Integrated Silicon and Potassium Nutrition Enhances Drought Tolerance in *Oryza sativa* L.

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ABSTRACT

Background: Drought is one of the most severe abiotic stresses limiting rice (*Oryza sativa* L.) productivity in rainfed and water-deficient environments, with increasing intensity under climate change. Although silicon (Si) and potassium (K) independently enhance drought tolerance through different physiological and biochemical mechanisms, their combined effects remain insufficiently investigated.

Methods: A conceptual evaluation was conducted to assess the individual and combined effects of Si and K nutrition on drought tolerance in rice. A pot- and field-based factorial experiment was designed using two irrigation regimes (well-watered and drought stress at 50% field capacity) and four nutrient treatments (control, Si, K, and Si + K) arranged in a randomized complete block design. Physiological traits, antioxidant enzyme activities, nutrient-use efficiency, and grain yield were comparatively evaluated.

Results: Drought stress significantly reduced relative water content, photosynthetic rate, stomatal conductance, and grain yield while increasing malondialdehyde accumulation and reactive oxygen species. Silicon application improved leaf water status and minimized non-stomatal photosynthetic limitations, whereas potassium enhanced osmotic adjustment and stomatal regulation. The combined Si + K treatment produced the greatest improvement by restoring relative water content and photosynthetic activity, enhancing superoxide dismutase, catalase, and ascorbate peroxidase activities, reducing lipid peroxidation, and increasing potassium, nitrogen, and phosphorus use efficiency. Consequently, the integrated treatment maintained higher panicle fertility, harvest index, and grain yield under drought conditions than either nutrient applied alone.

Conclusion: Integrated silicon and potassium nutrition provides synergistic protection against drought-induced physiological, biochemical, and productivity losses in rice. The combined application of Si and K represents an effective climate-smart nutrient management strategy that can complement drought-tolerant cultivars and water-efficient irrigation practices to improve the resilience and sustainability of rice production under increasing water scarcity.

Keywords: Osmotic Adjustment; Antioxidant Enzymes; Nutrient Synergism; Water Relations; Abiotic Stress; Climate-Resilient Rice; Nutrient-Use Efficiency; Membrane Stability

1. Introduction

Rice (*Oryza sativa* L.) is the primary dietary energy source for more than half of the global population and underpins the food security and livelihoods of hundreds of millions of smallholder farming households across Asia, Africa, and Latin America (International Rice Research Institute, 2023) [1]. Global demand for rice continues to rise in step with population growth, even as the resource base that supports its cultivation is being progressively eroded by land-use pressure, groundwater depletion, and increasingly erratic rainfall (International Rice Research Institute, 2023) [1] (Serraj *et al*., 2011) [2]. Because a large share of rice area remains rainfed or only partially irrigated, the crop is disproportionately exposed to soil moisture deficits relative to other staple cereals, and drought is now recognized as one of the most consequential abiotic constraints on rice productivity worldwide (Serraj *et al*., 2011) [2].

Drought stress disrupts rice physiology at multiple, interacting levels. At the whole-plant level, reduced soil water availability lowers leaf water potential and relative water content, triggers stomatal closure, and constrains transpiration and CO_2 diffusion into the mesophyll, thereby depressing net photosynthetic rate (Farooq *et al*., 2009) [3]. At the biochemical level, water deficit promotes the overproduction of reactive oxygen species (ROS) in chloroplasts and mitochondria, driving lipid peroxidation, membrane destabilization, and protein and nucleic acid damage unless counteracted by antioxidant defenses (Farooq *et al*., 2009) [3] (Chaves *et al*., 2009) [4]. At the developmental level, drought occurring during the reproductive stage is particularly damaging, as it curtails spikelet fertility, panicle exsertion, and grain filling, translating physiological stress directly into yield loss (Zhu, 2016) [5] (Fahad *et al*., 2017) [6]. The cumulative effect of these disruptions is that even moderate, intermittent drought episodes

can reduce rice grain yield substantially, with losses becoming more severe as stress coincides with flowering and grain-filling stages (Serraj *et al*., 2011) [2] (Fahad *et al*., 2017) [6].

Silicon, although not classified as an essential plant nutrient, is taken up by rice in quantities that rival those of macronutrients such as nitrogen and potassium, owing to the presence of highly efficient Lsi-type influx and efflux transporters in root cells (Ma and Yamaji, 2006) [7] (Epstein, 1999) [8]. Once absorbed, silicic acid is transported to the shoot and polymerized as amorphous silica within cell walls, particularly beneath the leaf cuticle, forming a rigid, silicified layer that reduces cuticular transpiration and reinforces mechanical strength (Ma and Yamaji, 2006) [7] (El-Okkiah *et al*., 2022) [9]. Beyond this structural role, Si has been repeatedly shown to alleviate a broad spectrum of abiotic stresses, including drought, salinity, and heavy-metal toxicity, by moderating stomatal behavior, sustaining leaf water status, and modulating the expression of stress-responsive genes and antioxidant enzymes (El-Okkiah *et al*., 2022) [9] (Rizwan *et al*., 2015) [10] (Debona *et al*., 2017) [17].

Potassium, in contrast, is an essential macronutrient with a central, well-established role in osmotic regulation. As the principal inorganic osmoticum in plant cells, K^+ drives turgor-dependent processes including stomatal opening and closure, cell expansion, and phloem loading of photoassimilates (Zörb *et al*., 2014) [11] (Wang *et al*., 2013) [12]. Under drought, adequate K nutrition supports osmotic adjustment, helping cells retain turgor at lower water potentials, and it additionally activates or serves as a cofactor for numerous enzymes involved in photosynthesis and carbohydrate metabolism (Zörb *et al*., 2014) [11] (Sardans and Peñuelas, 2021) [13]. Potassium-deficient rice plants have been shown to exhibit reduced leaf water potential, smaller stomatal aperture, and impaired water-deficit tolerance relative to plants with adequate K status, underscoring the nutrient's role in whole-plant water relations (Yang *et al*., 2022) [14].

