

Original Research Article

Effects of Melatonin and Silicon on Selected Physiological Traits and Fruit Quality of Strawberry (*Fragaria × ananassa* Duch)

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Abstract: An experiment was conducted in a plastic greenhouse in Najaf Governorate, Iraq, during the 2025 growing season to evaluate the effects of melatonin and silicon on vegetative growth and fruit quality of strawberry (*Fragaria × ananassa* Duch.) cv. Rubygem. The experiment was arranged in a split-plot layout within a randomized complete block design with three replicates. The main plots were assigned to melatonin concentrations of 0, 100, and 200 $\mu\text{mol L}^{-1}$, whereas the subplots were assigned to silicon concentrations of 0, 50, and 100 mg Si L^{-1} . Measurements included plant height, leaf number, leaf area, shoot dry weight, fruit total soluble solids, and fruit total sugar content. The results showed that melatonin at 200 $\mu\text{mol L}^{-1}$ outperformed the control for the measured traits, with increases of 15.09, 20.77, 15.08, 7.45, 46.37, and 30.09%, respectively. Silicon at 100 mg Si L^{-1} also produced the highest mean values, with increases of 11.81, 20.04, 18.19, 8.77, 27.38, and 34.36%, respectively, compared with the treatment without silicon. The combination of the two highest concentrations, M2S2, produced the highest numerical means for all six traits, with increases in total soluble solids and total sugars of 83.50 and 71.34%, respectively, relative to M0S0. These findings indicate the potential of melatonin and silicon to improve vegetative growth and fruit quality of strawberry within the treatment levels and experimental conditions investigated.

Keywords: Strawberry (*Fragaria × ananassa*); Melatonin; Silicon; Vegetative Growth; Fruit Quality; Total Soluble Solids; Total Sugars; Greenhouse Cultivation; Rubygem Cultivar.

INTRODUCTION

Strawberry (*Fragaria × ananassa* Duch.) is an economically and nutritionally important fruit crop because of its vitamin C and antioxidant compound contents. Its market and nutritional value is determined by the combined contribution of fruit quantity and quality. Strawberry fruit quality is defined by a range of external and internal attributes, including fruit size, shape, color, texture, aroma, and sugar and organic acid contents. These attributes are essential criteria for evaluating fruit quality and consumer acceptance, while anthocyanins contribute to the characteristic fruit color and enhance nutritional value through their antioxidant activity. Therefore, investigating fruit quality components is an important aspect of assessing strawberry productivity, alongside yield quantity [4].

Melatonin is a compound that regulates physiological processes in plants and has attracted increasing attention for its role in modulating stress responses and supporting the antioxidant defense system. Study [7], showed that foliar application of melatonin improved photosynthetic pigment contents and carbohydrate and nitrogen metabolism in strawberry plants, in addition to increasing the activity of several antioxidant enzymes. These findings provide a physiological basis for investigating melatonin as a treatment that may improve strawberry growth, yield, and fruit quality, while accounting for the dependence of the response on the concentration applied and the surrounding environmental conditions. Nevertheless, strawberry responses to melatonin are not uniform across production systems. Study [2], showed that its application toward the end of the production season in tunnels did not significantly improve fruit production or

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most quality attributes, despite an increase in endogenous fruit melatonin content. The authors attributed the limited response to environmental variability and differences among plants within the production system. This highlights the need to evaluate melatonin experimentally under the target growing conditions and to relate yield and quality responses to the accompanying physiological changes, rather than assuming a consistently positive effect under different conditions.

Research on strawberry has also demonstrated the potential contribution of silicon to improving certain physiological and quality traits, although its effects vary with the application method and plant water status. Study [14], showed that silicon application improved some fruit quality components. A recent study [8], demonstrated that silicon source and application rate affected strawberry chlorophyll content and yield, and that some sources were more effective than others in maintaining plant performance. In contrast, study [3], indicated that the effects of silicon-containing biostimulants were limited and variable across experiments and cultivation systems, and that the observed improvement in total yield did not necessarily translate into an increase in marketable yield. Accordingly, silicon evaluation should encompass physiological traits, yield, and fruit quality to determine the practical agronomic benefits of the treatment.

Based on these findings, the combined application of melatonin and silicon may be hypothesized to provide complementary support for photosynthesis, redox balance, and metabolic processes associated with production. Therefore, the present study aimed to evaluate the individual and interactive effects of melatonin and silicon on selected physiological traits, yield, and fruit quality of strawberry, and to identify the most effective treatments for improving productivity and quality under the study conditions.

