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Improving vegetative growth and floral performance of tuberose (*Agave amica* medik. L. cv. 'Single') through combined soil and foliar applications of silica oxide (SiO_2)

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ABSTRACT

Silicon (Si) plays a crucial role in enhancing plant growth, structural integrity, and stress tolerance; however, its role in tuberose (Agave amica Medik.) remains insufficiently explored. A major challenge in tuberose cultivation is the limited understanding of how different modes and concentrations of Si application influence vegetative growth and floral quality under field conditions. Additionally, evidence-based recommendations on the optimal concentration and method of SiO_2 application are still lacking. The present study aimed to evaluate the effects of soil and foliar applications of silica oxide (SiO_2) on the growth, flowering, and postharvest attributes of tuberose. A factorial randomized block design (FRBD) comprising different combinations of soil and foliar SiO_2 treatments was employed, and vegetative as well as floral parameters were recorded at successive growth stages. Statistical analysis revealed significant ($p < 0.05$) main and interaction effects of SiO_2 treatments on all measured parameters. Among the treatments, T_{15} (S_3F_3: 8.8 g/m^2 soil + 3% foliar) exhibited superior performance, achieving the maximum plant height (46.43 cm), leaf count (20.78 at 60 DAP), spike length (46.43 cm), and the earliest spike emergence (73.00 days). Postharvest evaluation showed that T_{19} (S_4F_3) recorded the longest vase life (12.89 days), followed by T_{15} (12.67 days), indicating a notable enhancement in floral longevity. These improvements may be attributed to silicon-mediated strengthening of cell walls, better water retention, and delayed senescence. Overall, this study provides new evidence on the optimised application of SiO_2 in tuberose, demonstrating that integrated soil and foliar supplementation at higher concentrations significantly improves morpho-physiological traits, postharvest performance, and ornamental value. The findings highlight the potential of SiO_2 application as a sustainable strategy for commercial tuberose production.

Keywords: *Silicon, Tuberose, Silica oxide, Soil and Foliar application, Vegetative growth, Floral attributes, Postharvest attributes, Morpho-physiological response, Growth enhancement, Sustainable flower production.*

Introduction

Tuberose (*Agave amica* Medik.), a perennial bulbous plant belonging to the Asparagaceae family, is an ornamental species of major global economic importance. It is highly valued for its intensely fragrant, pure white flowers (1) and is widely used both in the cut flower industry and for essential oil extraction (2). In contemporary floriculture, precise nutrient management is recognised as a fundamental requirement for optimising the yield and quality of tuberose (3).

Silicon (Si) is considered a beneficial element and often described as a quasi-essential nutrient due to its ability to significantly enhance plant growth, development, and resistance to various biotic and abiotic stresses (4, 5, 6). Although it is not essential for all metabolic processes, extensive research has documented its advantages, including improved mechanical strength and enhanced nutrient use efficiency (7). When applied appropriately, Si can increase plant vigour and disease resistance, correct or mitigate nutritional disorders, improve product quality, and enhance overall crop yield (8, 9).

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In floriculture crops, Si application has been reported to promote upright plant growth and extend flower longevity (10, 11, 12). Several studies also indicate that Si is effective in preventing stem bending in cut flowers and improving overall produce quality (13). The physiological basis for these benefits is attributed to multiple mechanisms, including strengthened cell walls through silicification, enhanced photosynthetic efficiency, improved coordination between source and sink tissues, and modulation of plant hormonal balance (14).

Positive effects of Si application have been documented in several ornamental species such as marigold (15, 16), damask rose (17), and gladiolus (18). However, despite these advancements, there remains a notable lack of detailed and systematic research on silicon nutrition in tuberose, particularly regarding optimal methods and concentrations for Si application (19). Based on this gap, the present study was formulated with the premise that the combined use of silica oxide as both a soil and foliar application may exert a synergistic effect, enhancing growth and flowering in tuberose by improving Si uptake and utilisation. Therefore, this research aimed to evaluate the effects of integrated soil and foliar applications of SiO_2 on vegetative growth, floral characteristics, yield, and postharvest behaviour of tuberose, and to identify the most effective application strategy for commercial production.

Materials and Methods

The research was conducted at the Model Floriculture Centre, G.B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, during 2023-24. The experimental site consisted of sandy loam soil with good water-holding capacity and adequate drainage. The field experiment was laid out in a Factorial Randomized Block Design (FRBD) comprising two factors: soil application of silica oxide (SiO_2) and foliar application of SiO_2. Twenty treatment combinations were established using five soil application rates (0, 2.9, 5.9, 8.8, and 11.8 g/m^2) and four foliar concentrations (0%, 1%, 2%, and 3%). Soil application was carried out at the time of planting, whereas foliar sprays were administered at 30, 60, and 90 days after planting (DAP).

Uniform and healthy bulbs of *Agave amica* Medik. cv. 'Single' were planted at a spacing of 25 × 25 cm with three replications. Standard intercultural practices, including irrigation, weeding, and plant protection measures, were followed to ensure healthy crop growth. Fertilizers were applied at the recommended NPK dose of 120:60:60 kg/ha, using urea, single super phosphate, and muriate of potash as nutrient sources.

Measurements were recorded for vegetative and floral parameters, including plant height (cm), leaf width (cm), and number of leaves at 30, 60, and 90 DAP. Floral observations included days to spike emergence, number of spikes per plant, number of florets per spike, total number of florets, number of open and unopened florets per spike, and vase life. The collected data were analysed using two-way analysis of variance (ANOVA) in AgriAnalyzer statistical software. Significant differences among treatment means were determined using Tukey's HSD test at the 5% probability level ($p < 0.05$). Statistical computations were additionally supported using R Studio software.

Results

Vegetative Parameters

All vegetative growth parameters showed a considerable response to silica oxide (SiO_2) application.