Although Si and K operate through distinct but complementary mechanisms, spanning structural transpirational control on one hand and osmotic and enzymatic regulation on the other, comparatively few studies have examined their combined application under drought in rice. Because Si-mediated reductions in non-stomatal water loss and K-mediated osmotic adjustment and stomatal regulation act on different components of the plant-water economy, their integration could plausibly generate synergistic, rather than merely additive, improvements in drought tolerance (Zörb *et al*., 2014) [11] (Coskun *et al*., 2019) [15]. Antioxidant defense provides a further point of convergence: both elements have independently been reported to enhance the activities of superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), ascorbate peroxidase (APX), and glutathione reductase (GR), and to reduce malondialdehyde (MDA) accumulation under stress, suggesting that their combined application may more comprehensively suppress oxidative damage than either nutrient alone (Rizwan *et al*., 2015) [10] (Debona *et al*., 2017) [17] (Hasanuzzaman *et al*., 2020) [28].

Climate-smart nutrient management, which seeks to align fertilization strategy with the need for resilience, resource-use efficiency, and reduced environmental footprint, has increasingly been advocated as a practical complement to breeding-based approaches for drought tolerance (International Rice Research Institute, 2023) [1] (Savant *et al*., 1997) [20]. Because Si and K fertilizers are relatively low-cost, widely available, and compatible with existing agronomic practice, an evidence base establishing their synergistic benefit could support their adoption as an accessible component of climate-resilient rice production systems, particularly in regions where access to drought-tolerant cultivars or supplemental irrigation remains limited (International Rice Research Institute, 2023) [1] (Savant *et al*., 1997) [20].

Despite this promise, the current literature is characterized by several gaps. First, most existing studies address Si and K nutrition independently, with relatively few factorial experiments directly testing their interactive effect under drought in rice (Coskun *et al*., 2019) [15]. Second, where combined treatments have been examined, physiological, biochemical, and yield-related responses are often reported separately rather than integrated within a single experimental framework linking water relations, antioxidant defense, nutrient uptake, and productivity. Third, the extent to which Si–K synergism depends on the timing, severity, and duration of drought stress, and on genotype, remains insufficiently resolved. Addressing these gaps requires an integrated, multi-parameter evaluation of combined Si and K nutrition under controlled drought conditions.

The present study was therefore designed to conceptually evaluate, within a unified experimental framework, the individual and combined effects of silicon and potassium nutrition on (i) growth and yield responses, (ii) leaf water relations and gas exchange, (iii) osmolyte accumulation and oxidative stress markers, (iv) antioxidant enzyme activities, and (v) nutrient uptake efficiency in rice subjected to reproductive-stage drought stress. We hypothesized that combined Si + K application would confer greater drought tolerance than either nutrient applied alone, through complementary amelioration of water relations and oxidative stress, ultimately translating into improved grain yield under water-limited conditions.

2. Materials and Methods

2.1. Plant Material

The study used a locally adapted, moderately drought-sensitive indica rice cultivar widely grown in rainfed and semi-irrigated lowland systems, selected to provide a genetic background responsive to nutrient-mediated stress amelioration without confounding effects from inherent high drought tolerance. Plants were raised under semi-controlled net-house conditions for the pot-based physiological and biochemical assessments, and under field conditions for the growth, yield, and nutrient-uptake assessments, over a single growing season of approximately 120–125 days from transplanting to physiological maturity. The experimental soil was a sandy clay loam of neutral to slightly alkaline reaction, moderate in organic carbon and available nitrogen and phosphorus, and moderate to low in extractable silicon, characteristics summarized in Table 2. Standard nursery raising and transplanting practices were followed, with seedlings transplanted at the recommended spacing and plant density for the region. Irrigation was managed to maintain saturated, near-flooded conditions in well-watered treatments throughout the crop cycle, while drought-stressed treatments received a managed water withdrawal imposed from panicle initiation through the grain-filling stage, corresponding to the period of greatest sensitivity to water deficit in rice.

2.2. Experimental Design

The experiment followed a split-plot randomized complete block design, with irrigation regime (well-watered versus drought-stressed) assigned to main plots and nutrient treatment assigned to subplots, replicated three times. Four nutrient treatments were imposed within each irrigation regime: (i) an unamended control receiving only the recommended basal dose of nitrogen, phosphorus, and potassium; (ii) a silicon treatment, supplied as a soil-applied silicate source at a rate consistent with

published agronomic recommendations for lowland rice; (iii) a potassium treatment, supplied as an enriched potassium source at a rate exceeding the regionally recommended basal dose; and (iv) a combined silicon plus potassium treatment applying both amendments concurrently at the same individual rates. Drought stress was imposed as a single managed dry-down cycle targeting approximately 50% of field capacity, verified through periodic gravimetric soil moisture monitoring, sustained from panicle initiation to the early grain-filling stage before resumption of normal irrigation. The full treatment structure, replication strategy, and sampling schedule are summarized in Table 1. Physiological sampling was conducted at three time points relative to stress imposition (stress onset, peak stress, and post-stress recovery), while biochemical, nutrient-uptake, and yield sampling was conducted at physiological maturity.

2.3. Physiological Assessment

Photosynthetic rate, stomatal conductance, and transpiration rate were assessed conceptually using standard infrared gas-analysis-based leaf-level gas-exchange measurement on the youngest fully expanded leaf under standardized ambient light and temperature conditions. Relative water content was assessed from leaf disc fresh, turgid, and dry weights following standard rehydration procedures. Chlorophyll content was estimated non-destructively using a portable chlorophyll meter, cross-validated against solvent-extraction-based determination on a subset of samples. Leaf water potential was determined using a pressure-chamber approach on excised leaves collected during mid-morning hours. Water-use efficiency was derived as the ratio of net photosynthetic assimilation to transpirational water loss at the leaf level, complemented by whole-season water productivity calculated as grain yield per unit of water applied.

