https://doi.org/10.17221/539/2025-PSE

Foliar silicon modulates structural and biochemical responses of buckwheat to water deficit

*Jiri Krucky, Vaclav Hejnak, Pavla Vachova, Jana Ceska, Jan Kubes, Milan Skalicky**

Department of Botany and Plant Physiology, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences Prague, Prague, Czech Republic

**Corresponding author: skalicky@af.czu.cz*

Citation: Krucky J., Hejnak V., Vachova P., Ceska J., Kubes J., Skalicky M. (2026): Foliar silicon modulates structural and biochemical responses of buckwheat to water deficit. Plant Soil Environ., 72: 66–75.

Abstract: Drought is a major abiotic stressor that limits crop growth and is often associated with oxidative stress. We evaluated whether foliar silicon (Si) application affects primary root anatomy, plant height, and phenolic metabolism in three common buckwheat (*Fagopyrum esculentum*) cultivars (La Harpe, Panda, and Smuga) exposed to water deficit. Plants were grown under controlled conditions in four treatments: control; drought; control + Si, and drought + Si. Qualitative anatomical assessment revealed that Si promoted more advanced development of the primary root central cylinder, most notably in La Harpe under drought conditions, where a continuous ring of secondary xylem and a well-developed pith were observed. Drought significantly reduced plant height in all cultivars; Si partially alleviated this reduction in La Harpe and Panda, but not in Smuga. Drought generally increased total phenolic content (TPC) and phenolic acid content (PAC) in both leaves and roots, and Si further enhanced these responses, with the highest values under drought + Si. Overall, the results indicate cultivar-dependent effectiveness of foliar silicon (Si) and suggest that Si contributes to coordinated structural and biochemical adjustments under water deficit conditions. To assess the transferability of these responses, further verification across a broader range of genotypes and under different intensities and durations of drought is warranted.

Keywords: xylem development; growth inhibition; phenolic compounds; water stress; cultivar specificity

Drought severely constrains crop growth and productivity and is frequently associated with oxidative stress (Bashir et al. 2021, Ahsan et al. 2023). Therefore, there is increasing interest in approaches that enhance structural stability and antioxidant defence under water deficit (Hussain et al. 2019, Lux et al. 2020, Ahmad and Hassim 2024).

Silicon (Si) treatment can mitigate the adverse effects of drought by activating defence mechanisms at the structural, morphological, and metabolic levels (Wang et al. 2021, Manivannan et al. 2023, Zahedi et al. 2023, Krucky et al. 2025). Foliar Si application is an effective way to supply Si, which promotes the development and stability of plant tissues, strengthening cell walls, stimulating xylem differentiation, and improving the hydraulic integrity of roots (Vaculík et al. 2012, Lux et al. 2020, Saja-Garbarz et al. 2024). In addition to its structural function, Si also plays a crucial role in regulating the growth and development of both root and shoot systems (Ahmad and Hassim 2024, Mastalerczuk et al. 2025). At the same time, it affects the synthesis of secondary metabolites, particularly phenolic compounds (PCs) and phenolic acids (PAs), which are effective antioxidants that stabilise cell membranes and protect plants against oxidative damage (Carneiro-Carvalho et al. 2020, Dar et al. 2022, Mahmoud et al. 2023). The interconnection of these anatomical, morphological, and

Supported by the Czech Science Foundation (GACR), Project No. 23–04221 L.

https://doi.org/10.17221/539/2025-PSE

biochemical processes determines the overall plant resistance to water stress.

Common buckwheat (*Fagopyrum esculentum* Moench.) is a valuable pseudocereal with high nutritional quality, but it exhibits pronounced sensitivity to water deficit (Aubert et al. 2021, Germ et al. 2025). Previous studies have demonstrated that buckwheat genotypes vary in their capacity to regulate the antioxidant system and accumulate secondary metabolites in response to water stress (Oksana et al. 2023, Hossain et al. 2024). However, comprehensive information is still lacking on how foliar-applied Si affects root anatomy, plant growth parameters, and phenolic metabolism in different buckwheat cultivars exposed to drought (Thorne et al. 2021, Wang et al. 2021, Krucky et al. 2025). Such knowledge is essential for a better understanding of plant adaptation mechanisms and for the more effective use of Si in agronomic practice.

Therefore, we selected three buckwheat cultivars (La Harpe, Panda, and Smuga) representing contrasting drought responses and different geographic origins. The rationale for their selection, along with supporting evidence, is provided in the Material and Methods section. This study aimed to elucidate the effects of foliar Si application on the anatomical structure of the primary root, plant height, and biochemical indicators in three buckwheat cultivars differing in their sensitivity to drought. We hypothesised that Si (*i*) promotes the development of root anatomy and partially alleviates drought-induced growth inhibition; (*ii*) stimulates phenolic metabolism contributing to the mitigation of oxidative stress, and (*iii*) exhibits differential efficiency among cultivars.

MATERIAL AND METHODS

Plant material and growth conditions. Three cultivars of common buckwheat (*Fagopyrum esculentum* Moench.), La Harpe (France), Panda and Smuga (both Poland) were selected for the experiment. These cultivars were selected based on reported differences in phenotypic and physiological responses to water deficit (Antala et al. 2025, Krucky et al. 2025) and supported by preliminary screening conducted in collaboration with the Poznan University of Life Sciences under a Czech-Polish bilateral research project. This selection enabled a comprehensive comparison of genotypic responses to foliar Si application under drought conditions. Buckwheat achenes of the selected cultivars were surface sterilised by immersion in a 1% sodium hypochlorite (NaClO) solution for 5 min, followed by thorough rinsing with distilled water. The achenes were then dried on paper towels to reach their natural moisture content, and sown in plastic pots (11 × 11 × 23 cm) filled with a peat-based growing substrate (Klasmann TS2, Geeste, Germany). The pot experiment was conducted in a controlled-environment growth chamber (Conviron E8, Winnipeg, Canada) equipped with a CMP6050 control system for artificial light intensity of 750 μmol/m^2/s, photoperiod of 14/10 h (day/night), temperature of 23 °C/18 °C (day/night), and relative humidity of 50% (day) and 60% (night). The selected light intensity was based on published values used for buckwheat (Hornyák et al. 2020, Oksana et al. 2023) and on preliminary chamber settings to avoid plant elongation at lower light intensity and an undesired temperature increase at higher light intensity.

