Silicon (2024) 16:4867–4881
https://doi.org/10.1007/s12633-024-03058-w

RESEARCH

Effect of Silicon Application Method on Morpho-Physio-Biochemical Traits of Cucumber Plants under Drought Stress

Akhter Ul Alam[1,2] · Hayat Ullah[1] · Sushil Kumar Himanshu[1] · Rujira Tisarum[3] · Patchara Praseartkul[3] · Suriyan Cha-um[3] · Avishek Datta[1]

Received: 9 January 2024 / Accepted: 6 June 2024 / Published online: 13 June 2024

Abstract

Drought, one of the most frequent natural disasters, is a devastating abiotic stress that arises unpredictably, develops gradually, and carries long-lasting repercussions even after it ceases. The duration and severity of drought markedly impact plant growth, development, and yield by disrupting normal morpho-physio-biochemical processes. Silicon (Si) is regarded as a crucial element for mitigating the detrimental effects of abiotic stress, including drought. The objective of this study was to evaluate the effect of Si application method on morpho-physio-biochemical traits of cucumber plants under drought stress. Two independent polyhouse experiments were conducted where cucumber (*Cucumis sativus* L.) plants were grown under four levels of soil moisture that included 40%, 60%, 80%, and 100% field capacity (FC) and Si was applied either in the form of seed priming (Experiment 1) or as soil drench (Experiment 2). For the seed priming study, four doses of Si (in the form of monosilicic acid with 20% Si content) applied were 0.25, 0.5, 1.0, and 2.0 mM along with a control in which seeds were sown directly without any priming. For the soil application study, four doses of Si (in the form of monosilicic acid with 20% Si content) applied were 15, 30, 60, and 120 kg ha^{-1} along with a control. The minimal soil moisture level (40% FC) resulted in 55–68% and 53–76% reduction in root dry matter in Experiment 1 and Experiment 2, respectively, in comparison to that at 100% FC throughout Si doses. Fruit yield, irrigation water productivity, and net photosynthetic rate exhibited a respective reduction of 77–84% and 78–84%, 25–52% and 13–47%, and 37–46% and 26–33% in Experiment 1 and Experiment 2, respectively, at 40% FC than those at 100% FC throughout Si doses. The exogenous application of Si was equally efficient irrespective of application methods. Seed priming with 0.5 mM Si outperformed all other doses and resulted in an increase of 199–284%, 169–263%, and 20–59% in fruit yield, irrigation water productivity, and net photosynthetic rate, respectively, in comparison to the control throughout soil moisture levels. Among different soil application doses of Si, 60 kg ha^{-1} was the most efficient, which resulted in 217–293%, 198–307%, and 11–33% enhancement in fruit yield, irrigation water productivity, and net photosynthetic rate, respectively, in comparison to the control throughout soil moisture levels. Exogenous incorporation of Si as seed priming at 0.5 mM and as soil drench at 60 kg ha^{-1} is recommended for cucumber cultivation in drought-affected areas.

Keywords Abiotic stress · Application method · Beneficial element · *Cucumis sativus* L. · Vegetable crop · Water-deficit stress · Water productivity

1 Introduction

Multiple climate models have assessed the impacts of global climate change, and it has been projected that changes in rainfall patterns could cause droughts and floods. Additionally, rising global surface temperatures are projected to transform larger regions into arid and semi-arid areas [1]. Human activities are largely responsible for altering the global pattern of precipitation, which in turn leads to more frequent drought events negatively impacting crop yields. Recurrent drought cycles cause enormous financial losses and have an adverse economic impact on resource-poor farmers and communities in the long run [2]. It has been reported that abiotic stress is directly responsible for 51–82% of crop yield loss [3]. In order to address the declining state of the agricultural food production system and fulfill the nutritional needs of the continuously expanding global population, enhancing crop resilience to adverse climatic

Extended author information available on the last page of the article

factors is of paramount importance. It is projected that the combination of increasing temperatures and erratic precipitation patterns would result in a 10% increase in irrigation water requirements by 2050 [4]. Approximately, 30% of the earth's land area is estimated to undergo severe drought conditions, with roughly 70% of the annual crop yield losses has been attributed to abiotic stress factors where drought stands out as the primary abiotic stressor [5, 6]. Drought-induced negative impacts on plants include disturbance in water and nutrient relations, heightened cellular dehydration, decreased photosynthetic process, disruption in assimilate partitioning, and increased oxidative damage because of the overproduction of reactive oxygen species [7], and consequently reduced growth and productivity. Drought-mediated yield losses in cereals over the past 50 years have been estimated to be approximately 10%, and projections indicate that approximately 50% of the arable land would be negatively impacted by 2050 [8].

Silicon (Si) is not classified as an essential element but is regarded as a beneficial element due to its valuable roles in various plant metabolic and physiological processes. The accumulation of Si markedly varies across plant species, ranging from 0.1 to 10% Si of the dry weight of plants [9]. It plays an important role in plant protection and is essential for enhancing growth and productivity of plants, especially in stressful environments. The application of Si enhances mechanical strength of cell wall and modulates the expression of aquaporin regulatory genes to boost root water uptake under drought stress [10]. The concentration of Si in plants regulates various physiological and metabolic functions, such as water uptake by roots and its internal transport through vascular tissue, stomatal opening/closing and transpirational moisture loss from leaves, CO_2 concentration in intercellular spaces, net photosynthetic rate, and accumulation of solutes and osmoregulatory substances [9, 11, 12]. The supplementation of Si, either as a seed priming or as a soil drenching material, has previously been reported to be beneficial in several crops, particularly in alleviating drought stress [13, 14]. This leads to the optimization of turgor pressure, proper root elongation with improved water use efficiency, and increased activity of antioxidant enzymes [15, 16].

Cucumber (*Cucumis sativus* L.), a widely-grown vegetable crop, is enriched with vitamins, minerals, antioxidants, and low level of calories. The area of cucumber cultivation under protected environmental conditions is increasing due to its high output and income [17]. Cucumber is susceptible to drought, and it requires a higher amount of water than grain crops because fruit yield and quality development are highly dependent on optimum soil moisture supply [18, 19]. During the flowering and fruiting stage, which is a crucial growth phase for cucumber, soil moisture deficit can lead to flower abortion and consequently less fruit production [20]. Furthermore, insufficient soil moisture can also result in additional problems, such as limited development of female flowers, delayed growth of fruits, and mineral nutrition irregularities [21, 22].

Evaluating drought impacts on cucumber is not a novel approach, but the exogenous incorporation of Si as a seed priming and soil drenching material to mitigate drought stress on cucumber is rarely examined. It was hypothesized that the exogenous supplementation of Si as a seed priming and soil drenching material would enhance the tolerance of cucumber plants to drought. The objective was to evaluate the effect of Si application method on morpho-physio-biochemical traits of cucumber plants under drought stress.

2 Materials and Methods

2.1 Experimental Details

The experiments were carried out over the period from September to November 2022 at the polyhouse of the Asian Institute of Technology, Klong Luang, Pathum Thani, Thailand. The geographical placement of the experimental site is 14°04′53" N latitude and 100°36′33" E longitude, with an altitude of about 2.27 m above mean sea level. The experiments were conducted in natural conditions (temperatures of 25–34 °C and relative humidity levels of 75–85%). Cucumber seeds (cv. Pretty, Advance Seed Co., Ltd., Pathum Thani, Thailand), procured from a local Thai market, were surface sterilized with 3% H_2O_2, followed by washing three times with distilled water before sowing on nursery trays. Two separate and independent pot experiments were simultaneously conducted. In both experiments, Si was supplied as monosilicic acid containing 20% Si, which was collected locally (Thai Green Agro Co. Ltd.). In the first experiment, five doses of Si (0, 0.25, 0.5, 1.0, and 2.0 mM) were applied as seed priming. Solutions were prepared by adding 0, 35, 70, 140, and 280 mg monosilicic acid L^{-1} water, respectively [23]. In the case of the second experiment, Si was supplied as soil drench in five doses: 0, 15, 30, 60, and 120 kg soluble Si ha^{-1} (0, 0.0075, 0.015, 0.03, and 0.06 g soluble Si kg^{-1} soil), which is equivalent to 0, 75, 150, 300, and 600 kg monosilicic acid ha^{-1} [23, 24]. Both experiments were maintained under four levels of soil moisture consisting of 40%, 60%, 80%, and 100% field capacity (FC). Bangkok clay soil containing 22% sand, 17% silt, 61% clay, 2.5% organic matter with a pH of 5.2, and 0.011% exchangeable Si was used to grow the plants. Black plastic pots of 30 cm height, 36 cm top diameter, and 28 cm bottom diameter were filled with 15 kg of soil that was previously dried in the air under shade. Seedlings were initially grown in sterilized trays filled with peat moss under polyhouse environment. After transplanting the seedlings into pots, they were provided with adequate irrigation for a period of two weeks for the appropriate establishment of seedlings. This initial irrigation ensured that the plants had sufficient water supply to establish their roots and adapt to the new environment. Following this initial irrigation period, the target soil moisture levels, as outlined in the experimental design, were implemented. Artificial water-deficit stress was induced by withholding irrigation until desired levels of soil moisture were achieved. Following the procedure as outlined by Datta et al. [25], 46% soil moisture content was computed at 100% FC. At 80%, 60%, and 40% FC, the soil moisture content was 37%, 28%, and 19%, respectively. Throughout the crop growth period, moisture content of soil in every experimental pot was monitored daily using a handheld soil moisture sensor (SM150 Soil Moisture Sensor; SM150, Delta-T Devices Ltd., Cambridge, UK). Whenever soil moisture level in the pots dropped below the target level, pots were irrigated to bring the moisture level back to its intended level. Every pot received standard fertilization (initial dose of NPK 15:15:15 at 124 kg ha^{-1} [0.062 g kg^{-1} soil] as basal, top-dressing of urea at 186 kg ha^{-1} [0.093 g kg^{-1} soil] one week after transplanting, and final dose of NPK 15:15:15 at 124 kg ha^{-1} [0.062 g kg^{-1} soil] during flowering) as depicted by the Department of Agriculture, Royal Thai Government for cucumber cultivation. The fertilizers, marketed by the Rabbit Fertilizer company in Thailand, were purchased from a local agriculture market. Flowers were hand-pollinated to ensure fertilization and fruit establishment. As the plants were grown inside a polyhouse, vegetative growth was supported by keeping the plant upright with the help of a nylon trellis mesh net.

