

## **Response of Gynoecious Cucumber Hybrids to Foliar Application of Silicon Dioxide Nanoparticles under Heat Stress Conditions**

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### **Abstract**

The present study aimed to evaluate the response of five gynoecious cucumber hybrids to foliar application of silicon dioxide nanoparticles (SiO<sub>2</sub> -NPs) under heat stress conditions and to identify the most effective hybrid-SiO<sub>2</sub> -NP combination for improving vegetative growth, fruit characteristics, and yield. This study was conducted in the greenhouses of the College of Agriculture, University of Anbar, during the spring season of 2025–2026 to evaluate the response of five gynoecious cucumber hybrids to foliar application of silicon dioxide nanoparticles (SiO<sub>2</sub> -NPs) under heat stress conditions. The experiment was arranged in a randomized complete block design (RCBD) using a split-plot arrangement with three replicates. Cucumber hybrids were assigned to the main plots, while three concentrations of SiO<sub>2</sub> -NPs (0, 50, and 100 mg L<sup>-1</sup>) were allocated to the subplots. Vegetative growth traits, total number of flowers, selected fruit characteristics, and yield were evaluated. Significant differences among the hybrids were observed for plant height, dry weight, fruit diameter, rind thickness, and yield, whereas internode length, stem diameter, and total number of flowers were not significantly affected. Foliar application of SiO<sub>2</sub> -NPs improved most of the studied traits, with the concentration of 100 mg L<sup>-1</sup> producing the greatest enhancement in vegetative growth and yield. In contrast, the highest rind thickness was recorded at 50 mg L<sup>-1</sup>, while fruit diameter was not significantly influenced by the applied concentrations. The interaction between hybrids and SiO<sub>2</sub> -NP concentrations was significant for most of the evaluated traits. Hybrid H1, particularly when treated with 100 mg L<sup>-1</sup> SiO<sub>2</sub> -NPs, exhibited superior performance in several vegetative growth traits and yield. These findings suggest that foliar application of 100 mg L<sup>-1</sup> SiO<sub>2</sub> nanoparticles may be adopted to improve cucumber productivity under greenhouse heat stress conditions.

**Keywords:** *Cucumis sativus* L., Silicon dioxide nanoparticles (SiO<sub>2</sub> -NPs), Heat stress, Greenhouse cultivation, Gynoecious hybrids, Yield.

\*A research paper extracted from a Master's thesis by the first researcher

### **Introduction**

Cucumber (*Cucumis sativus* L.) is one of the most important vegetable crops of the family *Cucurbitaceae* owing to its high nutritional and economic value. Its cultivation has expanded widely under greenhouse conditions to ensure year-round production and increase economic

returns [24]. However, cucumber is highly sensitive to elevated temperatures, particularly during vegetative growth and flowering, making heat stress one of the major constraints limiting greenhouse production [12].

In Iraq, greenhouse-grown cucumber is frequently exposed to high temperatures,

especially when planting is delayed until the end of the growing season. Such conditions often exceed the optimum temperature required for normal growth, leading to reduced photosynthetic efficiency, excessive accumulation of reactive oxygen species (ROS), impaired water balance, and ultimately lower vegetative growth, fruit set, yield, and fruit quality [8, 18, 25].

Improving plant tolerance to abiotic stress has become an important objective in modern crop production. Silicon has attracted considerable attention because it enhances photosynthetic efficiency, maintains cell membrane integrity, reduces water loss, and strengthens antioxidant defense mechanisms under stress conditions [2, 16]. Compared with conventional silicon sources, silicon dioxide nanoparticles ( $\text{SiO}_2$  -NPs) possess greater biological activity due to their small particle size and high specific surface area, resulting in improved absorption and translocation within plant tissues [20]. Consequently,  $\text{SiO}_2$  -NPs have shown promising potential for alleviating heat stress and enhancing plant growth and productivity [4, 7].

The response of cucumber hybrids to heat stress varies according to their genetic background, making the evaluation of hybrid performance under modern management practices essential. Despite the increasing interest in silicon nanoparticles for vegetable production, information regarding the response of gynoecious cucumber hybrids to  $\text{SiO}_2$  -NPs under heat stress, particularly under Iraqi greenhouse conditions, remains limited. Therefore, the present study aimed to evaluate the response of selected gynoecious cucumber hybrids to foliar application of silicon dioxide nanoparticles and to identify the most effective hybrid– $\text{SiO}_2$  -NP combination for improving

vegetative growth, yield, and selected fruit characteristics under heat stress conditions.

## **Materials and Methods**

### **Experimental Site**

A field experiment was conducted during the spring growing season of 2025–2026 in the greenhouses of the Department of Horticulture and Landscape Gardening, College of Agriculture, University of Anbar, Iraq. Before transplanting, the greenhouse soil was prepared through leveling and standard field preparation practices. The greenhouse was divided into six planting beds, each 42 m in length. Every two beds represented one block and were further divided into 18 experimental units measuring  $4.2 \times 0.8$  m ( $3.36 \text{ m}^2$ ). Each bed contained 105 plants, resulting in a total of 630 plants in the experiment.