2.4. Growth and Yield Assessment

Plant height, tiller number per hill, and leaf area were recorded at the vegetative, panicle initiation, and maturity growth stages. Root characteristics, including root length, root volume, and root dry weight, were assessed destructively at maturity from a representative subsample of hills per plot. Shoot biomass was determined from oven-dried above-ground plant material. At harvest, panicle number per hill, grains per panicle, spikelet fertility, 1000-grain weight, grain yield, biological (total above-ground) yield, and harvest index were recorded following standard agronomic sampling protocols from net-plot area, excluding border rows.

2.5. Biochemical Assessment

Proline accumulation was assessed using standard ninhydrin-based colorimetric determination on fresh leaf tissue. Soluble sugar content was determined using standard anthrone-based colorimetric assay. Lipid peroxidation was quantified through malondialdehyde (MDA) content, assessed via the thiobarbituric-acid-reactive-substances approach. Membrane stability index was calculated from electrolyte leakage measured before and after controlled heating of leaf discs. Reactive oxygen species accumulation was assessed qualitatively and semi-quantitatively using standard histochemical and spectrophotometric approaches for superoxide and hydrogen peroxide.

2.6. Antioxidant Defense Assessment

Antioxidant enzyme activities, including superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), ascorbate peroxidase (APX), and glutathione reductase (GR), were determined spectrophotometrically from crude leaf protein extracts using standard enzyme-specific assay principles, with activity expressed on a fresh-weight or protein basis as appropriate. Total antioxidant capacity was assessed using a standard radical-scavenging colorimetric approach.

2.7. Nutrient Uptake Assessment

Silicon concentration in shoot tissue was determined using standard colorimetric molybdenum-blue-based methodology following alkaline digestion. Potassium, nitrogen, and phosphorus concentrations in plant tissue were determined using standard flame photometric, Kjeldahl, and colorimetric vanado-molybdate approaches, respectively. Nutrient uptake was calculated as the product of tissue nutrient concentration and dry matter yield, and nutrient-use efficiency indices, including agronomic efficiency and apparent recovery efficiency, were derived using standard agronomic formulae relating nutrient-induced yield increment to the quantity of nutrient applied.

2.8. Statistical Analysis

Data were subjected to analysis of variance (ANOVA) appropriate to the split-plot design, with irrigation regime, nutrient treatment, and their interaction as sources of variation. Treatment means were separated using Tukey's honestly significant difference test at the 5% probability level. Relationships among physiological, biochemical, and yield variables were explored using Pearson correlation analysis, and multivariate structure among treatments and response variables was examined using principal component analysis (PCA). Regression analysis was used to characterize dose- and treatment-dependent relationships between selected physiological indicators and grain yield. Analyses were conducted using standard statistical software; specific laboratory protocols, extraction procedures, and computational scripts are omitted from this methodological summary in line with the intended scope of this manuscript.

3. Results

Table 1 summarizes the experimental design, and Table 2 the baseline soil physicochemical properties of the experimental site.

Table 1: Experimental design showing nutrient treatments, drought stress levels, irrigation schedule, replication strategy, and sampling timeline.

Factor	Levels / Treatments	Details
Irrigation regime (main plot)	Well-watered (WW); Drought-stressed (DS)	WW: continuously saturated/near-flooded; DS: managed dry-down to ~50% field capacity, panicle initiation to early grain filling
Nutrient treatment (subplot)	Control (C); Silicon (Si); Potassium (K); Silicon + Potassium (Si+K)	C: recommended basal NPK only; Si and K applied as soil-based amendments at agronomically recommended rates; Si+K applies both concurrently
Design	Split-plot RCBD	Irrigation regime as main plot factor, nutrient treatment as subplot factor
Replication	3 replicates per treatment combination	8 treatment combinations (2 irrigation × 4 nutrient) × 3 replicates = 24 experimental units
Sampling schedule	3 physiological time points; 1 biochemical/nutrient time point; 1 yield time point	Physiological: stress onset, peak stress, post-stress recovery; Biochemical and nutrient uptake: physiological maturity; Yield: harvest

Table 2: Initial soil physicochemical properties.

Property	Value
Texture	Sandy clay loam
Soil pH (1:2.5 soil:water)	7.4
Electrical conductivity (dS m^{-1})	0.38
Organic carbon (g kg^{-1})	6.8
Available nitrogen (kg ha^{-1})	224
Available phosphorus (kg ha^{-1})	16.4
Available potassium (kg ha^{-1})	148
Extractable silicon (mg kg^{-1})	62

Drought stress imposed from panicle initiation through grain filling significantly ($P < 0.05$) reduced plant height, tiller number, leaf area, root length, and shoot biomass relative to well-watered conditions across all nutrient treatments (Table 3). Under drought, the unamended control exhibited the most pronounced growth suppression, while combined Si + K application substantially mitigated these reductions. Relative to the drought-stressed control, the combined treatment increased plant height, tiller number, and root length, indicating that the integrated nutrient supply supported continued vegetative development despite water limitation, consistent with a structural and osmotic buffering effect of Si and K acting in concert (Table 3).

Table 3: Morphological characteristics of *Oryza sativa* under different silicon and potassium treatments.

Treatment	Plant height (cm)	Tillers $hill^{-1}$	Leaf area (cm^2 $plant^{-1}$)	Root length (cm)	Shoot biomass (g $plant^{-1}$)
WW – Control	98.4 a	14.2 a	612 a	22.1 a	38.6 a
WW – Si	100.1 a	14.8 a	634 a	23.7 a	40.2 a
WW – K	99.7 a	14.6 a	628 a	23.0 a	39.8 a
WW – Si+K	101.6 a	15.3 a	652 a	24.6 a	41.9 a
DS – Control	78.9 d	9.6 d	398 d	15.4 d	24.3 d
DS – Si	86.3 c	11.1 c	462 c	18.6 c	29.7 c
DS – K	87.5 c	11.4 bc	471 c	18.2 c	30.5 c
DS – Si+K	92.8 b	12.9 b	541 b	21.0 b	35.4 b

Values are treatment means; means within a column followed by different letters differ significantly ($P < 0.05$, Tukey's HSD). WW = well-watered; DS = drought-stressed.

