants was 0.33 mm. The combined application of 1.0 mM Si under well-watered conditions increased leaf thickness to 0.44 mm (35% higher than control). Drought slightly reduced leaf thickness to 0.29 mm (10% decrease), whereas the combined 1.0 mM Si treatment increased it to 0.41 mm (39% higher than drought without Si) (Table 1). Fresh mass of control plants averaged 34.34 g. Under well-watered conditions, combined applications of 0.5 and 1.0 mM Si increased FM to 39.87 g and 39.72 g, respectively. Drought stress reduced FM to 10.62 g (69% decrease), whereas combined 1.0 mM Si increased FM to 16.32 g (54% higher than drought without Si) (Table 1). The dry mass of control plants was 5.4 g. Combined application of 0.5 and 1.0 mM Si under well-watered conditions increased DM to 6.66 g (23%) and 6.4 g (19%), respectively. Drought stress reduced DM to 0.83 g (85% decrease), whereas combined 1.0 mM Si increased DM to 1.64 g (96% higher than drought without Si) (Table 1). The SPAD value of control plants averaged 35.18. Foliar application of 0.5 mM Si under well-watered conditions reduced SPAD to 30.72 (13% lower than control). In contrast, drought stress increased SPAD to 47.12 (34% higher than control).

Silicon treatments further enhanced SPAD values, with the combined 0.5 mM Si treatment showing the highest value (58.59), which was 24% higher than drought-stressed plants without Si (Table 1).

The morphological appearance of well-watered and drought-stressed plants is presented in Fig. 1. As shown, the plants grown under regular irrigation exhibited vigorous and healthy growth, characterized by greater plant height, more leaves, larger leaf area, thicker stems, and increased flowering compared to drought-stressed plants. In contrast, drought-stressed plants (30% FWC, no Si) showed visible wilting symptoms, reduced plant height, fewer leaves, and smaller leaf size. However, Si-treated plants under drought conditions appeared healthier and more robust than untreated drought-stressed plants. Among all treatments, the combined application of 1.0 mM Si through seed priming and foliar spray produced the most vigorous plants, with noticeably greater height, leaf number, and leaf size compared to other Si-treated plants (Fig. 1).

Relative water content and electrolyte leakage:

The average RWC of control plants (80% FWC, no Si) was 83.3%. Silicon-treated plants under well-watered conditions showed slightly higher RWC, but the differences were not significant. In contrast, drought stress (30% FWC, no Si) reduced RWC to 59.3% (23% lower than the control). Under drought conditions, Si supplementation improved RWC across treatments by approximately 30–33% compared with drought-stressed plants without Si (Fig. 2A). The EL of control plants averaged 50.7%. Under well-watered conditions, Si treatments slightly reduced EL, with the lowest value observed with foliar application of 1.0 mM Si (about 6% lower than control). Drought stress increased EL to 63.8% (13% higher than control). However, Si supplementation under drought significantly reduced EL, reaching levels comparable to Si-treated plants under well-watered conditions.



Fig. 1. Morphological appearance of common buckwheat under control (80% FWC) and drought (30% FWC) conditions at 49 DAS.

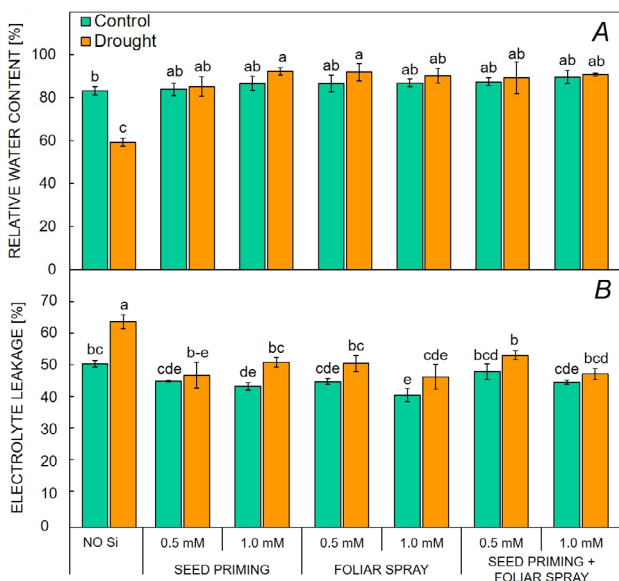


Fig. 2. Effect of seed priming and foliar silicon supplementation on the (A) relative water content and (B) electrolyte leakage of common buckwheat under control (80% FWC) and drought (30% FWC) conditions. Means with different letters differ significantly at $p \leq 0.05$. Error bars represent standard error ($n = 5$).

The combined application of 1.0 mM Si *via* seed priming and foliar spray produced the lowest EL (47.6%), about 16% lower than drought-stressed plants without Si (Fig. 2B).