2.2 Experimental Design and Treatment

Experiment 1: Seed Priming with Si by Soil Moisture Study The experimental treatments comprised of five doses of Si (0 [control], 0.25, 0.5, 1.0, and 2.0 mM) supplied in the form of seed priming and four levels of soil moisture (40%, 60%, 80%, and 100% FC). Pots were laid out in a completely randomized design where each treatment was replicated four times. For seed priming with Si, seeds were soaked in five specific Si solutions with periodic gentle stirring for 24 h at ambient temperature (25 ± 2 °C) under laboratory conditions. Seeds were immersed in the respective treatment solutions at the ratio of 1:5 (w/v) seeds to solution. Upon priming, seeds were air-dried for 48 h under ambient temperature to attain their initial moisture content. Non-primed seeds (dry seeds without prior presoaking) were directly used as the control. Peat moss substrate was used for seed germination in the plastic trays and for initial seedling growth. Seedlings were transplanted in the main pot when they were 15-day old (two-true leaf stage). Only a single healthy and vigorously-growing seedling was allowed to grow per pot, and each pot was considered as a single treatment combination. After transplanting, the seedlings were irrigated daily for two weeks to overcome initial transplanting shock, followed by the implementation of respective soil moisture levels. Soil moisture status was regularly monitored using the SM150 Soil Moisture Sensor (SM150, Delta-T Devices Ltd., Cambridge, UK).

Experiment 2: Soil Application of Si by Soil Moisture Study In the second experiment, peat moss substrate was used to raise seedlings on plastic trays in similar ways to that of in Experiment 1. Seedlings were later transplanted to each pot when they had two-true leaves. The application of Si was made as soil drench in five doses consisting of 0, 15, 30, 60, and 120 kg soluble Si ha^{-1}. As outlined in Experiment 1, soil moisture levels were established and maintained. Pots were arranged in a completely randomized design with four replications of each treatment combination. Finally, only one healthy and vigorously-growing seedling was allowed to grow in each pot, which was considered as a single treatment combination.

2.3 Data Collection

Growth, Fruit Yield, and Irrigation Water Productivity Parameters A measuring tape was used for the measurement of plant height from the soil surface to the apex of the shoot. After harvesting, the root samples were manually washed and cleaned to remove soil particles and other debris. The aboveground biomass (shoots) and belowground parts (roots) were separately chopped, oven-dried at 80 °C till constant weight, and measured in an electronic balance for recording shoot dry matter and root dry matter, respectively.

At harvest, fruit number in each plant was manually counted. Fruit length was determined with a centimeter scale, and fruit diameter was measured using a vernier caliper. After the fruits were harvested, fruit yield data were collected using an electronic balance. Irrigation water productivity was quantified by dividing the total fruit yield (kg) by the total irrigation water applied (m^3) in each pot throughout the cropping duration [24, 26].

Physio-Biochemical Parameters Leaf greenness (SPAD value) was recorded after four weeks of drought exposure using a handheld SPAD meter (SPAD-502 Plus, Konica Minolta Corporation Ltd., Osaka, Japan) from the topmost fourth leaf of each plant. Leaf relative water content (LRWC) was measured according to Jones and Turner [27]. Briefly, fresh leaf samples from the mid-level height of each plant were collected, stored in airtight zip-lock bags, and immediately brought to the laboratory. Samples were then weighed in an electronic balance to record the fresh weight. Afterwards, samples were kept immersed in distilled water (in a petri dish) for 24 h, and re-weighed to record the turgid weight. Next, the samples were oven-dried at 80 °C till a constant weight and the dry weight was recorded. Finally, LRWC of the samples were extracted using the following formula:

$$\text{LRWC}(\%) = \frac{(\text{Fresh weight} - \text{Dry weight})}{(\text{Turgid weight} - \text{Dry weight})} \times 100$$

The oxidative damage was calculated from the measurement of electrolyte leakage, which reflects membrane permeability. The method of Camejo et al. [28] was followed during the measurement of electrolyte leakage. Fresh leaf samples from the mid-level height of each plant were collected, washed thrice using deionized water to remove surface contamination, and cut into a disc of 1 cm diameter. The samples were then stored in precleaned test tubes containing 20 mL of deionized water, placed in a rotary shaker, and incubated at 25 °C for 24 h. Electrical conductivity (EC_1) of the solution upon incubation was recorded using an electrical conductivity meter (Model Eutech CON 150) manufactured by the Thermo Scientific, Eutech Instruments, Singapore. Each sample was then autoclaved at 120 °C using a pre-heated autoclave for 20 min and the final electrical conductivity (EC_2) was measured after equilibration at 25 °C. The following formula was used for the measurement of electrolyte leakage:

$$\text{Electrolyte leakage}(\%) = \frac{EC_1}{EC_2} \times 100$$

Immediately after fruit harvest, total soluble solids (TSS) content (%) of fruits were determined using a digital refractometer (Model HI96801) manufactured by the Hanna Instruments, Woonsocket, RI, USA.

Gas exchange parameters, namely net photosynthetic rate (μmol CO_2 m^{-2} s^{-1}), stomatal conductance (mmol H_2O m^{-2} s^{-1}), and transpiration rate (mmol H_2O m^{-2} s^{-1}), were quantified using a portable photosynthesis system (LI-6400XT, LI-COR, Lincoln, NE, USA) from the fully-expanded middle leaf between 09.30 am and 11.30 am at 45 days after sowing. Measurements were carried out at a CO_2 concentration of approximately 370 ± 20 μmol mol^{-1} with an atmospheric temperature of 28 ± 1 °C within the assimilation chamber. A gas exchange flow rate was set at 500 μmol s^{-1}. Leaves were artificially illuminated with a red-blue 6400-02B light-emitting diode light with a photosynthetic photon flux density of 1,000 μmol m^{-2} s^{-1} [29].

Table 1 Significance levels in two-way ANOVA of the effect of silicon (Si) seed priming, Si soil application, soil moisture level, and their interaction on growth, fruit yield parameters, irrigation water productivity, and physio-biochemical parameters of cucumber

Parameter	Experiment 1			Experiment 2		
	Seed priming with Si (Si-SP)	Soil moisture level (ML)	Si-SP × ML	Soil application of Si (Si-SA)	Soil moisture level (ML)	Si-SA × ML
Growth parameter						
Plant height (cm)	**	**	**	**	**	**
Shoot dry matter (g $plant^{-1}$)	**	**	**	**	**	**
Root dry matter (g $plant^{-1}$)	**	**	**	**	**	**
Fruit yield parameter and irrigation water productivity						
Fruit number per plant	**	**	**	**	**	**
Fruit length (cm)	**	**	*	**	**	**
Fruit diameter (cm)	**	**	**	**	**	**
Fruit yield (g $plant^{-1}$)	**	**	**	**	**	**
Irrigation water productivity (kg m^{-3})	**	**	*	**	**	**
Physio-biochemical parameter						
SPAD value	**	**	*	**	**	**
Leaf relative water content (%)	**	**	ns	**	**	*
Electrolyte leakage (%)	**	**	**	**	**	**
Total soluble solids (%)	**	**	**	**	**	ns
Net photosynthetic rate (μmol CO_2 m^{-2} s^{-1})	**	**	**	**	**	**
Stomatal conductance (mmol H_2O m^{-2} s^{-1})	**	**	**	**	**	**
Transpiration rate (mmol H_2O m^{-2} s^{-1})	**	**	**	**	**	ns
Osmotic potential (MPa)	**	**	**	**	**	*
Free proline concentration (μg g^{-1} fresh weight)	**	**	**	**	**	**

*, **, and ns indicate significant ($P \leq 0.05$), highly significant ($P \leq 0.01$), and nonsignificant, respectively

Osmotic potential of the fully-expanded leaf from the middle portion of each plant was determined following the method of Hasanuzzaman et al. [30]. Samples were collected, placed in a 2 mL centrifuge tube, kept at –20 °C overnight, and crushed for obtaining cell sap. Approximately 10 µL of cell sap from each leaf sample was used for the measurement of leaf osmolality (*c*) utilizing a Vapor Pressure Osmometer (Vapro® model 5520) manufactured by the Wescor Inc., Logan, UT, USA. The following Van't Hoff's equation, which relates osmolality (mmol kg^{-1}) to osmotic potential (MPa) at 25 °C, was used for the measurement of leaf osmotic potential:

$$\text{Leaf osmotic potential (MPa)} = c\left(\text{mmol} \bullet \text{kg}^{-1}\right) \times 2.4789 \times 10.^{-3}$$

Free proline concentration in the fully-expanded leaf from the shoot tip was measured following the method as described by Bates et al. [31]. Free proline concentration was quantified based on fresh weight (mg proline g^{-1} fresh weight).

2.4 Statistical Analysis

The data analysis was performed using the STAR 2.0.1 software (Statistical Tool for Agricultural Research, version 2.0.1) [32]. A two-way analysis of variance (ANOVA) was conducted to determine the significance of treatment effects. A post-hoc analysis was conducted using Tukey's honest significant difference test to separate the means of significant treatment effects. In all analyses, differences were considered significant at $P \leq 0.05$. Data for significant treatment effect are presented and discussed based on the highest order of factorial combination that was significant in the ANOVA.

3 Results

3.1 Experiment 1: Seed Priming with Si by Soil Moisture Study

The interactive effects between Si and soil moisture level were statistically significant for all examined growth, yield, and physio-biochemical parameters, except for LRWC (Table 1). A drastic drop in the range of 36–49%, 37–49%, and 55–68% in plant height, shoot dry matter, and root dry matter, respectively, was recorded at 40% FC in comparison to those at 100% FC throughout Si doses as evidenced by the significant two-way interaction (Table 2). Plants emerged from the seeds primed with 0.5 mM Si outperformed other plants and caused an increase in the range of 30–68%, 19–68%, and 16–67% in plant height, shoot dry matter, and root dry matter, respectively, compared with the control plants across soil moisture levels. Fruit number per plant, fruit length, fruit diameter, fruit yield, and irrigation water productivity exhibited a decrease in the range of 50–70%, 33–38%, 5–17%, 77–84%, and 25–52%, respectively, at the lowest soil moisture level of 40% FC in comparison to the responses observed at 100% FC throughout Si doses (Table 3). These parameters were enhanced by seed priming with Si with the highest increase at 0.5 mM Si dose. The same particular Si dose also had 60–100% higher fruit number per plant than that of the control throughout soil moisture levels. The corresponding increases for fruit length, fruit diameter, fruit yield, and irrigation water productivity were in the range of 12–22%, 2–18%, 199–284%, and 169–263%, respectively.

