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RESEARCH ARTICLE

Use of Si-based fertilizer significantly improves the performance of 'Sanren' botanical seed-derived shallot

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ABSTRACT

Shallots (*Allium cepa* L. var. *aggregatum* G. Don) are extensively cultivated in Indonesia and exhibit significant market importance. Planting of botanical seed (true shallot seed, TSS) is a promising alternative to seed-bulbs due to increased productivity. However, its implementation at the farmer level needs to be optimized. The TSS from three cultivars with different Si fertilization treatments was tested. The trial used a randomized complete block design (RCBD) with three shallot cultivars (Sanren, Lokananta, and Merdeka) and Si concentrations (0, 5, and 10 mL L^{-1}). Significant interactions ($p < 0.05$) were seen in Si content, cuticle thickness, plant height, leaf count, tillers, and bulb diameter. Si absorption was highest in 'Sanren' treated with 10 mL L^{-1} Si (5.39%), leading to a 121% increase in leaf cuticle thickness (14.10 µm) compared to the control (6.36 µm). Si increased photosynthesis and growth. In 'Sanren', leaf number increased from 13.94 (0 mL L^{-1}) to 29.81 (10 mL L^{-1}) and tiller number from 3.38 to 4.94. With 10 mL L^{-1} Si, yields improved: Bulb number increased from 4.50 to 7.38 per plant, and bulb diameter increased from 2.31 to 2.86 cm. Si treatment raised harvest index from 0.78 to 0.88 across cultivars but extended harvest age by 1.5-6.0 d (62-68 DAP). The principal component analysis showed higher Si absorption lowered leaf Pb, Cu, and Cd. Adding 10 mL L^{-1} Si fertilizer to 'Sanren' increased growth and yield by 30%-70%, highlighting the viability of using TSS in shallot farming.

Key words: *Allium cepa* var. *aggregatum*, Lokananta, Merdeka, Sanren, shallot, silica fertilizer, silicon, true shallot seed.

INTRODUCTION

Shallots (*Allium cepa* L. var. *aggregatum* G. Don, previously classified as *A. cepa* L. var. *ascalonicum* auct.) represent a significant agricultural commodity in Indonesia. They are extensively used daily as a fresh culinary spice. The demand for shallots for domestic consumption has risen significantly (Saptana et al., 2021). Indonesia produced 2 004 590 t in 2021, 1 982 360 t in 2022, and rose to 1 985 233 t in 2023 from approximately 181 467 ha of cultivated area. Its domestic consumption reached over 800 000 t in 2022 and is expected to grow at

1.94% (Adiyoga, 2023). The price of shallots fluctuates depending on their harvest season and their availability in the market. Hence, ensuring the availability of shallots in the market is crucial. However, not all the produced shallots are sold in the market for consumption. Some of them are used as vegetative planting material for cultivation, presenting various challenges, including the deterioration of seed quality (Adiyoga, 2021).

True seed of shallots (TSS), or botanical seed of shallots, is an alternative planting material for shallot cultivation; it is obtained from the pollinated flowers of shallots. The use of TSS offers various advantages over seed-bulbs such as a reduced seed requirement (only 3.0-7.5 kg ha^{-1}), higher productivity compared to bulb seed, a straightforward distribution process, lower transportation costs, and a longer storage capability (Marais et al., 2019). Atman et al. (2021) reported that the use of TSS 'Lokananta', 'Sanren', 'Trisula', and 'Bima' exhibited superior growth (leaf number, number of bulbs) and harvest (bulb weight and bulb diameter) performance. On the other hand, Adiyoga (2023) and Kurnia et al. (2023) found that the growth and yield performance of TSS are variety-dependent. 'Sanren' showed superior performance in terms of yield and bulb number per plant than that of 'Maserati' and 'Trisula'. However, 'Maserati' exhibited a greater bulb diameter than 'Sanren' and 'Trisula' (Adiyoga, 2023). Despite its advantages, the utilization of TSS poses various challenges. It can have low germination rates and low seed resistance to environmental conditions (Adiyoga, 2023; Pangestuti et al., 2023). Improvement in cultivation methods, such as agronomic practices and fertilization, is crucial to ensure the optimum performance of TSS.

Nutrient availability is essential to support plant growth, is a key requirement for enhanced crop production. Silica-based fertilizer is currently gaining interest, acting as a protective agent for plants and can modulate photosynthesis and enzymatic activity. This fertilizer contains elevated levels of Si, and contributes to improved growth and nutrient availability, enhanced plant resistance to pests and diseases, and increased yield (Triharyanto et al., 2022; Syaiful et al., 2025).