Seeds of five gynoecious cucumber hybrids were sown on 2 February 2026 in 209-cell seedling trays filled with peat moss as the growing medium. Seedlings were transplanted into the greenhouse on 23 February 2026. Planting was intentionally delayed to ensure that all plants were exposed to naturally occurring heat stress during the vegetative and reproductive growth stages, thereby providing a uniform level of heat stress across all experimental treatments throughout the study. Throughout the growing season, greenhouse temperatures (recorded by a data logger) ranged from  $38\text{--}42^\circ\text{C}$  (max) to  $22\text{--}25^\circ\text{C}$  (min), exceeding the optimal  $25\text{--}30^\circ\text{C}$  range for cucumber and confirming severe heat stress. Air temperature, relative humidity, and light intensity inside the greenhouse were monitored throughout the experimental period to ensure the occurrence of heat stress under natural greenhouse conditions.

### **Experimental Factors**

ISSN 2072-3857

## Cucumber Hybrids

Five gynoecious cucumber hybrids were evaluated in this study. Three hybrids (H1, H2, and H3) were developed by the Department of Horticulture and Landscape Gardening, College of Agriculture,

University of Anbar, whereas two commercial hybrids (H4 and H5) were obtained from the Horticulture Research Center, Ministry of Agriculture, Iraq. The characteristics of the evaluated hybrids are presented in (Table 1).

**Table 1.** General characteristics of the gynoecious cucumber hybrids used in the study.

| General characteristics                                                                             | Hybrid pedigree | Hybrid code |
|-----------------------------------------------------------------------------------------------------|-----------------|-------------|
| Hybrid characterized by vigorous vegetative growth, cylindrical fruits, and high yield potential.   | 1 × 4           | H1          |
| Hybrid with moderate vegetative growth, elongated cylindrical fruits, and moderate yield potential. | 9 × 6           | H2          |
| Hybrid exhibiting vigorous vegetative growth, dark green fruits, and moderate yield potential.      | 9 × 5           | H3          |
| Hybrid producing cylindrical fruits with slight ribbing and an attractive glossy green color.       | Kenz cucumber   | H4          |
| Hybrid producing uniform cylindrical fruits with a glossy dark green color and abundant fruit set.  | Majd cucumber   | H5          |

## Silicon Dioxide Nanoparticles (SiO<sub>2</sub> - NPs)

The second experimental factor consisted of three foliar application levels of silicon dioxide nanoparticles (SiO<sub>2</sub> -NPs):

- **B0:** Distilled water (control).
- **B1:** SiO<sub>2</sub> -NPs at 50 mg L<sup>-1</sup>.
- **B2:** SiO<sub>2</sub> -NPs at 100 mg L<sup>-1</sup>.

The selected concentrations were based on the recommendations of [7]. Foliar spraying was performed three times during the growing season. The first application was carried out at the 3–4 true-leaf stage, followed by two additional applications at 15-day intervals, according to [9]. Silicon dioxide nanoparticles (SiO<sub>2</sub> -NPs) with a purity of 99.5%, particle size of 15–30 nm, specific surface area of 160–240 m<sup>2</sup> g<sup>-1</sup>, and amorphous spherical morphology were used in this

study. The nanoparticles were obtained in powder form and used to prepare the foliar spray solutions at the required concentrations.

## Nanomaterial

Silicon dioxide nanoparticles (SiO<sub>2</sub> -NPs) with a purity of 99.5% were obtained from **US Research Nanomaterials, Inc. (USA)**.

## Experimental Design and Statistical Analysis

The experiment was arranged as a split-plot design within a randomized complete block design (RCBD) with three replicates. Cucumber hybrids were assigned to the main plots, whereas SiO<sub>2</sub> -NP concentrations were allocated to the subplots. Data were statistically analyzed using **GenStat** software, and treatment

means were compared using the Least Significant Difference (LSD) test at the 5% probability level [5].

### **Measured traits**

The following growth and yield traits were evaluated:

**Plant height (cm):** Measured at the end of the growing season from the soil surface to the apical growing point using a measuring tape.

**Internode length (cm):** Calculated by dividing plant height by the total number of nodes per plant.

**Stem diameter (mm):** Measured 5 cm above the soil surface using a digital Vernier caliper on five randomly selected plants from each experimental unit.

**Shoot dry weight (g plant<sup>-1</sup>):** Five previously labeled plants were harvested from each experimental unit, air-dried, and subsequently oven-dried at 60–70°C until a constant weight was reached before weighing with a digital balance.

**Total number of flowers (flowers plant<sup>-1</sup>):** Recorded throughout the growing season.

**Fruit diameter (mm):** Determined as the average of ten fruits sampled after the third foliar application by measuring the middle portion of each fruit using a digital Vernier caliper.