Leaf greenness (SPAD value) generally remained lower at higher soil moisture levels regardless of Si doses as indicated by a significant interactive effect between Si and soil moisture level, whereas LRWC of plants at 100% FC was 15% higher than that at 40% FC (Table 4). Priming seeds with 0.5 mM Si caused an increase of 9% in LRWC compared

Table 2 Interactive effect of seed priming with silicon (Si) and soil moisture level on growth parameters (plant height, shoot dry matter, and root dry matter) of cucumber (Experiment 1)

Factor		Plant height (cm)	Shoot dry matter (g $plant^{-1}$)	Root dry matter (g $plant^{-1}$)
Si dose (mM) × soil moisture level				
0	40% FC	110.0 ± 6.14 fg	14.5 ± 0.51hi	0.6 ± 0.01j
	60% FC	127.3 ± 3.57f	16.8 ± 0.31gh	1.2 ± 0.02 h
	80% FC	162.3 ± 4.09e	21.3 ± 0.60ef	1.6 ± 0.05ef
	100% FC	172.5 ± 3.80de	22.9 ± 0.78d-f	1.9 ± 0.02b
0.25	40% FC	102.3 ± 4.03 g	13.5 ± 0.15i	0.6 ± 0.03j
	60% FC	158.8 ± 3.97e	21.1 ± 0.24ef	1.4 ± 0.05gh
	80% FC	166.5 ± 4.09e	22.0 ± 0.57ef	1.7 ± 0.01e
	100% FC	178.5 ± 5.74c-e	23.7 ± 0.63c-e	1.9 ± 0.07b
0.5	40% FC	132.3 ± 5.01f	17.2 ± 0.48 g	1.0 ± 0.04i
	60% FC	214.0 ± 4.92ab	28.3 ± 0.62ab	1.7 ± 0.04de
	80% FC	219.0 ± 5.35ab	28.8 ± 0.82ab	1.9 ± 0.02bc
	100% FC	224.8 ± 7.60a	29.7 ± 0.58a	2.2 ± 0.01a
1.0	40% FC	101.8 ± 3.64 g	13.4 ± 0.19i	0.7 ± 0.01j
	60% FC	158.3 ± 6.61e	20.8 ± 1.15f	1.6 ± 0.10ef
	80% FC	174.0 ± 2.65de	22.5 ± 0.82ef	1.8 ± 0.01b-d
	100% FC	200.3 ± 3.18bc	26.1 ± 1.24bc	2.1 ± 0.04a
2.0	40% FC	99.5 ± 3.66 g	13.2 ± 0.23i	0.7 ± 0.04j
	60% FC	159.0 ± 4.42e	21.3 ± 0.52ef	1.4 ± 0.03 fg
	80% FC	180.8 ± 5.12c-e	23.6 ± 0.92c-e	1.8 ± 0.04 cd
	100% FC	190.0 ± 4.10 cd	25.2 ± 0.62 cd	2.0 ± 0.02b

Means followed by the same letters within a column are statistically similar based on Tukey's honest significant difference test at $P \leq 0.05$; FC, field capacity; data are means of four replications ± standard errors

Table 3 Interactive effect of seed priming with silicon (Si) and soil moisture level on fruit yield parameters (fruit number per plant, fruit length, fruit diameter, and fruit yield) and water productivity of cucumber (Experiment 1)

Factor		Fruit number per plant	Fruit length (cm)	Fruit diameter (cm)	Fruit yield (g plant^{-1})	Water productivity (kg m^{-3})
Si dose (mM) × soil moisture level						
0	40% FC	1.0 ± 0.01f	7.7 ± 0.09 k	3.4 ± 0.07 h	62.0 ± 1.95 h	5.2 ± 0.04i
	60% FC	2.0 ± 0.02e	11.2 ± 0.09 h	3.5 ± 0.04gh	157.3 ± 7.73gh	6.5 ± 0.03i
	80% FC	2.3 ± 0.25e	11.7 ± 0.15gh	3.6 ± 0.06e-h	237.2 ± 9.85e-g	6.9 ± 0.08hi
	100% FC	3.0 ± 0.02 cd	12.5 ± 0.02c-e	4.1 ± 0.11a-c	272.9 ± 9.18d-g	5.7 ± 0.06i
0.25	40% FC	1.0 ± 0.01f	8.8 ± 0.09j	3.4 ± 0.05 h	71.0 ± 5.81 h	5.3 ± 0.04i
	60% FC	2.0 ± 0.02e	11.7 ± 0.17f-h	3.5 ± 0.04gh	194.4 ± 6.49f-h	9.5 ± 0.15f-i
	80% FC	3.0 ± 0.03 cd	12.2 ± 0.03ef	3.6 ± 0.07f-h	284.0 ± 10.94d-g	8.8 ± 0.21f-i
	100% FC	3.0 ± 0.04 cd	13.2 ± 0.09b	4.1 ± 0.05a-c	332.7 ± 12.31de	7.7 ± 0.29 g-i
0.5	40% FC	2.0 ± 0.02e	9.4 ± 0.07i	4.0 ± 0.02a-d	185.6 ± 3.64fgh	14.0 ± 0.77c-f
	60% FC	3.5 ± 0.29bc	12.6 ± 0.09c-e	4.1 ± 0.02a-c	604.2 ± 43.52b	23.6 ± 2.13a
	80% FC	4.0 ± 0.04b	13.1 ± 0.06b	4.2 ± 0.03a	745.5 ± 46.36a	22.0 ± 1.34ab
	100% FC	4.8 ± 0.25a	14.2 ± 0.02a	4.2 ± 0.06a	871.3 ± 50.19a	19.4 ± 1.88a-c
1.0	40% FC	1.3 ± 0.25f	8.9 ± 0.05ij	3.7 ± 0.06e-g	102.9 ± 20.46 h	8.4 ± 1.24 g-i
	60% FC	3.0 ± 0.17 cd	12.3 ± 0.26de	3.8 ± 0.05d-f	399.7 ± 43.22 cd	17.5 ± 1.88b-d
	80% FC	3.0 ± 0.02 cd	13.0 ± 0.12bc	3.9 ± 0.06c-e	484.8 ± 21.51bc	15.2 ± 1.50c-e
	100% FC	4.0 ± 0.05b	13.9 ± 0.32a	4.2 ± 0.03a	609.8 ± 26.09b	12.6 ± 0.75d-g
2.0	40% FC	1.0 ± 0.01f	8.8 ± 0.15j	3.5 ± 0.05f-h	79.4 ± 5.85 h	5.9 ± 0.48i
	60% FC	2.0 ± 0.02e	12.1 ± 0.04e-g	3.6 ± 0.09e-h	292.6 ± 38.79d-f	12.3 ± 1.74d-h
	80% FC	2.5 ± 0.29de	12.8 ± 0.02b-d	3.9 ± 0.04b-e	367.2 ± 31.97c-e	10.1 ± 0.72e-i
	100% FC	3.3 ± 0.25c	13.3 ± 0.18b	4.1 ± 0.02a-c	482.8 ± 43.73bc	10.2 ± 0.79e-i

Means followed by the same letters within a column are statistically similar based on Tukey's honest significant difference test at $P \leq 0.05$; FC, field capacity; data are means of four replications ± standard errors

with the control plants. Electrolyte leakage and TSS content remained higher at lower soil moisture levels with a respective increase within the range of 48–85% and 43–67% at 40% FC in comparison to those at 100% FC across Si doses. Seed priming with 0.5 mM Si caused 13–30% decline in electrolyte leakage and 6–25% enhancement in TSS content in comparison to their respective control throughout soil moisture levels. Net photosynthetic rate, stomatal conductance, and transpiration rate were decreased by 37–46%, 46–68%, and 32–52% at 40% FC in comparison to those at 100% FC throughout Si doses (Table 5). Nevertheless, these parameters exhibited an increase of 20–59%, 5–71%, and 40–61% for plants raised from seeds primed with 0.5 mM Si in comparison to the control plants. Osmotic potential generally remained lower and free proline concentration remained generally higher for plants grown under water-deficit than the ones grown with ample water supply regardless of Si doses (Table 5). Seed priming with 0.5 mM Si was found to be the most effective, which caused an increase of –0.23 to –0.55 MPa in osmotic potential and an increase of 30–44% in free proline concentration compared with the control plants across soil moisture levels.

3.2 Experiment 2: Soil Application of Si by Soil Moisture Study

Except for TSS content and transpiration rate, all other evaluated growth, yield, and physio-biochemical parameters were influenced significantly due to the interactive effects of soil application of Si and soil moisture level (Table 1). A drastic reduction in plant height (41–49%), shoot dry matter (37–49%), and root dry matter (53–76%) was evident at 40% FC in comparison to those at 100% FC throughout Si doses as indicated by the interactive effect between Si and soil moisture level (Table 6). These parameters were significantly increased by 31–68%, 20–50%, and 50–125%, respectively, with the application of 60 kg ha^{-1} Si application in comparison to their respective control. Likewise, fruit yield and yield-related traits as well as irrigation water productivity also exhibited a similar trend. For instance, fruit number per plant, fruit length, fruit diameter, fruit yield, and irrigation water productivity exhibited a respective decrease of 58–70%, 28–41%, 7–19%, 78–84%, and 13–47% at 40% FC in comparison to those at 100% FC throughout Si doses (Table 7). Soil application of Si at 60 kg ha^{-1} was found to be the most effective, as it caused an increase of 92–100%,

Table 4 Effect of seed priming with silicon (Si) and soil moisture level on SPAD value, leaf relative water content, electrolyte leakage, and total soluble solids content of cucumber (Experiment 1)