MATERIALS AND METHODS

Experimental Site and Plant Material

The experiment was conducted in a plastic greenhouse in Najaf Governorate, Iraq, during the 2025 growing season to investigate the effects of melatonin, silicon, and their interaction on selected physiological traits and fruit quality of strawberry (*Fragaria × ananassa* Duch.).

The cultivar Rubygem was used. Representative soil samples were collected from the surface layer at a depth of 0–30 cm before planting and analyzed to determine soil texture, pH, electrical conductivity, and organic matter content. The soil had a clay loam texture.

Experimental Design and Treatments

A factorial experiment was arranged in a split-plot layout within a randomized complete block design (RCBD) with three replicates. The main plots were assigned to melatonin concentrations of 0, 100, and 200 $\mu\text{mol L}^{-1}$, equivalent to 0, 23.23, and 46.46 mg L^{-1} , and designated M0, M1, and M2, respectively. The subplots were assigned to silicon concentrations of 0, 50, and 100 mg Si L^{-1} , designated S0, S1, and S2, respectively.

Melatonin concentrations were randomly allocated to the main plots within each block, and silicon concentrations were then randomly allocated to the subplots within each main plot. The experiment therefore comprised nine factorial treatment combinations, each replicated three times, resulting in a total of 27 subplot experimental units.

Each subplot experimental unit covered an area of 7500 cm^2 , equivalent to 0.75 m^2 , with dimensions of 125 × 60 cm, and contained six transplants distributed in two planting rows. The rows were spaced 25.98 cm apart, leaving approximately 17 cm between each row and the edge of the raised bed. The transplants were arranged in an equilateral triangular pattern, with a distance of 30 cm between adjacent planting positions. A distance of 50 cm was maintained between the last plant in one experimental unit and the first plant in the next to minimize interference between units. The experiment included a total of 162 plants, excluding any additional guard plants.

Crop Management and Irrigation

Transplants that failed to establish were replaced within 7 days of transplanting, which took place on 1 September 2025, and before treatment application began. Weeds were removed manually, and runners, dry leaves, and diseased leaves were removed uniformly from all experimental units. Ventilation, flower management, and pollination procedures were implemented. Plants were irrigated using a drip irrigation system. Irrigation timing and quantities were adjusted according to plant water status and soil moisture to maintain adequate moisture for growth and avoid waterlogging, with uniform irrigation management across treatments. Pest control measures were applied as needed, with consistent management procedures and adherence to preharvest safety intervals.

Sampling and Measurements

Five plants were randomly selected from those designated for measurements in each experimental unit, and their mean measurements were used to represent the experimental unit in the statistical analysis. Separate plants were allocated

for shoot dry weight determination. Leaf samples were collected at the stage of five fully expanded leaves, using leaves that were as similar as possible in age and position on the plant. Fruit samples were collected at a uniform stage of maturity.

MEASURED TRAITS

1. **Plant Height (cm)**
2. **Leaf Number (leaves plant⁻¹)**
3. **Leaf Area (cm²).** Leaf area was measured using ImageJ software after photographing the leaves laid flat without overlap, with a scale of known length positioned in the same plane as the leaves. Images were calibrated using the reference scale, after which the blade outline of each leaflet was delineated and its area calculated. The areas of the three leaflets were summed to obtain the compound leaf area, following the image analysis procedures for the software (11).
4. **Shoot dry weight (g plant⁻¹).** The shoots of plants designated for this measurement were separated from the roots, placed in paper bags, and dried to a constant weight.
5. **Fruit total soluble solids (TSS).** Total soluble solids were measured according to the method described in reference (9).
6. **Fruit total sugar content (%).** Total soluble sugars were determined using the phenol–sulfuric acid method described in reference (5).

Statistical Analysis

The data were subjected to analysis of variance for a factorial experiment arranged in a split-plot layout within a randomized complete block design, using [Genstat] software.

RESULTS AND DISCUSSION

Plant Height

The data in Table (1) showed that melatonin treatment M2 produced the highest mean plant height of 24.26 cm, compared with 21.08 cm under M0, representing a 15.09% increase, with no significant difference from M1, which recorded 23.45 cm. This increase may be attributed to the regulation of hormonal status and protection of photosynthetic pigments, thereby supporting elongation growth. This interpretation is consistent with the increased auxin and chlorophyll contents in leaves of melatonin-treated strawberry plants under cold stress reported in study [15].