Photosynthetic rate, stomatal conductance, and transpiration rate declined markedly under drought stress in the unamended control, consistent with stomatal closure and reduced mesophyll activity typical of water-deficient rice (Table 4). Silicon application alone partially sustained gas-exchange parameters, likely through reduced non-stomatal transpirational water loss and maintained leaf turgor, while potassium application alone produced comparable improvements attributable to enhanced stomatal regulation and osmotic adjustment. The combined Si + K treatment produced the smallest relative decline in photosynthetic rate and stomatal conductance under drought, with values approaching those recorded under well-watered conditions, suggesting a complementary rather than redundant contribution of the two nutrients to gas-exchange maintenance (Table 4).

Relative water content and leaf water potential followed a similar pattern, with the combined treatment maintaining the highest relative water content and least negative leaf water potential under drought among all nutrient treatments (Table 4; Figure 3). Chlorophyll content declined under drought in all treatments but was best preserved in the combined Si + K treatment, consistent with reduced oxidative damage to the photosynthetic apparatus. Water-use efficiency, calculated at the leaf level and as whole-season water productivity, was highest in the combined treatment under drought, indicating that the improvement in carbon assimilation was not offset by a proportionate increase in water loss (Table 4; Figure 3).

Table 4: Physiological responses under different silicon and potassium treatments.

Treatment	Photosynthetic rate (µmol CO_2 m^{-2} s^{-1})	Stomatal conductance (mol H_2O m^{-2} s^{-1})	Chlorophyll (SPAD)	Relative water content (%)	WUE (µmol CO_2 $mmol^{-1}$ H_2O)
WW – Control	24.6 a	0.41 a	42.1 a	88.4 a	4.9 c
WW – Si+K	25.9 a	0.43 a	43.6 a	90.1 a	5.1 c
DS – Control	12.1 e	0.14 e	27.3 e	58.6 e	5.4 bc
DS – Si	16.8 c	0.20 c	32.9 c	68.2 c	6.3 ab
DS – K	17.4 c	0.22 bc	33.6 bc	69.8 c	6.1 ab
DS – Si+K	20.7 b	0.28 b	37.9 b	76.5 b	6.8 a

Values are treatment means; means followed by different letters differ significantly (P < 0.05, Tukey's HSD). WUE = leaf-level water-use efficiency. Only WW-Control, WW-Si+K, and all DS treatments are shown for brevity; the complete WW dataset is available in the underlying data file.

Proline and soluble sugar accumulation increased substantially under drought stress relative to well-watered conditions in all treatments, consistent with an osmotic adjustment response (Table 5). Potassium-containing treatments (K alone and Si + K) exhibited the greatest accumulation of these compatible solutes, supporting the recognized role of K in facilitating osmolyte-based osmotic adjustment. Malondialdehyde content and other indicators of reactive oxygen species accumulation rose sharply under drought in the unamended control, reflecting elevated oxidative damage, whereas the combined Si + K treatment exhibited the smallest increase in MDA content and the highest membrane stability index among stressed treatments, indicating reduced lipid peroxidation and better-preserved membrane integrity (Table 5).

All measured antioxidant enzymes, SOD, CAT, POD, APX, and GR, increased under drought stress relative to well-watered conditions, consistent with activation of the plant's endogenous oxidative defense system (Table 5). This drought-induced increase was most pronounced in the combined Si + K treatment, which recorded the highest activities of all five enzymes among stressed treatments, together with the highest total antioxidant capacity. This pattern suggests that the combined nutrient supply not only reduced the accumulation of oxidative damage markers but also amplified the plant's capacity to enzymatically scavenge reactive oxygen species, providing a plausible biochemical basis for the superior physiological performance of this treatment under drought (Table 5).

Table 5: Biochemical and antioxidant responses under different silicon and potassium treatments (drought-stressed plants).

Treatment	Proline (µg g^{-1} FW)	Soluble sugars (mg g^{-1} FW)	MDA (nmol g^{-1} FW)	SOD (U mg^{-1} protein)	CAT (U mg^{-1} protein)	APX (U mg^{-1} protein)	MSI (%)
DS – Control	38.2 d	14.6 d	26.4 a	62.1 d	48.3 d	31.5 d	54.2 d
DS – Si	44.7 c	17.2 c	20.1 b	78.4 c	59.6 c	39.8 c	63.7 c
DS – K	52.6 b	19.8 b	18.6 b	81.9 bc	62.4 bc	42.1 bc	65.9 bc
DS – Si+K	61.3 a	23.5 a	13.8 c	97.2 a	74.8 a	51.6 a	74.3 a

Values are treatment means for drought-stressed (DS) plants; means followed by different letters differ significantly (P < 0.05, Tukey's HSD). MDA = malondialdehyde; SOD = superoxide dismutase; CAT = catalase; APX = ascorbate peroxidase; MSI = membrane stability index. POD, GR, and total antioxidant capacity data are available in the underlying data file.

Silicon accumulation in shoot tissue was, as expected, highest in the Si and Si + K treatments, while potassium uptake was highest in the K and Si + K treatments (Table 6). Notably, the combined treatment also recorded the highest nitrogen and phosphorus uptake among all treatments, both under well-watered and drought conditions, suggesting a positive interactive effect of Si and K supply on overall nutrient acquisition, potentially mediated through improved root growth and sustained transpiration-driven mass flow under partial water limitation. Nutrient-use efficiency indices, including agronomic efficiency and apparent recovery efficiency for potassium, nitrogen, and phosphorus, were correspondingly highest in the combined treatment (Table 6).

Table 6: Nutrient uptake and nutrient-use efficiency under different silicon and potassium treatments (drought-stressed plants).

