

## 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

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### Abstract

A field experiment was conducted to evaluate the effects of calcium (Ca), potassium (K), and silicon (Si) nanoparticles on growth and production under water stress conditions. The combined application of Ca, K, and Si significantly improved the growth of drought-stressed cucumber plants compared to untreated plants. All nanoparticles similarly enhanced total chlorophyll levels, chlorophyll fluorescence (Fv/Fm), photosynthetic rates, and water use efficiency, as well as the accumulation of indole-acetic acid (IAA) and essential nutrients [magnesium (Mg), potassium (K), calcium (Ca), phosphorus (P), and nitrogen (N)] in the leaves of drought-stressed cucumber plants. The foliar application of combined K, Ca, and Si nanoparticles increased the activity of antioxidant enzymes, alleviating drought stress and scavenging reactive oxygen species (ROS). In contrast, the combined application of Ca, K, and Si nanoparticles resulted in a significant reduction in malondialdehyde (MDA) and abscisic acid (ABA) levels compared to the control treatment. Furthermore, the use of K, Ca, and Si nanoparticles, either alone or in combination, notably improved total yield and its components, including fruit weight and the number of fruits. Compared to untreated plants, the combined application of Ca, K, and Si nanoparticles also increased carbohydrates, total soluble solids, ascorbic acid, and total phenol content, while reducing cucurbitacin content.

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**Keywords:** *Cucumis sativus*; nano-element application; agro-physiological properties; enzymatic antioxidants; water stress; yield

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## Introduction

The world population is rapidly increasing each year, leading to a growing demand for food. The global population is projected to reach between 9 and 10 billion by 2050, necessitating an expansion of agricultural areas and inputs (Bahar *et al.*, 2020; Abdalla *et al.*, 2023). Despite the need for increased productivity, arable land worldwide is limited and cannot adequately support this growing population. A swift 70% increase in global crop yield is required to meet the food needs of the world's population by 2050 (Abdalla *et al.*, 2023; Rockström *et al.*, 2017; Asghar *et al.*, 2024). Additionally, the anticipated adverse effects of climate change on food crops contribute to an uncertain future for agriculture and fulfilling dietary requirements if arable lands are exclusively dedicated to crop production (Práválie *et al.*, 2021; Akça *et al.*, 2022). Consequently, multiple reports have emphasized the importance of considering the earth's marginal lands to ensure food security. Moreover, utilizing marginal soils for food crop production, especially in developing countries, increases the available land for agricultural development and helps secure food for impoverished populations living in these areas (Hussain *et al.*, 2020).

On the other hand, marginal soils may be subjected to various environmental stresses, such as inappropriate temperatures, low soil fertility, limited availability of fresh water, poor water quality, high temperatures, intense light, and salinity (Alhaji *et al.*, 2024). Limited availability of fresh water, also known as water stress, is regarded as one of the key challenges hindering agricultural extension and impeding food security development, especially in arid and semi-arid regions (Abdelaziz *et al.*, 2021). Additionally, numerous studies have shown that insufficient irrigation water in marginal soils adversely affects plant growth, functions, and chemical properties, resulting in lower chlorophyll levels, reduced photosynthesis, decreased nutrient absorption, and diminished production of plant hormones (Abdelaziz *et al.*, 2021; Shehata *et al.*, 2022). Ultimately, these changes lead to a reduction in both vegetative growth and the quality of cucumber plant yields.

The cucumber plant (*Cucumis sativus*) is considered a major vegetable cash crop belonging to the *Cucurbitaceae* family. Cucumber fruits are rich in vitamin C, vitamin K, minerals, polyphenols, and dietary fibers, which offer many health benefits. Cucumber plants are particularly sensitive to water shortages (Abdelaziz *et al.*, 2021). To mitigate the harmful effects of drought stress, the use of nanoparticles of calcium, silicon, and potassium has been shown to enhance plants' ability to cope with water shortages and other challenging conditions (Mahmoud *et al.*, 2021). Recently, the application of nanofertilizers has gained popularity, particularly on poor-quality soil, due to the various advantages associated with this technology (Malik *et al.*, 2021; Irewale *et al.*, 2024; Gab Allah *et al.*, 2025).

Nano-fertilizers consist of small particles that encapsulate essential nutrients in nanomaterials, which facilitate better management of nutrient release and reduce nutrient loss from the soil (Benavides-Mendoza *et al.*, 2024). These fertilizers can be utilized in marginal soils to enhance nutrient availability and decrease soil fixation (Abdelsattar *et al.*, 2024). Furthermore, the small size and large surface area of nano-fertilizers enable more effective absorption by plants compared to conventional fertilizers (Ali *et al.*, 2025). The nano-fertilizers include calcium (Ca), potassium (K), and silicon (Si), which are vital for plant growth and productivity. Various studies have indicated that the nano form of calcium (Ca), potassium (K), and silicon (Si) is more effective than conventional forms in improving leaf area, chlorophyll content, nutrient levels in plant tissues, leaf water content, plant biomass, total yield, photosynthesis rate, and plant hormones, as well as both enzymatic and non-enzymatic antioxidants in different crops under normal and stress conditions (Mahmoud *et al.*, 2023). To date, no research has been conducted to evaluate the combined effects of calcium (Ca), potassium (K), and silicon (Si) as foliar applications on the growth and yield of drought-stressed cucumber plants in greenhouse conditions. This study aims to assess the effectiveness of silicon (Si-NP), potassium (K-NP), and calcium (Ca-

NP) nanoparticles, applied either separately or in combination, on the growth performance, photosynthesis, plant hormones, antioxidant enzymes, leaf nutrient content, yield quantity, and fruit quality of cucumber plants cultivated in sandy soil with limited water.

## Materials and Methods

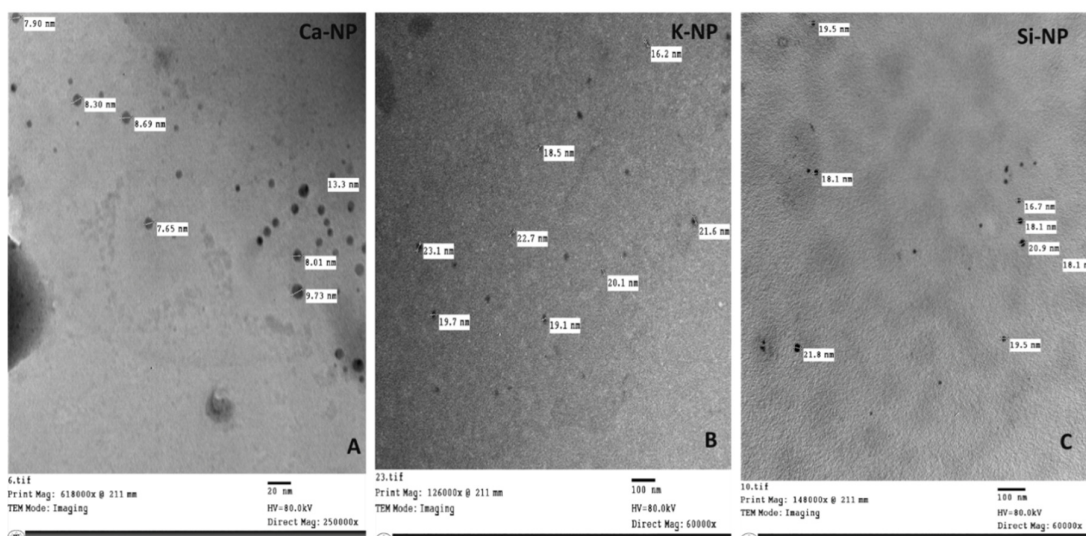
### *Synthesis and characterization of K, Ca, and Si-NP*

The reagents employed in this study were of analytical grade, and the nanoparticles were synthesized from their respective precursors: potassium persulfate ( $K_2S_2O_8$ ), silicon tetrachloride ( $SiCl_4$ ) and calcium carbonate ( $CaCO_3$ ), calcium fluoride ( $CaF_2$ ). All these reagents were acquired from Sigma Chemical Co. (St. Louis, Missouri, USA). Potassium nanoparticles (Figure 1A) were synthesized following the method outlined by Dong *et al.* (2018) and (Mahmoud and Swaefy, 2020), with modifications. These modifications involved the use of methacrylic acid polymerization in a chitosan solution (Amjad *et al.* 2024) as a carrier, followed by coating in a buffer solution for 18 hours at ambient temperature. The preparation occurred in two distinct stages. In the initial stage, 0.25 g of chitosan was dissolved in an aqueous solution of 0.5% (v/v) methacrylic acid, with magnetic stirring for 5 hours. In the second stage, while stirring continued, 0.2 mmol of potassium persulfate ( $K_2S_2O_8$ ) and 0.4 mmol of potassium sulfate ( $K_2SO_4$ ) were introduced, and the mixture was stirred until it turned clear. Polymerization then proceeded at 75°C under continued magnetic stirring for 7 hours, resulting in the formation of a nanoparticle suspension. This suspension was subjected to 1.5 psi pressure intermittently for 3 days, with 7-hour sessions each day. Afterward, the solution was centrifuged at 500 rpm for 30 minutes and then cooled in an ice bath for 2 hours.