Leaf Growth and Development

The application of SiO_2 had a significant influence on leaf production throughout the growth cycle of tuberose. A clear interaction between soil and foliar treatments was observed, resulting in enhanced leaf growth and demonstrating a distinct dose-dependent response to SiO_2 application (Table 1). At 30 days after planting (DAP), treatment T_{19} (S_4F_3) recorded the highest number of leaves (12.89), representing a 31.9% increase over the control (T_0). A similar pattern was observed at 60 DAP, where treatment T_{15} produced the maximum number of leaves (20.78), showing a 24.7% improvement compared to the control. By 90 DAP, most SiO_2 treatments performed statistically at par with one another but remained significantly superior to the control, indicating sustained vegetative vigour throughout the growth period (Figure 1).

These improvements in leaf production are consistent with the findings of (20) and (21), who reported that silicon enhances leaf development by promoting cell division and cell expansion. The increased number of leaves observed in the present study may be attributed to silica deposition in the epidermal tissues, which enhances photosynthetic capacity through improved light interception (6). Additionally, the strengthening of cell walls through silicification may support more efficient leaf initiation and development, as stronger structural integrity allows plants to allocate resources more effectively toward new growth rather than solely maintaining existing tissues. The sustained improvement across all growth stages suggests that SiO_2 not only stimulates early vegetative development but also maintains metabolic efficiency during later stages. This is particularly important in commercial tuberose cultivation, where prolonged vegetative vigour is directly associated with improved bulb quality and enhanced subsequent flowering performance.

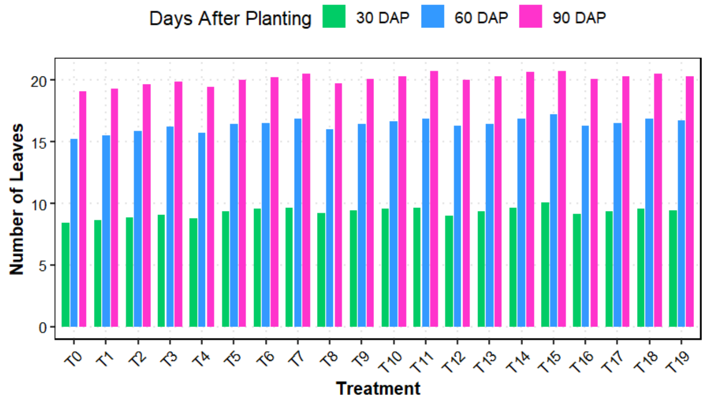

Figure 1: The effect of different doses of silica oxide (SiO_2) on the number of leaves of tuberose at 30, 60 and 90 DAP

Leaf Expansion

A progressive improvement in leaf width was observed with SiO_2 treatments, following a clear dose-dependent response pattern (Table 1). The maximum leaf width of 2.07 cm was recorded in treatment T_{15} (S_3F_3) at 90 DAP, representing a 26.2% increase compared to the control (Figure 2). Leaf expansion advanced steadily across all growth stages, with optimal results obtained in treatments combining higher foliar concentrations (F_2 and F_3) with intermediate soil application rates (S_2 and S_3).

The enhanced leaf expansion can be attributed to silicon's multifaceted role in plant physiology. The wider leaves recorded under optimal treatments likely result from improved turgor pressure and enhanced cell wall extensibility, as Si strengthens cell wall structure while concurrently improving water relations within the plant (22). This mechanical reinforcement through silicification enables cells to expand more efficiently without compromising structural integrity.

Furthermore, the synergistic effect of integrated soil and foliar applications appears to optimise Si availability during critical periods of leaf development. Soil application ensures a consistent baseline supply through root uptake, whereas foliar sprays supply Si directly to actively expanding leaf tissues during rapid growth phases. The dose-response pattern—particularly the superior performance seen at intermediate concentrations—suggests the presence of an optimal threshold for Si accumulation in leaf tissues. Beyond this threshold, excessive Si may interfere with the uptake or utilisation of other essential nutrients or saturate silicon transport mechanisms (14), which may explain why the highest doses did not yield proportionally greater benefits. These results align with findings in other ornamental species, such as marigold (15) and narcissus (23), further validating the beneficial role of balanced silicon nutrition in floriculture.

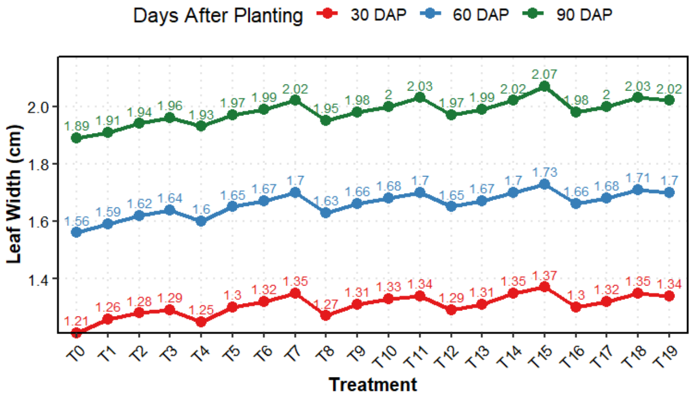

Figure 2: The effect of different doses of silica oxide (SiO_2) on leaf width of tuberose at 30, 60 and 90 DAP

Plant Height Elongation

Plant height was significantly influenced by silica oxide (SiO_2) applications, showing a progressive increase over time (Table 1). The tallest plants (46.43 cm at 90 DAP) were obtained under treatment T_{15} (S_3F_3), representing a 34.6% increase compared to the control (Figure 3). The growth pattern indicated a phase of accelerated elongation between 60 and 90 DAP in silica-treated plants, suggesting enhanced metabolic activity during this rapid growth period.