Gas-exchange parameters: The P_N of control plants (80% FWC, no Si) was about $0.6 \mu\text{mol}(\text{CO}_2) \text{ m}^{-2} \text{ s}^{-1}$. Under well-watered conditions, Si application increased P_N , with the combined treatment of 1.0 mM Si through seed priming and foliar spray producing the highest value [$2.05 \mu\text{mol}(\text{CO}_2) \text{ m}^{-2} \text{ s}^{-1}$]. In contrast, drought stress (30% FWC, no Si) drastically reduced P_N to $-0.22 \mu\text{mol}(\text{CO}_2) \text{ m}^{-2} \text{ s}^{-1}$, indicating severe inhibition of photosynthesis. However, Si supplementation significantly alleviated this decline, with the combined 1.0 mM Si treatment showing the greatest improvement [$1.87 \mu\text{mol}(\text{CO}_2) \text{ m}^{-2} \text{ s}^{-1}$] under drought conditions (Fig. 3A). The g_s of control plants was $20.94 \text{ mmol}(\text{H}_2\text{O}) \text{ m}^{-2} \text{ s}^{-1}$. Silicon application increased g_s under well-watered conditions, with the highest value [$95.28 \text{ mmol}(\text{H}_2\text{O}) \text{ m}^{-2} \text{ s}^{-1}$] observed in the combined 1.0 mM Si treatment. Drought stress sharply reduced g_s to $3.67 \text{ mmol}(\text{H}_2\text{O}) \text{ m}^{-2} \text{ s}^{-1}$ (82% lower than control). Silicon supplementation markedly improved g_s under drought, with the combined 1.0 mM Si treatment reaching $49.35 \text{ mmol}(\text{H}_2\text{O}) \text{ m}^{-2} \text{ s}^{-1}$, about 13.4 times higher than drought-stressed plants without Si (Fig. 3B). The E of control plants was $0.20 \text{ mmol}(\text{H}_2\text{O}) \text{ m}^{-2} \text{ s}^{-1}$. Under well-watered conditions, the combined 1.0 mM Si treatment produced the highest E [$0.73 \text{ mmol}(\text{H}_2\text{O}) \text{ m}^{-2} \text{ s}^{-1}$], 3.7 times higher than the control. Drought stress reduced E to $0.035 \text{ mmol}(\text{H}_2\text{O}) \text{ m}^{-2} \text{ s}^{-1}$ (82% decrease), whereas Si supplementation significantly improved E , with the combined 1.0 mM Si treatment reaching $0.46 \text{ mmol}(\text{H}_2\text{O}) \text{ m}^{-2} \text{ s}^{-1}$, about 13.2 times higher than drought-stressed plants without Si (Fig. 3C). The C_i in control plants was 354.58 ppm, while drought stress increased C_i to 490.03 ppm (38% higher

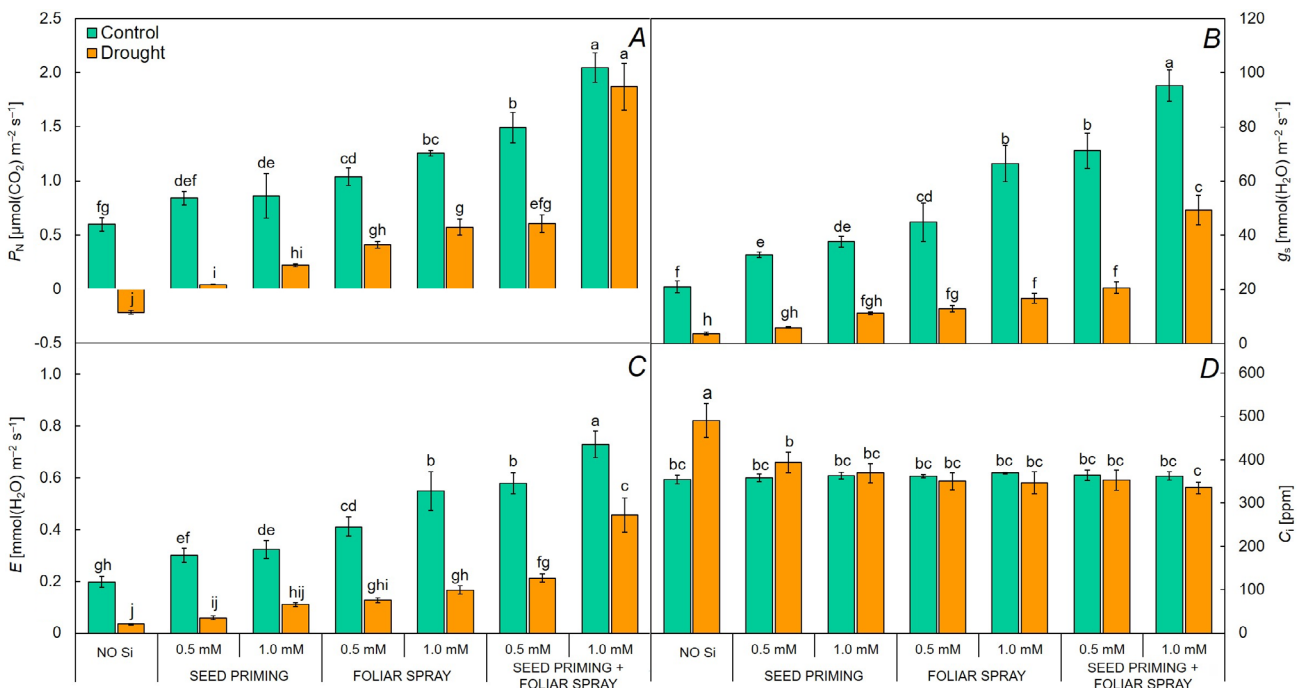


Fig. 3. Effect of seed priming and foliar silicon supplementation on the (A) photosynthetic rate (P_N), (B) stomatal conductance (g_s), (C) transpiration rate (E), and (D) intercellular CO_2 concentration (C_i) of common buckwheat under control (80% FWC) and drought (30% FWC) conditions. Means with different letters differ significantly at $p \leq 0.05$. Error bars represent standard error ($n = 5$).

than control). Silicon application reduced C_i under drought conditions, with the combined 1.0 mM Si treatment showing the greatest reduction to 335.19 ppm, about 32% lower than drought-stressed plants without Si (Fig. 3D).