Silicon nanoparticles (Figure 1B), as described by (Zhu and Gong, 2014), were synthesized using mild reagents, specifically (3-aminopropyl) trimethoxysilane and sodium ascorbate, in a rapid reaction conducted in a standard round-bottom flask at ambient temperature and pressure. An aqueous mixture of trimethoxysilane (97%) and sodium ascorbate was prepared in a 1:4 molar ratios, with continuous stirring. To this mixture, 1.25 mL of 0.1 M sodium ascorbate was added, and the solution was stirred for 40 minutes. The reaction was then subjected to intermittent pressure of 1.5 psi for 5 days, with 8-hour sessions each day. Following this, the resulting precipitate was dried in an oven at 80°C for 10 hours.

Nano-calcium (Figure 1C), in the form of calcium oxide ( $CaO$ ), was synthesized following the method that modifications based on Mahmoud *et al.* (2022). A solution of calcium hydroxide ( $Ca(OH)_2$ , 3 mmol) was gradually added dropwise to 1.5 grams of calcium carbonate ( $CaCO_3$ ) powder at 25°C over a 2-hour period. Subsequently, 3 ml of dilute phosphoric acid (98%) solution was incorporated, and the mixture was stirred magnetically for 30 minutes. The resulting product was then dried in an oven at 85°C for 5 hours. After drying, the material was filtered and thoroughly washed using deionized water in a water/toluene mixture with high-speed stirring, followed by a rinse with deionized water for 20 minutes. In the next step, a 1 M calcium fluoride ( $CaF_2$ ) solution was added and stirred magnetically for 2 hours. The solution was then filtered, centrifuged at 1200 rpm for 25 minutes, and subjected to intermittent pressure of 1.5 psi for 3 days, with 3-hour daily sessions.

A JEOL 1010 transmission electron microscope, operating at 80 kV (JEOL, Japan), was used to examine the size and morphology of the nanoparticles. A single drop of the nanoparticle suspension was placed onto a copper grid coated with carbon and permitted to air dry at ambient temperature before being analyzed using transmission electron microscopy (TEM). The Image-Pro Plus 4.5 software was used to directly measure the sizes of the nanoparticles from the TEM images, and the size reported is the average of three separate measurements (Figure 1).



**Figure 1.** Transmission electron microscopy (TEM) for synthesized potassium (K-NP, A), calcium (Ca-NP, B), and silicon (Si-NP, C) nanoparticles

*Characteristics of study site*

A greenhouse experiment was conducted on cucumber (*Cucumis sativus* cv. Laurens) on a private farm from the first of April to the 29<sup>th</sup> of July during two successive seasons of 2022-2023. Before cucumber cultivation, the physicochemical attributes of the experimental soil (Table 1) and the chemical composition of the compost utilized (Table 2) were determined using the methods outlined by Klute (Holliday, 1990).

**Table 1.** Physicochemical properties of experimental soil

| Physical properties |          |          | Texture | Chemical properties |           |          |         |                                |                  |                 |                |                              |                 |                              |
|---------------------|----------|----------|---------|---------------------|-----------|----------|---------|--------------------------------|------------------|-----------------|----------------|------------------------------|-----------------|------------------------------|
| Sand (%)            | Silt (%) | Clay (%) |         | pH                  | EC (dS/m) | *SOC (%) | T.N (%) | Cations (meq.L <sup>-1</sup> ) |                  |                 |                | Anion (meq.L <sup>-1</sup> ) |                 |                              |
|                     |          |          |         |                     |           |          |         | Ca <sup>++</sup>               | Mg <sup>++</sup> | Na <sup>+</sup> | K <sup>+</sup> | HCO <sub>3</sub>             | Cl <sup>-</sup> | SO <sub>4</sub> <sup>-</sup> |
| 90.5                | 6.50     | 3.0      | sandy   | 7.82                | 1.35      | 0.38     | 0.03    | 4.16                           | 1.52             | 3.24            | 0.21           | 0.54                         | 3.3             | 2.13                         |

\*SOC= Soil organic Carbon

The experiment was conducted in a thoroughly controlled greenhouse set in a local climate characterized as arid, with a chilly winter and a humid summer. The cucumber growth cycle necessitated adjustments to both temperature and humidity within the greenhouse. The temperature was maintained at 28 ± 2°C during the day and 20 ± 2°C at night, while the average relative humidity was set at 80%. Additionally, the average solar radiation measurement was approximately 389.50 W/m<sup>2</sup>.

**Table 2.** Chemical properties of applied compost

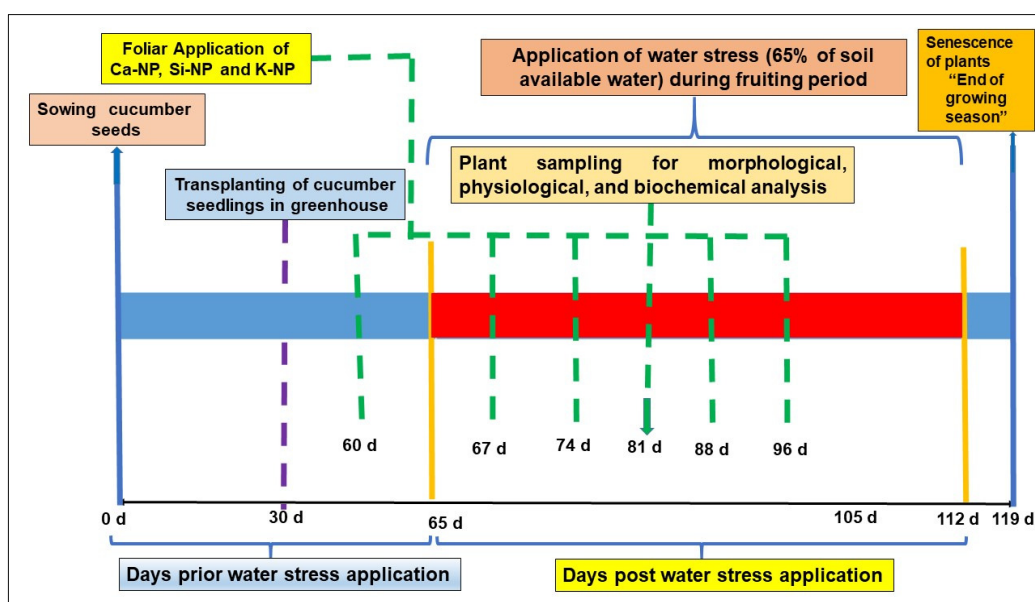
| pH  | EC (dS.m <sup>-1</sup> ) | OM (%) | OC (%) | Total content of bacteria | Phosphate dissolving bacteria | *T.N (%) | TK (%) | pP (%) | C/N ratio | Fe (ppm) | Mn (ppm) | Cu (ppm) | Zn (ppm) |
|-----|--------------------------|--------|--------|---------------------------|-------------------------------|----------|--------|--------|-----------|----------|----------|----------|----------|
| 7.5 | 2.4                      | 70     | 33.11  | 2.5 x 10 <sup>7</sup>     | 2.5 x 10 <sup>6</sup>         | 1.82     | 1.25   | 1.29   | 16.1      | 829      | 110      | 158      | 268      |

\*T.N= Total nitrogen

*Experimental layout and treatments*

Cucumber seeds (*Cucumis sativus* cv. Laurens) were planted in cell trays filled with a growing medium composed of peat moss, vermiculite, and perlite in a 1:1:1 ratio on the 1<sup>st</sup> of February, 2022 and 2023 at a fiberglass greenhouse. After four weeks, cucumber seedlings were transported and transplanted in a controlled greenhouse. Cucumber seedlings were transplanted at space of 1.0 m among rows and 0.50 m among plants.