Experimental design and treatments. The cultivation phase lasted for 18 days, during which all plants were regularly watered to support uniform growth until the development of the 3rd to 5th true leaf stage. After this period, the experiment entered its treatment phase. For each cultivar, five pots per treatment (typically four plants per pot) were randomly assigned to one of four treatment groups: control (well-watered, without Si); drought (non-irrigated, without Si); control + Si (well-watered, with Si), and drought + Si (non-irrigated, with Si). For subsequent measurements and sampling, one plant was taken from each pot (n = 5). A solution of 0.5 mmol sodium metasilicate nonahydrate ($Na_2SiO_3 \cdot 9\ H_2O$; Merck KGaA, Darmstadt, Germany) in distilled water was sprayed on the leaves at the onset of the experiment (BBCH 13–15) using a handheld pressurised sprayer (SOLO 402, Kleinmotoren GmbH, Sindelfingen, Germany), ensuring uniform coverage of the leaf surface. To prevent contamination of the substrate during application, the soil surface in each pot was covered with aluminium foil, which was removed only after the foliar spray had completely dried.

Substrate water-holding capacity (WHC) was determined gravimetrically using a saturation-based approach modified from Junker et al. (2015). Briefly, pots filled with the substrate were saturated with water and allowed to equilibrate to a constant wet weight (W_wet). The substrate was then dried to constant weight to obtain the dry reference (W_dry). Pot tare and plant support material were accounted for. Target pot weights (W_target) corresponding

https://doi.org/10.17221/539/2025-PSE

to 80% (well-watered) and 40% (drought) substrate moisture were calculated as $W\_target = W\_dry + f \times (W\_wet - W\_dry)$, where $f = 0.80$ or 0.40.

The watering program was monitored through regular gravimetric measurements. Every two days, the moisture content in each pot was measured and adjusted as necessary to maintain 80% of the substrate's water-holding capacity in the irrigated treatments (control; control + Si), ensuring optimal hydration. Drought stress was induced by withholding irrigation, allowing the substrate moisture to gradually decrease to 40% of its water-holding capacity (drought; drought + Si) and maintaining this level throughout the 12-day experimental phase, after which plants were approximately within the BBCH 51–61 range. Subsequently, plant material was collected, and various parameters were measured.

Anatomical structure of vegetative organs. Transverse, unstained sections were cut and examined using a Nikon Eclipse 50i microscope equipped with a Nikon DS-Fi2 camera (Nikon Corporation, Tokyo, Japan). Image acquisition and analysis were carried out using NIS-Elements AR imaging software (Nikon Instruments Inc., New York, USA). Sections were taken at 3 cm from the root collar for the primary root (100× magnification), 3 cm from the substrate surface for the stem (100× magnification), and in the middle of the blade next to the central vein for the leaf (400× magnification). Within the vegetative organs, the characteristics of the primary cortex parenchyma, the region of the middle cylinder, and the leaf mesophyll were observed, and the anatomical structures were digitally recorded. The anatomical assessment was performed qualitatively; morphometric quantification was not part of this study.

Plant height. The buckwheat plants were removed from the pots and carefully cleaned of substrate. The plant height was measured in five biological replicates per treatment (one plant per pot; $n = 5$) using a ruler and expressed in cm.

Phenolic compounds. Plant extracts for the determination of total phenolic content (TPC) and total phenolic acid content (PAC) were prepared according to a modification of the procedure described by Howladar (2014). Briefly, 0.5 g samples of fresh plant material (leaves and thoroughly cleaned roots) were frozen and pulverised in a mortar with pestle using liquid nitrogen. Then, they were rapidly mixed and extracted by stirring with 80% ethanol. The extracts were separated through filtration paper, and the TPC and PAC in the filtrates were determined. TPC was measured using the method of Singleton and Rossi (1965). An aliquot of the ethanolic extract was mixed with Folin-Ciocalteu reagent (0.75 mL), and after 5 min, 7% sodium carbonate (0.8 mL) was added. The absorbance of the reaction mixture was measured at 765 nm using a UV/Vis spectrophotometer (Evolution 201; Thermo Scientific, Waltham, USA) against a blank sample. Results were expressed as mg of gallic acid equivalents (GAE), per g of fresh plant material (mg GAE/g FW).

PAC was assessed using a modified protocol of Szaufer-Hajdrych (2004). The ethanolic extract of buckwheat leaves was mixed with 0.5 mol/L HCl, Arnow's reagent, and 1 mol/L NaOH. Absorbance was measured at 490 nm against a blank, and PAC was expressed as caffeic acid equivalents per g fresh weight (mg CAE/g FW (fresh weight)).

Statistical analysis. All statistical analyses were conducted using R software (version 4.3.0, R Core Team 2023). Data processing and statistical evaluations were conducted using the R packages dplyr, tidyr, emmeans, multcomp, and multcompView. Graphical outputs were generated using ggplot2.

For each variable, differences among experimental variants were evaluated using a one-way analysis of variance (ANOVA), in which each cultivar × treatment combination was treated as an independent level. This approach allowed direct comparison among all experimental variants within a single model.

