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Synergistic Effects of Silicon and Potassium in Enhancing Plant Tolerance to Abiotic Stresses: A Comprehensive Review

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Abstract

Alliance of Research and College Potential Hydro seeding Drought resistance is an important part of limiting crop production. Mineral nutrition is being more and more investigated in an integrated approach to stress management; silicon (Si) and potassium (K) are of particular interest because they provide complementary functions. Silicon is an advantageous element that, in the leaf and other external tissues of plants, strengthens tissues, influences water relations, and limits translocation of potentially toxic ions, whereas K is an essential macronutrient with critical roles in osmotic regulation by modifying tissue osmoregulation via control of stomatal function, enzyme activation, and maintenance of ionic balance through different cellular compartments. Recent factorial experiments show improved protection against selected stress systems with combined Si and K supply, and there is evidence that such treatment tends to provide greater protective effects than either treatment alone; however, the strength of this evidence differs according to stress systems. Herein, we summarize the most recent understanding of Si and K uptake and function together with their interaction via ion homeostasis, water relations, antioxidant regulation, and structural protection based on experiments reflecting salinity-, drought-, and metal-toxicity-induced responses. It also separates direct evidence of Si-K interaction from studies with potassium silicate, since the individual contributions of Si and K cannot be experimentally separated, and classifies priority conclusions by field validation and agronomic optimization.

Keywords: silicon; potassium; synergism; abiotic stress; salinity; drought.

1. Introduction

Drought and other interacting abiotic constraints, like soil and irrigation-water salinity (particularly in arid environments), temperature extremes, and metal toxicity, are critical to crop production. Such stresses interfere with water relations, ion balance, membrane stability, and metabolism, with even greater adverse effects when more than one stress is simultaneous. Silicon nutrition has previously been extensively studied as a means of mitigating many of these disturbances, particularly under water deficit and salinity; broader reviews also detail its role in responses to metal toxicity and other environmental stress (1,2).

Nutrient management can manipulate the potential of plants to sustain growth under stress, but the elements involved utilize different physiological pathways. Potassium- an essential macronutrient that is involved in osmotic adjustment, stomatal movement, enzyme activation (2), membrane

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function and the long-distance transport of assimilates [3]. Although Silicon is not an essential nutrient for most species, it is considered a beneficial element today, whose deposition can increase the structural strength of tissues and can indirectly facilitate resistance to physiological stress or the modulation of biochemical stress responses [1,2]. This divergent function offers a physiological background to study Si and K together, rather than considering them separate inputs.

Because the two factors are manipulated independently, direct evidence for a Si-K interaction is strongest. In the same way, factorial Si and K treatments studied under saline irrigation increased nutritional status, gas exchange, relative water content, and growth of yellow passion fruit seedlings (4). Combined K and Si also improved tolerance of quinoa exposed to Cd and Pb (5), while a three-factor experiment in rice showed that Si and K together produced broader protection against ferrous-iron toxicity than either nutrient alone for many physiological and biochemical traits (6). These studies support the concept of complementary action, but they also show why the term synergy should be reserved for designs that can separate the individual and combined effects of the two elements.

Evidence from nutrient-deficiency research further strengthens the functional link between the two elements. A meta-analysis of 183 observations from 13 peer-reviewed studies found that Si application under K deficiency improved photosynthetic performance, antioxidant activity, water-use efficiency, and K-use efficiency while reducing markers of oxidative damage (7). However, studies using potassium silicate as a single treatment cannot by themselves distinguish a specific Si effect from a K effect. In this review, such studies are therefore treated as evidence for the agronomic performance of a combined Si-K source, whereas factorial studies are used when discussing interaction or synergy.

The goal of this review is to chart that intersection. To summarize what is known separately about Si and K in plant stress physiology; to explore the mechanistic pathways ionic, osmotic, enzymatic, and structural by which both elements seem to reinforce one another; to evaluate the experimental evidence stress by stress, from salinity to drought, heavy metals to extreme temperatures, and be honest about where the evidence is still sparse, so that future research can be directed in a useful direction rather than repeating what has already been well established; to translate this information into practical advice for field and greenhouse use; and to be candid about the areas where the evidence base is still incomplete, so that future research can be targeted in a useful way.