After 60 days of transplanting, cucumber seedlings fertilized with five nano-treatments, including, 1- nano-potassium (K-NP), 2- nano-calcium (Ca-NP), and 3- nano-silicon (Si-NP), at rates of 75 ppm, 40 ppm, and 20 ppm, respectively. Each nano-treatment was sprayed once per week on cucumber plants at 60, 67, 64, 81, 88, and 96 days after transplanting. Furthermore, the control (CON) was sprayed with distilled water. For each growing season, a randomized complete block design was used, with every treatment replicated ten times. Drip irrigation is a system used to irrigate the cucumber plants during the experimentation. Meanwhile, water stress was applied during the fruiting period of cucumber plants. All treated and untreated cucumber plants were subjected to one level of water stress (65% of soil accessible water) for 47 days, starting from days 65 to 112 of seedling transplantation (Figure 2). Prior to applying water stress, the available water in the experimental soil was obtained by measuring the distinction between permanent wilting point (PWP) and field capacity (FC) and then the taking into account soil depth in drip irrigation, where water zones overlap along the line. Time Domain Reflectometry (TDR) was utilized to measure accessible water and monitor irrigation duration. After 50 days of seedling cultivation, samples of cucumber plants were collected randomly to determine the morphological, physiological, and biochemical measurements.



**Figure 2.** Graphical schema shows the timetable of nano-treatment (Ca-NP, Si-NP, and K-NP) application and sampling of cucumber plants subjected to water stress (65% of soil available water) for 47 days during the fruiting period

#### *Data recorded*

##### Agronomical measurements

After 80 days of seedling transplanting, five water-stressed cucumber plants from every treatment were selected randomly to assess the height of plant, number of branches, and leaf area. The number of fruits per plant, the average fruit weight, and fruit output of cucumber plants were also recorded during the water stress periods (days 65– 112) and the total yield was presented as Kg/ plant.

##### Leaf chlorophyll content

Fresh leaves of water-stressed cucumber plants were determined utilizing the technique of Lichtenthaler and Buschmann (2001). Approximately 5 g of fresh leaves were homogenized in acetone (80%), then the

homogenate was centrifuged (1500xg for 15 min at 5°C) and the extracts were measured spectrophotometrically using 96-well plates. The value of total chlorophyll was defined as a mg.g<sup>-1</sup> FW.

#### Leaf photosynthetic measurements and chlorophyll fluorescence

Photosynthesis measurements, such as the net photosynthesis rate, transpiration rate, and water use efficiency, were taken from three different cucumber leaves for each treatment using the LICOR 6400 infrared gas analyzer. Furthermore, chlorophyll fluorescence was assessed with an FMS-2 fluorometer to find important values like the steady-state fluorescence yield (FS), the highest fluorescence yield when the plant is kept in the dark (FM), and the lowest fluorescence yield in the dark (F0). These measurements were repeated four times.

#### Leaf nutrients content

The content of leaf nutrients was determined as mentioned in a previous article published by Mahmoud *et al.* (2022). The leaf samples were positioned in a forced-air oven and dried at 75°C for two days and then finely powdered for assessment of element concentration in leaf tissues. In the solution containing sulfuric and perchloric acids, 200 mg of powdered leaf samples underwent digestion. Thereafter, the mixture was heated for ten minutes. Subsequently, 0.5 mL of perchloric acid was added, and heating was carried on until the solution became clear. The content of total Kjeldahl nitrogen was estimated utilizing the modified micro-Kjeldahl process as defined by Jackson (1973). Phosphorus was evaluated by a colorimetric method employing the chlorostannous molybdophosphoric blue color in sulfuric acid. By multiplying the total Kjeldahl nitrogen constant factor (6.25), the total protein content was calculated, as stated by Boulos *et al.* (2020). Leaf potassium and calcium content were assessed employing flame photometry (CORNING M 410, Sherwood Scientific Ltd., Cambridge, UK). An atomic absorption spectrophotometer (Pye-Unicam model SP-1900, US) was utilized to detect the concentration of Zn, Fe, and Mn in leaf tissues.

#### Leaf plant hormones content

Cucumber leaves were freeze-dried and ground into a fine powder. A 10 mg sample of the powdered leaves was washed three times with a solution composed of 80% methanol and 2,6-bis(1,1-dimethylethyl)-4-methylphenol at 5°C in darkness. The mixture was then centrifuged at 4000 rpm for 5 minutes, and the supernatant was collected, pH-adjusted to 8.6, and extracted with an equal volume of pure ethyl acetate, repeating the washing process three times. Anhydrous sodium sulfate was used to dehydrate the ethyl acetate extracts, which were then filtered. After evaporation and methylation of filtrate, indole-3-acetic acid (IAA) and abscisic acid (ABA) were quantified by Ati-Unicum gas-liquid chromatography and peak identification. The results of the plant hormones, abscisic acid (ABA) and indole-3-acetic acid (IAA), were expressed in µg.g<sup>-1</sup> (Vogel, 1974).

#### Free proline in plant leaves

The concentration of free proline in leaf samples was measured utilizing the process outlined by Bates *et al.* (1973). A cold extraction process was employed by homogenizing 20 mg of freeze-dried leaf material in 0.5 mL of a 60:80 ethanol-water mixture (v/v). The homogenate was incubated overnight, then centrifuged at 15,000xg for 5 minutes and filtered. A 1 mL portion of the ethanol extract was mixed with 5 mL of ninhydrin and 5 mL of glacial acetic acid. The resulting solution was then heated in a water bath at 100°C for 45 minutes. The reaction was halted by transferring the test tubes to an ice bath. The content of proline in the leaf samples was quantified using a spectrophotometer, with absorbance measured at 546 nm.

#### Leaf antioxidant enzymes

Leaf samples from cucumber plants were collected for the analysis of antioxidant enzyme activity, specifically superoxide dismutase (SOD) and catalase (CAT), following the protocol outlined by Polle *et al.* (1994). Approximately 5 g of the fifth mature leaves were frozen in liquid nitrogen, then ground and

homogenized in 5 mL of potassium phosphate buffer. The resulting homogenate was centrifuged at 1200×g for 24 minutes at 5°C, and the supernatant was utilized to measure CAT activity using the method outlined by Aebi (1984), and SOD according to the process of Beauchamp and Fridovich (1973). The results were documented as units.mg<sup>-1</sup> protein.

#### Fruit carbohydrate content

The total carbohydrate content in fruit samples was determined. A 200 mg sample was homogenized in 10 mL of 80% ethanol. Whatman filter paper was employed to filter the resulting mixture, and the filtrate and supernatant were collected separately. The alcohol extract was then combined with 5 mL of concentrated HCl and 150 mL of distilled water. The mixture was hydrolyzed for 30 minutes and then allowed to cool to ambient temperatures. Sodium carbonate (Na<sub>2</sub>CO<sub>3</sub>) was added gradually to adjust the pH of the solution to 7 (neutral). A 0.5 mL aliquot of the extract was mixed with 1 mL of Somogyi's reagent in a test tube. The test tubes were submerged in a water bath for 30 minutes and then permitted to cool to ambient temperatures. Afterward, 1 mL of arsenomolybdate reagent was added, and the final solution was diluted to a volume of 10 mL. Carbohydrate content was quantified by assessing the absorbance at 560 nm utilizing a spectrophotometer and values were expressed as g.100g<sup>-1</sup> fresh fruit weight.

#### Fruit total soluble solids content (TSS)

Fruit samples from each treatment were taken and milled in the blender to extract the juice. The TSS was assessed employing a digital refractometer (model PAL-1, Atago, Tokyo, Japan). The findings were presented as a percentage on the Brix° scale.

#### Fruit ascorbic acids content

Ascorbic acid was assessed using a titration procedure based on the Association of Official Analytical Chemists (A.O.A.C.). Around 10 g of fruit cucumber samples were homogenized with 90 mL of oxalic acid (6%) and filtered using filter paper Whatman (No.1). A 25 mL portion of the filtrate was then transferred to an Erlenmeyer flask and titrated with 2,6-dichlorophenol indophenol. The finding was documented as mg.100 g<sup>-1</sup> of fruit fresh weight.

#### Fruit phenol content

The total phenol content of cucumber fruit was assessed employing the Folin–Ciocalteu technique, with minor modification. Briefly, 5 g of cucumber fruits was homogenized with 50 mL of methanol (50%). The homogenate was shaken for 30 min filtered using Whatman filter paper. Following that, 0.2 mL of filtrate was mixed with Folin–Ciocalteu reagent (1mL) and Na<sub>2</sub>CO<sub>3</sub> (8%). The mixture was incubated in darkness for one hour and used a spectrophotometer to measure the absorbance at a 765 nm wavelength.