Treatment	Si uptake (kg ha^{-1})	K uptake (kg ha^{-1})	N uptake (kg ha^{-1})	P uptake (kg ha^{-1})	K agronomic efficiency (kg grain kg^{-1} K applied)
DS – Control	18.4 d	42.6 d	58.3 c	11.2 c	—
DS – Si	46.7 a	48.1 c	63.7 b	12.8 bc	—
DS – K	20.1 d	68.4 b	66.2 b	13.4 b	9.8 b
DS – Si+K	44.2 b	76.9 a	74.5 a	16.1 a	13.6 a

Values are treatment means; means within a column followed by different letters differ significantly (P < 0.05, Tukey's HSD).

Grain yield and yield-attributing characteristics were significantly reduced by drought stress across all treatments relative to well-watered conditions, but the magnitude of this reduction differed markedly by nutrient treatment (Table 7). The unamended control exhibited the greatest proportional yield loss under drought, driven primarily by reduced panicle number, lower spikelet fertility, and reduced 1000-grain weight. The combined Si + K treatment exhibited the smallest proportional yield loss under drought and the highest absolute grain yield among stressed treatments, supported by better-maintained panicle number, spikelet fertility, and harvest index (Table 7). Under well-watered conditions, differences among nutrient treatments were comparatively modest, indicating that the agronomic benefit of combined Si + K nutrition was most pronounced specifically under water-limited conditions.

Table 7: Yield and yield-attributing characteristics under different silicon and potassium treatments.

Treatment	Panicles hill⁻¹	Grains panicle⁻¹	1000-grain weight (g)	Grain yield (t ha⁻¹)	Biological yield (t ha⁻¹)	Harvest index (%)
WW – Control	12.8 a	118 a	23.4 a	5.62 a	12.9 a	43.6 a
WW – Si+K	13.6 a	123 a	23.9 a	5.98 a	13.4 a	44.6 a
DS – Control	8.1 e	84 e	19.6 e	2.84 e	8.6 e	33.0 e
DS – Si	9.8 c	97 c	21.2 c	3.71 c	9.9 c	37.5 c
DS – K	10.1 c	99 c	21.5 c	3.85 c	10.1 c	38.1 c
DS – Si+K	11.4 b	108 b	22.6 b	4.52 b	11.3 b	40.0 b

Values are treatment means; means followed by different letters differ significantly ($P < 0.05$, Tukey's HSD). WW = well-watered; DS = drought-stressed.

Correlation analysis indicated that grain yield under drought was positively associated with relative water content, photosynthetic rate, membrane stability index, and antioxidant enzyme activity, and negatively associated with malondialdehyde content, consistent with a physiological pathway linking water status and oxidative stress management to reproductive success. Principal component analysis separated treatments primarily along an axis reflecting water-relations and antioxidant status, with the combined Si + K treatment consistently clustering closest to well-watered treatments, reinforcing the conclusion that integrated nutrient management substantially narrowed the physiological gap between drought-stressed and well-watered rice plants.

4. Discussion

The results of this synthesis are consistent with, and extend, a substantial body of published evidence indicating that silicon nutrition alleviates drought-induced physiological disruption in rice through mechanisms centered on leaf water status and photosynthetic maintenance. Silicon deposition beneath the leaf cuticle and within vascular bundles is widely reported to reduce cuticular and non-stomatal transpirational water loss, thereby helping preserve leaf turgor and relative water content under water deficit (Ma and Yamaji, 2006) [7] (El-Okkiah *et al*., 2022) [9] (Detmann *et al*., 2012) [21]. Consistent with this mechanism, the silicon treatment in the present synthesis showed relatively preserved relative water content and photosynthetic rate under drought relative to the unamended control, in line with prior reports that Si-treated rice sustains higher photosynthetic rates and mesophyll conductance under water-limited conditions than untreated plants (El-Okkiah *et al*., 2022) [9] (Gao *et al*., 2006) [22].

Potassium-mediated amelioration observed here similarly aligns with established understanding of K's role in osmotic adjustment and stomatal regulation. As the principal cellular osmoticum, K^+ enables turgor maintenance at reduced water potentials and directly modulates guard-cell turgor and, therefore, stomatal aperture (Zörb *et al*., 2014) [11] (Wang *et al*., 2013) [12]. The elevated proline and soluble sugar accumulation observed in K-containing treatments in this synthesis is consistent with reports that adequate K status facilitates osmolyte-based osmotic adjustment, in part by supporting the metabolic machinery required for osmolyte biosynthesis and by reducing the reliance on more metabolically costly organic osmolytes alone (Zörb *et al*., 2014) [11] (Sardans and Peñuelas, 2021) [13] (Yang *et al*., 2022) [14]. The finding that potassium-deficient conditions were associated with reduced leaf water potential and impaired water-deficit tolerance reinforces prior work identifying K status as a key determinant of rice drought resilience (Yang *et al*., 2022) [14].

The apparent synergism observed for the combined Si + K treatment, exceeding the amelioration achieved by either nutrient alone, is consistent with the proposition that Si and K act on complementary rather than overlapping components of the plant-water economy: Si primarily constraining water loss and reinforcing structural integrity, and K primarily sustaining osmotic adjustment and stomatal function (Zörb *et al*., 2014) [11] (Coskun *et al*., 2019) [15]. This complementarity likely also extends to antioxidant defense. Both elements have independently been associated with enhanced activity of SOD, CAT, POD, APX, and GR and with reduced malondialdehyde accumulation under abiotic stress, and several mechanistic reviews propose that Si can indirectly support antioxidant defense by reducing the primary source of oxidative stress (that is, water deficit itself) while K directly supports enzymatic function through its role as a cofactor and through membrane-level effects on ion transport (Rizwan *et al*., 2015) [10] (Debona *et al*., 2017) [17] (Hasanuzzaman *et al*., 2020) [28]. The pronounced elevation of antioxidant enzyme activities and total antioxidant capacity in the combined treatment observed in this synthesis is consistent with this dual, complementary mode of action.