The substantial increase in plant height can be attributed to silica's positive effects on multiple physiological processes. Silica is known to improve mechanical strength and promote an upright growth habit (24), (25). By reinforcing cell walls through silica deposition, plants expend less energy on structural support, allowing greater allocation of photosynthates toward vertical growth (12), (23). This improved resource allocation is particularly evident during the rapid elongation phase observed between 60 and 90 DAP.

The pronounced effect of treatment T_{15} suggests that the combination of 8.8 g/m^2 soil application with a 3% foliar spray creates an optimal internal silica gradient, maximising growth hormone activity and cell elongation. Silica has been reported to influence plant hormone balances especially auxin and gibberellin pathways, which are key regulators of stem elongation (14). Additionally, improved photosynthetic efficiency resulting from silica application, supported by the enhanced leaf parameters discussed earlier, provides the increased carbohydrate supply necessary to sustain rapid vertical growth.

The foliar applications at 30, 60, and 90 DAP were strategically timed to coincide with critical growth stages, ensuring silica availability during peak elongation phases. This has important commercial implications, as increased plant height in tuberose enhances aesthetic value and often correlates with longer spikes and a greater number of florets. These findings align with previous studies on other floriculture crops, including *Salvia splendens* (26) and Damask rose (17), which also reported improvements in vegetative growth following silicon application.

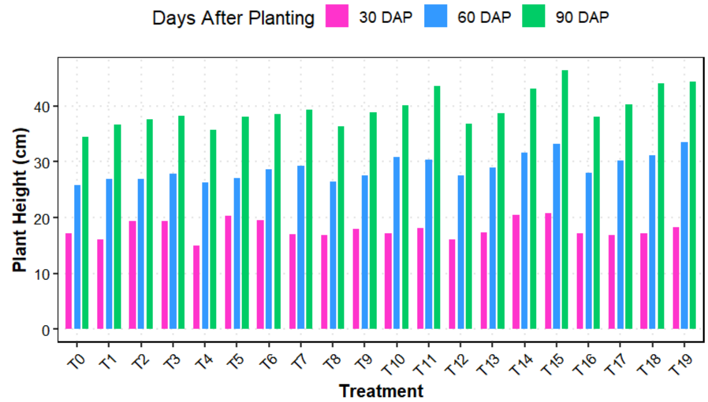

Figure 3: The effect of different doses of silica oxide (SiO_2) on plant height of tuberose at 30, 60 and 90 DAP

Table: 1. Effect of silica oxide treatments on vegetative characteristics of tuberose (Agave amica Medik.) Var. 'Single'

Treatments	No. of Leaves			Leaf width (cm)			Plant height (cm)		
	30 DAP	60 DAP	90 DAP	30 DAP	60 DAP	90 DAP	30 DAP	60 DAP	90 DAP
T_0 (S_0F_0)	9.77^{efg}	16.66^{efghi}	23.88^{b}	1.04^{f}	1.35^{fg}	1.64^{g}	17.11^{de}	25.76^{k}	34.48^{g}
T_1 (S_0F_1)	9.33^{fg}	16.11^{hi}	25.77^{ab}	1.23^{def}	1.41^{defg}	1.74^{defg}	16.01^{ef}	26.89^{hijk}	36.6^{1efg}
T_2 (S_0F_2)	9.33^{fg}	16.44^{fghi}	26.77^{a}	1.24^{def}	1.41^{defg}	1.73^{efg}	19.42^{abc}	26.99^{hijk}	37.56^{efg}
T_3 (S_0F_3)	10.11^{defg}	18.11^{bcdefg}	27.33^{a}	1.30^{bcde}	1.43^{cdefg}	1.82^{cdef}	19.43^{abc}	27.82^{ghijk}	38.19^{efg}
T_4 (S_1F_0)	8.77^{g}	15.89^{i}	25.66^{ab}	1.13^{ef}	1.31^{g}	1.66^{fg}	14.92^{f}	26.30^{jk}	35.66^{fg}
T_5 (S_1F_1)	9.89^{efg}	16.55^{efghi}	26.56^{a}	1.26^{cde}	1.45^{cdefg}	1.77^{cdefg}	20.27^{ab}	27.1^{hijk}	38.12^{efg}
T_6 (S_1F_2)	10.56^{cdef}	$17.55^{bcdefghi}$	27.12^{a}	1.33^{abcde}	1.46^{cdefg}	1.81^{cdef}	19.59^{abc}	28.66^{efghij}	38.58^{defg}
T_7 (S_1F_3)	11.22^{bcde}	18.12^{bcdefg}	26.77^{a}	1.38^{abcd}	1.48^{bcdef}	1.9^{bcd}	17.03^{de}	29.25^{cdefgh}	39.34^{cdef}
T_8 (S_2F_0)	9.55^{fg}	16.22^{ghi}	25.67^{ab}	1.22^{def}	1.38^{efg}	1.66^{fg}	16.88^{def}	26.53^{ijk}	$36.31.83^{efg}$
T_9 (S_2F_1)	10.55^{cdef}	$17.22^{cdefghi}$	26.77^{a}	1.21^{def}	1.46^{bcdef}	1.80^{cdefg}	17.90^{cde}	27.63^{hijk}	38.83^{defg}
T_{10} (S_2F_2)	11.22^{bcde}	$17.66^{bcdefghi}$	26.57^{a}	1.38^{abcd}	1.52^{abcde}	1.87^{bcde}	17.24^{de}	30.83^{bcde}	40.17^{bcdef}
T_{11} (S_2F_3)	11.56^{abcd}	18.45^{bcde}	26.78^{a}	1.47^{abc}	1.58^{abc}	1.99^{ab}	18.2^{cd}	30.44^{cdef}	43.55^{abc}
T_{12} (S_3F_0)	10.55^{cdef}	16.77^{efghi}	27.11^{a}	1.23^{def}	1.42^{defg}	1.82^{cdef}	16.13^{ef}	27.60^{hijk}	36.78^{efg}
T_{13} (S_3F_1)	11.33^{abcde}	$18.0^{bcdefgh}$	27.03^{a}	1.38^{abcd}	1.52^{abcde}	1.75^{defg}	17.4^{de}	28.9^{defghi}	38.68^{defg}
T_{14} (S_3F_2)	11.88^{abc}	18.89^{abcd}	26.11^{ab}	1.41^{abcd}	1.56^{abcd}	1.91^{abc}	20.43^{a}	31.59^{abc}	43.18^{abcd}
T_{15} (S_3F_3)	12.77^{ab}	20.78^{a}	27.66^{a}	1.49^{ab}	1.62^{ab}	2.07^{a}	20.76^{a}	33.25^{ab}	46.43^{a}
T_{16} (S_4F_0)	10.44^{cdef}	17.00^{defghi}	27.22^{a}	1.27^{cde}	1.44^{cdefg}	1.75^{defg}	17.19^{de}	28.03^{fghijk}	38.15^{efg}
T_{17} (S_4F_1)	11.6667^{abcd}	18.33^{bcdef}	26.57^{a}	1.37^{abcd}	1.53^{abcde}	1.87^{bcde}	16.8^{def}	30.24^{cdefgh}	40.33^{bcde}
T_{18} (S_4F_2)	12.33^{ab}	19.0^{abc}	27.33^{a}	1.39^{abcd}	1.54^{abcd}	1.93^{abc}	17.21^{de}	31.15^{abcd}	44.05^{ab}
T_{19} (S_4F_3)	12.89^{a}	19.45^{ab}	27.67^{a}	1.55^{a}	1.64^{a}	1.99^{ab}	18.34^{bcd}	33.56^{a}	44.35^{ab}
CD 5%	**0.8371**	**1.0567**	**1.2938**	**0.1168**	**0.0842**	**0.0856**	**1.0641**	**1.3075**	**2.4601**
$SE_{(m)}$	**0.2924**	**0.3691**	**0.4519**	**0.0408**	**0.0294**	**0.0299**	**0.3717**	**0.4567**	**0.8593**