PhotosynQ parameters: Drought stress (30% FWC, no Si) significantly reduced the Φ_{PSII} , Φ_{NPQ} , and q_L by 39, 27, and 34%, respectively, compared with control plants (80% FWC, no Si) (Fig. 4A,B,D). In contrast, the Φ_{NO} increased about 5.2-fold under drought stress (Fig. 4C). Silicon application markedly improved PSII performance under drought conditions. The combined application of 1.0 mM Si *via* seed priming and foliar spray produced the greatest increase in Φ_{PSII} (112% higher than drought-stressed plants without Si) (Fig. 4A). Φ_{NPQ} also increased with Si treatments, with 0.5 mM Si seed priming showing the highest enhancement (38%) compared with the drought-stressed control (Fig. 4B). Conversely, Φ_{NO} decreased substantially in Si-treated plants, showing a 75–77% reduction relative to untreated drought-stressed plants (Fig. 4C). Similarly, q_L improved following Si supplementation, with the combined 1.0 mM Si treatment showing the highest increase (34%) compared with drought-stressed plants without Si (Fig. 4D).

Chlorophyll fluorescence and OJIP parameters: The normalized fluorescence intensity (F/F_0) from the O to P phases is shown in Fig. 5A–C. Drought-stressed plants (30% FWC, no Si) initially exhibited fluorescence levels (O phase) similar to those of control plants

(80% FWC, no Si). However, a clear decline appeared from the J phase onward, becoming more pronounced at the I and P phases, indicating impaired electron transport beyond Q_A under drought stress. Silicon application through seed priming, foliar spray, or their combination improved the fluorescence curves of drought-stressed plants, with elevated I and P phases and more stable OJIP transients. The combined 1.0 mM Si treatment produced the most improved OJIP curve, closely resembling that of well-watered control plants (Fig. 5C), suggesting effective mitigation of drought-induced PSII damage and improved electron transport.

Radar plots (Fig. 5D–F) illustrate relative changes in key JIP-test parameters normalized to the control. Under drought stress, F_0 , F_m , F_v , V_L , Ψ_0 , and Φ_{EO} decreased by 8, 24, 27, 10, 15, and 19%, respectively, indicating reduced primary photochemistry and energy transfer efficiency. In contrast, V_J , M_0 , Φ_{DO} , and S_m increased by 15, 26, 21, and 27%, reflecting enhanced energy dissipation and restricted electron transport. The greatest recovery was observed with the combined 1.0 mM Si treatment, where F_m , F_v , Ψ_0 , and Φ_{EO} increased by 36, 45, 30, and 38%, respectively, while V_J , M_0 , Φ_{DO} , and S_m decreased by 23, 23, 22, and 10% compared with drought-stressed plants without Si. These results indicate that combined Si application improved PSII integrity and reduced excess energy dissipation under drought stress.

The F_v/F_m in drought-stressed plants (30% FWC, no Si) decreased by about 5% compared with control plants (80% FWC, no Si). Silicon application improved F_v/F_m

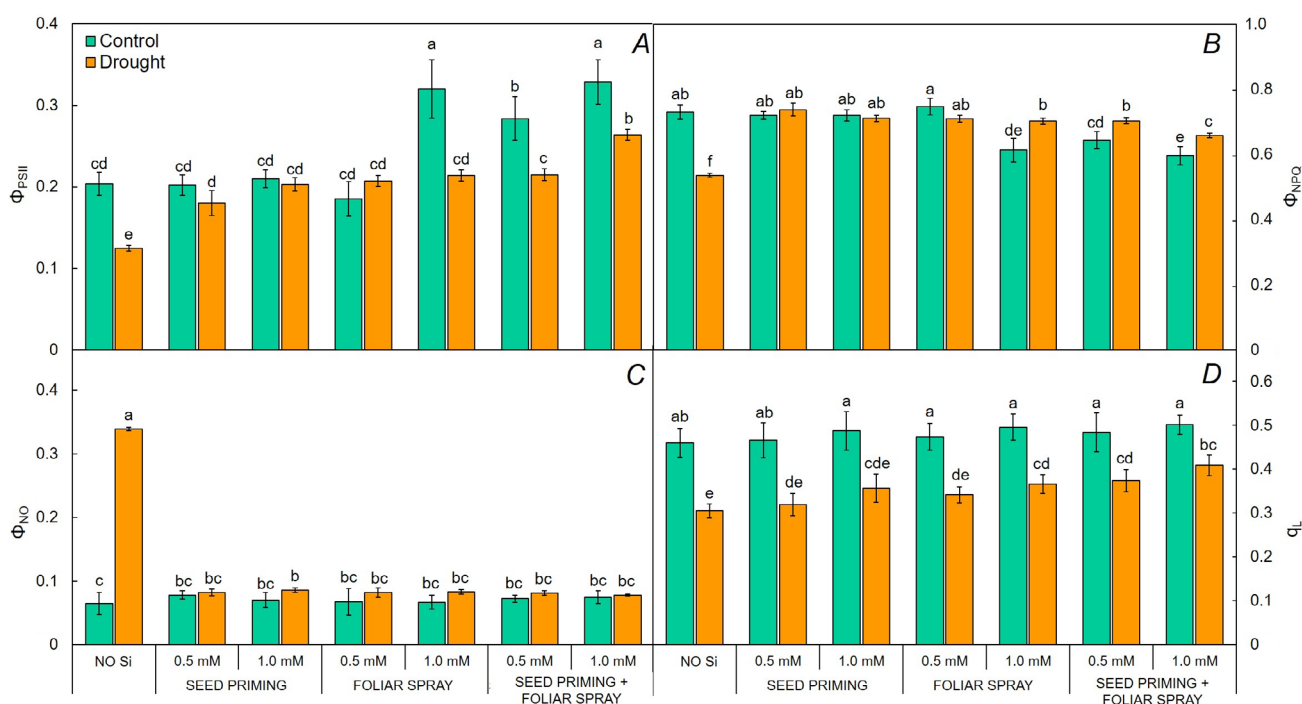


Fig. 4. Effect of seed priming and foliar silicon supplementation on the (A) effective quantum yield of PSII (Φ_{PSII}), (B) quantum yield of light-induced energy dissipation in PSII (Φ_{NPQ}), (C) quantum yield of light-independent energy dissipation in PSII (Φ_{NO}), and (D) photochemical quenching of variable fluorescence (q_L) of common buckwheat under control (80% FWC) and drought (30% FWC) conditions. Means with different letters differ significantly at $p \leq 0.05$. Error bars represent standard error ($n = 5$).