The main component, Si, is acknowledged as a beneficial element for crop growth, mainly because of its ability to alleviate biotic and abiotic stress in plants (Chaiwong and Prom-u-thai, 2022). Its application is associated with accumulation in various plant tissues, leading to enhanced nutrient uptake, photosynthetic rate, leaf cell rigidity, increased thickness of the stem, and the production of phenolics and lignin. This leads to increased resistance to lodging. It also plays an important role in providing mechanical resistance to diseases and insect damage, as well as in facilitating biochemical changes associated with plant defenses against biotic stress (Jiang and Zhang, 2021; Song et al., 2021; Hadiawati et al., 2023).

Silica application has been reported to positively affect the growth and yield performance of cultivated plants. Foliar application of Si increased rice grain yield by 19% under N-deficient conditions, attributed to increased lignin synthesis and chlorophyll content (Huang and Ma, 2020). Research by Goyal et al. (2025) indicated that applying Si fertilizer to garlic plants (7.5, 10.0, and 12.5 mL L^{-1} SiO_2) increased diameter and weight of garlic bulbs. However, reports on its application on shallots are currently limited. Responses of plants to growth regulators and fertilizers are known to differ among varieties. Evaluation of its effect on the growth performance, yield, and bulb quality is needed to better understand its usage in the optimization of shallot cultivation from TSS planting material. This research evaluated the response of three TSS cultivars ('Sanren', 'Lokananta', 'Merdeka') to silica applications at concentrations of 0, 5, and 10 mL L^{-1}. Assessments were performed on leaf structure, growth patterns, mineral content, and yield factors. The objective was to identify the cultivar with the highest responsiveness and the optimal silica concentration for enhancing TSS productivity.

MATERIALS AND METHODS

Materials

The true shallot (*Allium cepa* L. var. *aggregatum* G. Don) seed (TSS) planting materials of 'Sanren', 'Lokananta' and 'Merdeka' were obtained from local suppliers (PT, East West Seed Indonesia, Purwakarta). The KNO_3 fertilizer (Merah Pak Tani, CV. Saprotan Utama, Semarang), P_2O_5 fertilizer (SP-36, PT. Petrokimia Gresik, Gresik), K_2O+S fertilizer (ZK Petro, PT. Petrokimia Gresik, Gresik), silica foliar fertilizer (Pupuk Silika, BrMP Pasca Panen, Bogor) were purchased from local suppliers. Chemicals for analysis were of analytical grade. The doses of fertilizers are described in Table 1.

Table 1. Dosage of NPK and Si fertilizer applied during the trial.

Time of application (days post-planting)	Fertilizer type	Dosage	Dosage	Spray volume per plot	Spray volume per plant
		kg ha^{-1}	g m^{-2}	mL	mL
14	NPK (16:16:16)	80	8	-	-
15	Si spray	-	-	100	4
28	NPK (16:16:16)	80	8	-	-
30	Si spray	-	-	150	6
35	NPK (16:16:16)	120	12	-	-
42	NPK (16:16:16)	120	12	-	-
45	Si spray	-	-	200	8
48	K_2O + S	60	6	-	-

Location and time

The study was carried out in Bantul Regency (8°0'9" S, 110°15'39" E; 10 m a.s.l.), Special Region of Yogyakarta, Indonesia, during the wet season of 2024/2025. The annual rainfall was 2194.44 mm, average temperature was 32 °C, and soil pH levels were between 6.0 and 7.0. The soil texture is classified as sandy, comprising a sand fraction of 92.23%, a silt fraction of 6.81%, a clay fraction of 0.96%, water content is 0.45%; total organic carbon is 0.18%; total nitrogen is 0.015%; C/N ratio is 14.34 (Herawati et al., 2023). An anatomical analysis of leaf tissue was conducted at the Plant Structure and Development Laboratory (SPT) of the Faculty of Biology, Universitas Gadjah Mada, and the Plant Cultivation Technology Laboratory (TBT) of Universitas Pembangunan Nasional (UPN) "Veteran" Yogyakarta.

Experimental design

The research employed a field experiment structured as a randomized complete block design (RCBD), incorporating two factors with three levels. The first factor was the shallot cultivar ('Sanren', 'Lokananta', 'Merdeka') and the second factor was the concentration of Si fertilizer (0, 5 and 10 mL L^{-1} SiO_2). Each combination was done in four replicates, yielding a total of 36 experimental units. Each experimental unit was comprised of 25 plants, with four sample plants per unit, yielding a total of 900 plants. A total of 2700 plants were organized for this study.

TSS Nursery

A growing medium (soil:manure:rice husks, 2:1:1) was used in seedling trays (60 × 70 cm). The TSS was sown in the tray, with a density of 400 seedlings per tray. Each hole contained four to five TSS. Watering was done every morning. The KNO_3 fertilizer was applied by pouring (4 g L^{-1}) 18 d after sowing (DAS). The TSS were maintained for 28 d until they were ready for transplantation.