#### Cucurbitacin content

Cucumber fruits were collected and stored at -20°C until required for extraction. The frozen fruits were crushed in petroleum ether, and the solid residue was separated via vacuum filtration. The residue was then extracted with methanol, and the methanol extract obtained was concentrated by applying decreased pressure. After concentration, the extract was dissolved in water and subjected to successive extractions with petroleum ether and dichloromethane. A minimal volume of methanol was used to re-suspend the evaporated dichloromethane extract. Following the procedure outlined by Peters *et al.* (1997), cucurbitacin C was isolated and purified utilizing high-performance liquid chromatography (HPLC). The HPLC setup included an injector, a photodiode array detector, and a pump. A 5 mL aliquot of the methanol suspension was introduced into the system, using a mobile phase composed of methanol and water (55:45) at a flow rate of 4 mL/min. A CAPCELLPAK C18 UG80 column (250 mm × 20 mm., Shiseido, Japan) was employed for separation. As referenced by Enslin *et al.* (1957), the spectra acquired from the photodiode array detector were analyzed to

identify the cucurbitacin peak. The purified fraction was freeze-dried, yielding a white powder. The HPLC analysis confirmed the presence of a single peak, while the electron ionization (EI) mass spectrum revealed characteristic  $m/z$  fragments of 470, 482, and 500, confirming the identity of cucurbitacin C, as reported by Rice *et al.* (1981).

#### *Statistical analysis*

The obtained data during the two growing seasons of this study (2022 and 2023) were subjected to combined after doing the normality distribution test (Shapiro and Wilk, 1965) and homogeneity test (Hartley, 1950), at probability 0.05 ( $p \leq 0.05$ ). The experimental data was analyzed with statistical analysis employing statistica 7 software. Two-way analysis of variance (ANOVA) and mean values were compared using the Tukey HSD test at a confidence level of 95%. All results are shown as mean values of interaction between treatment and growing seasons (years) with standard errors (SE). Additionally, a correlation matrix and heatmap visualization of the relationships between the studied variables were generated using the Science and Research online plot (SR plot), a web-based platform for data analysis.

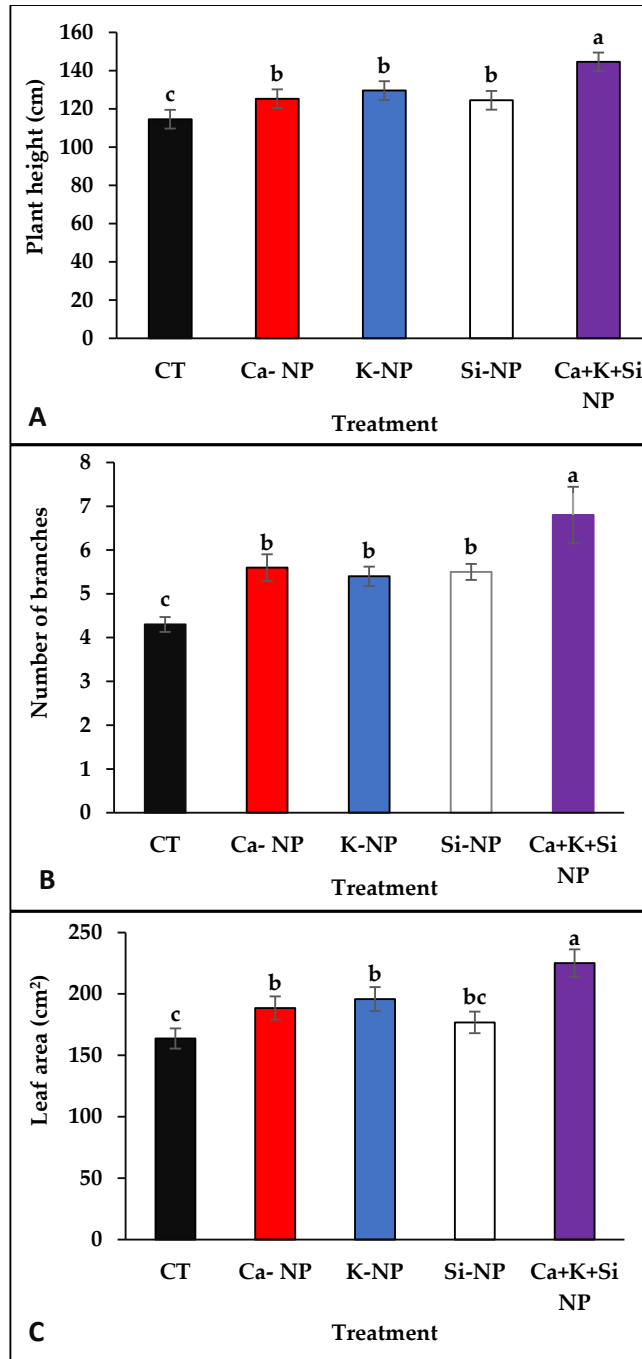
## **Results**

#### *Vegetative growth measurements*

As demonstrated in Figure 3 (A, B, and C), the foliar application of nano-treatments and water stress ( $p \leq 0.05$ ) strongly influence the growth response of cucumber plants. During water stress circumstances, foliar treatment of nano-treatment (Ca-NP, K-NP, Si-NP, and Ca+K+Si-NP) promoted the leaf area of cucumber plants, number of branches, and plant height more than control plants (CT). The maximum value of the previous parameters was observed in drought-stressed cucumber plants subjected to combination nano-treatment (Ca+K+Si-NP) followed by Ca-NP, K-NP, and Si-NP compared to control plants (CT). Compared with the CT treatment, the combination treatment led to a substantial increase in plant height (20.75%), leaf area (27.24%), and number of branches (36.76%).

#### *Leaf chlorophyll content, chlorophyll fluorescence and photosynthetic measurements*

Table 3 shows how nano-elements and water stress affect leaf pigments and photosynthesis, including the photosynthetic rate, water use efficiency, transpiration rate, and  $F_v/F_m$ . Under water stress conditions, foliar application of nano-elements (Ca-NP, K-NP, Si-NP, and Ca+K+Si-NP) significantly increased the chlorophyll content and photosynthetic parameters of cucumber leaves relative to the control ( $p \leq 0.05$ ). The cucumber plants that were treated with a mix of Ca-NP, K-NP, and Si-NP had the highest levels of chlorophyll, photosynthesis rate, water use efficiency, and  $F_v/F_m$ , while the control plants (CT) had the lowest levels. The combined treatment (Ca+K+Si-NP) raised chlorophyll levels by 18.49%, increased the photosynthesis rate by 33.79%, improved water use efficiency by 60.94%, and boosted  $F_v/F_m$  by 22.50% compared to the control treatment. On the contrary, the foliar application of Ca-NP, K-NP, Si-NP, and the combination treatment during water stress led to a significant decrease in the leaf transpiration rate by -41.16%, -44.5%, -43.66%, and -69.10%, respectively, compared to the control treatment.



**Figure 3:** Effect of nano-treatments on plant height (A), number of branches (B) and leaf area (C) of cucumber plants grown in water stress conditions. Columns indicated by the same small letters show are not statistically significant among treatments according to Tukey HSD test ( $p \leq 0.05$ ). The standard error is indicated by the bar above the columns

**Table 3.** Effect of nano-treatments on leaf pigments, and photosynthetic parameters of cucumber plants grown amid water stress conditions. Means indicated with the same small letters are not statistically significant between treatments according to Tukey HSD test ( $p \leq 0.05$ );  $\pm$  value denotes the standard error

| Treatment    | Total chlorophyll (mg·g <sup>-1</sup> FW leaves) | Photosynthetic rate ( $\mu\text{mol CO}_2 \text{ m}^{-2}\text{s}^{-2}$ ) | Transpiration rate (mmol H <sub>2</sub> O m <sup>-2</sup> s <sup>-1</sup> ) | Fv/Fm*       | WUE* ( $\mu\text{mol CO}_2 \text{ mmol H}_2\text{O}$ ) |
|--------------|--|--|---|--------------|--|
| Control (CT) | 0.97±0.12c                                       | 7.33±0.31c   | 4.87±0.24a  | 0.658±0.001c | 1.50±0.01c   |
| Ca-NP        | 1.06±0.23b                                       | 9.14±0.11b   | 3.45±0.09b  | 0.718±0.012b | 2.64±0.03b   |
| K-NP         | 1.09±0.14b                                       | 9.32±0.09b   | 3.37±0.07b  | 0.729±0.011b | 2.78±0.03b   |
| Si-NP        | 1.05±0.20bc                                      | 9.17±0.03b   | 3.39±0.05b  | 0.716±0.009b | 2.70±0.05b   |
| Ca+K+Si-NP   | 1.19±0.15a                                       | 11.07±0.03a  | 2.88±0.12c  | 0.78±0.017a  | 3.84±0.01a   |