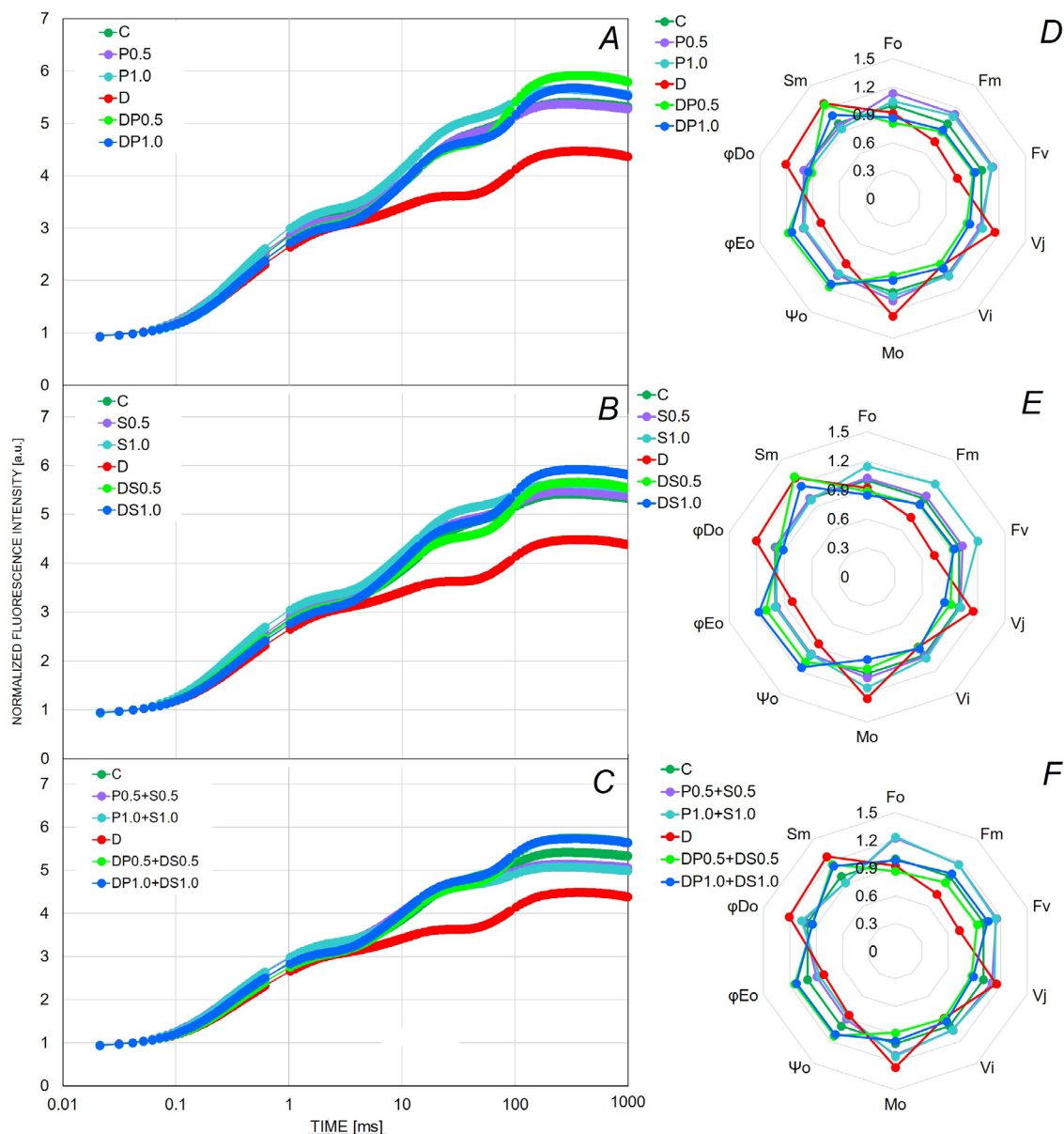


Fig. 5. Effect of seed priming and foliar silicon supplementation on the chlorophyll *a* fluorescence (OJIP) transient of common buckwheat under control (80% FWC) and drought (30% FWC) conditions. Normalized fluorescence intensity (F/F_0 ; A–C) and spider plots of key OJIP parameters (D–F) are shown under different treatment conditions. For better visualization, seed priming, foliar spraying, and their combined application are presented separately alongside the control and drought-stressed treatments. Here, F_0 = minimal fluorescence when all PSII RCs are open; F_m = maximal fluorescence when all PSII RCs are closed; F_v = maximal variable fluorescence; V_j = relative variable fluorescence in step J; V_i = relative variable fluorescence in step I; M_0 = approximated initial slope of the fluorescence transient; Ψ_0 = probability (at $t = 0$) of electron transport outside Q_A^- ; Φ_{EO} = quantum yield of electron transport (at $t = 0$); Φ_{DO} = quantum yield of energy dissipation (at $t = 0$); and S_m = normalized total area above the OJIP curve.

under drought by 6–7% relative to untreated drought-stressed plants. Although differences between Si treatments were not statistically significant, 0.5 mM Si seed priming and 1.0 mM Si foliar spray showed the greatest increases (7 and 6.9%, respectively) (Fig. 6A). The PI_{ABS} declined by about 46% under drought stress compared with the control. Silicon application markedly enhanced PI_{ABS} under drought conditions, with 0.5 mM Si seed priming and 1.0 mM Si foliar spray increasing PI_{ABS} by 2.61- and

2.68-fold, respectively. The combined 1.0 mM Si treatment increased it by 2.65-fold relative to drought-stressed plants without Si (Fig. 6B). Drought stress increased ABS/RC , TR_0/RC , and DI_0/RC by 15, 9, and 39%, respectively, and reduced ET_0/RC by 6% compared with the control. Silicon application alleviated these effects under drought conditions. The greatest reductions in ABS/RC and TR_0/RC (both 16%) were observed with 0.5 mM Si seed priming, followed by 1.0 mM foliar Si (13%) (Fig. 6C,D).