Factor		SPAD value	Leaf relative water content (%)	Electrolyte leakage (%)	Total soluble solids (%)
Seed priming with Si (mM)					
0		41.4 ± 1.33d	78.9 ± 1.14c	57.7 ± 2.07a	3.3 ± 0.15c
0.25		43.2 ± 1.34c	80.4 ± 1.50bc	53.6 ± 2.15b	3.4 ± 0.13b
0.5		48.3 ± 1.92a	86.3 ± 1.11a	45.8 ± 2.63d	3.7 ± 0.12a
1.0		45.5 ± 1.57b	82.5 ± 1.20b	49.2 ± 2.44c	3.7 ± 0.14a
2.0		44.5 ± 1.51bc	80.8 ± 1.29bc	54.0 ± 2.36b	3.4 ± 0.15b
Soil moisture level					
40% FC		51.6 ± 0.87a	76.2 ± 0.59d	64.8 ± 0.81a	4.2 ± 0.04a
60% FC		47.2 ± 0.91b	79.5 ± 1.17c	54.8 ± 1.14b	3.7 ± 0.04b
80% FC		43.8 ± 0.50c	84.1 ± 0.76b	47.9 ± 1.24c	3.4 ± 0.04c
100% FC		35.8 ± 0.46d	87.3 ± 0.59a	40.8 ± 1.32d	2.7 ± 0.05d
Seed priming with Si × soil moisture level					
0	40% FC	47.3 ± 0.77c-e	74.6 ± 1.26	68.7 ± 0.45a	4.0 ± 0.01 cd
	60% FC	43.0 ± 0.45e-g	75.9 ± 1.64	59.5 ± 0.70de	3.6 ± 0.02e
	80% FC	42.1 ± 0.52 g	81.4 ± 1.22	56.6 ± 0.42ef	3.3 ± 0.02f
	100% FC	33.3 ± 0.08i	83.8 ± 0.87	46.3 ± 0.53 h-k	2.4 ± 0.02i
0.25	40% FC	49.3 ± 0.25bc	75.0 ± 1.64	65.2 ± 0.40bc	4.0 ± 0.05c
	60% FC	45.9 ± 0.65c-g	76.4 ± 2.26	57.0 ± 0.93ef	3.6 ± 0.01e
	80% FC	42.2 ± 0.48 g	83.7 ± 2.32	48.5 ± 0.87hi	3.3 ± 0.02f
	100% FC	35.6 ± 0.98hi	86.4 ± 1.21	43.6 ± 0.60kl	2.6 ± 0.03 h
0.5	40% FC	56.9 ± 2.31a	79.3 ± 0.54	60.0 ± 0.28de	4.3 ± 0.03ab
	60% FC	51.8 ± 0.42b	87.6 ± 0.52	49.3 ± 0.77 h	3.8 ± 0.03 cd
	80% FC	47.0 ± 0.18c-f	88.1 ± 1.04	41.2 ± 0.52 l	3.6 ± 0.03e
	100% FC	37.6 ± 0.71 h	90.2 ± 0.24	32.5 ± 0.57n	3.0 ± 0.05 g
1.0	40% FC	52.4 ± 0.49b	76.5 ± 1.01	61.9 ± 0.45 cd	4.4 ± 0.02a
	60% FC	48.4 ± 2.51b-d	80.8 ± 1.58	52.9 ± 2.53 g	3.8 ± 0.15d
	80% FC	44.9 ± 0.80d-g	84.3 ± 0.17	45.7 ± 0.47i-k	3.6 ± 0.03e
	100% FC	36.4 ± 1.04hi	88.5 ± 0.54	36.3 ± 0.60 m	2.9 ± 0.04 g
2.0	40% FC	52.0 ± 0.32b	75.9 ± 1.06	68.2 ± 0.86ab	4.2 ± 0.03b
	60% FC	47.2 ± 0.76c-e	77.0 ± 1.40	55.2 ± 0.97 fg	3.6 ± 0.03e
	80% FC	42.8 ± 0.20 fg	82.8 ± 0.41	47.4 ± 0.76 h-j	3.3 ± 0.03f
	100% FC	36.2 ± 0.34hi	87.6 ± 0.27	45.1 ± 0.54jk	2.6 ± 0.02 h

Means followed by the same letters within a column are statistically similar based on Tukey's honest significant difference test at $P \leq 0.05$; FC, field capacity; data are means of four replications ± standard errors

13–24%, 10–25%, 217–293%, and 198–307% in fruit number per plant, fruit length, fruit diameter, fruit yield, and irrigation water productivity, respectively, in comparison to their respective control regardless of soil moisture levels.

Leaf greenness (SPAD value) was increased by 42–55%, whereas LRWC was reduced by 6–14% at 40% FC in comparison to those at 100% FC throughout Si doses (Table 8). Electrolyte leakage for the same soil moisture levels was increased in the range of 29–64% across Si doses. Soil application of Si at 60 kg ha^{-1} exhibited an overall superior performance with 10–20% and 6–12% increase in SPAD value and LRWC, and 19–31% decrease in electrolyte leakage in comparison to their respective control throughout soil moisture levels. TSS content at 40% FC was found 52% higher than that observed at 100% FC and the same was increased by 16% in plants treated with 60 kg ha^{-1} Si in comparison to the control plants (Table 8). Net photosynthetic rate and stomatal conductance of plants exhibited a respective reduction in the range of 26–33% and 43–69% when grown under 40% FC in comparison to those grown under 100% FC throughout Si doses (Table 9). The same parameters were significantly improved with soil application of Si at 60 kg ha^{-1} with a respective increase of 11–33% and 26–90% compared with the control plants across soil moisture levels. The highest transpiration rate was observed under 100% FC and 60 kg ha^{-1} Si dose. Osmotic potential was also found the highest when ample water was supplied (100% FC); however, gradual reduction in soil moisture levels caused

Table 5 Interactive effect of seed priming with silicon (Si) and soil moisture level on net photosynthetic rate, stomatal conductance, transpiration rate, osmotic potential, and free proline concentration of cucumber (Experiment 1)

Factor		Net photosynthetic rate (μmol CO_2 m^{-2} s^{-1})	Stomatal conductance (mmol H_2O m^{-2} s^{-1})	Transpiration rate (mmol H_2O m^{-2} s^{-1})	Osmotic potential (MPa)	Free proline concentration (μg g^{-1} fresh weight)
Si dose (mM) × soil moisture level						
0	40% FC	6.1 ± 0.10i	0.13 ± 0.01f-i	1.2 ± 0.03i	–2.01 ± 0.05i	30.9 ± 2.57c-g
	60% FC	8.1 ± 0.12e-g	0.19 ± 0.01d-h	1.7 ± 0.03gh	–1.83 ± 0.03f-h	28.1 ± 2.49d-i
	80% FC	8.7 ± 0.38d-g	0.20 ± 0.01d-f	1.8 ± 0.04f-h	–1.72 ± 0.03d-f	26.8 ± 2.09e-j
	100% FC	9.7 ± 0.13b-e	0.24 ± 0.01c-e	2.5 ± 0.04de	–1.56 ± 0.01bc	20.5 ± 1.76ij
0.25	40% FC	6.3 ± 0.08hi	0.12 ± 0.01 g-i	1.6 ± 0.07 h	–2.01 ± 0.05i	30.2 ± 0.86d-h
	60% FC	8.7 ± 0.19d-g	0.20 ± 0.01d-f	1.9 ± 0.06f-h	–1.93 ± 0.03 g-i	28.5 ± 1.35d-i
	80% FC	10.1 ± 0.11b-d	0.23 ± 0.01c-e	2.5 ± 0.05c-e	–1.81 ± 0.03d-g	28.0 ± 2.40d-i
	100% FC	10.6 ± 0.07bc	0.35 ± 0.02ab	3.0 ± 0.04b	–1.67 ± 0.01c-e	22.9 ± 2.05 g-j
0.5	40% FC	8.0 ± 0.81e-h	0.13 ± 0.02f-i	1.8 ± 0.10f-h	–1.46 ± 0.02ab	44.5 ± 1.29a
	60% FC	9.7 ± 0.09b-e	0.20 ± 0.02d-g	2.4 ± 0.17de	–1.46 ± 0.02ab	36.4 ± 1.72b-d
	80% FC	13.8 ± 0.29a	0.31 ± 0.01bc	2.9 ± 0.07bc	–1.42 ± 0.04ab	34.9 ± 1.83c-e
	100% FC	14.7 ± 0.39a	0.41 ± 0.01a	3.5 ± 0.05a	–1.33 ± 0.02a	29.4 ± 1.39d-h
1.0	40% FC	7.9 ± 0.08f-h	0.12 ± 0.02hi	1.8 ± 0.06f-h	–1.94 ± 0.03 g-i	40.7 ± 1.54ab
	60% FC	10.5 ± 0.18bc	0.23 ± 0.03c-e	2.0 ± 0.15f-h	–1.82 ± 0.02e-g	35.5 ± 0.82b-d
	80% FC	11.2 ± 0.10b	0.22 ± 0.01c-e	2.2 ± 0.02d-f	–1.81 ± 0.02d-g	23.9 ± 0.69 g-j
	100% FC	14.3 ± 0.08a	0.28 ± 0.01b-d	2.7 ± 0.08b-d	–1.66 ± 0.02 cd	22.0 ± 0.96 h-j
2.0	40% FC	7.4 ± 0.14 g-i	0.10 ± 0.02i	1.7 ± 0.07gh	–1.98 ± 0.04hi	39.0 ± 0.15a-c
	60% FC	9.2 ± 0.09c-f	0.18 ± 0.01e-i	1.9 ± 0.11f-h	–1.94 ± 0.01 g-i	33.0 ± 1.88b-f
	80% FC	10.6 ± 0.04bc	0.24 ± 0.01c-e	2.1 ± 0.02e-g	–1.87 ± 0.03f-i	24.5 ± 1.60f-j
	100% FC	13.2 ± 0.20a	0.26 ± 0.02c-e	2.5 ± 0.07c-e	–1.66 ± 0.01 cd	18.5 ± 0.48j

Means followed by the same letters within a column are statistically similar based on Tukey's honest significant difference test at $P \leq 0.05$; FC, field capacity; data are means of four replications ± standard errors

gradual decline of osmotic potential (in the range of –0.18 to –0.25 MPa) irrespective of Si doses (Table 9). Free proline concentration was found higher at lower soil moisture levels and was the highest at 40% FC. Gradually increasing soil moisture level resulted in a gradual decline in free proline concentration confined within the range of 25–44% across Si doses. Control plants had –0.08 to –0.15 MPa lower osmotic potential than the plants raised with 60 kg Si ha^{-1} soil application dose throughout soil moisture levels. The same Si dose resulted in an increase of 15–51% in free proline concentration of plants compared with the control plants.