Values represent the means ± standard error. In each column, values with the same letter(s) are not significantly different at LSD (P≤0.05)

Spike Characteristics

Spike Emergence

The application of silica oxide (SiO_2) significantly influenced the reproductive development of tuberose cv. 'Single', most notably by reducing the time required for spike initiation. The earliest spike emergence occurred under treatment T_{15} (S_3F_3), at just 73.0 days after planting, which was 9.2 days earlier than the control (Figure 4). This notable advancement in reproductive maturity represents a critical improvement for commercial tuberose production, as it can extend the marketing period and enhance overall economic feasibility.

The accelerated flowering phenology observed in this study can be attributed to silica's effects on carbon metabolism and hormonal regulation. The shortened vegetative period aligns with silicon's well-documented role in enhancing photosynthetic efficiency and carbohydrate accumulation, thereby facilitating a faster transition from vegetative to reproductive growth (4, 5, 10, 27, 15). Silicon deposition in leaf tissues improves light interception and reduces transpirational water loss, resulting in increased photoassimilate production (28). This enhanced carbon assimilation enables the plant to accumulate the necessary reserves for floral initiation more rapidly compared with untreated controls.

From a physiological standpoint, the earlier spike emergence may also be linked to silicon's interaction with flowering-related hormones and signalling pathways. Previous studies suggest that silicon can influence the expression of genes involved in flowering time regulation, potentially affecting photoperiodic and vernalization pathways (29).

The 9.2-day advancement recorded in treatment T_{15} (Table 2) holds strong commercial significance, as earlier flowering allows growers to access premium early-season markets when prices are typically higher, thereby improving profitability. In certain climatic regions, this advancement may also allow for additional cropping cycles within a single season, further increasing production efficiency. The dose-response pattern observed across treatments indicates that combining a moderate soil application (8.8 g/m^2) with a higher foliar concentration (3%) creates an optimal silicon availability profile during the floral transition period.

The foliar applications at 30, 60, and 90 DAP were also well-timed to coincide with key developmental stages. These results align with findings in marigold (15, 16), where silicon similarly advanced flowering, although the extent of the effect varied depending on species-specific growth patterns. Overall, the earlier reproductive maturity achieved through optimized silicon nutrition presents a sustainable and economically advantageous strategy for strengthening the competitiveness of tuberose in commercial floriculture markets.

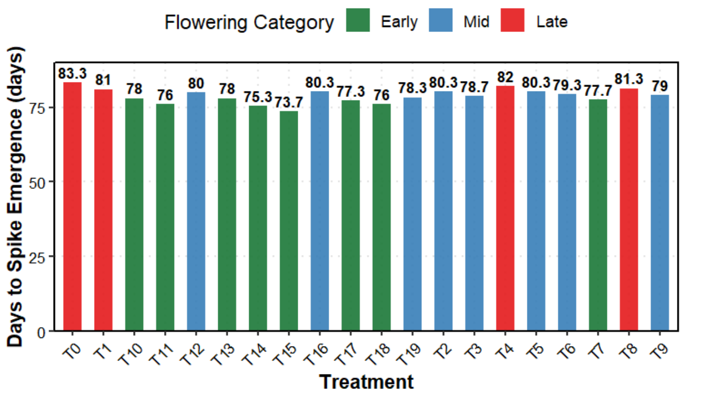

Figure 4: The effect of different doses of silica oxide (SiO_2) on days to spike emergence of tuberose

Spike Length and Number of Spikes/Plant

The key spike characteristics showed considerable improvements with SiO_2 treatments. Treatment T_{15} (S_3F_3) produced the longest spikes (91.0 cm), (Figure 5) and the highest number of spikes per plant (11.11), representing increases of 8.0% and 66.8%, respectively, over the control treatment (Figure 6). These improvements indicate stronger sink capacity and more efficient partitioning of assimilates to reproductive structures.