**Rind thickness (mm):** The fruit rind was carefully removed using a peeling tool,

and its thickness was measured at the middle of ten fruits sampled after the third foliar application using a digital Vernier caliper.

### **Greenhouse yield (t greenhouse<sup>-1</sup>):**

Estimated by multiplying the average yield per plant by the standard plant population of 1,200 plants per greenhouse.

## **Results and Discussion**

### **Plant height (cm plant<sup>-1</sup>)**

The results presented in table 2 revealed significant differences among gynoecious cucumber hybrids, silicon dioxide nanoparticle (SiO<sub>2</sub> -NP) concentrations, and their interaction with respect to plant height under heat stress conditions.

Among the evaluated hybrids, H1 produced the highest mean plant height (277.26 cm), followed by H2 (254.66 cm), whereas H3 recorded the lowest mean value (244.19 cm).

Regarding the effect of SiO<sub>2</sub> -NP concentrations, the S100 treatment produced the highest mean plant height (283.24 cm), whereas the control treatment (S0) recorded the lowest mean value (221.61 cm).

A significant interaction between the two experimental factors was also observed. The H2S100 treatment produced the greatest plant height (296.60 cm), whereas H3S0 recorded the lowest value (209.13 cm).

Table 2. Effect of silicon dioxide nanoparticle (SiO<sub>2</sub> -NP) concentrations, gynoecious cucumber hybrids, and their interaction on plant height (cm plant<sup>-1</sup>) under heat stress conditions.

| Mean          | Hybrids       |               |               |               |               | Nano SO     |
|---------------|---------------|---------------|---------------|---------------|---------------|-------------|
|               | H5            | H4            | H3            | H2            | H1            |             |
| <b>221.61</b> | 214.17        | 211.95        | 209.13        | 212.67        | 260.13        | <b>S0</b>   |
| <b>257.12</b> | 245.85        | 250.65        | 252.42        | 254.72        | 281.95        | <b>S50</b>  |
| <b>283.24</b> | 274.20        | 284.65        | 271.03        | 296.60        | 289.70        | <b>S100</b> |
|               | <b>244.74</b> | <b>249.08</b> | <b>244.19</b> | <b>254.66</b> | <b>277.26</b> | <b>Mean</b> |
| <b>H × S</b>  |               | <b>S</b>      |               | <b>H</b>      |               | <b>LSD</b>  |
| 17.82         |               | 11.36         |               | 7.97          |               | <b>0.05</b> |

### Internode length (cm)

The results presented in table 3 revealed that silicon dioxide nanoparticle (SiO<sub>2</sub>-NP) concentrations significantly affected internode length under heat stress conditions, whereas no significant differences were observed among gynoecious cucumber hybrids or in the interaction between the two experimental factors.

Regarding the effect of SiO<sub>2</sub>-NP concentrations, the S100 treatment produced the highest mean internode length (7.57 cm), although it did not differ significantly from the S50 treatment, which recorded a mean value of 7.52 cm. In contrast, the control treatment (S0) recorded the lowest mean internode length (7.02 cm).

No significant differences were observed among the interaction treatments.

Table 3. Effect of silicon dioxide nanoparticle (SiO<sub>2</sub> -NP) concentrations, gynoecious cucumber hybrids, and their interaction on internode length (cm) under heat stress conditions.

| Mean         | Hybrids     |             |             |             |             | Nano SO     |
|--------------|-------------|-------------|-------------|-------------|-------------|-------------|
|              | H5          | H4          | H3          | H2          | H1          |             |
| <b>7.02</b>  | 6.88        | 6.84        | 6.54        | 7.08        | 7.78        | <b>S0</b>   |
| <b>7.52</b>  | 7.18        | 7.55        | 7.63        | 7.20        | 8.06        | <b>S50</b>  |
| <b>7.57</b>  | 7.24        | 7.64        | 7.36        | 7.83        | 7.76        | <b>S100</b> |
|              | <b>7.10</b> | <b>7.34</b> | <b>7.18</b> | <b>7.37</b> | <b>7.87</b> | <b>Mean</b> |
| <b>H × S</b> |             | <b>S</b>    |             | <b>H</b>    |             | <b>LSD</b>  |

|     |      |     |             |
|-----|------|-----|-------------|
| N.S | 0.30 | N.S | <b>0.05</b> |
|-----|------|-----|-------------|

### Stem diameter (mm)

The data presented in table 4 showed that silicon dioxide nanoparticle (SiO<sub>2</sub> -NP) concentrations significantly affected stem diameter under heat stress conditions, whereas no significant differences were detected among the gynoecious cucumber hybrids.

Regarding the effect of SiO<sub>2</sub>-NP concentrations, the S100 treatment produced the highest mean stem diameter (15.36 mm), whereas the control treatment (S0) recorded the lowest mean value (13.50 mm).