2. Silicon in Plant Nutrition and Stress Physiology

2.1 Silicon Uptake, Transport, and Deposition

Although Si is abundant in the Earth's crust, plant uptake depends on the concentration of soluble monosilicic acid in the soil solution and on species-specific transport capacity. Grasses generally accumulate more Si than many dicot species. In rice and other model cereals, efficient uptake and distribution requires coordinated influx and efflux transport systems; Lsi1 acts as a Si-permeable channel, whereas Lsi2 mediates bulk-loaded Si redistribution toward the stele; concerted action from these mediated processes also facilitates shoot distribution (8- 10).

Silicon is transported to aerial organs and then deposited largely in the form of amorphous silica at or near epidermal and cell-wall structures. This deposition can enhance the rigidity of tissues, decrease non-stomatal water loss, and help to restrict the movement of ions as a consequence. This protective effect is not only due to a single modality: structural strength interacts with water dynamics, ion transport, and biochemical stress responses (1,10).

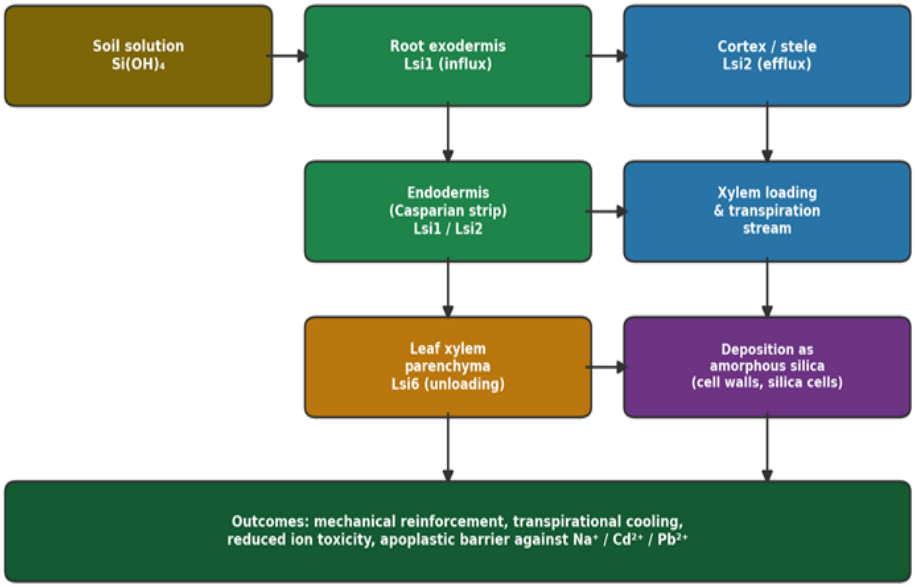


Figure 1. Root-to-shoot uptake and transport route of silicon in plants: the mechanism (Lsi transport system) and some potential functions (8-10).

2.2 Physiological Functions of Silicon during Abiotic Stress

Si function in abiotic stresses is not limited to tissue silicification. Under drought, Si can facilitate leaf water status and minimize water loss; under salinity, it may restrict Na+ accumulation and maintain ionic homeostasis; and in metal stress conditions, the reported effects of Si range from decreasing toxicity to controlling oxidative damage using physiological mechanisms combined with chemical reactions. Si treatment has also been linked to enhanced antioxidant capacity and modulation of stress-related signalling pathways (although the degree and mechanism of response varies by species, type of stress induced, and mode of Si application) [1,2,10].

3. Potassium in Plant Nutrition and Stress Physiology

3.1 Potassium Uptake and Physiological Functions

K has been targeted for biotechnological modification in agricultural crops to enhance K uptake or tolerance. Plants take up K primarily as charged ions. External K is known to be absorbed mainly in ionic forms [9]; specifically, potassium is taken up preferentially by an energy-dependent process whereby cation channels and cation transporters play key roles in determining K+ flux rates into the cytoplasm. The AKT and HAK/KUP/KT systems are involved in the uptake of root K, and further transport proteins assist intracellular distribution and xylem loading. Once involved in uptake, potassium remains largely ionic and is critical for supporting numerous systems such as enzyme activation, stomatal regulation, osmotic adjustment of the cell, membrane depolarization, which is vital for cell signaling in plants, phloem transport (accumulation of sugar), and general cellular turgor maintenance (3,11).