Land preparation and seedling transplantation

The land was prepared by several treatments including the addition of manure at 15 t ha^{-1} and dolomite at 0.75 t ha^{-1}. A trial bed of 1 × 1 m was prepared with a separation of 50 cm between beds and 100 cm between blocks. Prior to use, an organophosphate pesticide, diazinon, was applied (30 kg ha^{-1}, 3 g m^2) to manage pests such as mole crickets (*Gryllotalpa* spp.) Fertilizer of P_2O_5 (120 kg ha^{-1}, 12 g m^{-2}) and oxyfluorfen-based herbicide (1 L in 480 L water ha^{-1}) were then applied 3 d prior to transplantation of the TSS seedlings, which was conducted at 28 DAS. Three seedlings from a single plastic seedling tray were transplanted in each hole, a spacing of 20 cm × 20 cm.

Plant maintenance

Irrigation was applied through a misting system and conducted for 90 min in the morning and 30 min in the afternoon, and no irrigation was applied during rainy period. Weeding was performed manually every 7 d. Fertilization was done using NPK (16:16:16, applied at day 14, 28, 35, and 42 after planting) and K_2O+S fertilizer (48 d after planting) (Table 1). Application of Si, as the factor of the study, was done three times (day 15, 30, and 45 after planting, in the afternoon).

Sampling and harvesting

The sampling of plants was carried out 40, 50 and 60 d after planting for chlorophyll analysis. Chlorophyll measurements were performed on three healthy, intact leaves from each plant between 08:00 and 10:00 h. The second or third outermost leaves were chosen, ensuring they were neither too young nor exhibiting signs of yellowing. The measurement point was located at the central third of the leaf, starting from the base. Measurements were conducted in triplicate on each leaf. Growth performance parameters (plant height, number of leaves and tillers) were measured from the sample collected on day 60. Leaf samples for cuticle analysis were collected 7 d before harvest while the plants were in optimal condition. Harvesting was done when the plants were wilted (~62-68 DAP), the bulbs were firm, dark red-purple hue in appearance and visible above the soil, and the stem neck started to weaken and collapse. Shallot bulbs were gathered by uprooting the entire plant to obtain both the leaves and roots.

Characterization of the leaf

The analysis of leaf nutrient content was performed at the National Research and Innovation Agency of Indonesia (BRIN) laboratory. Cuticle thickness was determined by utilizing a digital microscope (OptiLab IRIS-4, PT Miconos, Yogyakarta, Indonesia). The leaf samples were cleaned with distilled water and immersed in 70% ethanol before being processed into a microscope specimen. The cuticle thickness was measured in µm. Elemental analysis was done utilizing a non-destructive X-ray fluorescence spectroscopy (XRF) (EDXRF Epsilon 4, Malvern Panalytical Ltd., Malvern, UK. Plant leaves were collected during harvesting and dried in an oven (Memmert UI 80, FT-C900, Fort, West Germany) at 50 °C for 3 d. The materials were then powdered and sieved (100-mesh) to obtain a fine powder. The samples (10 g) were then positioned in an EDXRF equipped with a Rh tube for elemental analysis. The procedure included X-ray irradiation, atomic excitation, emission of X-ray fluorescence, detection and measurement, followed by spectroscopic analysis.

Growth performance

The plants' height was measured from the base of the stem to the apex of the longest leaf. The quantity of leaves was determined by tallying the completely developed leaves on the sample plants. Tillers were determined as a group of leaves and a stem that constitute a bulb. Chlorophyll content was measured using a SPAD-502 Plus (Konica Minolta, Tokyo, Japan) from three leaves of the sample plants.

Characterization of the yield

Number of bulbs per plant was calculated by enumerating the bulbs produced on each sample plant. The bulb diameter was measured using vernier calipers. The harvest index (HI) was quantified as a plant's capacity to allocate assimilates, expressed as a unit-weighted measure. Calculations of HI were done based on the method of Rahmawati and Ladewa (2023), in which HI was the ratio of the weight of cured bulbs (economic yield) to that of the weight of cured bulbs and leaves (biological yield).

Statistical analysis

Two ways ANOVA followed by Duncan multiple range test (DMRT) at the 95% confidence level, and Pearson correlation analysis were done using SPSS Version 25 (IBM, Armonk, New York, USA). Principal component analysis based on the spectra of XRF was done using RStudio Version 4.5.0 (RStudio: Integrated Development Environment for R. Posit Software, PBC, Boston, Massachusetts, USA).