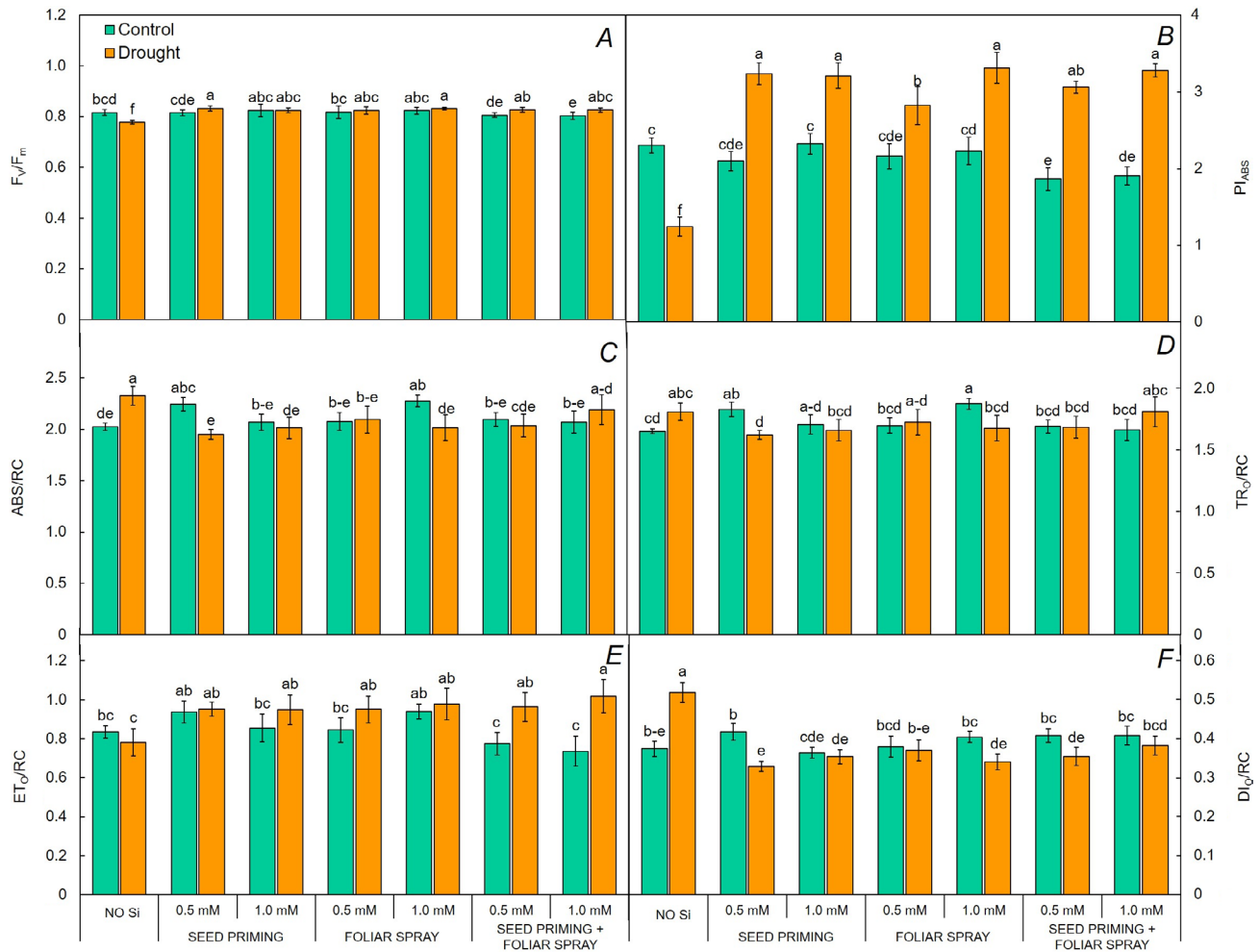


Fig. 6. Effect of seed priming and foliar silicon supplementation on (A) maximum photochemical efficiency of PSII (F_v/F_m), (B) performance index (PI_{ABS}), (C) absorption flux per one active RC (ABS/RC), (D) energy flux trapped by one active RC at $t = 0$ (TR_0/RC), (E) rate of electron transport by one active RC at $t = 0$ (ET_0/RC), and (F) dissipated energy flux by one active RC at $t = 0$ (DI_0/RC) of common buckwheat under control (80% FWC) and drought (30% FWC) conditions. Means with different letters differ significantly at $p \leq 0.05$. Error bars represent standard error ($n = 5$).

In contrast, ET_0/RC increased with Si treatments, with the combined 1.0 mM Si treatment showing the highest improvement (30%), followed by 1.0 mM foliar Si (25%) (Fig. 6E). DI_0/RC decreased across all Si treatments under drought by 26–37%, with the greatest reduction (37%) in 0.5 mM Si seed-primed plants (Fig. 6F).