When the ANOVA indicated a significant effect ($P < 0.05$), post hoc multiple comparisons were performed using Tukey's honestly significant difference (*HSD*) test. Estimated marginal means were calculated using the emmeans package, and compact letter displays were generated to denote statistically homogeneous groups. Treatments sharing at least one letter were considered not significantly different at $\alpha = 0.05$.

Results are presented as mean ± standard deviation (SD). Superscript letters derived from Tukey's test indicate statistically significant differences among cultivar × treatment combinations. For each trait, the F-value and corresponding P-value from the ANOVA are reported in figures.

RESULTS

Anatomy of vegetative organs. Transverse anatomical sections were prepared from roots, stems, and leaves, but no significant treatment- or cultivar-dependent structural differences were observed in the

https://doi.org/10.17221/539/2025-PSE

stem and leaf tissues. Therefore, this study presents and discusses only the anatomical features of the primary root, where the most distinct differences were observed, particularly in the central cylinder and its development in response to foliar Si application (Figure 1).

The most pronounced differences in root anatomy were found in the La Harpe cultivar. Under drought treatment, the presence of primary xylem within the central cylinder indicated slower tissue development. In the control, parenchymal pith was beginning to form, with visible poles of primary xylem. In contrast, both Si-treated variants (control + Si; drought + Si) exhibited fully developed pith and a continuous ring of secondary xylem, indicating advanced development of root tissues.

In the Panda cultivar, Si application had a moderate effect. The drought treatment displayed the least developed tissue structure, while the control and both Si-treated variants (control + Si and drought + Si) showed signs of pith formation, with more distinct development in the roots of plants after foliar Si treatment.

In Smuga, only minor differences were observed across treatments. The central root region was filled with parenchymal pith in all variants. Only the control + Si showed slight colour changes in the primary xylem, and the drought + Si retained traces of the original xylem pole structure. Overall, neither Si treatment nor drought stress caused notable anatomical changes in this cultivar.

No consistent differences were observed in the root cortex tissue across cultivars and treatments. These results suggest that Si had the most substantial anatomical effect on the La Harpe cultivar, especially in the development of the central cylinder. A moderate impact was seen in Panda, while no apparent effects were detected in Smuga.

Plant height. Plant height is a key indicator of growth dynamics and plant performance under stress. Drought stress resulted in a statistically significant reduction in plant height across all cultivars – La

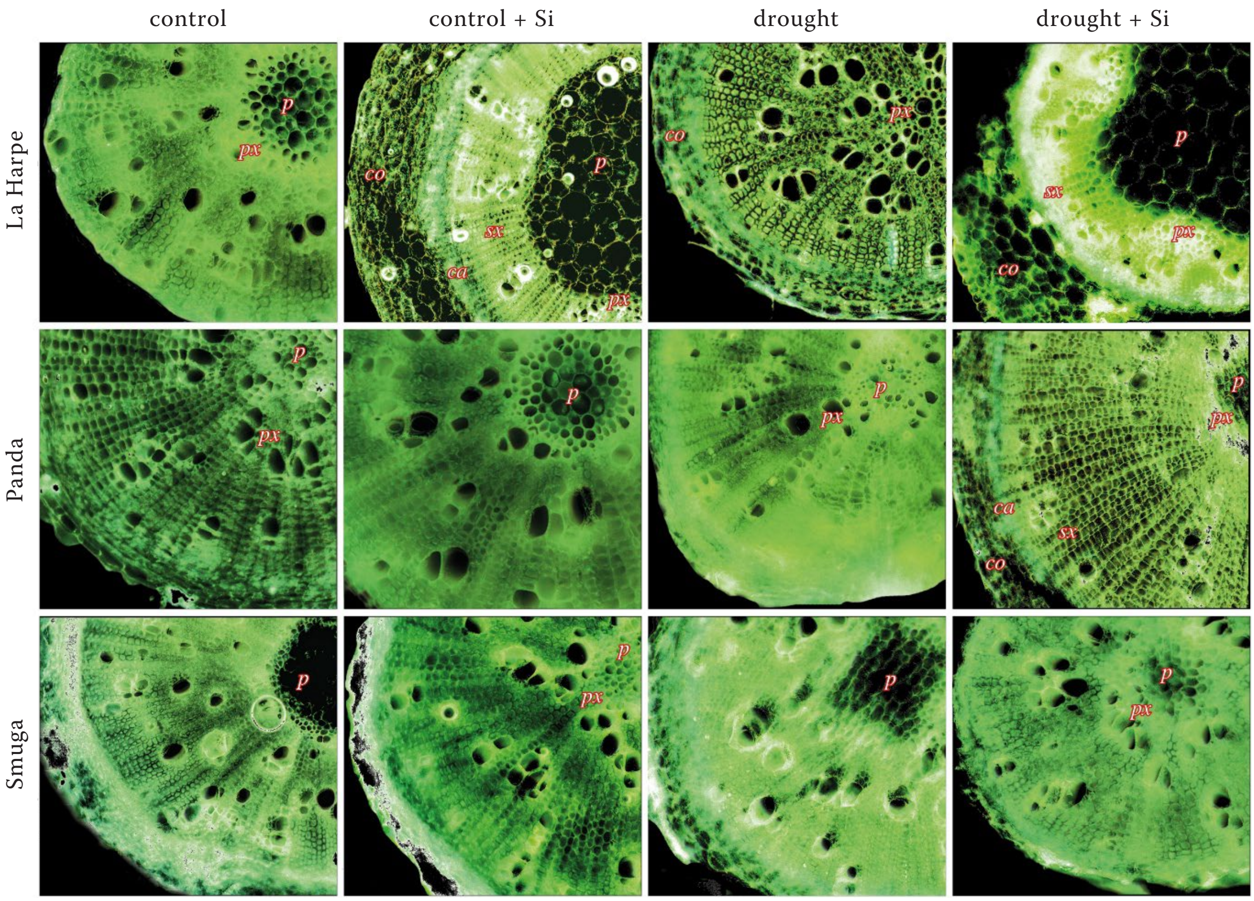

Figure 1. Effect of drought and foliar silicon (Si) application on anatomical structures of the primary root in three buckwheat cultivars. Magnification 100×; co – cortex; ca – cambium; sx – secondary xylem; px – primary xylem; p – pith