RESULTS AND DISCUSSION

Leaf characteristic of shallot from true shallot seed (TSS)

'Sanren' demonstrated the highest increase in leaf Si concentration, especially under the 10 mL L^{-1} treatment ($p < 0.05$), with leaf Si accumulation exceeding fourfold compared to other cultivars. The dose-responsive pattern was not observed in either 'Merdeka' or 'Lokananta'. This showed that different varieties have different mechanisms to absorb and accumulate Si. Plants exhibit distinct growth patterns and nutrient absorption capabilities, which is mostly contributed by genetic factors. Plants absorb Si through xylem tissue, and it is

transported with water to the leaves. Following water evaporation, Si precipitates and accumulates as amorphous Si in the epidermal layer of the leaves. Thus, the decreased Si content in 'Lokananta' and 'Merdeka' might be the result of Si translocation to another part of the plant rather than to the leaf. In 'Sanren', the increase in Si content in the leaf corresponded with the increase in cuticle thickness. However, similar trends were not shown in 'Lokananta' and 'Merdeka'. Thus, the increase in cuticle thickness might be induced by other mechanisms, most likely by plant-defense mechanisms involving Si as an indirect co-factor.

The elevated internal Si accumulation in 'Sanren' was associated with a notable increase in cuticle thickness, measuring 14.10 µm, which was the highest observed across all treatments (Table 2). The anatomical enhancement noted in 'Sanren' indicates its significant physiological ability to absorb, transport, and utilize Si effectively, as Si deposition strengthens epidermal cell structures. The cuticle layer constitutes the epidermal cell wall and prevents the penetration of fungi and other microorganisms. Thus, a thicker cuticle correlates with increased resistance to pathogen invasion. 'Sanren' exhibited the most substantial cuticle layer (Figure 1). Silica induces the synthesis of lignin and suberin in the cell wall, which fortifies the cell wall and inhibits pathogen penetration, significantly enhancing plants' resistance. Silica enhances plant resistance to pests and diseases by thickening the cuticle layer and fortifying plant tissue. It is expected that fewer pathogen attacks will lead to less stress on the plants, consequently improving the yield.

Table 2. Content of Si and thickness of leaf cuticle of shallot plants obtained from different Si fertilization treatments. Values with identical letters in the same row and column in the specific parameter showed nonsignificant difference according to the 5% DMRT test. The plus sign denotes an interaction between two factors.

	Content of Si in leaf (%)				Thickness of leaf cuticle (µm)			
Treatment	0 mL L^{-1}	5 mL L^{-1}	10 mL L^{-1}	Average	0 mL L^{-1}	5 mL L^{-1}	10 mL L^{-1}	Average
Sanren	1.19^{b}	1.41^{b}	5.39^{a}	2.66	6.36^{e}	10.51^{bc}	14.10^{a}	10.32
Lokananta	1.02^{b}	1.39^{b}	0.83^{b}	1.08	7.94^{de}	7.63^{de}	8.62^{d}	8.06
Merdeka	2.06^{b}	1.75^{b}	1.69^{b}	1.83	9.34^{cd}	8.19^{de}	11.60^{b}	9.71
Average	1.42	1.52	2.64	(+)	7.88	8.87	11.44	(+)

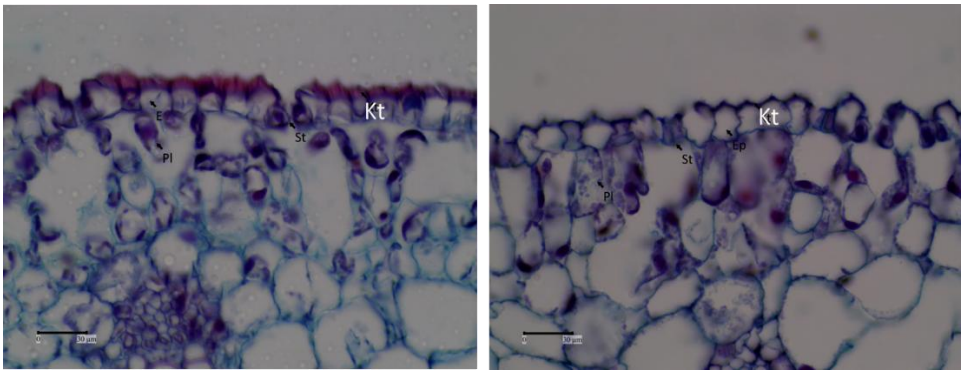

Figure 1. Cuticle (Kt) of leaves treated with 10 mL L^{-1} Si (left image) exhibits greater thickness compared to the cuticle of untreated leaves (right image). E: Epidermis; Pl: palisade tissue; St: stomata.