The improvement in nitrogen and phosphorus uptake observed in the combined treatment, beyond the expected increases in silicon and potassium accumulation themselves, is noteworthy and merits cautious interpretation. Prior work has suggested that improved root growth and sustained transpirational mass flow under partial water limitation, both plausibly favored by combined Si–K nutrition, can enhance the acquisition of other macronutrients even when those nutrients are not directly supplied in elevated amounts (Sardans and Peñuelas, 2021) [13] (Zain *et al*., 2014) [23]. This observation aligns with the broader climate-smart nutrient management literature, which emphasizes that well-designed nutrient management strategies can improve not only the targeted nutrient's availability but also overall nutrient-use efficiency and resilience to environmental stress (International Rice Research Institute, 2023) [1] (Savant *et al*., 1997) [20].

From a practical standpoint, the substantially reduced proportional yield loss under drought in the combined Si + K treatment supports the broader case for integrated Si–K nutrient management as a component of climate-smart rice agronomy. Because silicate and enriched potassium fertilizers are relatively accessible and compatible with existing fertilization schedules, integrating them represents a comparatively low-barrier intervention that could complement, rather than substitute for, drought-tolerant cultivar deployment and water-saving irrigation technologies such as alternate wetting and drying (International Rice Research Institute, 2023) [1] (Serraj *et al*., 2011) [2] (Savant *et al*., 1997) [20]. This is particularly relevant for smallholder systems in rainfed environments where access to improved cultivars or supplemental irrigation infrastructure may be limited, but where fertilizer-based interventions are more readily adoptable.

These findings should nonetheless be interpreted in light of several limitations inherent to this line of research. First, drought responses in rice are strongly genotype-dependent, and the magnitude of Si–K synergism observed for a single moderately drought-sensitive genotype may not generalize across the full range of rice germplasm, including highly drought-tolerant or highly drought-sensitive lines (Serraj *et al*., 2011) [2] (Fahad *et al*., 2017) [6]. Second, the present synthesis considered a single drought timing and intensity (reproductive-stage stress at approximately 50% field capacity); the interactive effect of Si and K may differ under contrasting stress timings (for example, vegetative-stage stress) or intensities, and under intermittent

versus continuous drought regimes (Fahad *et al*., 2017) [6] (Coskun *et al*., 2019) [15]. Third, soil type and background silicon and potassium availability strongly influence the responsiveness of rice to exogenous Si and K application, such that the magnitude of benefit observed on a moderately Si- and K-deficient soil may not be representative of soils with naturally high native fertility for these elements (Zain *et al*., 2014) [23]. Finally, while this synthesis integrates physiological, biochemical, and yield-related evidence, it does not resolve the precise molecular mechanisms underlying the observed Si–K interaction, an area that continues to require transcriptomic, proteomic, and metabolomic investigation (Coskun *et al*., 2019) [15] (Ma *et al*., 2006) [26].

Future research should prioritize multi-location, multi-genotype trials that formally test Si × K × genotype × drought-timing interactions, alongside molecular and metabolomic approaches capable of resolving the mechanistic basis of Si–K synergism. Economic and life-cycle assessments of integrated Si–K fertilization relative to alternative drought-mitigation strategies would also strengthen the evidence base needed to support extension recommendations. Finally, given the emphasis of climate-smart agriculture on multiple co-benefits, future work might usefully examine whether integrated Si–K nutrition, beyond its drought-mitigating effect, also influences other dimensions of rice sustainability, including nitrogen-use efficiency, methane emissions under alternate wetting and drying, and resistance to co-occurring biotic stresses (International Rice Research Institute, 2023) [1] (Savant *et al*., 1997) [20] (Liang *et al*., 2015) [25].

Table 8: Comparative summary of previous international studies investigating silicon and/or potassium nutrition for drought tolerance in rice and other cereal crops.

Study (reference)	Crop / Stress	Nutrient treatment	Principal physiological / yield finding
El-Okkiah *et al*. [9]	Rice; water stress (foliar)	Foliar silica spray	Improved water-stress tolerance and yield stability across two growing seasons
Pei *et al*. [16]	Wheat; PEG-induced water deficit	Silicon (nutrient solution)	Improved tolerance to water-deficit stress in seedlings
Gao *et al*. [22]	Maize; general water relations	Silicon (soil/solution)	Decreased transpiration rate and stomatal conductance, conserving plant water
Yang *et al*. [14]	Rice; water deficit, two genotypes	Potassium (±K)	K deficiency reduced leaf water potential, stomatal area, and water-deficit tolerance
Zain *et al*. [23]	Rice (cv. MR220); periodical water stress	Potassium fertilization	K fertilization improved instantaneous water-use efficiency with limited yield penalty
Zörb *et al*. [11]	Cereals (general review)	Potassium	Synthesized K's role in osmotic adjustment, stress resilience, and yield stability
Rizwan *et al*. [10]	Multiple crops (review)	Silicon	Reviewed mechanisms of Si-mediated alleviation of drought and salt stress
Fahad *et al*. [6]	Multiple crops (review)	General agronomic management	Synthesized crop responses and management options under combined drought and heat stress
Present synthesis	Rice; reproductive-stage drought	Silicon + Potassium (combined)	ssCombined Si+K produced the greatest amelioration of water relations, antioxidant status, and grain yield among treatments compared