WUE\*=Water use efficiency; Fv/Fm= Chlorophyll fluorescence

#### Leaf nutrient content

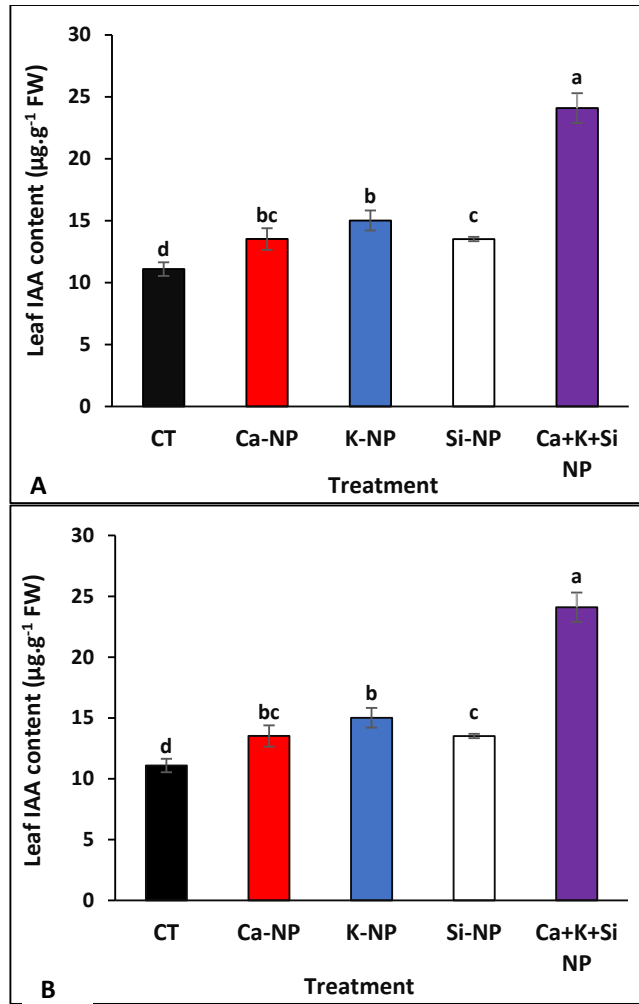
Nano-fertilizers application significantly influenced on the leaf nutrient accumulation ( $p \leq 0.05$ ) under water stress conditions, as given in Table 4. Nutrients accumulation in the leaves of cucumber plants increased due to foliar application of nano-elements either alone or in combination (Ca-NP, K-NP, Si-NP and Ca+K+Si-NP). Contrasted with the un-treated plants (CT), the greatest concentration of Fe, Mg, K, N, Ca, P, Zn, and Mn was noted in the leave of drought-stressed cucumber plants subjected to combined application (Ca+K+Si-NP) followed by Ca-NP, K-NP and Si-NP. Furthermore, the foliar application with combined nano-treatment (Ca+K+Si-NP) in cucumber under water stress was accompanied by an improvement in the N, Mn, Zn, Fe, Mg, Ca, K, and P concentration in leaves by 40.16%, 39.02%, 39.46%, 59.36%, 33.33%, 25.44%, 43.22%, and 49.38%, respectively, relative to the control treatment (CT).

**Table 4.** Impacts of nano-treatments on nutrient accumulation of cucumber plants grown under water stress conditions. Means indicated with the same small letters are not statistically significant between treatments according to the Tukey HSD test ( $p \leq 0.05$ ).  $\pm$  value denotes the standard error

| Treatment    | N (%)       | P (%)       | K (%)       | Ca (%)      | Mg (%)      | Fe (ppm)    | Zn (ppm)   | Mn (ppm)    |
|--------------|-------------|-------------|-------------|-------------|-------------|-------------|------------|-------------|
| Control (CT) | 2.13±0.09c  | 0.25±0.10c  | 2.47±0.099c | 0.89±0.036c | 0.26±0.010c | 106.4±4.3d  | 31.4±2.21c | 24.6±1.72d  |
| Ca-NP        | 3.06±0.12b  | 0.31±0.012b | 3.51±0.140b | 1.24±0.050b | 0.31±0.012b | 122.3±5.1c  | 37.2±2.61b | 29.8±2.09c  |
| K-NP         | 3.11±0.124b | 0.36±0.14b  | 3.71±0.148b | 1.28±0.067b | 0.36±0.02ab | 128.6±4.9b  | 40.1±3.01b | 33.4±2.33b  |
| Si-NP        | 3.04±0.12b  | 0.30±0.012b | 3.52±0.141b | 1.22±0.049b | 0.32±0.013b | 120.8±5.14c | 38.5±2.70b | 28.6±2.002c |
| Ca+K+Si-NP   | 3.56±0.14a  | 0.41±0.016a | 4.08±0.163a | 2.19±0.088a | 0.39±0.016a | 142.7±5.71a | 55.3±3.87a | 48.6±3.402a |

#### Leaf phytohormones content

Figure 4 displays how the levels of IAA and ABA in leaves were influenced by nano-fertilizers and water stress. Compared to the control treatment, application of Ca-NP, K-NP, Si-NP, and Ca+K+Si-NP on the leaves of cucumber plants under water stress increased IAA levels by 17.97%, 26.15%, 17.96%, and 53.97%. On the other hand, these nano-treatments caused a notable reduction in the leaf ABA level during drought stress by -21.24%, -69.41%, -29.56%, and -52.21%, respectively.



**Figure 4.** Impact of nano-treatments on (IAA- A), and (B- ABA) of cucumber plants grown under water stress conditions. Columns accompanied with the same small letters are not statistically significant between treatments according to Tukey HSD test ( $p \leq 0.05$ ). The standard error is indicated by the bar above the columns

*Oxidative stress characteristics and malondialdehyde*

The impact of water stress and nano-element application on the levels of proline, superoxide dismutase (SOD), catalase (CAT), and malondialdehyde (MDA) was presented in Table 5. The concentrations of proline, CAT, and SOD found in the cucumber leaves greatly raised in leaves of drought-stressed cucumber plants sprayed with using Ca-NP, K-NP, and Si-NP than control treatment plants. Conversely, the lowest level of the MDA was observed in the leaves of cucumber plants that were sprayed with nano-treatments (Ca-NP, K-NP, and Si-NP), while the highest amounts were seen in the control plants (CT).

**Table 5.** Effect of nano-treatments on proline, catalase (CAT), Superoxide dismutase (SOD) and malondialdehyde (MDA) of cucumber plants grown under water stress conditions. Means denoted with the same small letters are not statistically significant between treatments according to Tukey HSD test ( $p \leq 0.05$ ).  $\pm$  value denotes the standard error