The substantial enhancement in spike length and number can be attributed to Si's role in improving vascular tissue efficiency and nutrient translocation. The 8.0% increase in spike length observed with treatment T_{15} reflects improved silica deposition in the vascular bundles of the developing inflorescence, which enhances the transport of water, minerals, and photoassimilates from source leaves to the developing spike (22, 30). This improved vascular efficiency ensures that the rapidly elongating spike receives adequate resources to sustain growth, resulting in longer, more robust inflorescences.

The remarkable 66.8% increase in spike number (Table 2) represents a particularly significant finding for commercial production, as it directly translates to increased flower yield per unit area. This enhancement in spike production can be explained through multiple mechanisms. First, the improved vegetative growth parameters discussed previously particularly increased leaf number and width provide a larger photosynthetic surface area, generating surplus photoassimilates that can support the development of additional reproductive structures. Second, Si's role in optimizing source-sink relationships appears to facilitate the partitioning of resources toward spike formation rather than vegetative maintenance (10, 24). The plant essentially becomes more efficient at converting vegetative biomass into reproductive output, which is the primary objective in commercial floriculture.

The combined soil and foliar application strategy employed in treatment T_{15} appears to create sustained silicon availability throughout the critical period of spike initiation and development. Soil applications provide the foundational silicon supply for overall plant development, while the timed foliar applications at 30, 60, and 90 DAP deliver supplemental silicon during active growth phases. This dual approach ensures that silicon is available both systemically through root uptake and directly at actively growing tissues through foliar absorption (23, 19).

The superiority of intermediate doses over the highest concentrations suggests the existence of an optimal silicon concentration range, beyond which additional applications may not be beneficial or could potentially interfere with the uptake of other essential nutrients required for spike development. These findings align with research on gladiolus (18) and other bulbous ornamentals, where silicon application similarly enhanced inflorescence characteristics through improved resource allocation and vascular function.

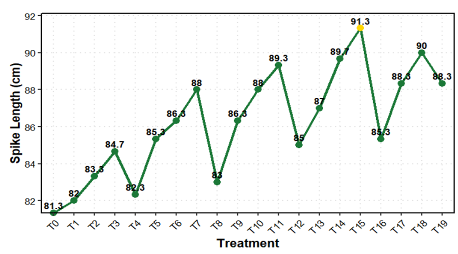

Figure 5: The effect of different treatment applications of silica oxide (SiO_2) on spike length of tuberose

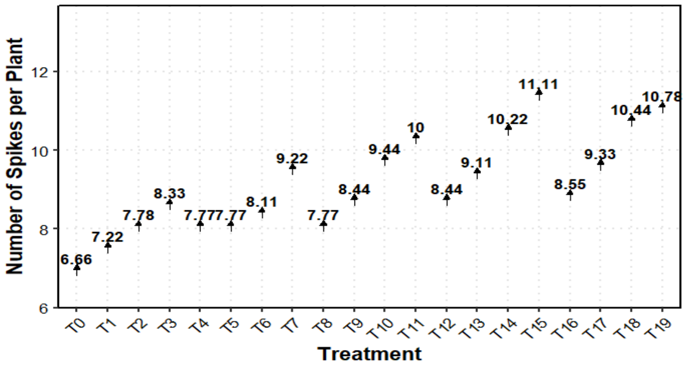

Figure 6: The effect of different doses of silica oxide (SiO_2) on number of spikes in tuberose

Floret Quality and Development

Parameters related to florets demonstrated significant enhancement with SiO_2 treatments. Treatment T_{15} (S_3F_3: 8.8 g/m^2 soil application combined with 3% foliar spray) recorded the highest number of florets per spike (43.33) and the highest number of open florets (40.66). The percentage of unopened florets decreased in optimal treatments, suggesting improved floret viability and more synchronized development (Figure 7). The ratio of open to unopened florets improved from 11.7:1 in the control to 15.3:1 in T_{15} (Table 2), indicating superior floral quality that is highly desirable for the cut flower market.

The enhancement in floret quality and development represents perhaps the most commercially significant outcome of this study, as floret number and uniformity are primary determinants of market value in tuberose. The increase in total floret number per spike observed with treatment T_{15} can be attributed to silicon's role in supporting the differentiation and development of floral primordia. During spike development, silicon appears to optimize the hormonal environment within the developing inflorescence, potentially through its influence on auxin, cytokinin, and gibberellin pathways, which regulate floral organ initiation and development (14). The improved nutrient translocation to the developing spike, facilitated by silica-strengthened vascular tissues, ensures that each developing floret receives adequate resources for complete differentiation and maturation.

The particularly noteworthy improvement in the ratio of open to unopened florets (from 11.7:1 to 15.3:1) indicates enhanced floret viability and more synchronized development along the spike. This improvement suggests that silicon application reduces developmental abnormalities and enhances the uniformity of floret maturation, which is crucial for commercial appeal. The synchronized flowering pattern likely results from silicon's role in maintaining stable physiological conditions within the spike, reducing stress-induced abortion of developing florets. Silicon's well-documented function in enhancing stress tolerance (8, 9) may protect developing florets from environmental fluctuations during the critical differentiation and development phases.

From a mechanistic perspective, the improved floret development may also be related to silicon's influence on hormone balances within the inflorescence. Research has shown that silicon can modulate ethylene production, a hormone that, when present in excess, can cause premature senescence and abortion of developing florets (18). By maintaining optimal hormonal balance, silicon treatment appears to support the complete development of a higher proportion of florets, reducing the number of unopened or aborted flowers.