4 Discussion

Drought poses a severe challenge to agricultural crop production worldwide, markedly impeding growth, development, and productivity of field crops and garden crops [33]. The results of the current study revealed that drought stress had a detrimental impact on morpho-physiological characteristics and fruit yield and its attributes of cucumber regardless of whether the plants were supplemented with Si or not. Severe drought stress causes stomatal closure, leading to reduced photosynthesis and transpiration, and consequently plant growth is adversely impacted, and cellular water potential is reduced [34]. Crop productivity is substantially reduced due to water scarcity as it causes a decrease in both sink and source activities, which are influenced by the duration and intensity of the stress experienced by the plant during its vegetative and reproductive growth stages [35]. All stages of crop growth are negatively affected by drought, but its impacts on the vegetative growth phases and flowering phases are regarded as the most crucial. As cucumber is regarded as a drought-sensitive crop, it is essential to provide the plants with adequate irrigation at all growth stages to prevent fruit yield reduction [36] caused due to flower and fruit shedding [21].

Several researchers have observed Si-induced enhancement in metabolic activities of plant cells under drought stress [37, 38] mainly through better nutrient uptake/transport and improvement in soil water status [16]. Root surface area and root length also increase with the improvement in the nutritional status of plants [5, 37]. Numerous mechanisms have been suggested rationalizing the positive impact of Si on crop growth and development regardless of the growth environments, such as (i) by boosting phytohormone

Table 6 Interactive effect of soil application of silicon (Si) and soil moisture level on growth parameters (plant height, shoot dry matter, and root dry matter) of cucumber (Experiment 2)

Factor		Plant height (cm)	Shoot dry matter (g plant^{-1})	Root dry matter (g plant^{-1})
Si dose (kg ha^{-1}) × soil moisture level				
0	40% FC	99.5 ± 3.66i	12.2 ± 0.51 l	0.6 ± 0.01 h
	60% FC	127.3 ± 3.57gh	13.2 ± 0.39kl	0.8 ± 0.02 h
	80% FC	162.3 ± 4.09ef	15.8 ± 0.39 h-k	1.3 ± 0.03 g
	100% FC	173.0 ± 3.74d-f	19.5 ± 0.68e-g	1.6 ± 0.03e-g
15	40% FC	102.5 ± 4.19i	12.6 ± 0.63kl	0.8 ± 0.01 h
	60% FC	159.3 ± 3.82ef	14.3 ± 0.55j-l	0.8 ± 0.03 h
	80% FC	166.5 ± 4.09ef	16.6 ± 0.84 g-j	1.4 ± 0.01 fg
	100% FC	179.5 ± 5.74c-f	22.3 ± 0.91c-e	2.2 ± 0.07bc
30	40% FC	110.0 ± 2.08hi	12.9 ± 0.74kl	0.8 ± 0.03 h
	60% FC	159.5 ± 4.27ef	14.5 ± 0.57i-l	0.9 ± 0.02 h
	80% FC	181.3 ± 5.31c-e	18.8 ± 0.71f-h	1.4 ± 0.02 fg
	100% FC	190.3 ± 4.13 cd	25.1 ± 0.44bc	1.7 ± 0.26d-f
60	40% FC	132.5 ± 4.97 g	14.7 ± 0.68i-l	0.9 ± 0.03 h
	60% FC	214.5 ± 5.06ab	18.2 ± 0.28f-h	1.8 ± 0.01de
	80% FC	219.0 ± 5.35ab	23.7 ± 0.46b-d	2.0 ± 0.02 cd
	100% FC	225.8 ± 7.60a	28.3 ± 0.48a	2.6 ± 0.04a
120	40% FC	102.3 ± 3.57i	14.7 ± 0.85i-l	0.6 ± 0.03 h
	60% FC	158.5 ± 4.09f	17.7 ± 0.56 g-i	0.9 ± 0.01 h
	80% FC	174.0 ± 3.54d-f	21.4 ± 0.48d-f	1.5 ± 0.04e-g
	100% FC	200.5 ± 4.29bc	26.0 ± 0.80ab	2.5 ± 0.05ab

Means followed by the same letters within a column are statistically similar based on Tukey's honest significant difference test at $P \leq 0.05$; FC, field capacity; data are means of four replications ± standard errors

production [39], (ii) by maintaining photosynthetic assimilation [40], (iii) by improving soil water status, especially water holding capacity and plant available water, thereby maintaining a high LRWC [40, 41], (iv) by encouraging cell elongation and expansion of cell wall [42], (v) by enhancing nutrient uptake and modifying potassium/sodium proportion [43, 44], (vi) by enhancing antioxidant enzyme activity [45], (vii) by preserving membrane integrity by lowering the biomembrane permeability of the leaf tissue [46], and (viii) by improving chloroplast ultrastructure [47].

The beneficial effects of seed priming with Si have been well established in various crops, including maize (*Zea mays* L.) [23, 48, 49], wheat (*Triticum aestivum* L.) [38, 50], and grape tomato (*Solanum lycopersicum* L. var. *cerasiforme*) [14]. One of the ways Si can contribute to drought tolerance is by maintaining water balance and minimizing water loss through transpiration [16]. Additionally, Si has been found to prevent xylem vessel compression, which can be beneficial under water-deficit environments [51]. Moreover, Si can create additional binding sites for the absorption of nearby ions [51]. These effects can contribute to improved nutrient acquisition/utilization and plant growth. The interaction between Si and soil moisture level indicated that priming seeds with Si enhanced vegetative growth, fruit yield traits, and physiological response of cucumber plants under drought stress. It was observed that seed priming with 0.5 mM Si was the most effective dose; however, higher doses of Si (1 and 2 mM) either remained ineffective or exhibited a negative impact on most of the evaluated parameters under limited soil moisture availability. The application of this priming dose (0.5 mM) resulted in significant improvements in key parameters, including fruit yield, irrigation water productivity, and net photosynthetic rate. These improvements were substantial enough that the values of these parameters were statistically similar between plants grown under 80% and 100% FC at 0.5 mM priming dose. The same can also be said for soil incorporation dose of 60 kg Si ha^{-1}; however, a high dose of 120 kg ha^{-1} remained largely ineffective. These results are in close agreement with the findings of Chakma et al. [14] who found that lower priming dose of Si promoted seed germination and growth of grape tomato, while higher dose of Si delayed these responses. Silicon can exhibit 'hormetic effects' where low doses produce beneficial effects, while higher doses may produce harmful effects. The optimal concentration of Si for drought mitigation may vary depending on plant species, application methods, environmental conditions, and soil properties. The 0.5 mM dose for seed priming and the 60 kg ha^{-1} dose for soil application might have reached to the optimal concentration for inducing beneficial effects, while higher doses (1 and 2 mM for seed priming and 120 kg ha^{-1} for soil application) might have surpassed the optimal level, leading to ineffective or even detrimental effects.

Drought stress increases the accumulation of reactive oxygen species, damages cell membrane, and increases the accumulation of hydrogen peroxide and malondialdehyde [52]. Plants harbor a comprehensive and efficient internal defense mechanism to cope with the generation of excessive reactive oxygen species and oxidative damage, particularly under drought conditions. This defense system involves various enzymatic and non-enzymatic antioxidants that work together to scavenge reactive oxygen species and protect plant cells from oxidative damage. Seed priming or soil application of Si has been reported as an alternative strategy for improving drought tolerance in plants [14, 24, 38]. Silicon functions as a mechanical barrier to limit water losses via transpiration under drought stress and mediates several metabolic, physiological, and biochemical pathways that increase drought tolerance. Silicon modulates drought tolerance responses in plants by boosting the functions of numerous metabolic enzymes, promoting plant physiological development, and increasing biomass. Several processes have been hypothesized by which Si may boost drought

Table 7 Interactive effect of soil application of silicon (Si) and soil moisture level on fruit yield parameters (fruit number per plant, fruit length, fruit diameter, and fruit yield) and irrigation water productivity of cucumber (Experiment 2)

Factor		Fruit number per plant	Fruit length (cm)	Fruit diameter (cm)	Fruit yield (g plant^{-1})	Water productivity (kg m^{-3})
Si dose (kg ha^{-1}) × soil moisture level						
0	40% FC	1.0 ± 0.01 g	7.8 ± 0.14j	3.2 ± 0.05j	60.1 ± 1.99j	5.4 ± 0.45j
	60% FC	1.8 ± 0.25e-g	11.3 ± 0.15gh	3.3 ± 0.06ij	158.1 ± 7.95 g-j	6.7 ± 0.36 h-j
	80% FC	2.0 ± 0.02ef	12.3 ± 0.16 fg	3.5 ± 0.10i	240.2 ± 10.11e-h	7.2 ± 0.71 h-j
	100% FC	2.5 ± 0.29de	13.3 ± 0.23c-f	3.9 ± 0.05b-e	276.8 ± 9.42d-g	6.2 ± 0.20ij
15	40% FC	1.0 ± 0.01 g	9.7 ± 0.12i	3.4 ± 0.04ij	72.9 ± 5.98ij	5.4 ± 0.74j
	60% FC	2.0 ± 0.02ef	12.7 ± 0.36-f	3.5 ± 0.07hi	199.7 ± 6.67f-i	9.9 ± 0.15f-j
	80% FC	3.0 ± 0.03 cd	12.6 ± 0.32ef	3.6 ± 0.04 g-i	291.9 ± 11.25d-g	9.1 ± 0.22f-j
	100% FC	3.0 ± 0.04 cd	13.4 ± 0.30c-e	4.2 ± 0.04ab	341.8 ± 12.65de	7.9 ± 0.29 g-j
30	40% FC	1.0 ± 0.01 g	9.9 ± 0.18i	3.5 ± 0.03hi	81.5 ± 6.02j	6.0 ± 0.58 h-j
	60% FC	2.0 ± 0.02ef	13.6 ± 0.08c-e	3.7 ± 0.03f-h	300.6 ± 39.86-f	11.8 ± 1.49d-h
	80% FC	2.5 ± 0.29de	13.9 ± 0.04a-d	3.9 ± 0.04b-e	377.2 ± 32.86 cd	11.2 ± 0.72e-i
	100% FC	3.3 ± 0.25b-d	14.4 ± 0.19a-c	4.1 ± 0.06a-c	496.1 ± 44.93bc	11.3 ± 1.68e-i
60	40% FC	2.0 ± 0.02ef	9.7 ± 0.13i	4.0 ± 0.07a-d	190.7 ± 3.75f-j	16.1 ± 0.69c-e
	60% FC	3.5 ± 0.29bc	13.2 ± 0.30d-f	4.1 ± 0.03a-c	620.8 ± 44.72b	27.3 ± 3.12a
	80% FC	4.0 ± 0.05ab	13.9 ± 0.08b-d	4.2 ± 0.02ab	766.0 ± 47.63a	23.8 ± 1.40ab
	100% FC	4.8 ± 0.25a	15.0 ± 0.22a	4.3 ± 0.04a	895.3 ± 51.58a	18.6 ± 0.84bc
120	40% FC	1.3 ± 0.25 fg	10.3 ± 0.15hi	3.7 ± 0.03e-h	105.7 ± 21.03 h-j	7.7 ± 1.24gh-j
	60% FC	3.0 ± 0.03 cd	13.0 ± 0.29d-f	3.8 ± 0.03d-g	410.7 ± 14.76 cd	17.4 ± 0.69 cd
	80% FC	3.0 ± 0.04 cd	14.1 ± 0.22a-d	3.9 ± 0.04c-f	498.1 ± 19.89bc	13.8 ± 0.69c-f
	100% FC	4.0 ± 0.05ab	14.8 ± 0.22ab	4.2 ± 0.05ab	626.6 ± 23.02b	13.4 ± 0.56c-g