https://doi.org/10.17221/539/2025-PSE

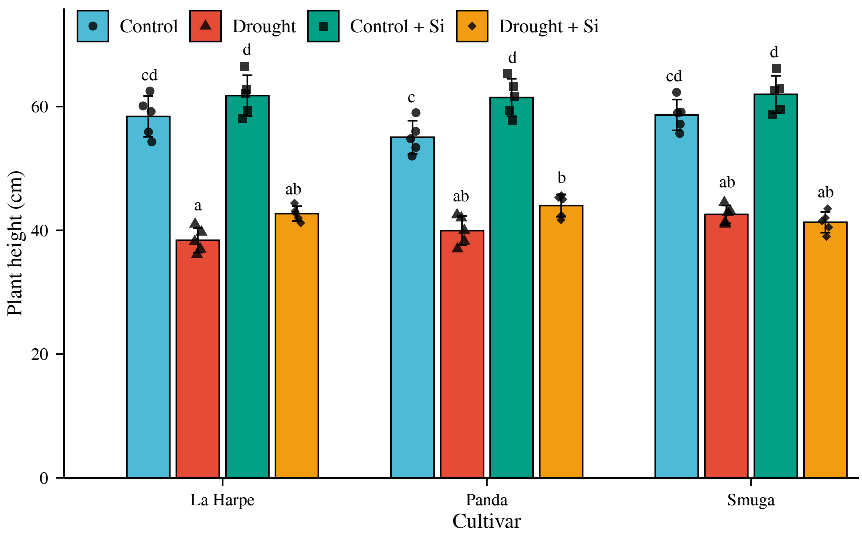

Figure 2. Effect of drought and foliar silicon (Si) application on plant height in three buckwheat cultivars. Data are presented as means ± SD (n = 5). ANOVA: F = 78.14; P < 0.001. Different letters indicate statistically significant differences among cultivar × treatment combinations (Tukey's *HSD* test, P < 0.05)

Harpe, Panda, and Smuga (Figure 2), which is also evident from the visual comparison (Figure 3). The most pronounced decrease was observed in La Harpe, with reductions of 34.26% (drought) and 26.88%

Figure 3. Visual comparison of three buckwheat cultivars under well-watered and drought conditions with and without foliar silicon (Si) application (scale bar = 5 cm)

https://doi.org/10.17221/539/2025-PSE

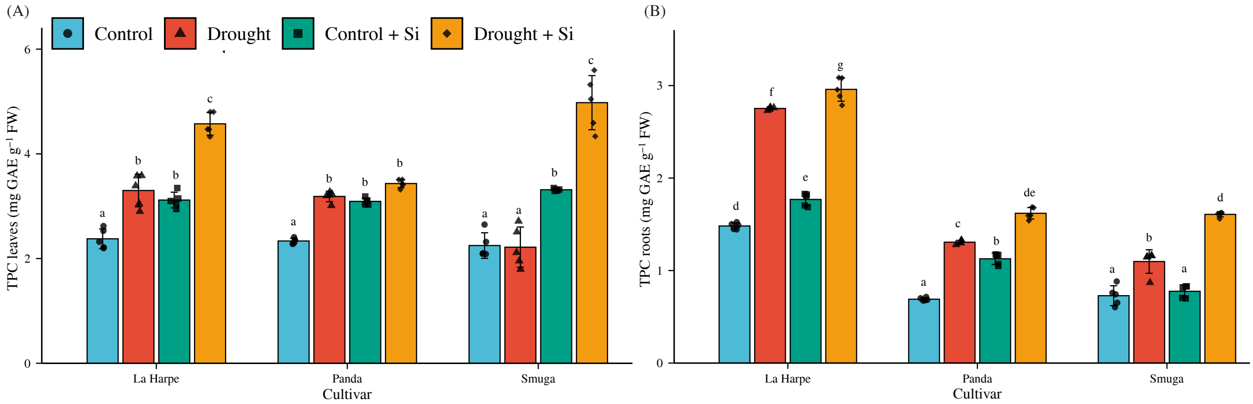

Figure 4. Effect of foliar silicon (Si) application on total phenolic content (TPC) in (A) leaves and (B) roots of three buckwheat cultivars under drought and well-watered conditions. Concentrations in mg of gallic acid equivalents (GAE) per g of fresh weight (FW) are presented as means ± SD (n = 5). ANOVA: leaves F = 65.58; P < 0.001; roots F = 506.05; P < 0.001. Different letters indicate statistically significant differences among cultivar × treatment combinations (Tukey's *HSD* test, P < 0.05)

(drought + Si) compared with the control. In Panda, plant height decreased by 27.42% (drought) and 20.06% (drought + Si), while in Smuga, the reduction was 27.41% (drought) and 29.57% (drought + Si) relative to the control.

Under well-watered conditions, foliar Si slightly increased plant height in all three cultivars – most notably in Panda (+11.66%), followed by La Harpe (+5.77%) and Smuga (+5.68%). Under drought, Si induced a mild positive effect in La Harpe and Panda, whereas in Smuga, no significant difference was detected between drought and drought + Si (Figure 2).

Phenolic compounds. Phenolic compounds (PCs), including phenolic acids (PAs), are a crucial group of secondary metabolites with antioxidant properties that protect plants against the effects of abiotic stress, such as drought. The determination of total phenolic content (TPC) and phenolic acid content (PAC) provides valuable information about the biochemical response of buckwheat to water deficit and foliar Si application.