3.2 Potassium and Cell Osmotic Regulation during Water Deficit

K directly participates in osmotic adjustment and wilting reduction during water deficit. It is also involved in photosynthesis and oxidative protection. A meta-analysis based on >2,300 paired observations observed enhanced biomass, gas

exchange, and antioxidant performance after K application under osmotic stress, with stronger cumulative effects in the case of drought as compared to salinity (3,12).

3.3 Potassium and Ionic Homeostasis during Salinity

Salinity provides an ionic component of osmotic stress due to Na+ competition for K uptake, transport, and retention. Therefore, maintaining a favourable cytosolic K+/Na+ balance is a key aspect of salt tolerance. High-affinity K transport systems, membrane potential and the machinery involving Na+ accumulation brought together act synergistically to maintain enzyme function and homeostasis (11,13).

4. Mechanistic Basis of the Silicon–Potassium Synergistic Interaction

The expected interaction between Si and K was interpreted as functional complementarity rather than simple redundancy. As a structural and apoplastic interface, silicon acts similarly as a strong barrier that is able to restrict water and ion loss; K+ in turn operates mainly as a mobile intracellular ion modulating osmotic potential, stomatal behavior, membrane traffic, and enzyme activity. Simultaneous increases in the external exclusion and internal ion balance, water relations, and maintenance of metabolic stability in a plant can be achieved when both functions are preserved under stress (1,3,4,6).

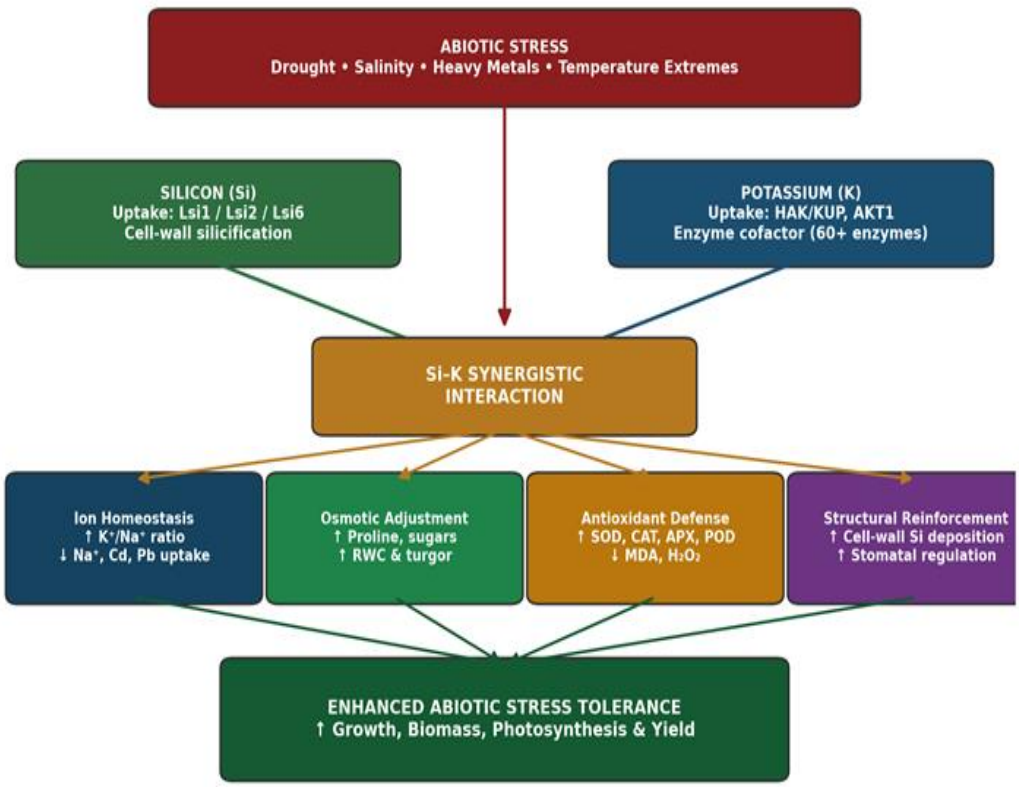


Figure 2. A conceptual scheme of complementary mechanisms by which silicon (Si) and potassium (K) can improve plant tolerance to abiotic stress (1,3,4,6).