Means followed by the same letters within a column are statistically similar based on Tukey's honest significant difference test at $P \leq 0.05$; FC, field capacity; data are means of four replications ± standard errors

tolerance in plants, including improved plant water status, higher photosynthetic activity, and improved ultrastructure of leaf organelles [53]. Priming cucumber seeds with Si (0.50 mM) and its soil supplementation (60 kg ha^{-1}) improved overall plant growth, fruit yield, irrigation water productivity, and physiological responses of cucumber plants, which could be credited to the combination of the above-mentioned positive impacts of Si. The application of Si helps plants maintain their water balance and aids in cell division, which promotes plant growth under normal and stressful conditions [54]. Silicon-induced improvement in growth, yield, irrigation water productivity, and plant physiological responses has revealed improved water and nutrient uptake, and better root systems development [55, 56]. Silicon improves the flow of water through the xylem, increasing water transportation/utilization efficiency. Additionally, it enhances the uptake of nitrogen, phosphorus, and potassium by plants under drought stress [57]. The addition of Si either as a seed priming material or soil drench was found effective in attenuating the detrimental effects of drought stress on cucumber plants, supporting the earlier findings on grape tomato [14] and cantaloupe (*Cucumis melo* L.) [13]. The exogenous application of Si has been reported to increase shoot growth of cucumber plants under osmotic stress by reducing the damage on leaf photosynthetic rate [58].

High level of compatible solutes (osmolytes) is a key component of the protective system that minimizes membrane damage and lowers the intensity of stress. One of the vital compatible solutes that often accumulate in response to environmental stress and crucial for osmotic adjustment is proline [59]. In the present studies, free proline concentration enhanced with increased severity of drought stress and seed priming or soil incorporation of Si. Proline is primarily used by plants for osmotic regulation, stabilizing subcellular structures, and free radical detoxification [60]. Drought stress positively affects the production and accumulation of osmolytes. Under adverse environmental conditions, these osmolytes increase cell survival rate and maintain osmotic balance [61]. Osmolytes accumulate in the plant cell's cytosol and play an intricate role in stress tolerance enhancement by preventing cellular oxidative injuries, participating in cellular integrity maintenance, and safeguarding the cellular machinery [62]. The application of Si helps plants further increase the level of proline under drought stress, thereby protecting the plant cells from oxidative stress. The elevated proline concentration

Table 8 Effect of soil application of silicon (Si) and soil moisture level on SPAD value, leaf relative water content, electrolyte leakage, and total soluble solids content of cucumber (Experiment 2)

Factor		SPAD value	Leaf relative water content (%)	Electrolyte leakage (%)	Total soluble solids (%)
Soil application of Si (kg ha^{-1})					
0		41.9 ± 1.42d	86.8 ± 1.16c	66.9 ± 3.15a	3.2 ± 0.14c
15		43.6 ± 1.62c	89.3 ± 1.32b	64.9 ± 2.74ab	3.3 ± 0.13bc
30		44.3 ± 1.62c	90.0 ± 0.88b	62.8 ± 2.39b	3.4 ± 0.15b
60		47.9 ± 1.97a	93.5 ± 0.68a	52.4 ± 1.66d	3.7 ± 0.12a
120		45.8 ± 1.72b	89.2 ± 1.12b	58.5 ± 2.92c	3.6 ± 0.13a
Soil moisture level					
40% FC		52.4 ± 0.80a	84.5 ± 0.90d	73.5 ± 2.10a	4.1 ± 0.04a
60% FC		47.7 ± 0.59b	89.1 ± 0.63c	65.5 ± 1.24b	3.6 ± 0.04b
80% FC		43.6 ± 0.50c	91.3 ± 0.54b	57.0 ± 1.55c	3.4 ± 0.05c
100% FC		35.2 ± 0.35d	94.1 ± 0.62a	48.6 ± 0.92d	2.7 ± 0.06d
Soil application of Si × soil moisture level					
0	40% FC	47.1 ± 0.56d	80.3 ± 1.53 h	83.6 ± 2.30a	3.9 ± 0.06
	60% FC	45.7 ± 0.65d-f	86.7 ± 0.38d-g	70.6 ± 1.75b-e	3.5 ± 0.04
	80% FC	41.8 ± 0.58 g	89.3 ± 0.35b-e	62.7 ± 0.75e-g	3.2 ± 0.02
	100% FC	33.2 ± 0.08 h	91.0 ± 1.45a-e	50.9 ± 1.18 h-j	2.4 ± 0.07
15	40% FC	51.8 ± 0.56bc	82.4 ± 1.23gh	78.2 ± 1.38ab	4.0 ± 0.06
	60% FC	45.8 ± 0.82de	89.0 ± 0.77b-e	69.6 ± 1.61b-f	3.5 ± 0.08
	80% FC	42.0 ± 0.48 fg	89.5 ± 1.13b-e	61.2 ± 1.93e-g	3.2 ± 0.05
	100% FC	34.7 ± 0.53 h	96.1 ± 0.71a	50.6 ± 1.64ij	2.6 ± 0.07
30	40% FC	52.2 ± 0.47b	86.1 ± 0.19e-g	74.8 ± 1.35a-c	4.1 ± 0.07
	60% FC	47.0 ± 1.26d	87.8 ± 0.54d-f	65.8 ± 0.70c-g	3.6 ± 0.10
	80% FC	42.5 ± 0.37e-g	91.8 ± 0.92a-d	60.5 ± 1.61f-h	3.2 ± 0.04
	100% FC	35.5 ± 0.47 h	94.2 ± 0.63ab	50.3 ± 2.24ij	2.6 ± 0.05
60	40% FC	56.7 ± 1.60a	90.1 ± 0.91bc-e	58.0 ± 2.69 g-i	4.3 ± 0.05
	60% FC	51.6 ± 0.40bc	93.8 ± 1.14ab	56.9 ± 0.57 g-i	3.8 ± 0.09
	80% FC	46.8 ± 0.57d	94.0 ± 0.84ab	49.8 ± 2.27j	3.6 ± 0.05
	100% FC	36.5 ± 0.74 h	96.1 ± 0.37a	45.0 ± 1.56j	3.0 ± 0.05
120	40% FC	54.2 ± 0.18ab	83.5 ± 1.34f-h	72.8 ± 2.22b-d	4.3 ± 0.06
	60% FC	48.2 ± 0.75 cd	88.4 ± 0.70c-f	64.5 ± 1.19d-g	3.8 ± 0.06
	80% FC	44.8 ± 0.80d-g	92.0 ± 1.08a-d	50.6 ± 1.79ij	3.6 ± 0.08
	100% FC	36.1 ± 0.83 h	93.1 ± 1.71a-c	46.2 ± 3.44j	2.9 ± 0.05

Means followed by the same letters within a column are statistically similar based on Tukey's honest significant difference test at $P \leq 0.05$; FC, field capacity; data are means of four replications ± standard errors

increases the affinity toward water, which enhances water retention capacity in the tissue and increases plant tolerance against drought.

5 Conclusion

Drought stress diminished growth and physiological response of cucumber plants compared with well-watered ones. However, seed priming with 0.5 mM and soil supplementation of 60 kg soluble Si ha^{-1} reduced the detrimental effects of drought stress and aided plant growth by improving most of the evaluated morpho-physiological traits. A substantial uplift in leaf relative water content, net photosynthetic rate, and free proline concentration, and a decrease in electrolyte leakage was observed, highlighting the positive roles of Si in drought mitigation. The key factors responsible for the positive effects of Si under drought stress were the improvement in gas exchange traits of leaf, notably net photosynthetic rate, and plant water status. Silicon application at 0.5 mM as seed priming and 60 kg ha^{-1} as soil drench is recommended for growing cucumber plants in drought-affected areas. Both seed priming and soil incorporation methods were equally effective in mitigating drought stress and promoting cucumber growth in water-limited environments. However, higher doses of Si under both application

Table 9 Effect of soil application of silicon (Si) and soil moisture level on net photosynthetic rate, stomatal conductance, transpiration rate, osmotic potential, and free proline concentration of cucumber (Experiment 2)