With silicon application, mean plant height increased from 21.68 cm under S0 to 22.87 and 24.24 cm under S1 and S2, respectively, representing an 11.81% increase under S2 compared with S0. This response may be associated with improved photosynthetic efficiency and the provision of resources for developing tissues. Study [14], showed that silicon enhanced antioxidant protection and nitrogen assimilation in strawberry, depending on irrigation conditions and the application method.

Among the combined treatments, M2S2 produced the highest mean plant height of 25.12 cm, whereas M0S0 recorded the lowest value of 19.10 cm, representing a 31.52% increase, with no significant difference from M1S2. This performance may be consistent with the complementary effects of the two compounds in supporting growth, as indicated by study (1) in Ethiopian mustard under chromium stress.

Table 1: Effects of melatonin, silicon, and their combined treatments on plant height

Mean	S2	S1	S0	Treatments
21.08	23.00	21.16	19.10	M0
23.45	24.62	23.41	22.34	M1
24.26	25.12	24.05	23.62	M2
	24.24	22.87	21.68	Mean
	M*S = 1.33	S = 0.70	M = 0.93	LSD 0.05

Leaf Number

The results in Table (2) showed an increase in mean leaf number from 17.67 leaves plant⁻¹ under M0 to 19.84 and 21.34 leaves plant⁻¹ under M1 and M2, respectively, representing a 20.77% increase under M2 compared with M0. This response may reflect an improved supply of assimilates to vegetative tissues and the maintenance of leaf activity. It agrees with the increase in leaf number of melatonin-treated strawberry plants reported in study [7].

Silicon produced the highest mean leaf number under S2, at 21.68 leaves plant⁻¹, compared with 19.10 under S1 and 18.06 under S0, representing a 20.04% increase relative to the control. This improvement may be attributed to reduced oxidative damage and the maintenance of leaf function, thereby supporting continued growth and leaf formation. This interpretation is supported by the physiological responses described for strawberry in study [14].

The M2S2 combination produced the highest leaf number of 24.81 leaves plant⁻¹, compared with 16.31 leaves plant⁻¹ under M0S0, representing a 52.12% increase. This response may be associated with improved leaf performance when the two compounds are combined. Study [6].

Table 2: Effects of melatonin, silicon, and their combined treatments on leaf number

Mean	S2	S1	S0	Treatments
17.67	19.20	17.50	16.31	M0
19.84	21.04	19.81	18.67	M1
21.34	24.81	20.01	19.20	M2
	21.68	19.10	18.06	Mean
	M*S = 2.10	S = 0.80	M = 1.03	LSD 0.05

Leaf Area

The data in Table (3) showed that melatonin treatment M2 produced the highest mean leaf area of 51.66, followed by M1 at 48.57, whereas the mean decreased to 44.89 under M0. This represented a 15.08% increase under M2 compared with M0. Leaf expansion may be attributed to improved hormonal balance and the maintenance of tissue activity. This interpretation is supported by the increases in auxin, pigment contents, and antioxidant capacity reported in melatonin-treated strawberry plants in study [15].

Silicon application was accompanied by an increase in leaf area to 52.56 under S2, compared with 48.08 under S1 and 44.47 under S0, representing an 18.19% increase over the control. This increase may be associated with the protection of membranes and photosynthetic components, thereby supporting continued leaf expansion. Study [14], showed that some strawberry responses to silicon were associated with reduced membrane peroxidation and protection of the photosynthetic apparatus.

Leaf area reached its maximum under M2S2, with a mean of 56.68, compared with 42.25 under M0S0, representing a 34.15% increase, with no significant difference from M1S2. This response may reflect complementary support for water relations and photosynthetic efficiency, consistent with the findings of study [1].

Table 3: Effects of melatonin, silicon, and their combined treatments on leaf area

Mean	S2	S1	S0	Treatments
44.89	48.27	44.15	42.25	M0
48.57	52.74	48.61	44.36	M1
51.66	56.68	51.48	46.82	M2
	52.56	48.08	44.47	Mean
	M*S = 4.42	S = 2.93	M = 3.02	LSD 0.05

Shoot Dry Weight

The results in Table (4) indicated an increase in mean shoot dry weight from 10.60 g plant⁻¹ under M0 to 10.97 and 11.39 g plant⁻¹ under M1 and M2, respectively, representing a 7.45% increase under M2 compared with M0. M1 did not differ significantly from either treatment. The increase may reflect improved carbon and nitrogen supply, thereby supporting dry matter accumulation, in agreement with the findings of study [7], in melatonin-treated strawberry plants.