The application of Si affected the absorption of various macro- and micro-nutrients and heavy metals. The XRF analysis showed that the concentration of K, S, Mg, Ca, Fe, Zn, Mn, Cu, Pb, and Cd elements in the leaf varied greatly among the treatments. A PCA biplot showed that the first principal component explained 37.5% of the variance, while the second principal component accounted for 19.3% (a total of 56.80%) (Figure 2). Biplot analysis indicated that Si was positioned in the lower right quadrant. In contrast, heavy metals (Pb, Cu, and Cd) were located in the opposite quadrant. Khan et al. (2021) reported that the application of Si restricts the uptake of heavy metals. This is affected by the deposition of Si in the root apoplast that prevents the entry of heavy metals

into the root cell wall. Hence, higher absorption of Si (as observed in 'Sanren' with 10 mL L^{-1} Si) resulted in lower absorption of heavy metals, restricting their accumulation in the leaf. In contrast, the treatment with the lowest Si absorption ('Lokananta') showed a predominance of the elements Pb, Cu, K, and S. 'Lokananta' at 5 mL L^{-1} Si showed a domination of Pb and Cu. The accumulation of Pb, Cu, and Cd in the leaf might indicate abiotic stress in the plant. On the other hand, the untreated (0 mL L^{-1} Si) 'Sanren', 'Lokananta', and 'Merdeka' were centralized and exhibited a domination of Ca, Mg, Na, P, and Zn. 'Merdeka' at 10 mL L^{-1} Si showed elevated Fe. This is typically linked to diminished soil conditions. An increased level of Si content is crucial for enhancing plant resilience against biotic and abiotic stress (de Carvalho et al., 2022; Crista et al., 2024; Padjung et al., 2024).

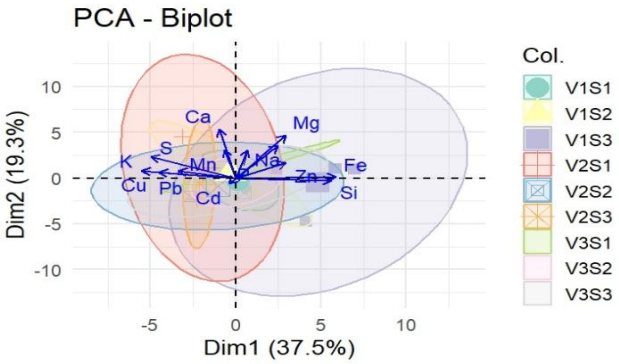

Figure 2. Biplot of principal components illustrating the relationship between mineral elements and treatments. V1: 'Sanren'; V2: 'Lokananta'; V3: 'Merdeka'; S1: 0 mL L^{-1} Si; S2: 5 mL L^{-1} Si; S3: 10 mL L^{-1} Si.

Application of Si fertilizer had a minimal effect on the chlorophyll content in the leaves. 'Sanren' showed higher chlorophyll content (54.38-59.09) than 'Lokananta' (53.13-57.05) and 'Merdeka' (53.58-57.62) (Table 3). The only significant changes in chlorophyll content ($p < 0.05$) were observed on 60 DAP, just before harvesting. There were nonsignificant changes in chlorophyll content during 40-50 DAP. Thus, Si application affected shallot productivity more by optimizing photosynthesis through the up righting and reorientation of the leaves rather than increasing the chlorophyll content. This was in agreement with Putri et al. (2017). Silica accumulation in leaves leads to increased uprightness and stretching, which enhances sunlight exposure on the leaf surface. This optimizes sunlight absorption for photosynthesis. Increased light capture enhances the photosynthesis process, leading to greater productivity (Rahmawati and Yasvi, 2024) and growth performance (Triharyanto et al., 2022; Syaiful et al., 2025).

Table 3. Chlorophyll content in the leaf of shallot obtained from different Si fertilization treatments. Values with identical letters in the same row and column showed nonsignificant difference according to the 5% DMRT test. The plus sign denotes an interaction between two factors. The negative sign denotes the absence of interaction.

Treatment	Leaf chlorophyll (SPAD)		
	40 DAP	50 DAP	60 DAP
Variety			
Sanren	54.38^{a}	55.94^{a}	59.09^{a}
Lokananta	53.13^{a}	54.74^{a}	57.05^{b}
Merdeka	53.58^{a}	54.62^{a}	57.62^{ab}
Concentration of Si			
0 mL L^{-1}	53.86^{p}	54.91^{p}	56.87^{q}
5 mL L^{-1}	53.96^{p}	54.83^{p}	58.10^{pq}
10 mL L^{-1}	53.26^{p}	55.56^{p}	58.79^{p}
Average	53.70	55.10	57.92
Interaction	-	-	-

Growth performance of shallot from TSS

The vegetative responses highlight the distinct sensitivity of 'Sanren' to Si. In this cultivar, there was a significant increase in plant height, leaf number, and tiller formation, with leaf production more than doubling at a concentration of 10 mL L^{-1} Si. The observed changes indicate improved photosynthetic efficiency and allocation of assimilates. In contrast, 'Lokananta' demonstrated no significant growth stimulation, while 'Merdeka' exhibited only partial and inconsistent responses (Table 4). This is in agreement with the report of Moeljani et al. (2022) and Ameliana et al. (2024). The Si-fertilized shallot showed improved stem support and enhanced the quality and quantity of the shallot produced. A previous report by Sharma et al. (2023) showed that Si supports plant height by thickening and strengthening the plant's cells, resulting in more upright and better leaf alignment. The significant differences among cultivars indicate that Si-mediated vegetative enhancement is highly dependent on genotype, with 'Sanren' exhibiting the greatest physiological compatibility.