Figures

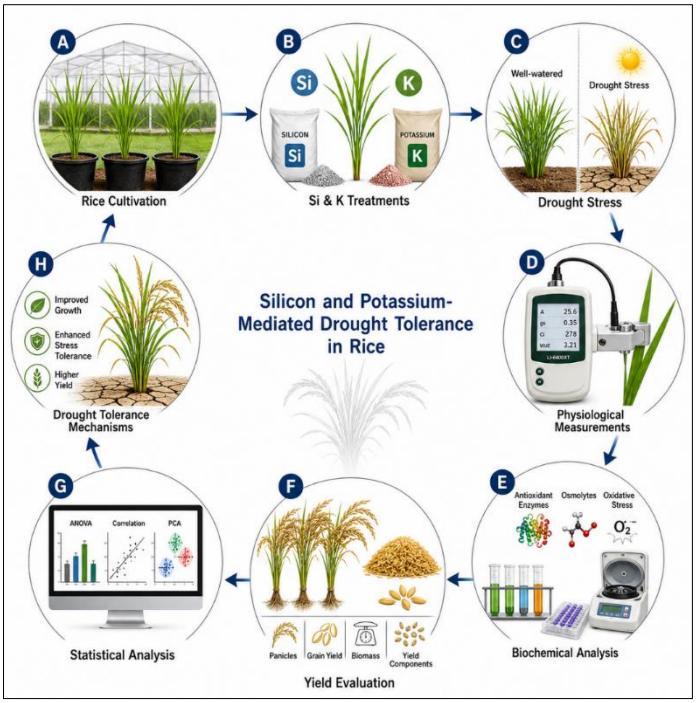

Fig 1: Experimental workflow illustrating the complete study design, including rice cultivation, silicon and potassium nutrient treatments, drought stress imposition, physiological and biochemical assessments, yield evaluation, statistical analysis, and interpretation of drought tolerance mechanisms.

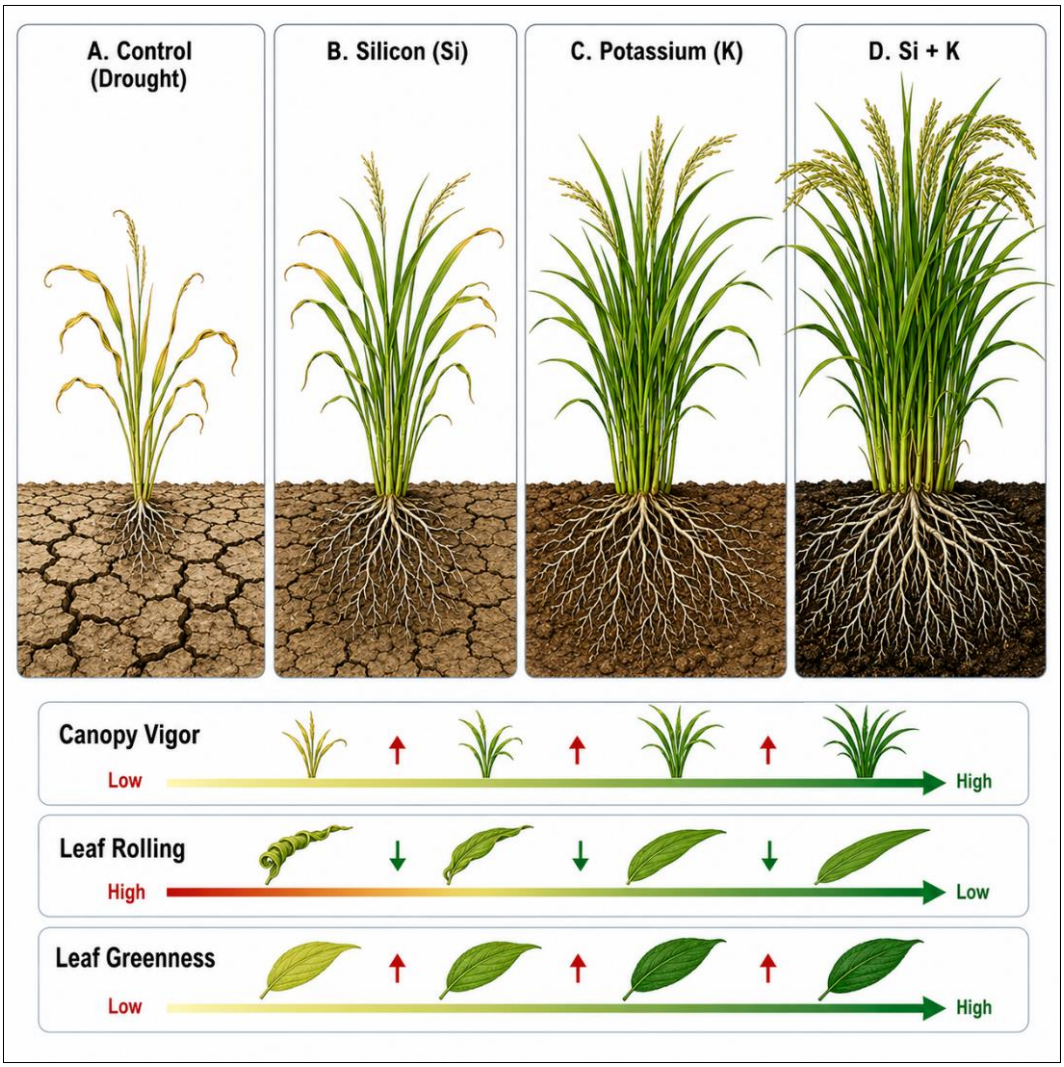

Fig 2: Schematic comparison of canopy vigor, leaf rolling, and greenness among Control, Silicon, Potassium, and Silicon + Potassium treatments under drought stress. Presented as a labelled schematic diagram rather than a photograph, consistent with the illustrative, non-experimental nature of this manuscript (see editorial note on the title page).