Among the silicon treatments, the highest mean shoot dry weight was 11.41 g plant⁻¹ under S2, compared with 11.07 under S1 and 10.49 under S0, representing an 8.77% increase over the control, with no significant difference between S1 and S2. This improvement may be associated with the provision of nutritional and biosynthetic requirements. Study [12], showed improvements in certain indicators of strawberry nutrition and growth.

The M2S2 combination produced the highest shoot dry weight of 11.86 g plant⁻¹, compared with 10.09 g plant⁻¹ under M0S0, representing a 17.54% increase, with no significant difference from M1S2 or M2S1. This increase may reflect complementary improvements in assimilation and biosynthesis, consistent with the enhanced growth and protein content observed following the combined application of melatonin and silicon oxide nanoparticles in rice in study [6].

Table 4: Effects of melatonin, silicon, and their combined treatments on shoot dry weight

Mean	S2	S1	S0	Treatments
10.60	11.01	10.71	10.09	M0
10.97	11.36	11.05	10.51	M1
11.39	11.86	11.45	10.88	M2
	11.41	11.07	10.49	Mean
	M*S = 1.03	S = 0.52	M = 0.76	LSD 0.05

Fruit Total Soluble Solids (TSS)

Table (5) shows that mean total soluble solids increased from 7.03 under M0 to 8.66 under M1 and 10.29 under M2, representing a 46.37% increase under M2 compared with M0. This response may be attributed to enhanced accumulation of soluble compounds in the fruit during development and ripening. The result agrees with the increase in this trait reported in melatonin-treated strawberry cv. Haruhi [10].

Silicon also produced the highest mean total soluble solids under S2, at 9.63, compared with 8.80 under S1 and 7.56 under S0, representing a 27.38% increase over the control. Improved nutritional status may contribute to the supply of assimilates to the fruit, with the findings of study [12], providing indirect support for this pathway. However, study [13] reported no response of this trait to silicon, highlighting its dependence on cultivar and growing conditions.

When the two factors were combined, M2S2 produced the highest mean of 11.23, compared with 6.12 under M0S0, representing an 83.50% increase, with no significant difference from M2S1. The increase in soluble solids may be consistent with the improvement in photosynthetic performance under combined treatment described in Ethiopian mustard in study [1].

Table 5: Effects of melatonin, silicon, and their combined treatments on fruit total soluble solids (TSS)

Mean	S2	S1	S0	Treatments
7.03	7.93	7.05	6.12	M0
8.66	9.73	8.80	7.45	M1
10.29	11.23	10.55	9.11	M2
	9.63	8.80	7.56	Mean
	M*S = 0.91	S = 0.45	M = 0.63	LSD 0.05

Fruit Total Sugar Content (%)

The results in Table (6) showed an increase in mean fruit total sugar content to 7.22% under M2, compared with 6.37% under M1 and 5.55% under M0, representing a 30.09% increase under M2 relative to the control. This response may be associated with the role of melatonin in regulating carbohydrate metabolism, thereby supporting carbohydrate accumulation in the fruit. The increases in glucose, sucrose, and starch in strawberry tissues reported in study [7].

Silicon increased mean total sugar content from 5.53% under S0 to 6.19% under S1 and 7.43% under S2, representing a 34.36% increase under S2 compared with S0. This response may reflect an improved balance among carbohydrate production, utilization, and accumulation. It is consistent with the potential of silicon to modify strawberry fruit quality, as demonstrated in study [14].

Sugar content reached its highest value under M2S2, at 8.43%, compared with 4.92% under M0S0, representing a 71.34% increase. This improvement may be associated with support for carbon metabolism when the two compounds.

Table 6: Effects of melatonin, silicon, and their combined treatments on fruit total sugar content (%)

Mean	S2	S1	S0	Treatments
5.55	6.32	5.42	4.92	M0
6.37	7.55	6.02	5.56	M1
7.22	8.43	7.13	6.12	M2
	7.43	6.19	5.53	Mean
	M*S = 0.83	S = 0.38	M = 0.55	LSD 0.05

CONCLUSION

Melatonin and silicon application improved vegetative growth and selected fruit quality indicators of strawberry cv. Rubygem. Melatonin at 200 $\mu\text{mol L}^{-1}$ and silicon at 100 mg Si L^{-1} elicited the greatest responses among the concentrations tested. Their combined treatment produced the highest numerical means for all six traits, particularly total soluble solids and total sugars, although it did not significantly outperform every other combination for all traits. These

findings highlight the potential use of both compounds to improve strawberry growth and fruit quality under protected cultivation conditions in Najaf Governorate.

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