A significant interaction between the two experimental factors was also observed. The H1S100 and H2S100 treatments produced the greatest stem diameter (15.65 mm), whereas H1S0 and H5S0 recorded the lowest value (12.78 mm).

Table 4. Effect of silicon dioxide nanoparticle (SiO<sub>2</sub> -NP) concentrations, gynoecious cucumber hybrids, and their interaction on stem diameter (mm) under heat stress conditions.

| Mean         | Hybrids      |              |              |              |              | Nano SO     |
|--------------|--------------|--------------|--------------|--------------|--------------|-------------|
|              | H5           | H4           | H3           | H2           | H1           |             |
| <b>13.50</b> | 12.78        | 14.13        | 13.81        | 14.13        | 12.78        | <b>S0</b>   |
| <b>14.25</b> | 14.07        | 14.48        | 14.69        | 14.48        | 14.07        | <b>S50</b>  |
| <b>15.36</b> | 15.65        | 15.61        | 15.30        | 15.61        | 15.65        | <b>S100</b> |
|              | <b>14.17</b> | <b>14.74</b> | <b>14.60</b> | <b>14.74</b> | <b>14.17</b> | <b>Mean</b> |
| <b>H × S</b> | <b>S</b>     |              | <b>H</b>     |              | <b>LSD</b>   |             |
| 1.28         | 0.52         |              | N.S          |              | <b>0.05</b>  |             |

### Shoot dry weight (g plant<sup>-1</sup>)

The results presented in table 5 revealed significant differences among gynoecious cucumber hybrids, silicon dioxide nanoparticle (SiO<sub>2</sub> -NP) concentrations, and their interaction with respect to shoot dry weight under heat stress conditions.

Among the evaluated hybrids, H1 produced the highest mean shoot dry weight (101.19 g plant<sup>-1</sup>), followed by H2 (94.54 g plant<sup>-1</sup>), whereas H5 recorded the lowest mean value (81.30 g plant<sup>-1</sup>).

Regarding the effect of SiO<sub>2</sub>-NP concentrations, the S100 treatment produced the highest mean shoot dry weight (106.84 g plant<sup>-1</sup>), whereas the control treatment (S0) recorded the lowest mean value (75.60 g plant<sup>-1</sup>).

A significant interaction between the two experimental factors was also observed. The H1S100 treatment produced the highest shoot dry weight (124.33 g plant<sup>-1</sup>), followed by H2S100 (111.03 g plant<sup>-1</sup>), whereas H4S0 recorded the lowest value (72.90 g plant<sup>-1</sup>).

**Table 5.** Effect of silicon dioxide nanoparticle (SiO<sub>2</sub> -NP) concentrations, gynoecious cucumber hybrids, and their interaction on shoot dry weight (g plant<sup>-1</sup>) under heat stress conditions.

| Mean          | Hybrids      |              |              |              |               | Nano SO     |
|---------------|--------------|--------------|--------------|--------------|---------------|-------------|
|               | H5           | H4           | H3           | H2           | H1            |             |
| <b>75.60</b>  | 73.63        | 72.90        | 73.77        | 78.40        | 79.30         | <b>S0</b>   |
| <b>90.17</b>  | 83.33        | 91.17        | 82.20        | 94.20        | 99.93         | <b>S50</b>  |
| <b>106.84</b> | 86.93        | 111.20       | 100.72       | 111.03       | 124.33        | <b>S100</b> |
|               | <b>81.30</b> | <b>91.76</b> | <b>85.56</b> | <b>94.54</b> | <b>101.19</b> | <b>Mean</b> |
| <b>H × S</b>  |              | <b>S</b>     |              | <b>H</b>     |               | <b>LSD</b>  |
| 11.42         |              | 5.11         |              | 5.26         |               | <b>0.05</b> |

#### **Total number of flowers (flowers plant<sup>-1</sup>)**

The results presented in table 6 revealed that silicon dioxide nanoparticle (SiO<sub>2</sub> -NP) concentrations and their interaction with gynoecious cucumber hybrids significantly affected the total number of flowers under heat stress conditions, whereas no significant differences were observed among the hybrids.

Regarding the effect of SiO<sub>2</sub>-NP concentrations, the S100 treatment

produced the highest mean total number of flowers (76.98 flowers plant<sup>-1</sup>), significantly exceeding the S0 (73.87 flowers plant<sup>-1</sup>) and S50 (70.62 flowers plant<sup>-1</sup>) treatments.

A significant interaction between the two experimental factors was also observed. The H1S50 treatment produced the highest total number of flowers (88.42 flowers plant<sup>-1</sup>), followed by H1S100 (87.83 flowers plant<sup>-1</sup>), whereas H3S50 recorded the lowest value (54.25 flowers plant<sup>-1</sup>).