4.1. Ion Homeostasis and Selective Ion Transport

One of the most clearly convergent points of ion homeostasis. Silicon helps decrease passive ion influx and modify Na+ distribution, whereas K feeding facilitates selective transport, ensuring the K+/Na+ ratio is balanced. In rice and cucumber under salt stress, Si application improved K status and attenuated the ionic effects of Na+ stress (13,14). Direct factorial investigations further reveal that Si + K treatments can outperform single-element treatments in certain systems, such as saline passion fruit and Fe2+ -stressed rice (4,6).

Mechanistic studies show that Si can affect K acquisition, retention, and redistribution. Additionally, Si increased K uptake, xylem loading, and root-to-shoot transport; this was associated with enhanced expression of OsAKT1, OsHAK1, and OsSKOR (13) in NaCl-exposed rice. In K-deficient barley, Si promoted mobilization of root K pools and modified expression of K-related transport genes (15). In cucumber, Si improved root K retention through stronger Na+ exclusion and antioxidant capacity (14), while root or foliar Si improved photosynthesis, water-use efficiency, and growth of K-deficient common bean (16). At the cellular level, potassium-silicate pretreatment also reduced cytosolic Na+ accumulation in wheat mesophyll protoplasts exposed to salt (17).

4.2 Osmotic Adjustment and Water Relations

Water relations provide a second point of complementarity. Silicon can reduce transpirational water loss and support tissue hydration, whereas K contributes directly to osmotic adjustment and stomatal control. Reviews of drought physiology therefore place both elements within the same functional network, but through partly different mechanisms (1,3,18).

Experiments with potassium silicate show that supplying both elements through the same compound can improve performance under water deficit. Positive responses have been reported for maize yield and water-use efficiency (19), relative water content and osmotic regulation in Bellis perennis (20), and physiological and agronomic traits of camelina under restricted irrigation (21). In terminally drought-stressed wheat, foliar K2SiO3 improved water status, photosynthesis, PSII performance, antioxidant defenses, and grain yield (22). Drought-related benefits have also been reported in squash and sugarcane (23,24). Because these experiments use potassium silicate as a combined source, they demonstrate agronomic efficacy but do not independently quantify the contribution of each element.

4.3 Coordinated Activation of the Antioxidant Defense System

Abiotic stress commonly increases reactive oxygen species, and excessive ROS can accelerate membrane lipid peroxidation and cellular injury. Both Si and K have been linked to stronger antioxidant protection, although through different physiological routes (1,3,18). Under combined Cd-Pb stress in quinoa, the joint K and Si treatment enhanced antioxidant enzyme activity and reduced oxidative-damage indicators relative to stressed plants without the combined treatment (5). These results support that antioxidant regulation is an important aspect of the Si-K response, yet we do not mean to imply that all antioxidant effects are always synergistic in every crop or stress condition. Lately, this view has been supported by studies that synthesize the current literature in a broader spectrum. Ferreira and Prado associated Si and K with coordinated regulation of water-use efficiency, osmotic control, and antioxidant protection under conditions of water and nutrient deficiency (18). A recent meta-analysis of studies conducted on K-deficient plants similarly showed that Si supply significantly improved antioxidant activity and reduced the oxidative-stress markers (7). Collectively, these findings link Si-mediated stress protection with K-dependent metabolic stability.