Drought stress generally increased both TPC (Figure 4) and PAC (Figure 5) in leaves and roots of the studied buckwheat cultivars (La Harpe, Panda, Smuga). The most pronounced increase was observed in La Harpe, where TPC values rose by 38.83% in leaves and 85.72% in roots, while PAC values increased by 25.02% in leaves and 144.74% in roots compared with the control. Panda showed a similar trend: leaf TPC increased by 36.42% and PAC by 21.23%, whereas in roots the increase reached 89.21% (TPC) and 65.76% (PAC). In Smuga, leaf TPC remained essentially

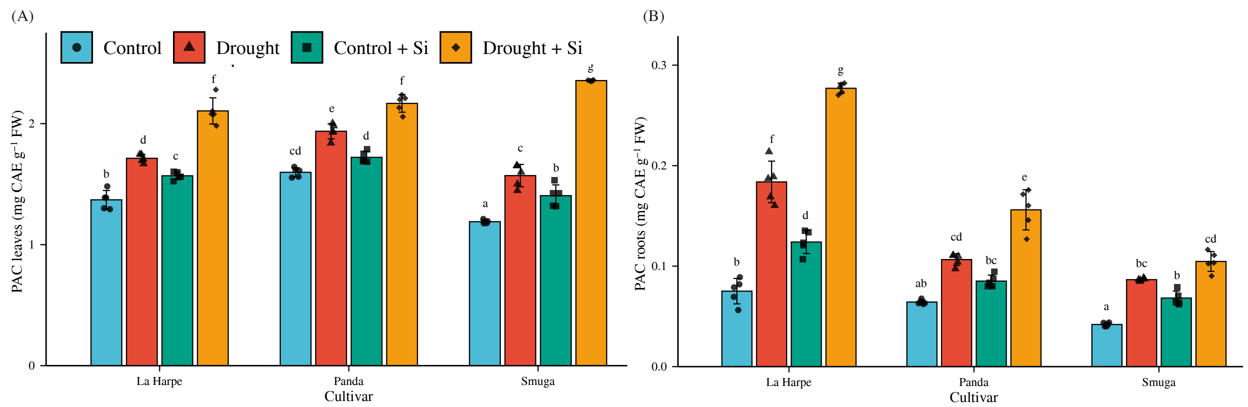

Figure 5. Effect of foliar silicon (Si) application on total phenolic acid content (PAC) in (A) leaves and (B) roots of three buckwheat cultivars under drought and well-watered conditions. Concentrations in caffeic acid equivalents (CAE) per g of fresh weight (FW) are presented as means ± SD (n = 5). ANOVA: leaves F = 149.91; P < 0.001; roots F = 184.31; P < 0.001. Different letters indicate statistically significant differences among cultivar × treatment combinations (Tukey's *HSD* test, P < 0.05)

https://doi.org/10.17221/539/2025-PSE

unchanged under drought (–1.39%), while leaf PAC increased by 32.01%, and an apparent increase was observed in roots (+50.70% TPC, +106.39% PAC).

The application of Si under well-watered conditions resulted in a slight increase in both TPC and PAC across all analysed plant parts. In contrast, drought + Si resulted in the highest TPC and PAC values in all cultivars. In Smuga, the highest concentrations were recorded in leaves (TPC 4.98 mg GAE/g FW, PAC 2.36 mg CAE/g FW), whereas La Harpe reached maximum values in roots (TPC 2.96 mg GAE/g FW, PAC 0.28 mg CAE/g FW). Overall, foliar Si had a positive influence on the accumulation of phenolic compounds and phenolic acids in both leaves and roots of the buckwheat cultivars, with drought + Si showing the greatest effect.

DISCUSSION

Our results confirmed that the response of buckwheat to Si application and water stress involved complex anatomical, morphological, and biochemical changes. All cultivars responded to drought by reducing growth (as measured by plant height) and increasing the synthesis of phenolics. Foliar Si partially mitigated these adverse drought effects, primarily through enhanced anatomical integrity, stimulation of growth, and antioxidant defence.

Anatomical plasticity is a typical defence response in plants to drought, as it enhances water transport efficiency, mechanical tissue stability, and hydraulic conductivity. In our study, the most significant anatomical changes were observed in the La Harpe cultivar under drought stress, where foliar Si led to the formation of a continuous ring of secondary xylem and a well-developed parenchymal pith. These changes reflect accelerated cambial differentiation and improved functional integrity of the central cylinder, which may contribute to maintaining water flow. Similar effects of Si on xylem and vascular bundle development were reported in *Lolium perenne* L. (Mastalerczuk et al. 2025) and *Oryza sativa* L. (Ahmad and Hassim 2024).

The development of secondary xylem in La Harpe is associated with enhanced lignification and polymerisation of cell walls, increased mechanical strength, and reduced risk of vascular collapse during drought. Silicon may also be deposited in the endodermis and pericycle, forming a semi-permeable barrier that limits water and ion losses while regulating radial transport (Vaculík et al. 2012, Lux et al. 2020, Sabir et al. 2024, Saja-Garbarz et al. 2024). These Si-mediated anatomical changes maintain hydraulic balance and improve water-use efficiency. Recent studies suggest that Si may also stimulate cambial activity, promote the development of secondary tissues, and restore conductive pathways (Mahmoud et al. 2023, Ahmad and Hassim 2024).