Factor		Net photosynthetic rate (μmol CO_2 m^{-2} s^{-1})	Stomatal conductance (mmol H_2O m^{-2} s^{-1})	Transpiration rate (mmol H_2O m^{-2} s^{-1})	Osmotic potential (MPa)	Free proline concentration (μg g^{-1} fresh weight)
Soil application of Si (kg ha^{-1})						
0		12.0 ± 0.46d	0.19 ± 0.01b	1.9 ± 0.06d	–1.40 ± 0.02d	29.4 ± 1.26d
15		12.4 ± 0.40 cd	0.21 ± 0.02b	2.0 ± 0.05 cd	–1.35 ± 0.02c	31.0 ± 1.05 cd
30		13.0 ± 0.39bc	0.21 ± 0.02b	2.1 ± 0.05bc	–1.31 ± 0.02ab	32.8 ± 1.64c
60		14.6 ± 0.50a	0.29 ± 0.03a	2.3 ± 0.06a	–1.29 ± 0.02a	40.6 ± 2.12a
120		13.4 ± 0.41b	0.19 ± 0.02b	2.1 ± 0.05b	–1.33 ± 0.02bc	36.7 ± 2.08b
Soil moisture level						
40% FC		10.7 ± 0.27d	0.12 ± 0.01d	1.8 ± 0.03d	–1.44 ± 0.01d	41.5 ± 1.68a
60% FC		12.9 ± 0.23c	0.20 ± 0.01c	1.9 ± 0.04c	–1.36 ± 0.01c	36.4 ± 1.50b
80% FC		13.7 ± 0.23b	0.25 ± 0.01b	2.1 ± 0.02b	–1.31 ± 0.01b	31.7 ± 0.61c
100% FC		15.0 ± 0.29a	0.30 ± 0.02a	2.4 ± 0.03a	–1.23 ± 0.01a	26.8 ± 0.81d
Soil application of Si × soil moisture level						
0	40% FC	9.0 ± 0.13i	0.13 ± 0.01f-h	1.6 ± 0.02	–1.52 ± 0.01 l	33.7 ± 2.60c-f
	60% FC	12.4 ± 0.33d-g	0.19 ± 0.01e-g	1.8 ± 0.02	–1.42 ± 0.02i-k	31.1 ± 1.07e-g
	80% FC	12.9 ± 0.39def	0.20 ± 0.01d-g	2.0 ± 0.05	–1.38 ± 0.01 g-j	29.6 ± 2.09e-g
	100% FC	13.5 ± 0.20c-e	0.23 ± 0.01c-e	2.2 ± 0.02	–1.27 ± 0.01b-e	23.3 ± 1.66 g
15	40% FC	10.0 ± 0.09hi	0.12 ± 0.01gh	1.8 ± 0.02	–1.44 ± 0.01jk	34.9 ± 0.80c-e
	60% FC	12.7 ± 0.23d-g	0.20 ± 0.01d-g	1.8 ± 0.01	–1.39 ± 0.01 g-j	31.7 ± 1.26ef
	80% FC	13.1 ± 0.37d-f	0.22 ± 0.01c-e	2.0 ± 0.02	–1.35 ± 0.02f-i	31.2 ± 2.41e-g
	100% FC	13.9 ± 0.16b-d	0.29 ± 0.02b-d	2.3 ± 0.01	–1.25 ± 0.01a-d	26.1 ± 2.06 fg
30	40% FC	11.1 ± 0.63gh	0.11 ± 0.04gh	1.9 ± 0.08	–1.40 ± 0.01 h-k	41.1 ± 1.27bc
	60% FC	12.7 ± 0.34d-g	0.21 ± 0.01c-f	1.9 ± 0.04	–1.35 ± 0.01f-i	33.0 ± 1.72d-f
	80% FC	13.2 ± 0.12de	0.22 ± 0.01c-e	2.1 ± 0.03	–1.28 ± 0.02b-f	31.4 ± 1.73e-g
	100% FC	15.1 ± 0.20a-c	0.30 ± 0.01bc	2.4 ± 0.02	–1.22 ± 0.02ab	25.9 ± 1.39 fg
60	40% FC	12.0 ± 0.21e-g	0.13 ± 0.03f-h	2.1 ± 0.02	–1.37 ± 0.01 g-j	50.8 ± 1.55a
	60% FC	13.8 ± 0.27 cd	0.24 ± 0.01c-e	2.2 ± 0.02	–1.34 ± 0.02e-h	45.5 ± 0.88ab
	80% FC	15.6 ± 0.41ab	0.38 ± 0.01ab	2.2 ± 0.02	–1.26 ± 0.02a-e	34.0 ± 0.63c-f
	100% FC	16.9 ± 0.25a	0.42 ± 0.02a	2.6 ± 0.03	–1.18 ± 0.00a	32.0 ± 1.00ef
120	40% FC	11.5 ± 0.24f-h	0.10 ± 0.01 h	1.9 ± 0.04	–1.48 ± 0.01kl	46.9 ± 0.14ab
	60% FC	12.8 ± 0.17d-f	0.18 ± 0.02e-h	2.0 ± 0.03	–1.33 ± 0.01d-h	41.0 ± 1.90b-d
	80% FC	13.5 ± 0.52c-e	0.24 ± 0.01c-e	2.1 ± 0.06	–1.31 ± 0.01c-g	32.4 ± 1.60ef
	100% FC	15.6 ± 0.21a	0.25 ± 0.02c-e	2.4 ± 0.05	–1.23 ± 0.02a-c	26.4 ± 0.46 fg

Means followed by the same letters within a column are statistically similar based on Tukey's honest significant difference test at $P \leq 0.05$; FC, field capacity; data are means of four replications ± standard errors

methods should be avoided (higher than 0.5 mM for seed priming and 60 kg ha^{-1} for soil application) as higher doses were largely found ineffective and even harmful for some parameters. Further studies involving more Si doses for both application methods and diverse soil types/soil moisture conditions could be useful to validate the present findings.

Acknowledgements All authors are thankful to the Asian Institute of Technology, Thailand for the facilities provided to conduct the research work.

Author Contributions Conceptualization and designing of the experiments were done by the combined efforts of all authors. Akhter Ul Alam conducted the investigation, collected outlined data, and analyzed the data. Hayat Ullah, Sushil Kumar Himanshu, and Avishek Datta guided the operations. Akhter Ul Alam prepared the first draft of the manuscript, which were sequentially reviewed and revised by Hayat Ullah, Sushil Kumar Himanshu, Rujira Tisarum, Patchara Praseartkul, Suriyan Cha-um, and Avishek Datta. All authors read and approved the final manuscript. The entire operation was supervised by Avishek Datta.

Funding The study was financially aided by the Bangabandhu Science and Technology Fellowship Trust, Ministry of Science and Technology, People's Republic of Bangladesh, and the Asian Institute of Technology, Thailand.

Data Availability The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Competing Interests The authors declare no competing interests.

References

1. Spinoni J, Barbosa P, Cherlet M, Forzieri G, McCormick N, Naumann G, Vogt JV, Dosio A (2021) How will the progressive global increase of arid areas affect population and land-use in the 21st century? Glob Planet Change 205:103597
2. Panda D, Mishra SS, Behera PK (2021) Drought tolerance in rice: focus on recent mechanisms and approaches. Rice Sci 28:119–132
3. dos Santos TB, Ribas AF, de Souza SGH, Budzinski IGF, Domingues DS (2022) Physiological responses to drought, salinity, and heat stress in plants: a review. Stresses 2:113–135
4. Soares D, Paço TA, Rolim J (2023) Assessing climate change impacts on irrigation water requirements under Mediterranean conditions—a review of the methodological approaches focusing on maize crop. Agronomy 13:117
5. Etesami H, Jeong BR (2018) Silicon (Si): Review and future prospects on the action mechanisms in alleviating biotic and abiotic stresses in plants. Ecotoxicol Environ Safe 147:881–896
6. Yadav S, Modi P, Dave A, Vijapura A, Patel D, Patel M (2020) Effect of abiotic stress on crops. In: Hasanuzzaman M, Teixeira Filho MCM, Fujita M, Nogueira TAR (Editors). Sustainable Crop Production. IntechOpen, London
7. Fahad S, Bajwa AA, Nazir U, Anjum SA, Farooq A, Zohaib A, Sadia S, Nasim W, Adkins S, Saud S, Ihsan MZ, Alharby H, Wu C, Wang D, Huang J (2017) Crop production under drought and heat stress: Plant responses and management options. Front Plant Sci 8:1147
8. Jochum MD, McWilliams KL, Borrego EJ, Kolomiets MV, Niu G, Pierson EA, Jo YK (2019) Bioprospecting plant growth-promoting rhizobacteria that mitigate drought stress in grasses. Front Microbiol 10:2106
9. Wang M, Wang R, Mur LAJ, Ruan J, Shen Q, Guo S (2021) Functions of silicon in plant drought stress responses. Hortic Res 8:254
10. Chen D, Wang S, Yin L, Deng X (2018) How does silicon mediate plant water uptake and loss under water deficiency? Front Plant Sci 9:281
11. Gong H, Chen K (2012) The regulatory role of silicon on water relations, photosynthetic gas exchange, and carboxylation activities of wheat leaves in field drought conditions. Acta Physiol Plant 34:1589–1594
12. Yin L, Wang S, Liu P, Wang W, Cao D, Deng X, Zhang S (2014) Silicon-mediated changes in polyamine and 1-aminocyclopropane-1-carboxylic acid are involved in silicon-induced drought resistance in *Sorghum bicolor* L. Plant Physiol Biochem 80:268–277
13. Alam A, Hariyanto B, Ullah H, Salin KR, Datta A (2021) Effects of silicon on growth, yield and fruit quality of cantaloupe under drought stress. Silicon 13:3153–3162
14. Chakma R, Saekong P, Biswas A, Ullah H, Datta A (2021) Growth, fruit yield, quality, and water productivity of grape tomato as affected by seed priming and soil application of silicon under drought stress. Agric Water Manag 256:107055
15. Sattar A, Sher A, Ijaz M, Ul-Allah S, Butt M, Irfan M, Rizwan MS, Ali H, Cheema MA (2020) Interactive effect of biochar and silicon on improving morpho-physiological and biochemical attributes of maize by reducing drought hazards. J Soil Sci Plant Nutr 20:1819–1826
16. Malik MA, Wani AH, Mir SH, Rehman IU, Tahir I, Ahmad P, Rashid I (2021) Elucidating the role of silicon in drought stress tolerance in plants. Plant Physiol Biochem 165:187–195
17. Zhao H, Zhai X, Guo L, Yang Y, Li J, Ren C, Wang K, Liu X, Zhan R, Wang K (2019) Comparing protected cucumber and field cucumber production systems in China based on emergy analysis. J Clean Prod 236:117648
18. Wang CJ, Yang W, Wang C, Gu C, Niu DD, Liu HX, Wang YP, Guo JH (2012) Induction of drought tolerance in cucumber plants by a consortium of three plant growth-promoting Rhizobacterium strains. PLoS ONE 7:e52565
19. Alam AU, Ullah H, Himanshu SK, Tisarum R, Cha-um S, Datta A (2023) Seed priming enhances germination and morphological, physio-biochemical, and yield traits of cucumber under water-deficit stress. J Soil Sci Plant Nutr 23:3961–3978
20. Kaya C, Higgs D, Kirnak H (2005) Influence of polyethylene mulch, irrigation regime, and potassium rates on field cucumber yield and related traits. J Plant Nutr 28:1739–1753
21. Parkash V, Singh S, Deb SK, Ritchie GL, Wallace RW (2021) Effect of deficit irrigation on physiology, plant growth, and fruit yield of cucumber cultivars. Plant Stress 1:100004
22. Odhiambo JA, Aguyoh JN (2022) Soil moisture levels affect growth, flower production and yield of cucumber. Agric Trop Subtrop 55:1–8
23. Sirisuntornlak N, Ghafoori S, Datta A, Arirob W (2019) Seed priming and soil incorporation with silicon influence growth and yield of maize under water-deficit stress. Arch Agron Soil Sci 65:197–207
24. Ullah H, Luc PD, Gautam A, Datta A (2018) Growth, yield and silicon uptake of rice (*Oryza sativa*) as influenced by dose and timing of silicon application under water deficit stress. Arch Agron Soil Sci 64:318–330
25. Datta A, Sindel BM, Kristiansen P, Jessop RS, Felton WL (2009) The effects of temperature and soil moisture on chickpea (*Cicer arietinum* L.) genotype sensitivity to isoxaflutole. J Agron Crop Sci 195:178–185
26. Maneepitak S, Ullah H, Paothong K, Kachenchart B, Datta A, Shrestha RP (2019) Effect of water and rice straw management practices on yield and water productivity of irrigated lowland rice in the Central Plain of Thailand. Agric Water Manag 211:89–97
27. Jones MM, Turner NC (1978) Osmotic adjustment in leaves of sorghum in response to water deficits. Plant Physiol 61:122–126
28. Camejo D, Rodríguez P, Morales MA, Dell'Amico JM, Torrecillas A, Alarcón JJ (2005) High temperature effects on photosynthetic activity of two tomato cultivars with different heat susceptibility. J Plant Physiol 162:281–289
29. Cha-um S, Supaibulwatana K, Kirdmanee C (2006) Water relation, photosynthetic ability and growth of Thai jasmine rice (*Oryza sativa* L. ssp. *indica* cv. KDML 105) to salt stress by application of exogenous glycine betaine and choline. J Agron Crop Sci 192:25–36
30. Hasanuzzaman M, Davies NW, Shabala L, Zhou M, Brodribb TJ, Shabala S (2017) Residual transpiration as a component of salinity stress tolerance mechanism: A case study for barley. BMC Plant Biol 17:107
31. Bates LS, Waldren RP, Teare ID (1973) Rapid determination of free proline for water-stress studies. Plant Soil 39:205–207