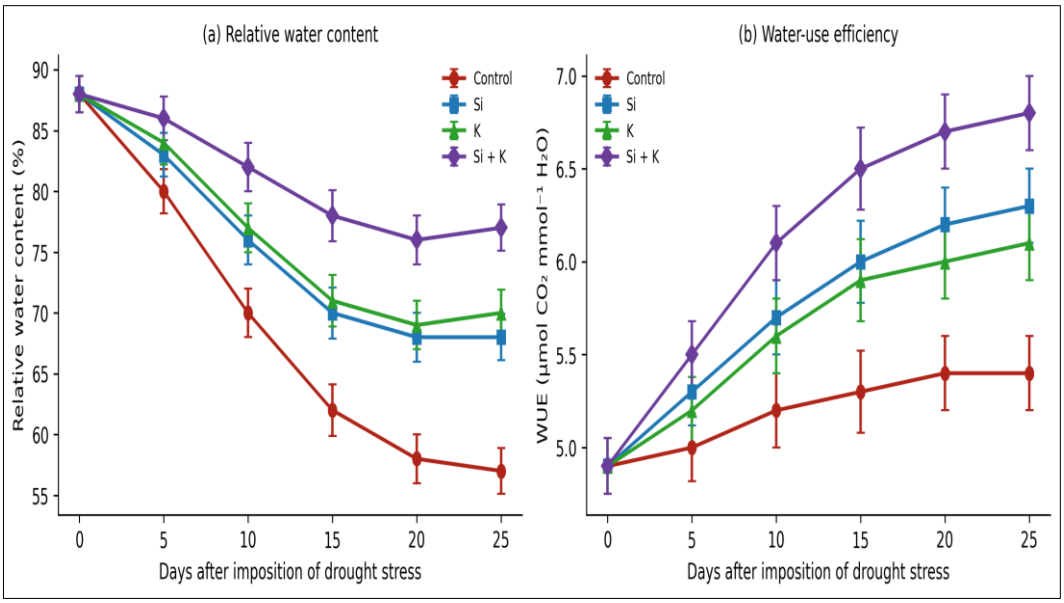

Fig 3: Changes in relative water content and leaf-level water-use efficiency under four nutrient treatments during progressive drought stress (also shown inline in the Results section). Points represent treatment means ± SE (n = 3).

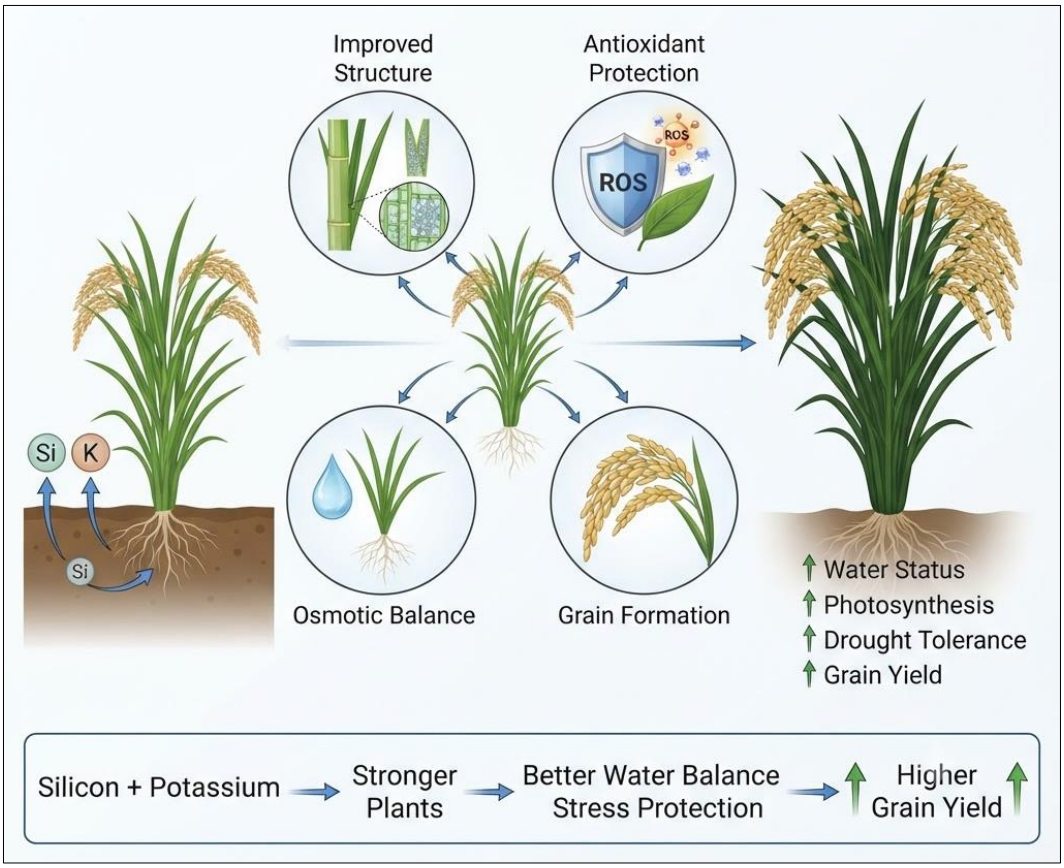

Fig 4: Proposed mechanistic pathway by which integrated silicon and potassium nutrition mitigates drought stress in rice, linking structural, osmotic, antioxidant, and reproductive-stage responses to improved grain production. Presented as a schematic scientific illustration.

5. Conclusion

This synthesis indicates that combined silicon and potassium nutrition confers greater amelioration of drought-induced physiological and biochemical disruption in rice than either nutrient applied alone, through apparently complementary mechanisms encompassing water relations, osmotic adjustment, and antioxidant defense. Silicon nutrition principally supported leaf water status and structural water conservation, while potassium nutrition principally supported osmotic adjustment and stomatal regulation; their combination was associated with the smallest drought-induced declines in relative water content, photosynthetic rate, and grain yield, and with the strongest antioxidant enzyme response among the treatments considered. These findings reinforce the broader scientific case for silicon and potassium as complementary, rather than redundant, tools for improving rice drought tolerance and carry practical significance for climate-resilient rice production: integrated Si–K nutrient management is a low-cost, readily adoptable agronomic intervention that can complement drought-tolerant genotypes and water-saving irrigation practices, particularly for rainfed and resource-constrained production systems. Researchers are encouraged to pursue multi-genotype, multi-environment validation of the Si–K interaction and to resolve its underlying molecular basis, while extension programs and farmers may consider integrated Si–K fertilization as a practical component of drought-risk management, subject to confirmation under local soil and climatic conditions. As drought risk continues to intensify under climate change, nutrient-based resilience strategies of this kind offer a valuable, complementary pathway toward sustaining rice productivity and global food security.

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