The Panda cultivar exhibited a smaller response, characterised by less developed pith, likely due to lower Si uptake/translocation or limited anatomical remodelling (Vaculík et al. 2012, Manivannan et al. 2023). Similar genotype-dependent specificity has been described in wheat under drought conditions (Thorne et al. 2021) and with Si (Ahmad and Hassim 2024). In the Smuga cultivar, there were no marked differences between treatments, indicating anatomical stability with fewer induced modifications similar to those observed in *L. perenne* (Mastalerczuk et al. 2025) and *O. sativa* (Ahmad and Hassim 2024).

No consistent differences were observed in the cortex, suggesting that Si accumulates primarily in the central part of the root, where it strengthens the structure of the xylem and surrounding tissues (Lux et al. 2020, Saja-Garbarz et al. 2024, Sabir et al. 2024). Si supports genotype-dependent anatomical adaptations enhancing hydraulic efficiency and mechanical resilience. Our findings demonstrate a close connection between the root structure and drought-induced changes in growth and biochemical responses (Desoky et al. 2021, Manivannan et al. 2023, Ahmad et al. 2024, Cheraghi et al. 2024). At the morphological level, Si partially mitigated drought-induced growth inhibition, as reflected by plant height. La Harpe and Panda showed a mild positive effect, while Smuga's response was limited. Similar findings have been reported in gerbera (Ahsan et al. 2023), maize (Sabir et al. 2024), rice (Ahmad and Hassim 2024), black gram (Ahmad et al. 2024), and chickpea (Ali et al. 2025), where Si increased plant height under drought conditions. Si enhances plant growth by improving water use efficiency, turgor, and photosynthesis.

Buckwheat cultivars exhibit strong genotype-dependent responses to silicon. La Harpe exhibited the most pronounced anatomical adjustments in the primary root (central cylinder) and showed a mild improvement in plant height under drought conditions with silicon. Panda showed a moderate anatomical response and a modest improvement in plant height under drought with Si, whereas Smuga displayed only minor anatomical changes and no

https://doi.org/10.17221/539/2025-PSE

growth improvement under drought with Si. These genotypic differences are consistent with previous findings, showing that Si response depended on genotype and the capacity to optimise structural and morphological traits under stress (Lux et al. 2020, Manivannan et al. 2023, Oksana et al. 2023, Hossain et al. 2024, Ali et al. 2025).

Our results confirm that Si not only supports anatomical traits and growth but is also associated with metabolic adjustments to drought stress (Desoky et al. 2021, Cheraghi et al. 2024, Mastalerczuk et al. 2025). Drought-induced changes in plant growth are often closely linked to metabolic processes, particularly the synthesis of phenolics and antioxidants (Lux et al. 2020, Oksana et al. 2023, Ahmad and Hassim 2024, Krucky et al. 2025), which protect plants from oxidative stress by neutralising ROS (Bashir et al. 2021, Ahsan et al. 2023, Manivannan et al. 2023, Morshedloo et al. 2025). Phenolic compounds produced through the phenylpropanoid pathway include simple phenolic acids, flavonoids, and lignin precursors that are activated under water deficit (Aubert et al. 2021, Oksana et al. 2023, Hossain et al. 2024). Our results showed that drought increased both TPC and PAC in the three cultivars, while foliar Si amplified this effect. These changes confirm that Si acts as a biochemical modulator, activating plant defence mechanisms under stress (Lux et al. 2020, Wang et al. 2021, Mahmoud et al. 2023, Krucky et al. 2025).

TPC was significantly affected by both drought and Si application, with the highest values recorded in La Harpe in the roots. The increase in TPC following Si application under stress corresponded with observations in other plant species, such as wheat (Akhtar and Ilyas 2022), strawberry (Zahedi et al. 2023), and chickpea (Ali et al. 2025), where Si stimulated the activity of phenylalanine ammonia-lyase (PAL) and enhanced the metabolic flux through the phenylpropanoid pathway (Vaculík et al. 2012, Lux et al. 2020, Dar et al. 2022, Sabir et al. 2024). In our experiments, the effect of Si was most pronounced under drought + Si treatment, suggesting that Si further promotes phenolic accumulation under stress by activating secondary metabolic pathways. This outcome is consistent with the literature, where Si functions as a biochemical modulator improving WUE, cell turgor, and ROS balance in plant tissues (Mahmoud et al. 2023, Sattar et al. 2023, Krucky et al. 2025, Morshedloo et al. 2025).

PAC followed a similar trend to TPC, with drought + Si resulting in the highest values for PAs such as ferulic, caffeic, and p-coumaric acid, which are antioxidants and structural components of cell walls that stabilise membranes and maintain osmotic balance (Gharibi et al. 2019, Carneiro-Carvalho et al. 2020, Oksana et al. 2023). The significant increase in PAC under the drought + Si treatment, particularly in La Harpe roots, suggests that Si promotes both the synthesis and translocation of PAs. A similar mechanism has been described in strawberries (Zahedi et al. 2023), where Si upregulates PA synthesis and enhances antioxidant activity (Ahmad and Hassim 2024, Cheraghi et al. 2024). This effect is likely associated with the activation of key enzymes in the phenylpropanoid pathway, such as PAL, whose activity in buckwheat increased following Si application (Dar et al. 2022).

Overall, the effect of Si on buckwheat represents a multidimensional adaptive mechanism to drought involving anatomical, growth (plant height), and biochemical changes. The reinforcement of xylem structure and the development of secondary tissue enabled more efficient water transport and mechanical stability (Lux et al. 2020, Ahmad and Hassim 2024, Sabir et al. 2024, Ali et al. 2025), while the increased synthesis of phenolic compounds and PAs mitigated oxidative damage (Dar et al. 2022, Oksana et al. 2023, Morshedloo et al. 2025). This linkage between structural stabilisation, growth performance, and metabolic activity supports Si's role as an integrative factor, enhancing drought resilience of plants (Desoky et al. 2021, Manivannan et al. 2023, Cheraghi et al. 2024, Mastalerczuk et al. 2025).