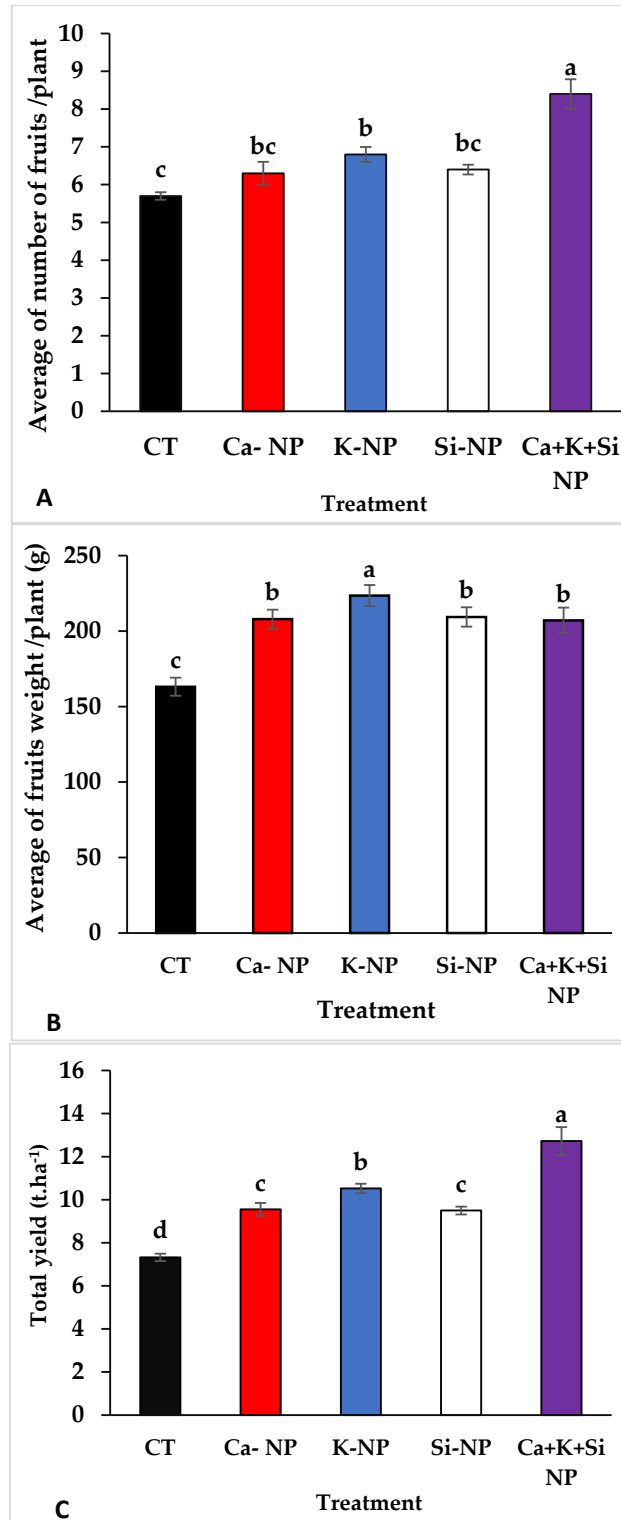
| Treatment  | Proline ( $\mu\text{M.g}^{-1}\text{FW}$ ) | Protein (%)        | MDA ( $\text{units mg}^{-1}\text{protein}$ ) | SOD ( $\text{units mg}^{-1}\text{protein}$ ) | CAT ( $\text{units mg}^{-1}\text{protein}$ ) |
|------------|---|--------------------|--|--|--|
| CT         | 4.06 $\pm$ 0.210c                         | 13.31 $\pm$ 0.089c | 8.71 $\pm$ 0.431a                            | 13.41 $\pm$ 0.67d                            | 9.772 $\pm$ 0.488d                           |
| Ca-NP      | 5.77 $\pm$ 0.29b                          | 19.13 $\pm$ 0.121b | 6.52 $\pm$ 0.325b                            | 18.61 $\pm$ 0.93b                            | 13.101 $\pm$ 0.66b                           |
| K-NP       | 5.801 $\pm$ 0.72b                         | 19.44 $\pm$ 0.124b | 6.034 $\pm$ 0.40b                            | 15.53 $\pm$ 0.77c                            | 11.03 $\pm$ 0.561c                           |
| Si-NP      | 5.77 $\pm$ 0.82b                          | 19.00 $\pm$ 0.122b | 6.711 $\pm$ 0.33b                            | 19.11 $\pm$ 0.95b                            | 13.104 $\pm$ 0.655b                          |
| Ca+K+Si-NP | 8.81 $\pm$ 0.44a                          | 22.25 $\pm$ 0.142a | 4.112 $\pm$ 0.206c                           | 21.71 $\pm$ 1.09a                            | 16.032 $\pm$ 0.81a                           |

#### *Total yield and its components*

Data on the total production and its components of cucumber plants are shown in Figure 5. All the nano-treatments significantly increased the number of fruits, fruit weight, and total output of cucumber plants ( $p \leq 0.05$ ). The maximum number of fruits and total output of cucumber plants were achieved in cucumber plants sprayed with combination treatment (Ca+K+Si-NP) relative to the other treatments. Relative to the control, the combination treatments improved the fruit number and total yield of cucumber by 32.14% and 42.44%, respectively. Conversely, the maximum fruit weight was documented in cucumber plants sprayed with K-NP, subsequently Ca-NP, Si-NP, and combination treatment, whereas the minimum value was observed in the control plants (CT). Furthermore, the fruit weight of cucumber plants treated with Ca-NP, K-NP, Si-NP, and combination treatment significantly increased by 21.53 %, 27.01%, 22.07%, and 21.23%; respectively, when compared with the control plants (CT).

#### *Fruit quality*

Table 6 shows that the chemical composition of cucumber fruits is influenced by the application of Ca-NP, K-NP, Si-NP and Ca+K+Si-NP under water stress conditions. In fact, spraying K-NP and the combination treatment (Ca+K+Si-NP) greatly increased the amounts of total carbohydrates (by 17.95% and 23.81%), total soluble solids (TSS) (by 18.85% and 37.76%), and ascorbic acid (AsA) (by 6.05% and 8.99%). In contrast, Ca-N and Si-NP treatments did not show any significant changes relative to the control plant. Regarding TPC, the use of nano-elements on the leaves increased the total phenol content in cucumber fruits. The highest amount of total phenol content was found in the cucumber fruits from plants treated with Ca+K+Si-NP, followed by those treated with Ca-NP, K-NP, and Si-NP, while the control plants had the lowest amount. On the contrary, spraying with those nano-elements, alone or in combination, on cucumber leaves causes a notable decrease in the cucurbitacin concentration in the cucumber fruits. Furthermore, the foliar application of Ca-NP, K-NP, Si-NP, and Ca+K+Si-NP on cucumber plants under drought stress conditions resulted in reductions of cucurbitacin concentration by -0.28%, -0.38%, -0.18%, and -0.60%, respectively, compared to the control plants.



**Figure 5.** Effect of nano-treatments on number of fruit (A), fruit weight (B) and Total production (c) of cucumber plants grown under water stress conditions. Columns accompanied with the same small letters are not statistically significant between treatments according to Tukey HSD test ( $p \leq 0.05$ ). The standard error is indicated by the bar above the columns.

**Table 6.** Impact of nano-treatments total carbohydrate, ascorbic acid (AsA), total soluble solids (TSS), total phenol content (TPC), cucurbitacin of cucumber fruits grown under water stress conditions. Means followed with the same small letters show are not statistically significant between treatments according to Tukey HSD test ( $p \leq 0.05$ ).  $\pm$  value presents the standard error

| Treatment  | Total carbohydrate (g.100g <sup>-1</sup> fruit) | AsA (mg.100g <sup>-1</sup> fruit) | TSS (%)           | TPC (mg GAE/g)     | Cucurbitacin ( $\mu$ g.kg <sup>-1</sup> FW) |
|------------|---|-----------------------------------|-------------------|--------------------|---|
| CT         | 3.2 $\pm$ 0.16b                                 | 2.09 $\pm$ 0.105c                 | 4.35 $\pm$ 0.217c | 11.51 $\pm$ 0.58c  | 13.9 $\pm$ 1.002a                           |
| Ca-NP      | 3.3 $\pm$ 0.17b                                 | 2.30 $\pm$ 0.114c                 | 4.51 $\pm$ 0.230c | 13.29 $\pm$ 1.01bc | 10.9 $\pm$ 1.040b                           |
| K-NP       | 3.9 $\pm$ 0.20ab                                | 2.60 $\pm$ 0.117b                 | 4.63 $\pm$ 0.301b | 15.71 $\pm$ 1.02b  | 10.1 $\pm$ 0.60b                            |
| Si-NP      | 3.2 $\pm$ 0.16b                                 | 2.27 $\pm$ 0.141c                 | 4.53 $\pm$ 0.227c | 13.31 $\pm$ 0.67bc | 11.8 $\pm$ 0.55b                            |
| Ca+K+Si-NP | 4.2 $\pm$ 0.21a                                 | 3.39 $\pm$ 0.169a                 | 4.78 $\pm$ 0.110a | 16.48 $\pm$ 0.82a  | 8.7 $\pm$ 0.440c                            |