Table 4. Plants height, number of leaves and tillers of shallot plants obtained from different SI fertilization treatments. Values with identical letters in the same row and column in the specific parameter showed nonsignificant difference according to the 5% DMRT test. The plus sign denotes an interaction between two factors.

	Plant height (cm)				Number of leaves				Number of tillers			
Treatment	0 mL L^{-1}	5 mL L^{-1}	10 mL L^{-1}	Average	0 mL L^{-1}	5 mL L^{-1}	10 mL L^{-1}	Average	0 mL L^{-1}	5 mL L^{-1}	10 mL L^{-1}	Average
Sanren	41.23^{bc}	44.18^{ab}	45.65^{a}	43.69	13.94^{bc}	19.69^{b}	29.81^{a}	21.15	3.38^{bcd}	4.31^{ab}	4.94^{a}	4.21
Lokananta	39.70^{c}	37.50^{c}	37.35^{c}	38.18	12.81^{c}	11.44^{c}	13.31^{bc}	12.52	3.50^{bcd}	3.25^{cd}	2.88^{cd}	3.21
Merdeka	39.62^{c}	44.51^{ab}	45.32^{a}	43.15	16.56^{bc}	17.56^{bc}	16.69^{bc}	16.94	3.88^{bc}	3.94^{bc}	4.13^{abc}	3.98
Average	40.18	42.06	42.77	(+)	14.44	16.23	19.94	(+)	3.58	3.83	3.98	(+)

Silica fertilizer affected the leaves' formation in shallot to various extents. 'Sanren' showed a huge increase in leaf count (from 13.94 to 29.81 for 0 to 10 mL L^{-1}, respectively). Surprisingly, nonsignificant changes in leaf count were observed on 'Lokananta' and 'Merdeka'. This aligns with the characteristics of 'Sanren' in cultivation. This variety is known to exhibit tall plants and a great number of leaves. This characteristic might be enhanced by Si application. Hersanti et al. (2023) reported that the incorporation of Si enhanced the absorption of additional nutrients by roots, particularly P, thereby influencing plant height and leaf count. Furthermore, Si was found to be able to regulate plant growth hormones, significantly affecting the productivity and yield of the plants (Sharma et al., 2023). These mechanisms might be the responsible factors affecting the leaf formation in 'Sanren'.

Similarly, the tiller count was found to be significantly changed in 'Sanren', but not in 'Lokananta' and 'Merdeka'. The tiller count for 'Sanren' at 10 mL L^{-1} Si was significantly higher than other treatments. Increased vegetative growth in 'Sanren' might facilitate the formation of tillers, leading to its increased quantity. Pertiwi et al. (2023) previously reported that Si enhanced the efficiency and rate of photosynthesis, resulting in an increased number of tillers. Similarly, Utami et al. (2020) found that enhanced photosynthesis elevated the translocation of photosynthates to plant organs, resulting in the increase in leaf number, and subsequently increased the tiller count. Each variety of shallot exhibited different responses toward environmental changes (including pests, plant diseases, temperature, soil acidity, light, climate, CO_2 levels) and agricultural practices. In this study, each variety of shallot showed a different response toward Si application. However, the application of Si seemed to have no effect on 'Lokananta'.

Harvest and yield performance of TSS-derived shallot

Application of Si prolonged the harvest age of the shallot, but no interaction was observed ($p > 0.05$) between variety and Si concentration. This indicates that the prolonged period of harvesting occurred on all samples, irrespective of variety. The harvest ages ranged from 62 to 68 DAP (Table 5). 'Merdeka' had a harvest age (~ 65 DAP) longer than 'Lokananta' (63 DAP) but was not significantly different from that of 'Sanren' (~ 65 DAP). Silica application extended the harvest age by 1.5 to 6 d. The extended harvest time might be associated with leaf uprightness, an effect of Si application. Shallots are usually harvested when the stem neck softens and starts to

bend over. Guerriero et al. (2020) indicated that Si contributes to improved leaf uprightness, facilitating better sunlight penetration to lower leaves increasing light interception and photosynthesis. Improved leaf uprightness could also delay the senescence process. However, this prolonged duration allowed for more growth on the bulbs, resulting in a higher harvest index.

Table 5. Harvest age, harvest index, number of bulbs per plant and diameter of bulbs of shallot obtained from different Si fertilization treatments. Values with identical letters in the same row and column in the specific parameter showed nonsignificant difference according to the 5% DMRT test. The plus sign denotes an interaction between two factors. The negative sign denotes the absence of interaction.