**Table 6.** Effect of silicon dioxide nanoparticle (SiO<sub>2</sub> -NP) concentrations, gynoecious cucumber hybrids, and their interaction on the total number of flowers (flowers plant<sup>-1</sup>) under heat stress conditions.

| Mean         | Hybrids |       |       |       |       | Nano SO     |
|--------------|---------|-------|-------|-------|-------|-------------|
|              | H5      | H4    | H3    | H2    | H1    |             |
| <b>73.87</b> | 79.75   | 61.67 | 72.41 | 74.25 | 81.25 | <b>S0</b>   |
| <b>70.62</b> | 71.17   | 54.25 | 67.00 | 72.25 | 88.42 | <b>S50</b>  |
| <b>76.98</b> | 78.92   | 65.25 | 76.83 | 76.09 | 87.83 | <b>S100</b> |

|       |       |       |       |       |       |      |
|-------|-------|-------|-------|-------|-------|------|
|       | 76.61 | 60.39 | 72.08 | 74.20 | 85.83 | Mean |
| H × S |       | S     |       | H     |       | LSD  |
| N.S   |       | 3.09  |       | 7.61  |       | 0.05 |

### Fruit diameter (mm)

The results presented in table 7 revealed significant differences among gynoecious cucumber hybrids and the interaction between hybrids and silicon dioxide nanoparticle (SiO<sub>2</sub> -NP) concentrations with respect to fruit diameter under heat stress conditions. However, SiO<sub>2</sub> -NP concentrations alone did not significantly affect this trait.

Among the evaluated hybrids, H4 produced the largest mean fruit diameter (26.36 mm), whereas H1 recorded the lowest mean value (22.23 mm). No significant differences were observed among the SiO<sub>2</sub> -NP concentrations.

A significant interaction between the two experimental factors was detected. The H4S50 treatment produced the largest fruit diameter (27.07 mm), followed by H2S0 and H3S0, both of which recorded 26.56 mm. In contrast, H1S50 produced the smallest fruit diameter (21.73 mm).

Table 7. Effect of silicon dioxide nanoparticle (SiO<sub>2</sub> -NP) concentrations, gynoecious cucumber hybrids, and their interaction on fruit diameter (mm) under heat stress conditions.

| Mean  | Hybrids |       |       |       |       | Nano SO |
|-------|---------|-------|-------|-------|-------|---------|
|       | H5      | H4    | H3    | H2    | H1    |         |
| 24.44 | 24.40   | 26.56 | 22.85 | 26.56 | 21.81 | S0      |
| 24.34 | 22.86   | 27.07 | 24.59 | 25.45 | 21.73 | S50     |
| 24.09 | 22.98   | 25.44 | 24.70 | 24.19 | 23.15 | S100    |
|       | 23.42   | 26.36 | 24.04 | 25.40 | 22.23 | Mean    |
| H × S |         | S     |       | H     |       | LSD     |
| 1.74  |         | N.S   |       | 2.68  |       | 0.05    |

### Rind thickness (mm)

The results presented in table 8 revealed significant differences among gynoecious cucumber hybrids, silicon dioxide nanoparticle (SiO<sub>2</sub> -NP) concentrations, and their interaction with respect to rind thickness under heat stress conditions.

Among the evaluated hybrids, H2 produced the highest mean rind thickness (1.4222 mm), whereas H1 recorded the lowest mean value (1.2356 mm).

Regarding the effect of SiO<sub>2</sub> -NP concentrations, the S50 treatment produced the highest mean rind thickness (1.3940 mm), although it did not differ significantly from the S100 treatment, which recorded a mean value of 1.3893

mm. In contrast, the control treatment (S0) produced the lowest mean rind thickness (1.2920 mm).

The H1S50 treatment produced the greatest rind thickness (1.6067 mm), whereas H2S50 recorded the lowest value (1.1233 mm).

A significant interaction between the two experimental factors was also observed.

**Table 8.** Effect of silicon dioxide nanoparticle (SiO<sub>2</sub> -NP) concentrations, gynoecious cucumber hybrids, and their interaction on rind thickness (mm) under heat stress conditions.

| Mean          | Hybrids       |               |               |               |               | Nano SO     |
|---------------|---------------|---------------|---------------|---------------|---------------|-------------|
|               | H5            | H4            | H3            | H2            | H1            |             |
| <b>1.2920</b> | 1.1767        | 1.5467        | 1.5467        | 1.1367        | 1.3300        | <b>S0</b>   |
| <b>1.3940</b> | 1.4300        | 1.3500        | 1.3500        | 1.1233        | 1.6067        | <b>S50</b>  |
| <b>1.3893</b> | 1.4367        | 1.2700        | 1.2700        | 1.4467        | 1.3300        | <b>S100</b> |
|               | <b>1.3478</b> | <b>1.3889</b> | <b>1.3889</b> | <b>1.2356</b> | <b>1.4222</b> | <b>Mean</b> |
| <b>H × S</b>  |               | <b>S</b>      |               | <b>H</b>      |               | <b>LSD</b>  |
| 0.0135        |               | 0.0060        |               | 0.0166        |               | <b>0.05</b> |

#### Greenhouse yield (t greenhouse<sup>-1</sup>)

The results presented in table 9 revealed significant differences among gynoecious cucumber hybrids, silicon dioxide nanoparticle (SiO<sub>2</sub> -NP) concentrations, and their interaction with respect to greenhouse yield under heat stress conditions.