Heatmap with clustered dendrogram: The heatmap with a clustered dendrogram illustrates the variation in growth, physiological, and photosynthetic parameters of buckwheat subjected to drought stress under different Si treatments. Hierarchical clustering revealed five distinct grouping patterns among the treatments. Under well-watered conditions, the combined applications of 0.5 mM and 1.0 mM Si through seed priming and foliar spraying formed a separate cluster, while the remaining treatments, including the control (80% FWC, no Si), were grouped, indicating similar physiological responses. Under drought conditions, three distinct clusters emerged. The drought-stressed plants (30% FWC, no Si) formed a separate group

characterized by the most negative parameter values, as indicated by the color gradients. Among the Si-treated plants under drought stress, the combined application of 1.0 mM Si through seed priming and foliar spraying was positioned distinctly from the other Si treatments, showing predominantly positive values across most traits. The remaining Si-treated drought groups clustered together, suggesting comparable levels of stress mitigation and physiological regulation among them (Fig. 7).

Discussion

This study elucidates the adverse effects of drought on the growth, physiological traits, and photosynthetic performance of buckwheat, while also demonstrating the mitigating potential of Si applied through seed priming and foliar supplementation, either individually or in combination. Drought stress caused significant reductions in key growth parameters, including plant height, stem diameter, leaf number per plant, leaf thickness, FM, and

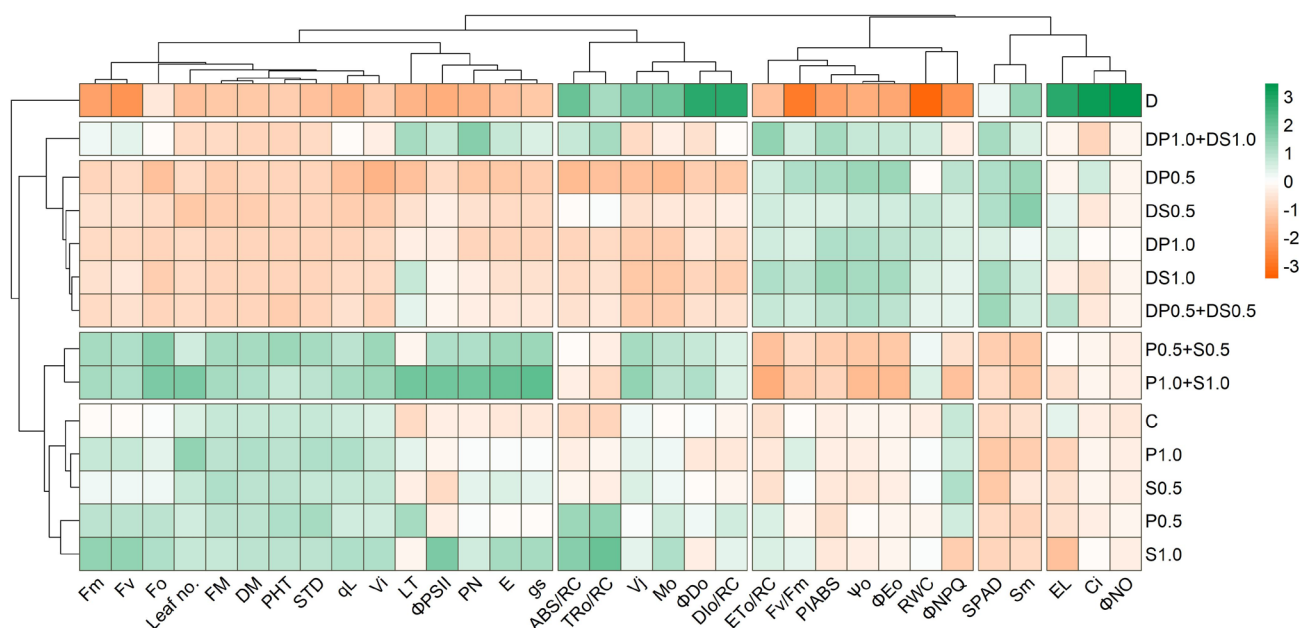


Fig. 7. Heatmap with clustered dendrogram of various growth, physiological, and photosynthetic parameters of common buckwheat under control (80% FWC) and drought (30% FWC) conditions. Here, C = 80% FWC, no Si, P0.5 = 80% FWC + 0.5 mM seed priming, P1.0 = 80% FWC + 1.0 mM seed priming, S0.5 = 80% FWC + 0.5 mM foliar spray, S1.0 = 80% FWC + 1.0 mM foliar spray, P0.5+S0.5 = 80% FWC + 0.5 mM seed priming + 0.5 mM foliar spray, P1.0+S1.0 = 80% FWC + 1.0 mM seed priming + 1.0 mM foliar spray, D = 30% FWC, no Si, DP0.5 = 30% FWC + 0.5 mM seed priming, DP1.0 = 30% FWC + 1.0 mM seed priming, DS0.5 = 30% FWC + 0.5 mM foliar spray, DS1.0 = 30% FWC + 1.0 mM foliar spray, DP0.5+DS0.5 = 30% FWC + 0.5 mM seed priming + 0.5 mM foliar spray, and DP1.0+DS1.0 = 30% FWC + 1.0 mM seed priming + 1.0 mM foliar spray. Green shades represent values higher than the overall mean (positive Z-scores), whereas orange shades represent values lower than the overall mean (negative Z-scores).