Additionally, the strengthened mechanical structure of silicon-treated spikes may reduce physical stress on developing florets, preventing damage during rapid spike elongation.

The comprehensive improvement in floret parameters observed with treatment T_{15} demonstrates the synergistic benefits of combined soil and foliar silicon application. The timing and dosage of applications appear optimally calibrated to support the sequential developmental processes involved in floret formation—from initial primordia differentiation through final anthesis. These findings are consistent with research on other ornamentals including New Guinea impatiens, Portulaca and Lobelia (25) and narcissus (23) where Si application similarly enhanced floral quality parameters. The practical implication for growers is substantial: spikes with more uniformly opened florets command premium prices in cut flower markets and provide extended display periods for consumers.

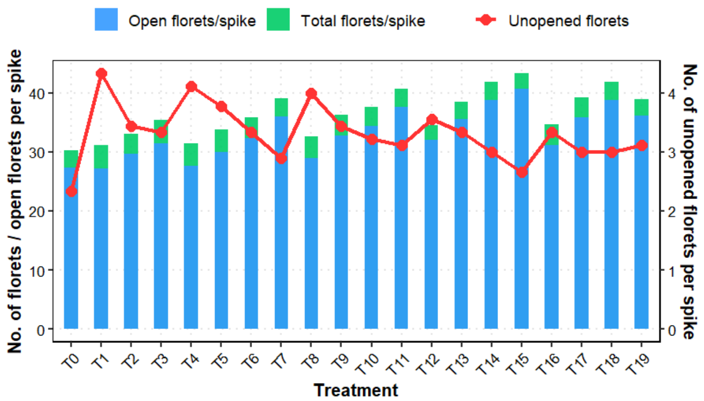

Figure 7: The effect of different doses of silica oxide (SiO_2) on the number of florets, number of open and unopened florets per spike in tuberose

Vase Life

Vase life is one of the most important postharvest parameters determining the market value of cut flowers. In the present study, SiO_2 treatments had a significant positive effect on the vase life of tuberose spikes (Table 2). The longest vase life (12.89 days) was recorded in treatment T_{19} (S_4F_3: 11.8 g/m^2 soil + 3% foliar spray), followed closely by T_{15} (S_3F_3: 8.8 g/m^2 soil + 3% foliar spray), which recorded 12.67 days. In contrast, the control (T_0) and lower SiO_2 concentration treatments showed the shortest vase life, with only 10.00 days (Figure 8).

The improvement in vase longevity under higher SiO_2 levels may be attributed to silicon-induced strengthening of epidermal tissues and improved vascular integrity, both of which help reduce transpiration losses and enhance water uptake during the vase period. Silicon is also known to promote antioxidant activity and stabilize cellular membranes, which delays floral senescence and maintains petal freshness for a longer duration. Similar enhancements in postharvest performance due to silicon application have been reported in gerbera (26) and cut roses (31), where Si supplementation improved petal turgidity and reduced oxidative stress.

The combined soil and foliar application used in treatments T_{15} and T_{19} appears to create a synergistic effect, ensuring a continuous supply of silicon through both root uptake and direct foliar absorption. This dual pathway likely maximizes silicon availability during flower development and extends postharvest life. Overall, the findings indicate that higher levels of combined SiO_2 application not only enhance vegetative and floral performance but also significantly prolong vase life, thereby improving the commercial marketability and consumer appeal of tuberose spikes.

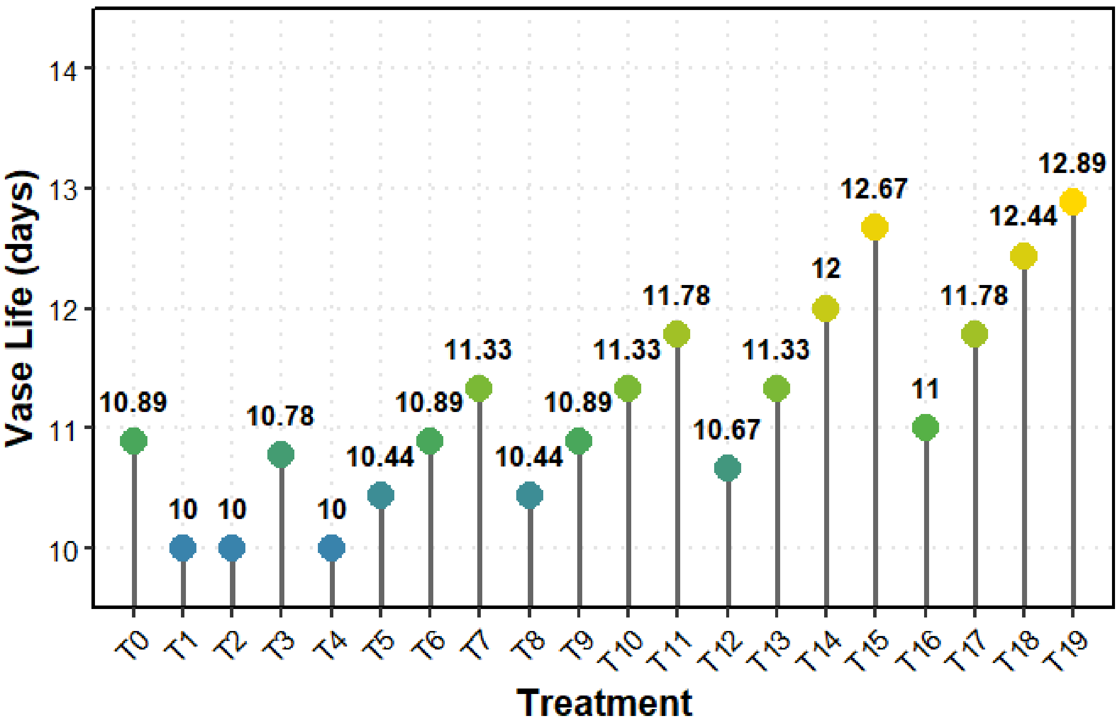

Figure 8: The effect of different doses of silica oxide (SiO_2) on the vase life of spikes in tuberose