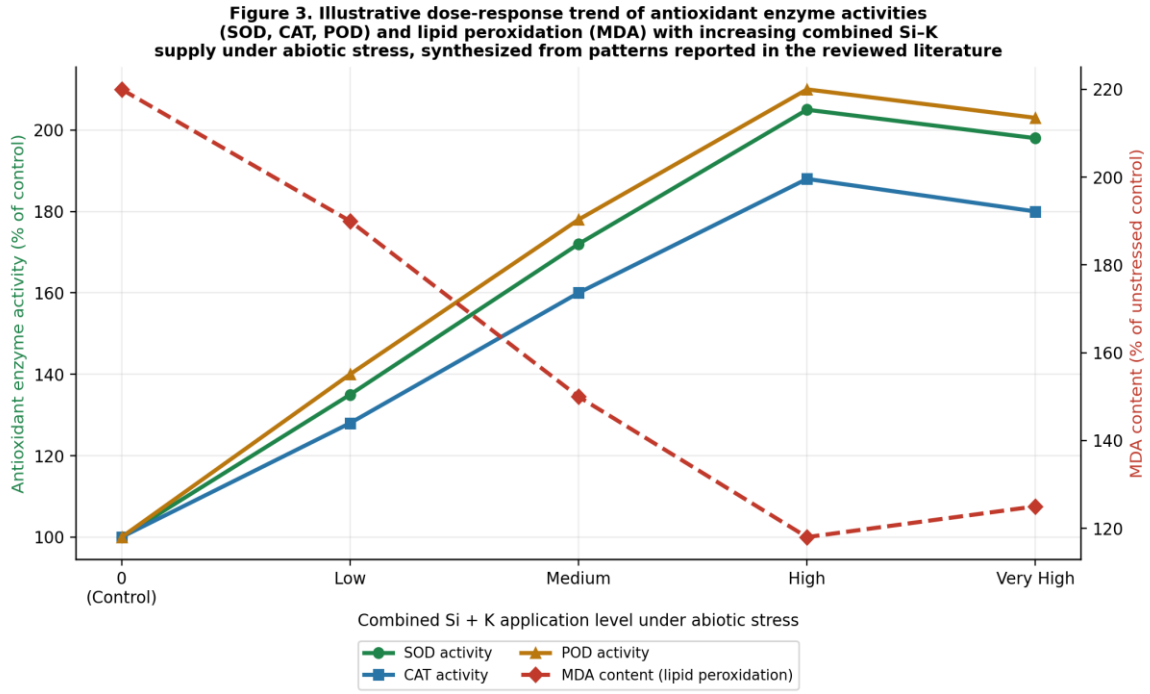


Figure 3. Response of antioxidant and lipid-peroxidation mechanisms across selected Si-K studies — a conceptual illustration; curves are schematic, non-pooled effect estimates (5,7,18).

4.4 Structural Reinforcement and Cell Wall Integrity

This silica, on the other hand, makes the cell wall and epidermal tissues stronger and also reduces permeability to water (and toxic ions?) in external pathways (10, 1). The other role of potassium is to contribute to maintaining turgor, membrane function, and metabolic activity needed for cell expansion and repair (3). Consequently, these two effects are complementary: Si protects structurally, and K supports physiologically the processes to maintain living tissue under stress.

These mechanisms lie at the heart of all humans as mutually independent. Enhanced iron homeostasis can attenuate photosynthesis; improved water status can minimize oxidative damage; antioxidant protection can maintain membranes and transducers. Data obtained via factorial studies coupled with Si and K treatments in passion fruit, quinoa, and rice suggest that a combined treatment can provide greater physiological protection than single-element treatments within those respective experimental systems (4-6).

5. Commonalities in Si–K Synergy across Major Abiotic Stress Types

5.1 Salinity Stress

Salinity offers very robust mechanistic support for the combination of Si and K, particularly because plants have to cope with both water deficit and mineral imbalance. In yellow passion fruit, a factorial design of four silicic acid doses and two K doses showed that the combined treatment improved nutrient availability, leaf ion status, gas exchange, relative water content, and biomass while decreasing indicators of salinity injury (4). Mixtures of Si and K were selected in this experiment as they could be varied independently to evaluate their interaction directly.