Taken together, our results support the proposed hypotheses that foliar Si application (*i*) promotes root anatomical development, most clearly evidenced by enhanced development of the central cylinder and secondary xylem in the La Harpe cultivar under drought; (*ii*) stimulates phenolic metabolism, as demonstrated by increased TPC and PAC in both leaves and roots, and (*iii*) shows cultivar-dependent efficiency, with La Harpe exhibiting the strongest overall responsiveness, Panda an intermediate response, and Smuga limited responsiveness. Collectively, these cultivar-specific responses suggest that the effectiveness of foliar Si under drought is influenced by genetic background. Therefore, it will be important to verify these findings across a broader range of genotypes and under different intensities and durations of water deficit to assess the transferability of Si-mediated drought responses in buckwheat and their potential use in subsequent breeding and confirmatory studies.

https://doi.org/10.17221/539/2025-PSE

Acknowledgement. The authors would like to thank Ing. Jana Krizkova and Ing. Veronika Petru for their assistance in establishing the pot experiment. Special thanks are also extended to Ing. Laura Tamayo and Dr. Aayushi Gupta for their help with the laboratory analyses.

REFERENCES

Ahmad A., Hassim M.F.N. (2024): Effects of silica nanoparticles on morpho-histological and antioxidant activities of rice seedlings under drought stress. South African Journal of Botany, 168: 497–508.

Ahmad W., Waraich E.A., Haider A., Mahmood N., Ramzan T., Alamri S., Siddiqui M.H., Akhtar M.S. (2024): Silicon-mediated improvement in drought and salinity stress tolerance of black gram (*Vigna mungo* L.) by modulating growth, physiological, biochemical, and root attributes. ACS Omega, 9: 37231–37242.

Ahsan M., Valipour M., Nawaz F., Raheel M., Abbas H.T., Sajid M., Manan A., Kanwal S., Mahmoud E.A., Casini R., Elansary H.O., Radicetti E., Zulfiqar H. (2023): Evaluation of silicon supplementation for drought stress under water-deficit conditions: an application of sustainable agriculture. Agronomy, 13: 599.

Akhtar N., Ilyas N. (2022): Role of nanosilica to boost the activities of metabolites in *Triticum aestivum* facing drought stress. Plant and Soil, 477: 99–115.

Ali M.F., Ahmed M., Mukhtar L., Ali N., Qadir G., Hayat R., Ahmad S. (2025): Foliar application of silicon alleviates drought stress in chickpea (*Cicer arietinum* L.) by improving growth, photosynthetic and antioxidant metabolism. Journal of Soil Science and Plant Nutrition, 25: 6678–6693.

Antala M., Kovar M., Sporinová L., Filacek A., Juszczak R., Zivcak M., Shomali A., Prasad R., Brestic M., Rastogi A. (2025): High-throughput phenotyping of buckwheat (*Fagopyrum esculentum* Moench.) genotypes under water stress: exploring drought resistance for sustainable agriculture. BMC Plant Biology, 25: 444.

Aubert L., Konrádová D., Barris S., Quinet M. (2021): Different drought resistance mechanisms between two buckwheat species, *Fagopyrum esculentum* and *Fagopyrum tataricum*. Physiologia Plantarum, 172: 577–586.

Bashir S.S., Hussain A., Hussain S.J., Wani O.A., Nabi S.Z., Dar N.A., Baloch F.S., Mansoor S. (2021): Plant drought stress tolerance: understanding its physiological, biochemical and molecular mechanisms. Biotechnology and Biotechnological Equipment, 35: 1912–1925.

Carneiro-Carvalho A., Aires A., Anjos R., Martins L., Pinto T., Peixoto F., Gomes-Laranjo J. (2020): The role of silicon fertilization in the synthesis of phenolic compounds on chestnut plants infected with *P. cinnamomi* and *C. parasitica*. Journal of Plant Diseases and Protection, 127: 211–227.

Dar F.A., Tahir I., Hakeem K.R., Rehman R.U. (2022): Silicon application enhances the photosynthetic pigments and phenolic/flavonoid content by modulating the phenylpropanoid pathway in common buckwheat under aluminium stress. Silicon, 14: 323–334.

Desoky E.-S.M., Mansour E., El-Sobky E.-S.E.A., Abdul-Hamid M.I., Taha T.F., Elakkad H.A., Arnaout S.M.A.I., Eid R.S.M., El-Tarabily K.A., Yasin M.A.T. (2021): Physio-biochemical and agronomic responses of faba beans to exogenously applied nano-silicon under drought stress conditions. Frontiers in Plant Science, 12: 637783.

Germ M., Golob A., Mikuš K.V., Likar M., Mravlje J., Pongrac P., Čermelj A.M., Park C.H., Park M.O., Kwiatkowski J., Regvar M. (2025): The potential of Si and Se as biostimulants to enhance resistance to climatic conditions and improve yields in common and Tartary buckwheat. Fagopyrum, 42: 19–28.

Gharibi S., Tabatabaei B.E.S., Saeidi G., Talebi M., Matkowski A. (2019): The effect of drought stress on polyphenolic compounds and expression of flavonoid biosynthesis related genes in *Achillea pachycephala* Rech.f. Phytochemistry, 162: 90–98.

Hornyák M., Płażek A., Kopeć P., Dziurka M., Pastuszak J., Szczerba A., Hura T. (2020): Photosynthetic activity of common buckwheat (*Fagopyrum esculentum* Moench) exposed to thermal stress. Photosynthetica, 58: 45–53.

Hossain M.S., Li J., Wang C., Monshi F.I., Tabassum R., Islam M.A., Faruquee M., Muktadir M.A., Mia M.S., Islam A.K.M.M., Hasan A.K., Sikdar A., Feng B. (2024): Enhanced antioxidant activity and secondary metabolite production in tartary buckwheat under polyethylene glycol (PEG)-induced drought stress during germination. Agronomy, 14: 619.