Table: 2. Effect of silica oxide (SiO_2) treatments on floral characteristics of tuberose (Agave amica Medik.) Var. 'Single'

Treatments	Days taken to spike Emergence	No. of spikes/plant	Spike Length (cm)	No. of florets/spike	No. of open florets/spike	No. of unopened florets/spike	Vase life
T_0 (S_0F_0)	82.23^{ab}	6.66^{h}	84.3^{ghi}	30.33^{j}	27.33^{i}	2.33^{g}	10.89^{fg}
T_1 (S_0F_1)	82.78^{a}	7.22^{gh}	82.96^{i}	31.11^{ij}	27.11^{i}	4.33^{a}	10.0^{h}
T_2 (S_0F_2)	81.33^{ab}	7.78^{fgh}	83.12^{i}	33.11^{ghij}	29.66^{ghi}	3.44^{bcdef}	10.0^{h}
T_3 (S_0F_3)	80.22^{abc}	8.33^{defg}	86.72^{cde}	35.33^{defgh}	31.44^{defghi}	3.33^{bcdef}	10.78^{fgh}
T_4 (S_1F_0)	82.22^{ab}	7.77^{fgh}	83.11^{i}	31.44^{hij}	27.55^{hi}	4.11^{ab}	10.0^{h}
T_5 (S_1F_1)	80.44^{abcd}	7.77^{fgh}	84.52^{fghi}	33.77^{fghi}	30.0^{fghi}	3.78^{abcd}	10.44^{gh}
T_6 (S_1F_2)	80.89^{abc}	8.11^{efg}	85.33^{efgh}	35.78^{defg}	32.33^{cdefg}	3.33^{bcdef}	10.89^{fg}
T_7 (S_1F_3)	80.12^{abcde}	9.22^{cde}	86.38^{def}	39.0^{bcd}	36.0^{bcd}	2.89^{efg}	11.33^{def}
T_8 (S_2F_0)	80.55^{abcd}	7.77^{fgh}	83.35^{hi}	32.67^{ghij}	28.88^{ghi}	4.0^{abc}	10.44^{gh}
T_9 (S_2F_1)	79.11^{bcdefg}	8.44d^{ef}	84.52^{fghi}	36.22^{defg}	32.77^{cdefg}	3.44^{bcdef}	10.89^{fg}
T_{10} (S_2F_2)	77.44^{defgh}	9.44^{bcd}	86.01^{defg}	37.66^{cdef}	34.33^{bcdef}	3.22^{cdef}	11.33^{def}
T_{11} (S_2F_3)	77.33^{defgh}	10a^{bc}	87.73^{bcd}	40.66^{abc}	37.55^{ab}	3.11^{defg}	11.78^{cde}
T_{12} (S_3F_0)	79.67^{abcdef}	8.44^{def}	84.35^{fghi}	34.44^{efghi}	32.0^{cdefgh}	3.55^{abcde}	10.67^{fgh}
T_{13} (S_3F_1)	77.55^{cdefgh}	9.11^{cde}	86.22^{defg}	38.44^{bcde}	35.55^{bcde}	3.33^{bcdef}	11.33^{def}
T_{14} (S_3F_2)	76.67^{fgh}	10.22^{abc}	88.59^{bc}	41.88^{ab}	38.77^{ab}	3.0^{defg}	12.0^{bcd}
T_{15} (S_3F_3)	73.0^{i}	11.11^{a}	91.0^{a}	43.33^{a}	40.66^{a}	2.66f^{g}	12.67^{ab}
T_{16} (S_4F_0)	79.33^{bcdef}	8.55^{def}	84.61^{fghi}	34.66^{efghi}	31.11^{efghi}	3.33^{bcdef}	11.0^{efg}
T_{17} (S_4F_1)	77.0^{efgh}	9.33^{bcd}	86.24^{defg}	39.22^{bcd}	35.89^{bcd}	3.0^{defg}	11.78^{cde}
T_{18} (S_4F_2)	75.89^{ghi}	10.44^{ab}	87.62^{bcd}	41.78^{ab}	38.77^{ab}	3.0^{defg}	12.44^{abc}
T_{19} (S_4F_3)	74.89^{hi}	10.78^{a}	89.06^{ab}	38.89^{bcd}	36.11^{abc}	3.11^{defg}	12.89^{a}
CD 5%	**1.8157**	**0.5966**	**1.1057**	**2.1758**	**2.4312**	**0.4518**	**0.4525**
$SE_{(m)}$	**0.6342**	**0.2084**	**0.3862**	**0.7600**	**0.8492**	**0.1578**	**0.1581**

Values represent the means ± standard error. In each column, values with the same letter(s) are not significantly different at LSD ($P \leq 0.05$)

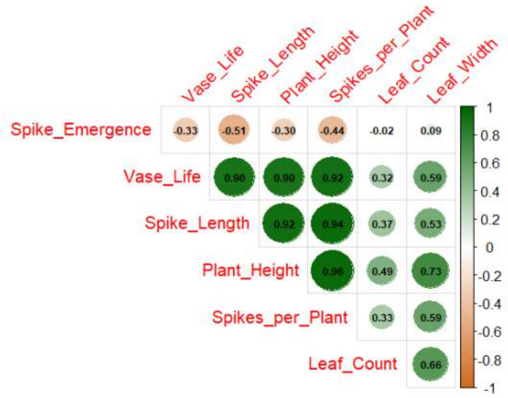

Figure 9. Pearson correlation analysis among vegetative, floral, and vase life parameters of tuberose (Agave amica Medik.) *as influenced by combined applications of soil and foliar of silicon oxide (SiO_2). Heatmap of Pearson correlation coefficient (r) values of variable traits, where the coloured scale indicates the positive (green) or negative (orange) correlation and the 'r' coefficient values (r = -1.0 to 1.0). Circle size corresponds to the magnitude of correlation (r). Strong positive correlations were observed among vegetative and floral traits such as plant height, leaf number, and spike length, whereas spike emergence showed moderate negative associations with several growth parameters. Data represent mean values across all SiO_2 treatment combinations under field conditions.*