Some of this response to salinity is explained at various levels. So far, successive selections of F1 hybrids have been tested as sensitive plants for their reaction against the damage caused by saline waters (14) and confirmed that, in hydroponic tomato, Si

supplied as K2SiO3 counterbalanced the detrimental effects on growth and yield due to salinity stress, but also improved performance of fruits in terms of size, color, and sugar contents [25]. Si improved K uptake and xylem transport under NaCl stress (13) in rice, while in cucumber it promoted root K retention, Na+ exclusion, and antioxidant capacity (14). Potassium-silicate pretreatment also attenuated the cytosolic Na+ concentration excess in wheat mesophyll protoplasts (17). Together, these studies highlight K retention and Na+ regulation as key drivers in the association between Si supply and salinity stress tolerance.

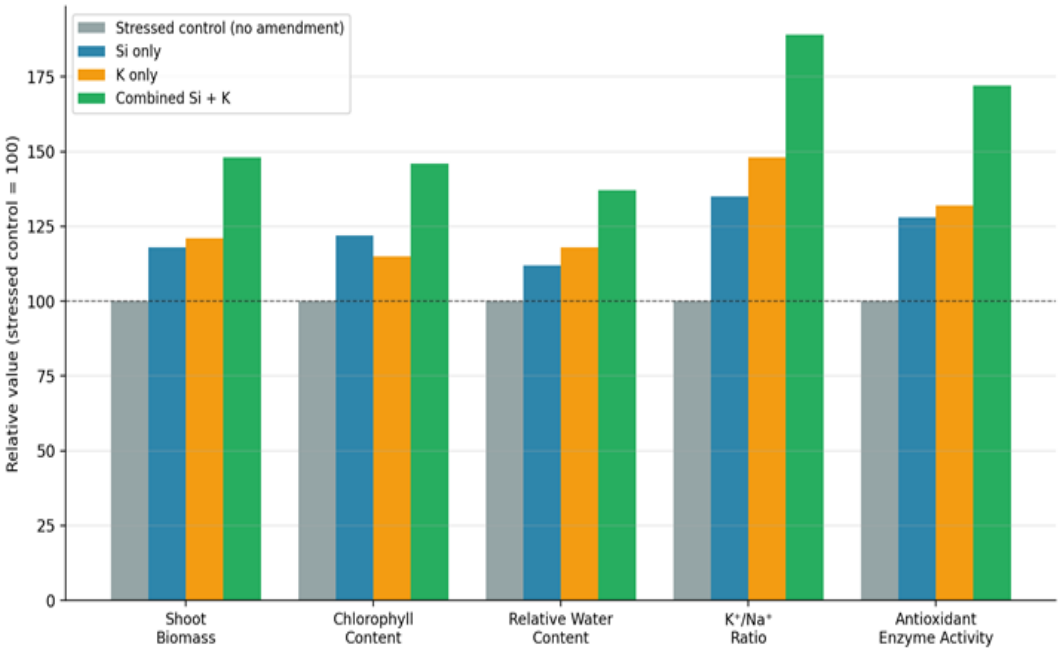


Figure 4. Summary of putative physiological responses reported for separate and combined Si and K treatments when plants are exposed to various abiotic stresses; qualitative schematic only (4-5).

5.2 Drought Stress

In drought conditions, K directly participates in stomatal regulation and osmotic adjustment, while Si can reduce water loss and contribute to structural and physiological stability. Thus, their functions converge on the maintenance of tissue water status, photosynthesis, and protection from secondary oxidative damage (3, 1, 18). Thus, the two forms of evidence should not be interpreted as equivalent because direct factorial evidence for Si-K synergy under drought is comparatively sparse relative to that for potassium-silicate treatments.

Potassium-silicate treatments have triggered beneficial drought responses across crop species, but the effect size depends on crop type, dose, and application method and stress intensity. Enhancements have been documented in maize (19), Bellis perennis (20), wheat (22), camelina (21), squash (23), and sugarcane (24). Responses include improved water status, photosynthetic performance, antioxidant function, biomass or yield (or parts thereof), but not all factorial experiments differentiate between Si-specific and K-specific effects.