Howladar S.M. (2014): A novel *Moringa oleifera* leaf extract can mitigate the stress effects of salinity and cadmium in bean (*Phaseolus vulgaris* L.) plants. Ecotoxicology and Environmental Safety, 100: 69–75.

Hussain S., Hussain S., Qadir T., Khaliq A., Ashraf U., Parveen A., Saqib M., Rafiq M. (2019): Drought stress in plants: an overview on implications, tolerance mechanisms and agronomic mitigation strategies. Plant Science Today, 6: 389–402.

Cheraghi M., Motesharezadeh B., Mousavi S.M., Basirat M., Alikhani H.A., Zarebanadkouki M. (2024): Application of silicon improves rhizosheath formation, morpho-physiological and biochemical responses of wheat under drought stress. Plant and Soil, 503: 263–281.

Junker A., Muraya M.M., Weigelt-Fischer K., Arana-Ceballos F., Klukas C., Melchinger A.E., Meyer R.C., Riewe D., Altmann T. (2015): Optimizing experimental procedures for quantitative evaluation of crop plant performance in high throughput phenotyping systems. Frontiers in Plant Science, 5: 770.

Krucky J., Hejnak V., Vachova P., Gupta A., Kubes J., Popov M., Skalicky M. (2025): Silicon application enhances drought resilience in buckwheat: a comparative study of three varieties. Frontiers in Plant Science, 16: 1635709.

Lux A., Lukačová Z., Vaculík M., Švubová R., Kohanová J., Soukup M., Martinka M., Bokor B. (2020): Silicification of root tissues. Plants, 9: 111.

https://doi.org/10.17221/539/2025-PSE

Mahmoud A.W.M., Rashad H.M., Esmail S.E.A., Alsamadany H., Abdeldaym E.A. (2023): Application of silicon, zinc, and zeolite nanoparticles – a tool to enhance drought stress tolerance in coriander plants for better growth performance and productivity. Plants, 12: 2838.

Manivannan A., Soundararajan P., Jeong B.R. (2023): Editorial: Silicon: A "Quasi-Essential" element's role in plant physiology and development. Frontiers in Plant Science, 14: 1157185.

Mastalerczuk G., Borawska-Jarmułowicz B., Sujkowska-Rybkowska M., Bederska-Błaszczyk M., Borucki W., Dąbrowski P. (2025): Silicon mitigates the adverse effects of drought on *Lolium perenne* physiological, morphometric and anatomical characters. PeerJ – the Journal of Life and Environmental Sciences, 13: e18944.

Morshedloo M.R., Saeidi S., Zahedi S.M., Jahantab E., Ghorbanpour M. (2025): Foliar-applied silicon and nano-silicon alter the product quality and defense system in ginger mint (*Mentha gracilis* R.Br.) under drought stress by inducing essential oil accumulation and antioxidant activity. Journal of Soil Science and Plant Nutrition, 25: 1913–1926.

Oksana S., Marek K., Marian B., Marek Z. (2023): Cultivar-dependent and drought-induced modulation of secondary metabolites, adaptative defense in *Fagopyrum esculentum* L. Physiology and Molecular Biology of Plants, 29: 1605–1618.

R Core Team (2023): R: A language and environment for statistical computing (Vienna: R Foundation for Statistical Computing). Available at: https://www.r-project.org (accessed 7. 7. 2025)

Sabir A., Waraich E.A., Ahmad M., Hussain S., Asghar H.N., Haider A., Ahmad Z., Bibi S. (2024): Silicon-mediated improvement in maize (*Zea mays* L.) resilience: unrevealing morpho-physiological, biochemical, and root attributes against cadmium and drought stress. Silicon, 16: 3095–3109.

Saja-Garbarz D., Libik-Konieczny M., Janowiak F. (2024): Silicon improves root functioning and water management as well as alleviates oxidative stress in oilseed rape under drought conditions. Frontiers in Plant Science, 15: 1359747.

Sattar A., Sher A., Ijaz M., Ul-Allah S., Hussain S., Rasheed U., Hussain J., Al-Qahtani S.M., Al-Harbi N.A., Mahmoud S.F., Ibrahim M.F.M. (2023): Modulation of antioxidant defense mechanisms and morpho-physiological attributes of wheat through exogenous application of silicon and melatonin under water deficit conditions. Sustainability, 15: 7426.

Singleton V.L., Rossi J.A. (1965): Colourimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents. American Journal of Oenology and Viticulture, 16: 144–158.

Szaufer-Hajdrych M. (2004): Phenolic acids in leaves of species of the *Aquilegia* L. genus. Herba Polonica, 50: 50–54.

Thorne S.J., Hartley S.E., Maathuis F.J.M. (2021): The effect of silicon on osmotic and drought stress tolerance in wheat landraces. Plants, 10: 814.

Vaculík M., Landberg T., Greger M., Luxová M., Stoláriková M., Lux A. (2012): Silicon modifies root anatomy, and uptake and subcellular distribution of cadmium in young maize plants. Annals of Botany, 110: 433–443.

Wang M., Wang R., Mur L.A.J., Ruan J., Shen Q., Guo S. (2021): Functions of silicon in plant drought stress responses. Horticulture Research, 8: 254.

Zahedi S.M., Hosseini M.S., Hoveizeh N.F., Kadkhodaei S., Vaculík M. (2023): Comparative morphological, physiological and molecular analyses of drought-stressed strawberry plants affected by SiO_2 and SiO_2-NPs foliar spray. Scientia Horticulturae, 309: 111686.

Received: December 1, 2025
Accepted: January 13, 2026
Published online: January 27, 2026