Among the evaluated hybrids, H1 produced the highest mean greenhouse yield (4.117 t greenhouse<sup>-1</sup>), whereas H5 recorded the lowest mean value (3.174 t greenhouse<sup>-1</sup>).

Regarding the effect of SiO<sub>2</sub> -NP concentrations, the S100 treatment produced the highest mean greenhouse yield (3.908 t greenhouse<sup>-1</sup>), significantly outperforming both the S50 (3.189 t greenhouse<sup>-1</sup>) and S0 (3.401 t greenhouse<sup>-1</sup>) treatments.

A significant interaction between the two experimental factors was also observed. The H1S100 treatment produced the highest greenhouse yield (4.282 t greenhouse<sup>-1</sup>), whereas H3S50 recorded the lowest yield (2.590 t greenhouse<sup>-1</sup>).

**Table 9.** Effect of silicon dioxide nanoparticle (SiO<sub>2</sub> -NP) concentrations, gynoecious cucumber hybrids, and their interaction on greenhouse yield (t greenhouse<sup>-1</sup>) under heat stress conditions.

| Mean         | Hybrids |       |       |       |       | Nano SO   |
|--------------|---------|-------|-------|-------|-------|-----------|
|              | H5      | H4    | H3    | H2    | H1    |           |
| <b>3.401</b> | 3.215   | 3.295 | 3.143 | 3.373 | 3.979 | <b>S0</b> |

|              |              |              |              |              |              |             |
|--------------|--------------|--------------|--------------|--------------|--------------|-------------|
| <b>3.189</b> | 2.688        | 2.835        | 2.590        | 3.739        | 4.092        | <b>S50</b>  |
| <b>3.908</b> | 3.620        | 3.768        | 3.935        | 3.933        | 4.282        | <b>S100</b> |
|              | <b>3.174</b> | <b>3.299</b> | <b>3.222</b> | <b>3.682</b> | <b>4.117</b> | <b>Mean</b> |
| <b>H × S</b> |              | <b>S</b>     |              | <b>H</b>     |              | <b>LSD</b>  |
| 0.702        |              | 0.270        |              | 0.486        |              | <b>0.05</b> |

The beneficial effects of foliar-applied silicon dioxide nanoparticles (SiO<sub>2</sub> -NPs) on cucumber performance under heat stress can be attributed to their ability to preserve key physiological processes during exposure to high temperatures. Heat stress is known to impair photosynthetic efficiency, accelerate the accumulation of reactive oxygen species (ROS), and disrupt cellular metabolism, ultimately restricting plant growth [13]. In the present study, SiO<sub>2</sub> -NP application alleviated these adverse effects by improving cellular water balance, reducing transpirational water loss, maintaining photosynthetic activity, and enhancing the antioxidant defense system, thereby sustaining normal metabolic activity under stressful conditions [11, 22 ].

The improvement in physiological performance was reflected in enhanced vegetative growth, as evidenced by increased plant height, internode length, stem diameter, and shoot dry weight. These responses are likely associated with improved cell division and elongation, together with greater carbohydrate production resulting from sustained photosynthesis [14, 1]. Furthermore, the higher accumulation of dry matter indicates that a greater proportion of photoassimilates was allocated to plant growth rather than being consumed in repairing heat-induced cellular damage[23].

Improved vegetative growth also contributed to enhanced reproductive performance. Plants with a well-developed

canopy are generally more efficient in producing and translocating photoassimilates to developing flowers and fruits, thereby promoting flower retention, fruit development, and ultimately increasing yield. These responses are further supported by the role of silicon in enhancing antioxidant activity, regulating plant water relations, improving nutrient uptake, and maintaining hormonal balance under stress conditions [17, 20].

Although SiO<sub>2</sub> -NPs generally improved fruit characteristics, the magnitude of the response varied among the evaluated traits. This variation suggests that the physiological response to silicon nanoparticles is trait-dependent and does not necessarily increase linearly with application rate. Similar observations have been reported by [3] . who demonstrated that SiO<sub>2</sub> nanoparticles alleviated heat stress in cucumber by enhancing photosynthetic efficiency and biomass accumulation. The superior performance of the H1 × 50 mg L<sup>-1</sup> interaction for total flower number and rind thickness reflects a genotype-specific response rather than the overall effect of the 50 mg L<sup>-1</sup> concentration. The overall superiority of the 100 mg L<sup>-1</sup> treatment in yield indicates that the optimum SiO<sub>2</sub> -NP concentration varied according to the trait and the genetic background of the hybrid.. Comparable responses were also reported by [22,15] in watermelon, confirming the positive role of silicon nanoparticles in improving growth

and productivity under heat stress conditions.