32. IRRI (International Rice Research Institute) (2014) Statistical Tool for Agricultural Research (STAR) v. 2.0.1. Available at: http://bbi.irri.org (Accessed on 20 January 2023)
33. Ganie SA, Ahammed GJ (2021) Dynamics of cell wall structure and related genomic resources for drought tolerance in rice. Plant Cell Rep 40:437–459
34. Ahanger MA, Qi M, Huang Z, Xu X, Begum N, Qin C, Zhang C, Ahmad N, Mustafa NS, Ashraf M, Zhang L (2021) Improving growth and photosynthetic performance of drought stressed tomato by application of nano-organic fertilizer involves up-regulation of nitrogen, antioxidant and osmolyte metabolism. Ecotoxicol Environ Safe 216:112195
35. Pinheiro C, Chaves MM (2011) Photosynthesis and drought: Can we make metabolic connections from available data? J Exp Bot 62:869–882
36. Rahil MH, Qanadillo A (2015) Effects of different irrigation regimes on yield and water use efficiency of cucumber crop. Agric Water Manag 148:10–15
37. Rizwan M, Ali S, Ibrahim M, Farid M, Adrees M, Bharwana SA, Zia-Ur-Rehman M, Qayyum MF, Abbas F (2015) Mechanisms of silicon-mediated alleviation of drought and salt stress in plants: A review. Environ Sci Pollut Res 22:15416–15431
38. Ahmed M, Qadeer U, Ahmed ZI, Hassan FU (2016) Improvement of wheat (*Triticum aestivum*) drought tolerance by seed priming with silicon. Arch Agron Soil Sci 62:299–315
39. Hamayun M, Sohn EY, Khan SA, Shinwari ZK, Khan AL, Lee IJ (2010) Silicon alleviates the adverse effects of salinity and drought stress on growth and endogenous plant growth hormones of soybean (*Glycine max* L.). Pak J Bot 42:1713–1722
40. Kuhla J, Pausch J, Schaller J (2021) Effect on soil water availability, rather than silicon uptake by plants, explains the beneficial effect of silicon on rice during drought. Plant Cell Environ 44:3336–3346
41. Jafari SR, Arvin SMJ, Kalantari KM (2015) Response of cucumber (*Cucumis sativus* L.) seedlings to exogenous silicon and salicylic acid under osmotic stress. Acta Biol Szeged 59:25–33
42. Hossain MT, Mori R, Soga K, Wakabayashi K, Kamisaka S, Fujii S, Yamamoto R, Hoson T (2002) Growth promotion and an increase in cell wall extensibility by silicon in rice and some other Poaceae seedlings. J Plant Res 115:23–27
43. Neu S, Schaller J, Dudel EG (2017) Silicon availability modifies nutrient use efficiency and content, C:N:P stoichiometry, and productivity of winter wheat (*Triticum aestivum* L.). Sci Rep 7:40829
44. Alsaeedi A, El-Ramady H, Alshaal T, El-Garawany M, Elhawat N, Al-Otaibi A (2019) Silica nanoparticles boost growth and productivity of cucumber under water deficit and salinity stresses by balancing nutrients uptake. Plant Physiol Biochem 139:1–10
45. Gong HJ, Chen KM, Chen GC, Wang SM, Zhang CL (2003) Effects of silicon on growth of wheat under drought. J Plant Nutr 26:1055–1063
46. Liang Y, Hua H, Zhu YG, Zhang J, Cheng C, Römheld V (2006) Importance of plant species and external silicon concentration to active silicon uptake and transport. New Phytol 172:63–72
47. Cao BL, Ma Q, Zhao Q, Wang L, Xu K (2015) Effects of silicon on absorbed light allocation, antioxidant enzymes and ultrastructure of chloroplasts in tomato leaves under simulated drought stress. Sci Hortic 194:53–62
48. Sirisuntornlak N, Ullah H, Sonjaroon W, Arirob W, Anusontpornperm S, Datta A (2021) Effect of seed priming with silicon on growth, yield and nutrient uptake of maize under water-deficit stress. J Plant Nutr 44:1869–1885
49. Sirisuntornlak N, Ullah H, Sonjaroon W, Anusontpornperm S, Arirob W, Datta A (2021) Interactive effects of silicon and soil pH on growth, yield and nutrient uptake of maize. Silicon 13:289–299
50. Rai-Kalal P, Tomar RS, Jajoo A (2021) Seed nanopriming by silicon oxide improves drought stress alleviation potential in wheat plants. Funct Plant Biol 48:905–915
51. Meena VD, Dotaniya ML, Rajendiran S, Coumar MV, Kundu S, Rao AS (2014) A case for silicon fertilization to improve crop yields in tropical soils. Proc Natl Acad Sci India Sect B Biol Sci 84:505–518
52. Ullah H, Santiago-Arenas R, Ferdous Z, Attia A, Datta A (2019) Improving water use efficiency, nitrogen use efficiency, and radiation use efficiency in field crops under drought stress: A review. Adv Agron 156:109–157
53. Coskun D, Britto DT, Huynh WQ, Kronzucker HJ (2016) The role of silicon in higher plants under salinity and drought stress. Front Plant Sci 7:1072
54. Ibrahim MA, Merwad ARM, Elnaka EA (2018) Rice (*Oryza sativa* L.) tolerance to drought can be improved by silicon application. Commun Soil Sci Plant Anal 49:945–957
55. Alzahrani Y, Kuşvuran A, Alharby HF, Kuşvuran S, Rady MM (2018) The defensive role of silicon in wheat against stress conditions induced by drought, salinity or cadmium. Ecotoxicol Environ Safe 154:187–196
56. Hussain S, Shuxian L, Mumtaz M, Shafiq I, Iqbal N, Brestic M, Shoaib M, Sisi Q, Li W, Mei X, Bing C, Zivcak M, Rastogi A, Skalicky M, Hejnak V, Weiguo L, Wenyu Y (2021) Foliar application of silicon improves stem strength under low light stress by regulating lignin biosynthesis genes in soybean (*Glycine max* (L.) Merr.). J Haz Mater 401:123256
57. Chen W, Yao X, Cai K, Chen J (2011) Silicon alleviates drought stress of rice plants by improving plant water status, photosynthesis and mineral nutrient absorption. Biol Trace Elem Res 142:67–76
58. Hattori T, Sonobe K, Inanaga S, An P, Morita S (2008) Effects of silicon on photosynthesis of young cucumber seedlings under osmotic stress. J Plant Nutr 31:1046–1058
59. Nayyar H, Walia DP (2003) Water stress induced proline accumulation in contrasting wheat genotypes as affected by calcium and abscisic acid. Biol Plant 46:275–279
60. Chen H, Jiang JG (2010) Osmotic adjustment and plant adaptation to environmental changes related to drought and salinity. Environ Rev 18:309–319
61. Raza A, Charagh S, Abbas S, Hassan MU, Saeed F, Haider S, Sharif R, Anand A, Corpas FJ, Jin W (2023) Assessment of proline function in higher plants under extreme temperatures. Plant Biol 25:379–395
62. Sharma A, Shahzad B, Kumar V, Kohli SK, Sidhu GPS, Bali AS, Handa N, Kapoor D, Bhardwaj R, Zheng B (2019) Phytohormones regulate accumulation of osmolytes under abiotic stress. Biomolecules 9:285

Authors and Affiliations

Akhter Ul Alam[1,2] · Hayat Ullah[1] · Sushil Kumar Himanshu[1] · Rujira Tisarum[3] · Patchara Praseartkul[3] · Suriyan Cha-um[3] · Avishek Datta[1]

✉ Avishek Datta
datta@ait.ac.th; avishek.ait@gmail.com

[1] Agricultural Systems and Engineering, Department of Food, Agriculture and Bioresources, School of Environment, Resources and Development, Asian Institute of Technology, Klong Luang 12120, Pathum Thani, Thailand

[2] On-Farm Research Division, Bangladesh Agricultural Research Institute, Agricultural Research Station, Alamnagar, Rangpur, Bangladesh

[3] National Center for Genetic Engineering and Biotechnology (BIOTEC), National Science and Technology Development Agency (NSTDA), Klong Luang 12120, Pathum Thani, Thailand