### Correlation study

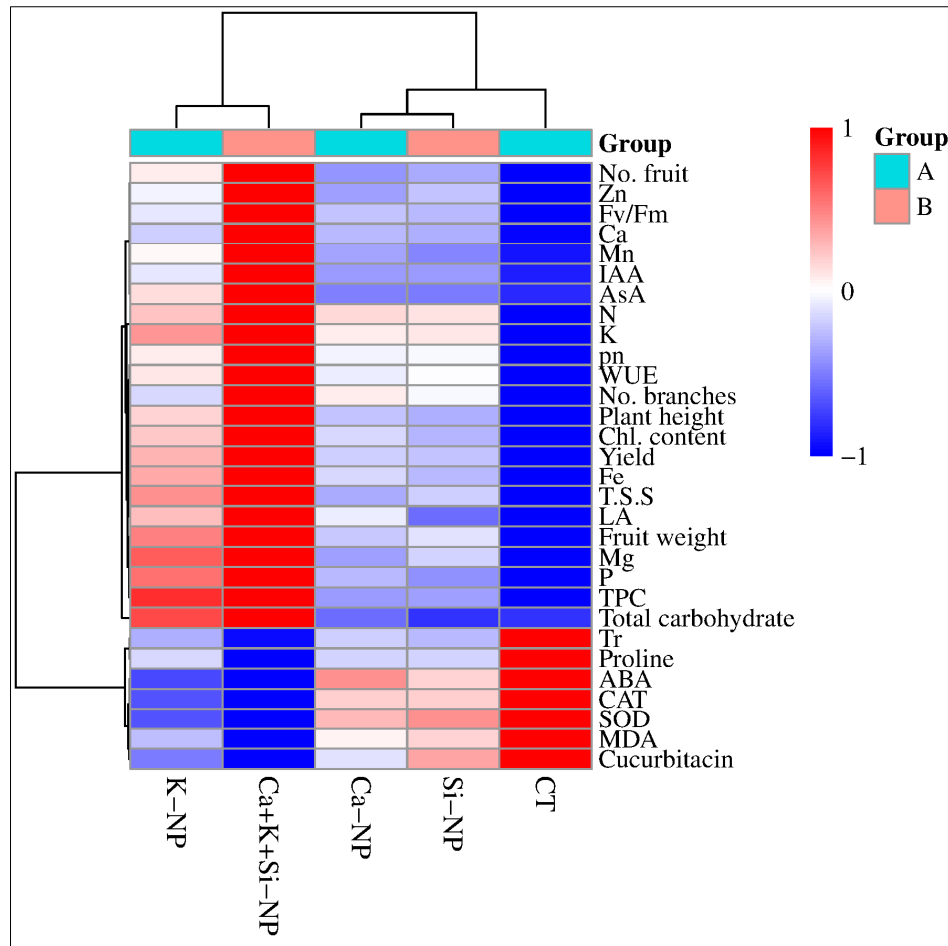
The matrix correlation and cluster heatmap analysis showed how the different nano-fertilizers (Ca-NP, K-NP, Si-NP, and Ca+K+Si-NP) related to the measurements from cucumber plants that were under drought stress (Figures 4 and 5). The cluster heatmap, which looked at 30 factors, clearly separated these factors into two groups (A and B). Group A includes K-NP, Ca-NP, and CT treatments, while Group B has the combined treatment (Ca+K+Si-NP) and Si-NP treatment (Figure 6). The cluster heatmap, which included 30 parameters, clearly divided these parameters into two groups (A and B). Group A includes K-NP, Ca-NP, and CT treatments, while Group B contains the combined treatment (Ca+K+Si-NP) and Si-NP treatment (Figure 6). The cluster heatmap containing 30 parameters distinctly separated them into two clusters (A and B). Cluster A consists of K-NP, Ca-NP, and CT treatments, and cluster B holds combined treatment (Ca+K+Si-NP) and Si-NP treatment (Figure 6). The cluster heatmap revealed that the combined treatment (Ca+K+Si-NP) greatly improved most of the measurements, except for Tr, ABA, MDA, and cucurbitacin content. Conversely, the control plants showed the positive impact with Tr, ABA, MDA, and cucurbitacin content and negative impacts with the rest of the studied measurements. These results indicated that the combined treatments reduced the adverse impacts of drought stress.

A comparable positive association was recorded between cucumber yield and photosynthesis parameters (Pn, WUE, Fv/Fm), plant hormones (IAA), fruit quality (total carbohydrate, TSS, and TPC), and fruit components (number and weight of cucumber fruit), as shown in figure 5. On the contrary, the fruit yield of cucumber plants correlated negatively with Tr, ABA, CAT, SOD, MDA, and cucurbitacin content. These findings proved that drought stress was accompanied by undesirable impacts, especially for untreated cucumber plants (CT), while treated plants were less affected.

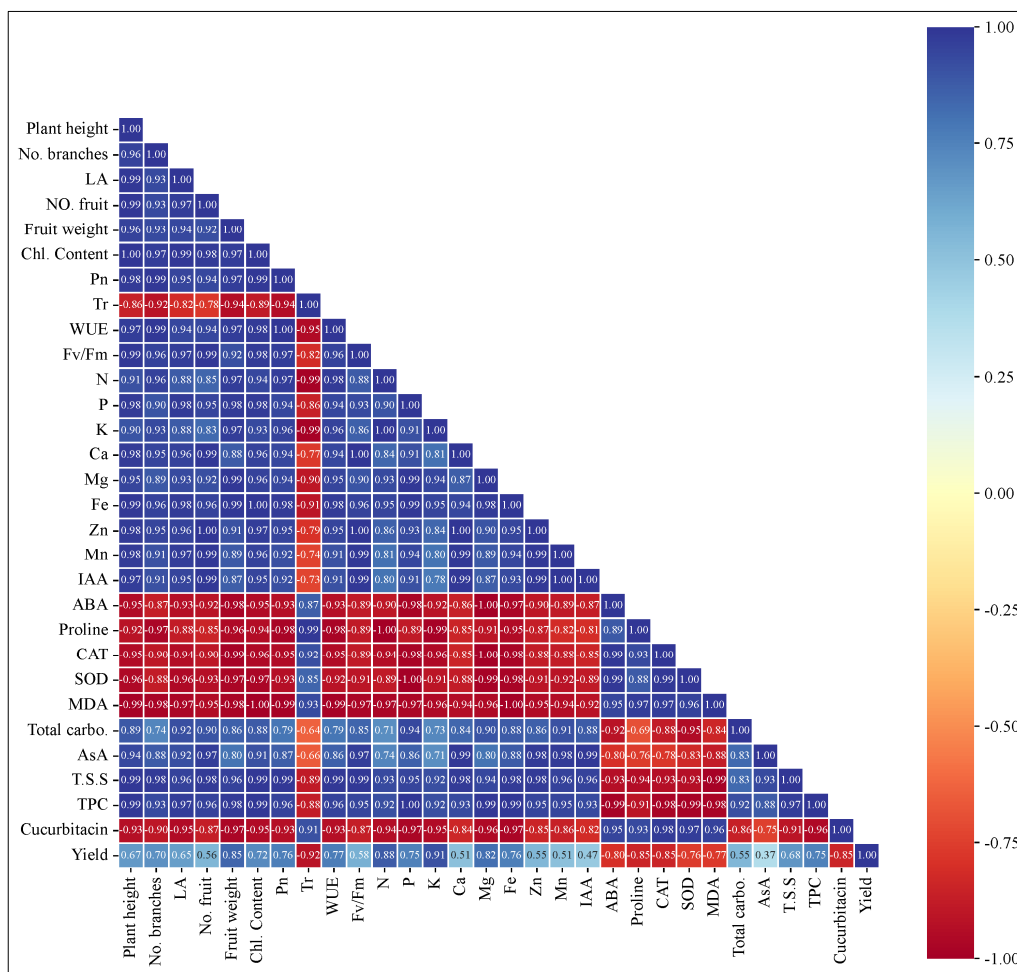
### Discussion

Water deficiency is considered one of the environmental variables that limit the cultivation of cucumber plants, particularly in semi-arid and arid areas. In those regions, irrigation serves as the primary means of hydrating plants, thereby influencing both the quantity and quality of cucumber fruits. The current study assessed the effectiveness of calcium, potassium, and silicon nanoparticles, alone or in combination, on drought tolerance in cucumber plants-based agro-physiological and biochemical attributes. According to the obtained findings in this study, it can be observed that the height of plant, number of branches, and leaf area of cucumber plants were significantly diminished by water stress (Shehata *et al.*, 2022). This reduction in the previous measurements under water stress conditions is probably due to decreasing photosynthetic function, production of phytohormones, nutrient uptake, and water absorption. This consequently caused a reduction in cell division and elongation (Mahmoud *et al.*, 2022; Mahmoud *et al.*, 2023). However, spraying calcium,

potassium, and silicon nano-particles, alone or in combination, improved the number of branches, plant height, and leaf area of drought-stressed cucumber plants (Figure 3). This improvement is likely due to the effective uptake of those nutrients (Ca, K, and Si) that help maintain cell pressure, which is essential for cell growth and division. (Akhtar *et al.*, 2022). Furthermore, the present study showed that water stress caused a significant reduction in the leaf pigments and photosynthetic measurements of cucumber plants as a result of the reduction of soil water content (Shehata *et al.*, 2022; Lahbouki *et al.*, 2023). The decrease in chlorophyll levels in plants under drought stress might be connected to higher activity of chlorophyllase or reactive oxygen species (ROS), which slow down the production of chlorophyll (Shin *et al.*, 2021). This finding also matched what Abdelaziz *et al.* (2021) and Mahmoud *et al.* (2022) reported, which was that drought stress significantly reduced the levels of chlorophyll a, chlorophyll b, and the genes related to their metabolism in the leaves of cucumber plants.