Integrated Treatment Performance

The comprehensive analysis of plant performance revealed that intermediate doses of silica oxide (SiO_2), specifically S_2 and S_3 for soil application combined with F_2 and F_3 for foliar application, yielded superior results compared to both the control and the highest concentration treatments. Treatment T_{15} (S_3F_3) emerged as the optimal combination, demonstrating clear synergistic effects between the soil application of 8.8 g/m^2 and the 3% foliar spray. The heat map visualization (Figure 9) clearly illustrates the superior performance of these intermediate treatments across multiple parameters, underscoring the non-linear nature of tuberose's response to silica oxide (SiO_2) application.

This pattern of optimal response at intermediate concentrations represents a critical finding that has both theoretical and practical implications. The superior performance of treatment T_{15} compared to higher doses (such as T_{19} with S_4F_3) suggests the existence of an optimal threshold for silicon benefits in tuberose. This phenomenon can be explained through several physiological mechanisms. First, at optimal concentrations, silicon enhances nutrient uptake efficiency and metabolic processes without interfering with the absorption or utilization of other essential elements (14). However, beyond this threshold, excessive silicon accumulation may lead to saturation of transport mechanisms or competition with other beneficial elements for uptake sites, resulting in diminishing returns or potential nutrient imbalances.

The synergistic effect observed between soil and foliar applications in treatment T_{15} demonstrates the value of integrated nutrient management strategies (23, 19). Soil applications of 8.8 g/m^2 provide a foundational, long-term supply of silicon that is continuously available through root uptake throughout the growing season. This baseline silicon supply supports fundamental processes such as cell wall strengthening, root development, and establishment of basic structural integrity. The foliar applications of 3% solution at 30, 60, and 90 DAP (days after planting) complement this baseline by providing supplemental silicon directly to actively growing tissues during critical developmental phases—early vegetative growth, rapid leaf expansion, and the transition to reproductive development, respectively.

The non-linear response pattern evident in the heat map visualisation (Figure 9) reveals that silicon's effects on plant performance are not simply additive but involve complex interactions between concentration, application method, and plant developmental stage. This complexity suggests that silicon acts through multiple pathways simultaneously, including mechanical reinforcement of tissues, modulation of hormone signalling, enhancement of photosynthetic efficiency, and optimisation of nutrient uptake (32, 33). The intermediate doses appear to strike an optimal balance across all these functions, whereas higher doses may over-emphasise certain mechanisms at the expense of others (34).

The practical implication of identifying treatment T_{15} as optimal is significant for commercial tuberose production. This specific combination—8.8 g/m^2 soil application at planting, combined with 3% foliar sprays at 30-day intervals—provides a concrete, implementable strategy that balances efficacy with cost-effectiveness. The consistent superiority of this treatment across both vegetative and floral parameters suggests that it optimises silicon availability throughout the entire growth cycle, from initial bulb sprouting through final spike harvest. Furthermore, the use of intermediate rather than maximum doses has economic advantages, reducing input costs while still achieving substantial improvements in crop quality and yield.

These findings align with the wider research on silicon nutrition in ornamental crops, which consistently demonstrates optimal responses at moderate application rates (31, 19, 7, 35). However, the present study provides specific dosage recommendations for tuberose that can be directly translated into commercial practice. The identification of an optimal treatment combination offers a sustainable approach to improving tuberose production by enhancing quality parameters without excessive resource inputs or environmental impact. This balanced approach to silicon nutrition represents a model for integrated nutrient management in floriculture, emphasising the importance of application method, timing, and dosage optimisation rather than simply maximising nutrient availability.

Conclusion

The present study clearly demonstrates that the application of silica oxide (SiO_2) through combined soil and foliar routes exerts a pronounced effect on the vegetative growth, flowering attributes, and postharvest quality of tuberose. Among the various treatments, T_{15} (S_3F_3: 8.8 g/m^2 soil + 3% foliar) and T_{19} (S_4F_3: 10.0 g/m^2 soil + 3% foliar) emerged as the most effective, promoting early spike initiation, longer spike length, higher floret count, and extended vase life. The beneficial influence of SiO_2 can be attributed to improved photosynthetic efficiency, enhanced nutrient translocation, and strengthened cellular structures that collectively delay senescence. These findings underscore the importance of silicon in floriculture and suggest that integrated soil and foliar silicon management offers a cost-effective and sustainable approach to improving the yield and aesthetic quality of tuberose. Future studies focusing on silicon bioavailability, enzymatic defence mechanisms, and postharvest physiology could further elucidate its multifunctional role in ornamental crops.

Future Scope

Future research should focus on understanding how silica oxide (SiO_2) interacts with tuberose at physiological and molecular levels, particularly in relation to nutrient uptake, stress tolerance, and delayed senescence.

Studies on different cultivars, varying environmental conditions, and long-term soil effects would help validate and refine the recommended SiO_2 doses. Further work on silicon bioavailability, its interaction with other nutrients or biostimulants, and its role in postharvest physiology could strengthen the practical application of SiO_2 in commercial floriculture. Additionally, evaluating alternative silicon sources and assessing the cost-benefit ratio of integrated soil and foliar application strategies would support the development of more efficient, sustainable production practices for tuberose.

Conflict of Interest

The authors declare that they have no conflict of interest.

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