5.3 Heavy Metal Toxicity

Research using heavy-metal stress directly demonstrates that the two can work in concert. Meanwhile, K and Si improved growth, stomatal conductance, pigment status, and antioxidant activity (5), concomitantly reducing oxidative-damage indicators as well as enhancing

phytostabilization in the presence of both Cd and Pb (5). These responses suggest that Si-K management may be conferring protection when ionic toxicity and H2O2-induced oxidative stress occur simultaneously.

An even clearer factorial test, we might argue, is ferrous-iron toxicity. Ahmed et al. independently manipulated Fe2+, Si, and K rice, cultivated them independently on the three elements Fe, Si, and K, and then examined a range of traits measured at harvest, including plant body weight. Overall, the presence of Si in combination with K was found to provide better protection from Fe-induced injury of chlorophyll, PSII function, membrane stability, antioxidant activity and net photosynthesis and biomass compared to untreated toxic-Fe (6). The design of our experiment therefore gives better evidence for interaction than studies based only on potassium silicate, due to the separation between Si and K.

5.4 Temperature Extremes

The literature reviewed here still provides little evidence for combined Si-K that is applied under heat or chilling. Silicon on its own has been linked to enhanced tissue stability, antioxidant protection, and water relations during temperature-related stress conditions, whereas sufficient K promotes membrane stability, control of osmotic potential, and partial stomatal opening (1–3). While these mechanisms provide a potential basis for complementarity, direct factorial Si × K experiments are necessary to yield the magnitude of any synergistic effect under temperature extremes.

5.5 Summary of Reviewed Experimental Evidence

Table 1 presents representative experimental evidence, which separates the direct factorial Si × K studies from experiments that assessed potassium silicate or evaluated the role of Si-mediated K homeostasis.

Crop species	Stress type	Si / K treatment	Key outcome relevant to Si-K interaction	Reference
Yellow passion fruit (Passiflora edulis)	Salinity	Factorial silicic acid × K doses	Improved nutrient status, gas exchange, relative water content and biomass; reduced salinity injury	(4)
Rice (Oryza sativa)	Ferrous-iron toxicity	Factorial Fe2+ × Si × K design	Combined Si + K produced broader protection of photosynthesis, membranes, antioxidant status, and biomass	(6)
Quinoa (Chenopodium quinoa)	Cd + Pb co-contamination	Combined K + Si treatment	Improved growth and antioxidant defense; reduced oxidative injury and supported phytostabilization	(5)
Rice (Oryza sativa)	Salinity	Si supplied; K uptake and transport quantified	Si increased K uptake, xylem loading and root-to-shoot K transport under NaCl stress	(13)

Crop species	Stress type	Si / K treatment	Key outcome relevant to Si-K interaction	Reference
Cucumber (Cucumis sativus)	Salinity	Si supplied; root K retention quantified	Improved K retention, Na+ exclusion and antioxidant capacity	(14)
Maize (Zea mays)	Water deficit	Foliar potassium silicate	Improved water-use efficiency and grain yield under reduced irrigation	(19)
Wheat (Triticum aestivum)	Terminal drought	Foliar K2SiO3	Improved water status, photosynthesis, antioxidant defenses and grain yield	(22)
Bellis perennis	Drought	Potassium silicate	Improved relative water content, chlorophyll, antioxidant activity and osmotic regulators	(20)

6. Comparative Overview of Silicon and Potassium Functions

Summary of Key Differences between Si & K as Taken Together in Table 2. The summary draws on well-established Si transport and stress-physiology literature (8,10) as well as reviews of K transport & stress function(3,11).