## Conclusions

This study demonstrated significant genotypic variation among female cucumber hybrids in their response to heat stress, highlighting differences in their inherent heat tolerance. Foliar application of nano-silicon oxide significantly improved vegetative growth and yield-related traits compared with the untreated control. Among the tested concentrations, 100 mg L<sup>-1</sup> consistently produced the greatest improvement in most evaluated parameters. Hybrid H1 exhibited superior performance for the majority of growth and yield traits, and its combination with 100 mg L<sup>-1</sup> nano-silicon oxide resulted in the most favorable overall response. These findings suggest that integrating heat-tolerant cucumber hybrids with foliar application of nano-silicon oxide can effectively mitigate the adverse effects of heat stress and enhance greenhouse cucumber growth and productivity. The results also provide a practical basis for improving cucumber production under high-temperature conditions and support the potential use of nano-silicon oxide as a sustainable management strategy in protected cultivation.

## References

- [1] Ahmad, B., Shabbir, A., Jaleel, H., Khan, M. M. A., and Sadiq, Y. 2023. Silicon nanoparticles as a sustainable strategy to improve plant resilience under abiotic stresses. *Plants*, 12(4), 847. <https://doi.org/10.3390/plants12040847>
- [2] Ali, S., Mehmood, A., and Khan, N. 2021. Uptake, translocation, and consequences of nanomaterials on plant growth and stress adaptation. *Journal of Nanomaterials*, 2021, 1–17. <https://doi.org/10.1155/2021/6677616>
- [3] Anwar, T., Qureshi, H., Fatimah, H., Siddiqi, E. H., Anwaar, S., Moussa, I. M., and Adil, M. F. (2023). Improvement of physio-biochemical attributes and mitigation of salinity stress by combined application of melatonin and silicon nanoparticles in *Brassica oleracea* var. botrytis. *Scientia Hort.* 322, 112456. doi: 10.1016/j.scienta.2023.112456
- [4] Basirat, M., and Mousavi, S. 2022. Effect of foliar application of silicon on regulation of yield and nutritional responses of greenhouse cucumber under high temperature. *Journal of Plant Growth Regulation*, 41(13). <https://doi.org/10.1007/s00344-021-10562-5>
- [5] Dar, A. A. 2024. Introduction to design of experiment: A comprehensive guide (for agriculture). Astitva Prakashan. ISBN: 935838171X..
- [6] da Silva, A. P. R., da Silva, L. J. R., Deus, A. C. F., Fernandes, D. M., Büll, L. T., and Büll, L. T. 2023. Silicon application methods influence the nutrient uptake of maize plants in tropical soil. *Silicon*, 15, 7327–7334.
- [7] El-Mogy, M. M., Abdeldaym, E. A., Abdelaziz, S. M., Ismail, A. M., El-Beltagi, H. S., Ramadan, K. M. A., Mahmoud, A. W. M., and Abdel Mottaleb, S. 2025. Foliar application of calcium, silicon, and potassium nanoparticles improves growth and fruit quality of drought-stressed cucumber plants through modulation of osmolytes, antioxidant enzymes, photosynthesis efficiency, and phytohormones. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, 53(2), 14470. <https://doi.org/10.15835/nbha53214470>