	Harvest age (d)				Harvest index				Number of bulbs per plant				Diameter of bulb (cm)			
Treatment	0 mL L^{-1}	5 mL L^{-1}	10 mL L^{-1}	Average	0 mL L^{-1}	5 mL L^{-1}	10 mL L^{-1}	Average	0 mL L^{-1}	5 mL L^{-1}	10 mL L^{-1}	Average	0 mL L^{-1}	5 mL L^{-1}	10 mL L^{-1}	Average
Sanren	62.00	63.75	68.00	64.58^{ab}	0.82	0.83	0.91	0.85^{a}	4.50	6.06	7.38	5.98^{a}	2.31^{cd}	2.44^{bc}	2.86^{a}	2.54
Lokananta	62.50	62.50	64.00	63.00^{b}	0.74	0.76	0.83	0.78^{b}	4.38	4.50	5.00	4.63^{b}	2.15^{d}	2.18^{d}	2.17^{d}	2.17
Merdeka	64.00	64.00	68.00	65.33^{a}	0.85	0.79	0.89	0.84^{a}	5.75	5.25	6.31	5.77^{a}	2.29^{cd}	2.52^{bc}	2.73^{ab}	2.51
Average	62.83^{q}	63.42^{q}	66.67^{p}	(-)	0.80^{q}	0.79^{q}	0.88^{p}	(-)	4.88^{q}	5.27^{q}	6.23^{p}	(-)	2.25	2.38	2.59	(+)

The variety and Si fertilizer concentration exhibited no interaction regarding harvest index (HI) (Table 5). But the HI of 'Sanren' and 'Merdeka' was higher ($P < 0.05$) than that of 'Lokananta'. In this study, the HIs were more than 0.7, which conformed with the result of Rahayu et al. (2019) who stated that the HI for shallots is a minimum of 0.7. The HI is associated with photosynthesis and assimilate partitioning, with a high HI indicating greater photosynthates are allocated to the bulb as nutrient storage than to foliage growth. An increase in the photosynthetic rate correlates with an increase in photosynthates (Mutia, 2019; Putri and Nihayati, 2024). Increased photosynthesis might be assisted by leaf uprightness as an effect of Si application, resulting in increased bulb counts/sizes (Putri et al., 2017).

The variety and concentration of silica fertilizer had a significant impact on the number of bulbs, despite no interaction being observed (Table 5). 'Sanren' and 'Merdeka' had more harvested bulbs than 'Lokananta'. On the other hand, the number of bulbs at a Si concentration of 10 mL L^{-1} was significantly greater than that at 0 and 5 mL L^{-1}. Considering these differences, Si application seemed to affect the outcome more than genetics. An increase in the number of tillers correlates with a greater production of bulbs within a plant. Kharolina et al. (2023) indicate that the quantity of tillers affects the number of bulbs. This increase in the number of tillers and leaves (Table 4) might be representative of the number of bulbs produced. The quantity of bulbs per plant is directly proportional to the number of tillers. Nonetheless, a reduction in the number of bulbs, as observed in 'Merdeka' (5 mL L^{-1} Si), resulted in an increase in bulb diameter.

The interaction between cultivar and Si fertilization significantly affected the harvested bulb diameter. 'Sanren' and 'Merdeka' showed large increases in bulb diameter after Si application. On the other hand, no change in bulb diameter was observed for 'Lokananta'. This showed that bulb diameter tends to be more influenced by plant genetics and environmental factors including light intensity. Increased plant height and leaf count in shallots (Table 2) led to enhanced photosynthesis, resulting in the formation of larger bulbs. This was in agreement with a previous study. Mandlik et al. (2020) reported that Si boosted photosynthesis in garlic plants. Bhangare and Shinde (2020) reported that the application of Si resulted in an increase in the diameter of onion bulbs. Bulb diameter is directly related to bulb weight, hence affecting the harvest index (Shen et al., 2022; Ameliana et al., 2024).

In this study, yield measurements further indicate that the benefits of Si application are most prominent in 'Sanren'. This cultivar yielded a greater number of bulbs per plant, exhibited larger bulb diameters, and demonstrated a superior harvest index in comparison to the other cultivars. While 'Merdeka' showed some improvement in yield, its overall magnitude and consistency were less than those of 'Sanren'. In contrast, 'Lokananta' exhibited minimal yield response, underscoring its low affinity for Si-driven physiological enhancement. The findings indicate a significant correlation between vegetative vigour and yield formation in 'Sanren', reflecting a comprehensive physiological pathway from Si uptake to productivity outcomes.