Attribute	Silicon (Si)	Potassium (K)
Essentiality	Beneficial element; essentiality is species-dependent and not universal	Essential macronutrient
Primary uptake form	Monosilicic acid, Si(OH)4	K+ ion
Key transporters	Lsi1 (influx, NIP aquaporin), Lsi2 (efflux), Lsi6 (xylem unloading)	AKT channels; HAK/KUP/KT transporters; SKOR and related transport systems
Principal mode of action	Structural reinforcement via cell-wall silicification; physical/apoplastic barrier	Osmotic adjustment, enzyme activation, stomatal and turgor regulation
Effect on ion toxicity	Reduces apoplastic bypass flow of Na+, Cd2+, Pb2+	Supports K+/Na+ balance through selective K transport and membrane regulation
Antioxidant contribution	Enhances SOD, CAT, APX, POD gene expression and activity	Supports metabolic and antioxidant processes that limit ROS injury

Sources for Table 2: (8,10,3,11).

7. Agronomic Implications and Application Strategies

Si-K physiology translation into field practice depends on the source, rate of application, method of application, crop species, and soil or irrigation solution chemistry. Application method should therefore be considered part of the biological treatment rather than just a logistical matter, as the same nominal Si or K rates can produce different outcomes via soil amendment, fertigation, or foliar application (7, 18).

This context is relevant for the interpretation of potassium-silicate studies. Their results show that a combined Si-K source can be agronomically effective, but they do not demonstrate the separate contribution of each element. Meta-analytic evidence further indicates that Si response under K deficiency varies with Si source, plant accumulation capacity, stress severity, and application method (7). Recommendations should therefore be crop- and system-specific rather than based on a single universal rate.

- Soil application: Solid silicate amendments can be useful where a longer-term Si supply is required, but their effectiveness depends on solubility, incorporation, soil pH, and the crop's capacity to acquire Si. Less soluble sources may require incorporation and time for release (18).
- Foliar application: Foliar potassium silicate has produced useful responses in several drought studies, including improved water status, photosynthetic performance, antioxidant function, and yield-related traits (20-23). Foliar responses remain dose- and crop-dependent, so concentration should be optimized experimentally.
- Fertigation: Soluble silicate sources can be integrated with irrigation systems and may improve the coordination of water and nutrient supply. Reviews identify fertigation as a promising route for Si delivery, while also noting the need to manage concentration, polymerization, and the risk of nutrient loss or leaching (18).
- Dose optimization: More input does not always yield a corresponding output improvement. Responses to potassium silicate in Bellis perennis, wheat, squash, and camelina vary along with both the Si-K concentration and magnitude of stress delivered, indicating that the agronomic optimum is a function of crop and environment, not a defined Si-K dose (20,22,23).

The integrated management of irrigation quality, baseline K fertility, and crop-specific nutrient requirements combined with Si-K is more likely to be a useful strategy in arid and semi-arid production systems with overlapping water limitation and salinity stress than applied as an independent stand-alone treatment (4, 19, 18).

8. Knowledge Gaps and Future Research Directions

Important gaps remain. While most of the direct evidence of Si-K interaction is observed from more controlled or semi-controlled experiments, fewer factorial Si × K studies have been conducted across diverse field soils where climatic and seasonal conditions differ. There are more potassium-silicate studies, but their design tends to confound Si- and K-effect separation. Much of the evidence is also available to support that responses can differ based on plant genotype and Si accumulation capacity, source, dose, and application route (7, 18). Clearly, subsequent work should emphasize multi-environment factorial trials, direct measurements of K and Si migration, molecular experiments exploring potential signaling cross-talk, and economic analysis of combined nutrient strategies before global recommendations can be proffered.

9. Conclusion

This review provides evidence for a synergistic role of Si and K in the tolerance of plants to stress, but this evidence differs in strength between categories of abiotic stresses and types of experimental systems. K is primarily involved in osmotic

adjustment, membrane function, stomatal control, and enzyme activity, while silicon plays a strong role in structural protection, ion exclusion, and stress-related physiological regulation. Direct factorial studies under salinity, heavy-metal toxicity, and Fe2+ toxicity demonstrate that for specific systems, combined treatment may offer wider protection than either factor alone (4-6). Potassium silicate usage in practical applications under drought and salinity illustrates this further, though it must be viewed as a combined source, not independent evidence of synergy (19, 20, 22, 25). The next step is to determine the geographical and contextual precision at which this interaction achieves efficacy in field applications, and to develop crop-specific rates and application protocols that are agronomically and economically justified.

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