- [8] **El-Remaly, E. 2023.** Morphological, physio-biochemical, and molecular indications of heat stress tolerance in cucumber. *Scientific Reports*, 13, 18729. <https://doi.org/10.1038/s41598-023-45163-7>
- [9] **González-García, Y., Flores-Robles, V., Cadenas-Pliego, G., and Juárez-Maldonado, A. 2022.** Application of two forms of silicon and their impact on the postharvest and the content of bioactive compounds in cucumber (*Cucumis sativus* L.) fruits. *BIOCELL*, 46(11), 2503–2514. <https://doi.org/10.32604/biocell.2022.021861>
- [10] **Grankina, A., and Bocharnikova, E. 2022.** Silicon-based biostimulators. In *Biostimulants Crop Production for Sustainable Agriculture* (Vol. 14, p. 85).
- [11] **Hassan, M. U., Kareem, H. A., Hussain, S., Guo, Z., Niu, J., Roy, M., Saleem, S., and Wang, Q. 2023.** Enhanced salinity tolerance in Alfalfa through foliar nano-zinc oxide application: Mechanistic insights and potential agricultural applications. *Rhizosphere*, 28, 100792. <https://doi.org/10.1016/j.rhisph.2023.100792>
- [12] **Hongal, D. A., Raju, D., Kumar, S., Talukdar, A., Das, A., Kumari, K., Dash, P. K., Chinnusamy, V., Munshi, A. D., Behera, T. K., and Dey, S. S. 2023.** Elucidating the role of key physio-biochemical traits and molecular network conferring heat stress tolerance in cucumber. *Frontiers in Plant Science*, 14, 1128928. <https://doi.org/10.3389/fpls.2023.1128928>
- [13] **Kareem, H. A., Hassan, M. U., Zain, M., Irshad, A., Shakoor, N., Saleem, S., Niu, J., Skalicky, M., Chen, Z., Guo, Z., and Wang, Q. 2022.** Nanosized zinc oxide (n-ZnO) particles pretreatment to alfalfa seedlings alleviate heat-induced morpho-physiological and ultrastructural damages. *Environmental Pollution*, 303, 119069. <https://doi.org/10.1016/j.envpol.2022.119069>
- [14] **Li, S., Liu, J., Wang, Y., Gao, Y., Zhang, Z., Xu, J., and Xing, G. 2021.** Comparative physiological and metabolomic analyses revealed that foliar spraying with zinc oxide and silica nanoparticles modulates metabolite profiles in cucumber (*Cucumis sativus* L.). *Food and Energy Security*, 10(1), e269. <https://doi.org/10.1002/fes3.269>
- [15] **Malik, M. S., Rehman, A., Shah, I. H., Arif, S., Nan, K., Yan, Y., Song, S., Hameed, M. K., Azam, M., and Zhang, Y. 2025.** Green synthesized silicon dioxide nanoparticles (SiO<sub>2</sub> NPs) ameliorated cadmium toxicity in melon by regulating antioxidant enzyme activity and stress-related gene expression. *Environmental Pollution*, 366, 125459. <https://doi.org/10.1016/j.envpol.2024.125459>
- [16] **Muslim, D. A., Al-Shareefi, M. J., and Mahmoud, S. S. 2023.** Effect of salicylic acid and nano silicon on the morphological traits of potato shoot grown in vitro under salt stress. *IOP Conference Series: Earth and Environmental Science*, 1158, 102005.
- [17] **Munir, F. D. A., Sulaiman, Z., Salisu, M. A., Radin Mohd Anwar, R. N., Shith, S., Roslan, M. A., Mohamad, N. A., and Uddin, M. K. 2023.** A comprehensive review on the potential effect of silicon fertilizer and its significance for agriculture. *ICRRD Quality Index Research Journal*, 4, 149–182.
- [18] **Rashwan, M. A., Al-Helal, I. M., Al-Showaiman, S. S., Fickak, A. A.,**  
ISSN 2072-3857

**Almasoud, W. A., Alkoaik, F. N., and Ibrahim, M. N. 2024.** Increasing the productivity and quality of cucumber crop by improving the performance of the evaporative cooling system. *Heliyon*, 10(17), e36997. <https://doi.org/10.1016/j.heliyon.2024.e36997>

**[19] Sayed, E. G., Mahmoud, A. W. M., El-Mogy, M. M., Ali, M. A. A., Fahmy, M. A. M., and Tawfic, G. A. 2022.** The effective role of nano-silicon application in improving productivity and quality of grafted tomato grown under salinity stress. *Horticulturae*, 8, 293. <https://doi.org/10.3390/horticulturae8040293>

**[20] Taiz, L., Zeiger, E., Møller, I. M., and Murphy, A. 2022.** Plant physiology and development (7th ed.). Oxford University Press.

**[21] Thakral, V., Bhat, J. A., Kumar, N., Myaka, B., Sudhakaran, S., Patil, G., Sonah, H., Shivaraj, S. M., and Deshmukh, R. 2021.** Role of silicon under contrasting biotic and abiotic stress conditions provides benefits for climate smart cropping. *Environmental and Experimental Botany*, 189, 104545.

**[22] Valdez-Aguilar, L. A., Alvarado-Camarillo, D., Solórzano-Martínez, P., García-Cerda, L. A., and Vera-Reyes, I. 2025.** Synergistic effects of zinc and silicon dioxide nanoparticles improve cucumber (*Cucumis sativus* L.) drought tolerance. *Plant Nano Biology*, 13, 100193. <https://doi.org/10.1016/j.plana.2025.100193>

**[23] Verma, K. K., Song, X. P., Tian, D. D., Singh, M., Zou, L., Chen, M. Y., Wang, Y. R., Li, D. D., and Li, Y. R. 2022.** Application of silicon nanoparticles in mitigating abiotic stresses in plants: A

review. *Frontiers in Plant Science*, 13, 925522. <https://doi.org/10.3389/fpls.2022.925522>

**[24] Wehner, T. C., Naegele, R. P., and Myers, J. R. 2020.** *Cucurbits: Crop production science in horticulture* (2nd ed.). CABI.

**[25] Xue, R., Zhang, C., Yan, H., Li, J., Ren, J., Akhlaq, M., Hameed, M. U., and Disasa, K. N. 2023.** Physiological response of tomato and cucumber plants to micro-spray in high-temperature environment: A scientific and effective means of alleviating crop heat stress. *Agronomy*, 13(11), 2798. <https://doi.org/10.3390/agronomy13112798>