Relevance to practical implementation

The results of this study showed that the application of Si fertilizer resulted in varied responses on the leaf characteristics, growth, harvest, and yield performance of shallot, depending on the cultivar. This emphasizes the importance of a better understanding of the characteristics of the cultivar used and its response to a specific fertilizer. Principal component analysis (PCA) offers further validation of the unique responsiveness of 'Sanren'. Treatments with this cultivar at high Si doses were closely associated with elevated Si levels and were positioned in contrast to heavy metals like Pb, Cu, and Cd, suggesting effective stress mitigation via Si deposition. This pattern was absent in 'Merdeka' and 'Lokananta', further confirming that Si benefits are most pronounced and physiologically integrated in 'Sanren'.

In this study, improved leaf characteristics and growth performance due to Si application significantly correlated ($p < 0.05$) with shallot productivity and yield (Figure 3). Enhanced leaf and growth performance resulted in a higher number of bulbs per plant ($r > 0.734$, $p < 0.05$) and bigger diameter of the bulbs produced ($r > 0.78$, $p < 0.05$). Thus, it was apparent that the mechanism of improved shallot productivity after Si application was due to enhanced growth performance. A higher rate of photosynthesis supported by a higher nutrient uptake resulted in higher shallot productivity and yield. Considering this correlation, it is thus easier for farmers to predict the increased productivity of TSS-derived shallot by evaluating the increased growth performance after fertilizer application. Furthermore, Si contributes to preventing heavy metal uptake and accumulation in the leaves. This may be beneficial for improving food safety for the consumer. Heavy metal contamination has been a rising health issue among food consumers and industries. A method to prevent, reduce, or eliminate these compounds is highly sought after. However, further analysis on the harvested bulbs should be done to better understand the physicochemical changes that have possibly happened as a result of Si application, related to quality changes and food safety.

	Plant Height	Number of Leaves	Number of Tillers	Harvest Age	Harvest Index	Number of Bulbs per plant	Diameter of Bulb	Content of Si	Thickness of Leaf Cuticle
Plant Height		0.738	0.865	0.677	0.580	0.734	0.909	0.546	0.657
Number of Leaves	0.738		0.906	0.717	0.718	0.905	0.837	0.92	0.862
Number of Tillers	0.865	0.906		0.708	0.636	0.885	0.87	0.797	0.838
Harvest Age	0.677	0.717	0.708		0.841	0.886	0.884	0.687	0.91
Harvest Index	0.580	0.718	0.636	0.841		0.875	0.78	0.645	0.796
Number of Bulbs per plant	0.734	0.905	0.885	0.886	0.875		0.878	0.803	0.963
Diameter of Bulb	0.909	0.837	0.87	0.884	0.78	0.878		0.756	0.83
Content of Si	0.546	0.92	0.797	0.687	0.645	0.803	0.756		0.796
Thickness of Leaf Cuticle	0.657	0.862	0.838	0.91	0.796	0.963	0.83	0.796	

1.0

0.5

Figure 3. Heatmap of the result of Pearson correlation analysis for responses obtained from different Si fertilization treatments.

In regard to the challenges faced by TSS to replace the use of bulbs as planting materials, TSS-derived shallot was reported to have a longer harvest time. In this study, we found that the use of TSS is still feasible. The harvest time of a plant is influenced by genetic and environmental factors (climatic conditions, water availability, and soil fertility). The physiological maturity level of the seeds or seedlings employed is also crucial. At optimum physiological maturity, seeds possess sufficient nutrient reserves to facilitate optimal germination and growth. In this study, TSS was first cultivated in a nursery before it was transplanted to the cultivation plot; hence, the TSS was proved to be able to grow in optimum condition. In total, the total duration for harvest from TSS was approximately 92 d (28 d in a nursery and 64 d in a cultivation bed), significantly longer than using bulbs (50-60 DAP) as planting material. However, since the nursery can be done in parallel with shallot cultivation, the use of TSS is still able to provide flexibility in planting and harvest arrangements. Furthermore, the advantages offered by TSS, such as lower requirements of planting materials needed and a more flexible option of storage, should ease the cultivation management for farmers. This will significantly improve the efficiency of shallot cultivation.

CONCLUSIONS

Si application was beneficial for shallots derived from true shallot seed; the degree of effectiveness was highly dependent on the variety used. The physiological, anatomical, vegetative, yield-related, and multivariate evidence collectively demonstrate that 'Sanren' is the most responsive cultivar to Si application. The ability to absorb and physiologically utilize Si leads to consistent enhancements in plant structure, growth performance, and yield. 'Merdeka' shows moderate responsiveness, whereas 'Lokananta' exhibits minimal to no compatibility with Si-based fertilization. The findings emphasize the significant influence of cultivar genetics on the effectiveness of Si application and highlight the necessity of choosing responsive cultivars to maximize agronomic advantages. Meanwhile, alternative fertilizers to optimize 'Merdeka' and 'Lokananta' should be evaluated due to their low response to Si-based fertilizer.

Author contribution

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Conflict of interest

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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