DM, reflecting impaired cellular integrity and restricted nutrient uptake (Iqbal *et al.* 2020). Drought-induced disruptions in plant–water relations lead to increased tissue dehydration due to enhanced water loss. This dehydration triggers osmotic stress, suppresses mitotic cell division, restricts cell expansion, and ultimately limits photosynthetic activity (Gowtham *et al.* 2022). In addition, drought negatively affects several physiological processes, including stomatal conductance, carbon dioxide diffusion, electron transport, water-use efficiency, respiration, transpiration, and membrane stability (Qi *et al.* 2020, Gheisary *et al.* 2025). Collectively, these physiological impairments contribute to reduced biomass accumulation and overall growth inhibition. Consistent with these observations, the present study recorded substantial declines in plant height, SPAD values, FM, and DM under drought conditions, corroborating earlier reports by Parveen *et al.* (2019) and Ahsan *et al.* (2023). However, plants subjected to combined Si treatments exhibited markedly improved performance. This enhanced response can be partly attributed to the physiological advantages associated with Si-mediated seed priming. Silicon-based seed priming accelerates and synchronizes early germination by facilitating the rapid completion of pre-germinative metabolic processes (Zheng *et al.* 2016). During germination, Si-induced regulation of hydrolases and other metabolic enzymes enhances metabolite synthesis, thereby promoting faster and more uniform seedling establishment (Parveen *et al.* 2019). Furthermore, seed priming contributes to membrane repair

following seed deterioration or exposure to prior abiotic stress (Zheng *et al.* 2016). It initiates key biochemical adjustments, including enzyme activation, dormancy release, degradation of germination inhibitors, and improved water imbibition. These processes collectively support vigorous early growth and enhance plant resilience under stress conditions (Ayed *et al.* 2022). Consequently, the integrated application of Si through seed priming and foliar spraying resulted in improved growth performance under drought stress. In addition to these improvements, Si-treated plants exhibited increased leaf thickness under drought conditions, indicating enhanced structural integrity and improved leaf hydration status. Silicon deposition in epidermal tissues has been shown to increase leaf thickness and promote a more erect leaf orientation, which can enhance light interception and maintain photosynthetic efficiency under stress conditions (Rastogi *et al.* 2021). This response reflects improved overall plant growth and highlights the important role of Si in maintaining growth performance and developmental stability under stress.

Drought also triggers excessive accumulation of reactive oxygen species, leading to oxidative damage of lipids, proteins, and nucleic acids, and ultimately constraining plant performance (Biju *et al.* 2017). In the present study, drought significantly reduced RWC and increased EL, indicating membrane destabilization and impaired water status. Similar responses have been reported in rice, where Si application improved leaf water potential and water-use efficiency under drought stress (Chen *et al.* 2011). Consistently, combined Si application

in the present experiment significantly increased RWC and reduced EL, in agreement with reports in wheat (Ashfaq *et al.* 2025) and soybean (Abdullah *et al.* 2025). The beneficial effects of Si on plant water relations are largely attributed to enhanced root hydraulic conductance across different plant strategies, including accumulator, intermediate, and excluder species (Wang *et al.* 2021). Silicon further stabilizes water balance by improving leaf osmotic potential and maintaining higher RWC (Ning *et al.* 2023, Saja-Garbarz *et al.* 2024), while Si-induced transcriptional upregulation of aquaporin genes enhances water uptake and transport under drought conditions (Liu *et al.* 2014). Water deficit also severely constrains photosynthesis, nutrient uptake, and assimilate distribution, while intensifying oxidative stress (Ahsan *et al.* 2023). In this study, drought markedly reduced P_N , g_s , and E , while C_i increased, indicating impaired CO_2 assimilation likely due to nonstomatal limitations. Notably, control plants under well-irrigated conditions exhibited relatively lower P_N values compared to Si-treated plants under the same irrigation regime, which may be attributed to growth stage-dependent differences and nitrogen remobilization (Wang *et al.* 2026). During the vegetative stage, nitrogen is predominantly allocated to leaves and stems to support photosynthetic capacity and vegetative growth, whereas at the reproductive stage, nitrogen is remobilized from vegetative tissues to develop reproductive organs, resulting in reduced photosynthetic enzyme content and activity in leaves (Ciampitti *et al.* 2013, Gregersen *et al.* 2013). Since the control plants had already entered the reproductive stage, this nitrogen remobilization likely contributed to the observed decline in P_N , a phenomenon consistent with ontogenetic reduction in photosynthetic activity previously documented in cotton (Qian *et al.* 2025) and maize (Wang *et al.* 2026). Silicon application, particularly the combined seed priming and foliar treatment, effectively restored gas-exchange attributes under both well-irrigated and drought-stressed conditions by enhancing photosynthetic rates through improved chlorophyll content and reduced degradation, improving stomatal regulation while maintaining favorable stomatal behavior, lowering intercellular CO_2 concentrations indicative of enhanced CO_2 assimilation, protecting PSII and PSI reaction centers to improve quantum efficiency and electron transport rates, and promoting Si accumulation beneath the cuticle which reduces transpiration and maintains higher tissue water content to support sustained photosynthesis (Mukarram *et al.* 2026). Furthermore, under drought stress, Si can activate defense mechanisms that promote favorable stomatal behavior and transpiration dynamics, thereby sustaining photosynthetic efficiency even under water-limiting conditions (Krucky *et al.* 2025). This collectively explains why Si-treated plants maintained higher P_N than untreated controls even under optimal irrigation. Additionally, Si reduces membrane damage by stimulating flavonoid synthesis and antioxidant defenses, thereby increasing total antioxidant capacity (Morshedloo *et al.* 2025). Emerging evidence also suggests that Si may influence stress tolerance through epigenetic regulation, including changes in DNA methylation patterns

associated with adaptive stress responses (Rao *et al.* 2024, Zi *et al.* 2024). Drought stress substantially impaired PSII functionality in the present study, as reflected by altered chlorophyll fluorescence parameters, OJIP kinetics, and *PhotosynQ*-derived indices. Reductions in F_v/F_m , Φ_{PSII} , q_L , Ψ_O , and Φ_{EO} , along with increases in Φ_{NO} , Φ_{DO} , and DI_O/RC , indicate decreased efficiency of PSII reaction centers, disrupted electron transport, and enhanced nonregulated energy dissipation. These changes are characteristic of PSII damage and reduced photosynthetic capacity under stress (Maghsoudi *et al.* 2015, Zhang *et al.* 2018). The OJIP transients further supported these findings, with drought increasing V_J and M_O while suppressing the I and P phases, reflecting Q_A^- accumulation and limitations on the PSII acceptor side. Silicon application mitigated these constraints by increasing Φ_{PSII} , F_v/F_m , PI_{ABS} , and Φ_{NPQ} , while reducing Φ_{NO} , V_J , and M_O . Partial restoration of the I and P steps in Si-treated plants, particularly under the combined 1.0 mM Si treatment, indicates improved electron transport stability. When plants activate efficient protective mechanisms, such as enhanced total flavonoid content and antioxidant capacity, drought-induced damage to PSII can be attenuated, allowing F_v/F_m values to approach those of non-stressed plants (Zhang *et al.* 2018, Mahmoud *et al.* 2023, Raihan *et al.* 2025). These results align with previous studies that PSII performance remains relatively stable under mild to moderate drought when effective defense mechanisms are engaged (Maghsoudi *et al.* 2015, Alinia *et al.* 2024, Gheisary *et al.* 2025, Morshedloo *et al.* 2025). Finally, cluster analysis further corroborated these findings, revealing strong negative effects of drought on physiological and photosynthetic traits. In contrast, Si-treated plants, particularly those receiving the combined 1.0 mM Si treatment, formed a distinct cluster characterized by improved functional performance. This clustering clearly demonstrates the robust protective role of integrated Si application in mitigating drought-induced impairments across multiple physiological and photosynthetic parameters. In summary, drought severely curtailed plant growth, physiology, and photosynthetic activity. Combined Si-seed priming and foliar application alleviated these effects by optimizing water relations, safeguarding PSII, and enhancing gas exchange attributes, positioning integrated Si as a potent strategy to improve resilience against drought.

Conclusions: The findings of this study clearly demonstrate that Si, as a quasi-essential element, plays a significant role in promoting drought tolerance in buckwheat plants. Exogenous application of Si improved plant growth and physiological performance by enhancing several key attributes, including water retention capacity, chlorophyll content, photosynthetic rate, and membrane stability. Among the examined treatments, the combined application of 1.0 mM Si through seed priming and foliar spraying proved to be the most effective in mitigating the adverse impacts of drought stress. This integrated approach contributed to improved photosynthetic efficiency, gas exchange, and overall plant vigor,

ultimately resulting in higher biomass accumulation under water-deficit conditions. The results indicate that Si supplementation could be a promising agronomic strategy for improving the growth and productivity of buckwheat, especially in regions facing frequent droughts. Its role in maintaining cellular and physiological stability under stress highlights Si's potential as a sustainable and environmentally friendly means of strengthening crop resilience. Nevertheless, the current findings are based on controlled conditions; therefore, further validation through field trials across different environments is essential to establish optimal application methods and dosages. Moreover, understanding the molecular and biochemical mechanisms underlying Si-mediated drought tolerance remains a crucial area for future research. Insights from such studies will not only deepen our understanding of Si's physiological significance but also guide the development of more efficient Si-based strategies for sustainable crop production in drought-prone regions.

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Appendix. A summary of the parameters and corresponding equations used to derive data from the chlorophyll *a* fluorescence transient. The OJIP transient parameters were computed based on the JIP test protocol, as described by Strasser *et al.* (2004) and Kalaji *et al.* (2017).

Parameters	Explanations
F _t	Fluorescence at time t when the actinic light illumination was turned on
F ₀	Minimal fluorescence when all the reaction centres (RC) of photosystem II (PSII) are open
F _m	Maximal fluorescence when all PSII RCs are closed
F _v	Maximal variable fluorescence
F _v /F _m	Maximum photochemical efficiency of PSII
V _J = (F _J – F ₀)/(F _m – F ₀)	Relative variable fluorescence at the step J after 2 ms
V _I = (F _I – F ₀)/(F _m – F ₀)	Relative variable fluorescence at the step I after 30 ms
S _m = Area/(F _m – F ₀)	Normalized total complementary area above the O-J-I-P transient
M ₀ = (ΔV/Δt) ₀ = 4 (F _{300μs} – F ₀)/(F _m – F ₀)	Approximated initial slope (per ms) of the fluorescence transient

Parameters	Explanations
$\Psi_o = ET_o/TR_o = (1 - V_j)$	Probability of electron transport outside Q_A^- at $t = 0$
$\Phi_{EO} = ET_o/ABS = [1 - (F_o/F_m)] \Psi_o$	Quantum yield of electron transport (at $t = 0$)
$\Phi_{DO} = 1 - \Phi_{PO} = (F_o/F_m)$	Quantum yield of energy dissipation (at $t = 0$)
$ABS/RC = M_o (1/V_j) (1/\Phi_{PO})$	Absorption flux per RC at time 0
$TR_o/RC = M_o (1/V_j)$	Energy flux trapped per active RC at time 0
$ET_o/RC = M_o (1/V_j) \Psi_o$	Rate of electron transport per active RC at time 0
$DI_o/RC = (ABS/RC) - (TR_o/RC)$	Energy flux not intercepted per RC at time 0
$PI_{ABS} = \frac{RC}{ABS} \times \frac{\Phi_{PO}}{1 - \Phi_{PO}} \times \frac{\Psi_o}{1 - \Psi_o}$	Performance index of PSII on absorption basis

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