**Figure 6.** Cluster heatmap shows the positive or negative impacts of the applied nano-fertilizers (Ca-NP, K-NP, Si-NP, and Ca+K+Si-NP) on the physiological, biochemical and agronomical features of water-stressed cucumber plants. Abbreviations: No= number, WUE= water use efficiency, Pn= photosynthesis rate, LA= leaf area, Chl.= chlorophyll, Tr= transpiration rate, ABA = abscisic acid, IAA = idole-3-acetic acid, CAT= catalase, SOD= superoxide dismutase, MDA= malondialdehyde, AsA= ascorbic acid, TSS= total soluble solids, TPC= total phenolic compounds



**Figure 7.** Matrix heatmap analysis shows the correlation between the physiological, biochemical and agronomical features of water-stressed cucumber plants treated sprayed with Ca-NP, K-NP, Si-NP, and Ca+K+Si-NP. Abbreviations: No= number, WUE= water use efficiency, Pn= photosynthesis rate, LA= leaf area, Chl.= chlorophyll, Tr= transpiration rate, ABA= abscisic acid, IAA = idole-3-acetic acid, CAT= catalase, SOD= superoxide dismutase, MDA= malondialdehyde, AsA= ascorbic acid, Total Carbo. = total carbohydrate, TSS= total soluble solids, TPC= total phenolic compounds

Photosynthetic measurements are considered an important tool for estimating the performance of plants in abiotic stresses, particularly water stress. Our results showed a decrease in chlorophyll pigments and photosynthesis parameters (*Pn*, *WUE*, and *Fv/Fm*) in the drought-stressed plants. This decrease is mostly related to the lower stomatal conductance, which reduces the amount of carbon dioxide (CO<sub>2</sub>) available in the spaces between plant cells (Vanlerberghe *et al.*, 2020; Deng *et al.*, 2021; Mahmoud *et al.*, 2023).

In the current study, the foliar application with calcium, potassium, and silicon nanoparticles enhances the photosynthesis rate, *Fv/Fm*, and water use efficiency. The combination treatment yielded the greatest improvement (Table 3). These findings could be related to the positive role of Ca, Si, and K in the photosystem processes of drought-stressed plants likely contributes to this enhancement. Deepa *et al.* (2014) reported that calcium acts as a regulator of enzyme activity in the carbon assimilation cycle and impacts stomatal movements, and affecting gas exchange. Furthermore, the Ca and K ratio plays an important role in the stomatal movements and cell hydration (Mahmoud *et al.*, 2023). Similarly, K and Si ions help increase the rate of photosynthesis by controlling to electrons move during photochemical reactions. (Zhu and Gong, 2014; Akhtar *et al.*, 2022).

These findings were matched with previous publications indicating that the foliar application of an appropriate amount of calcium, K and Si ions improved the chlorophyll content, thus enhancing the photosynthetic level of crops (Wijewardene *et al.*, 2021).

Water deficiency caused a reduction in the uptake of nutrients from the soil (Shehata *et al.*, 2022). This decrease in nutrient absorption may be due to several reasons, such as lower moisture in the soil, less root growth, and reduced activity of enzymes that help take in nutrients. However, the higher amounts of calcium and potassium found in the leaves of cucumber plants experiencing drought stress might be connected to the calcium and potassium supplied by the nano-fertilizers applied to the leaves. The heat map correlation showed that treating cucumber plants with K-NP and Ca+K+Si-NP increased the levels of K and Ca in the leaves. This result aligns with the previous researchers, who reported that calcium and potassium fertilizer application increased the leaf Ca and K content in cash crops (Figure 3). The buildup of other nutrients (N, Mg, P, Mn, Fe, and Zn) could be linked to improved root growth and activity, which increased nutrient absorption (Shehata *et al.*, 2022; Dong *et al.*, 2018).

Several researchers have shown a link between the production of phytohormones and the signaling pathways for various nutrients (Ghosh and Roychoudhury, 2024). In the current study, the combined treatment enhanced the IAA and reduced ABA. Spraying of Ca, K, and Si significantly increased IAA and decreased ABA in various plants grown under stressful conditions. This improvement related to the ions of those elements could conduct different signals that affect cell responses, leading to the accumulation of IAA production and reducing the ABA level in the cucumber leaves (Shehata *et al.*, 2022; Mahmoud *et al.*, 2023).

Proline and protein are recognized as important osmolytes that protect plants from abiotic and biotic stresses, which is essential for their survival in challenging environmental conditions (Sattar *et al.*, 2024; El-Bauome *et al.*, 2022). The potential role of proline in water-stressed plants may be associated with (i) its ability to balance the water potential within plants (Fariduddin *et al.*, 2009), (ii) its function in protecting enzymes from inhibition (Sharma and Dietz, 2006), and (iii) its antioxidant properties (Mahmoud *et al.*, 2023). The increased accumulation of protein in cucumber plants treated with nano-elements during periods of water stress could be attributed to these plants' ability to utilize nitrogen in the osmoregulation process. Similar results have been observed in various plants subjected to environmental stresses, such as drought, salt, and cadmium stress. These plants tend to adjust their protein synthesis to prioritize osmoregulatory proteins over those necessary for growth (Mahmoud *et al.*, 2022; Shehata *et al.*, 2022). Furthermore, the combined foliar application of calcium, silicon, and potassium can significantly enhance the accumulation of protein and proline in plants experiencing water stress. Many researchers have confirmed that the roles of calcium, potassium, and silicon in promoting proline and protein content may be linked to increased synthesis of these compounds, reduced proteolysis, and enhanced inhibition of related enzymes during environmental stresses (Dong *et al.*, 2018; Ahmad *et al.*, 2016).

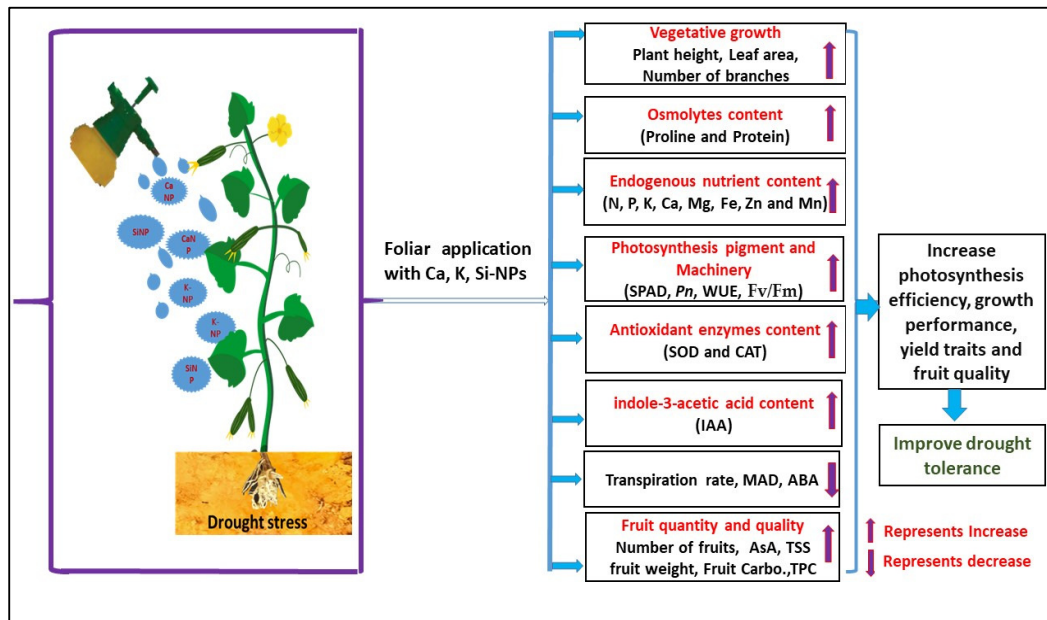
Furthermore, water stress enhances the activity of reactive oxygen species (ROS), which induces lipid peroxidation and results in the production of malondialdehyde (MDA) at the end of the oxidation process (Shin *et al.*, 2021). Drought stress can decrease membrane permeability and increase MDA production, as noted by Zafar *et al.* (2024). Our findings are consistent with previous research (Li *et al.*, 2016), which reported that water stress induces oxidative stress through increased MDA production in Arabidopsis. However, plants under drought stress that received treatments with calcium (Ca), potassium (K), and silicon (Si), either individually or in combination, exhibited reduced MDA levels. This reduction may be due to the role of antioxidant enzymes and proline in scavenging free radicals, thereby mitigating oxidative damage to membranes during drought stress. Calcium interacts with membrane phospholipids, reinforcing the lipid bilayer and maintaining structural integrity. This effect is evidenced by the lower MDA levels observed in plants treated with Ca (Li *et al.*, 2016). Potassium plays a crucial role in decreasing ROS production by reducing the activity of NAD(P)H oxidases and preserving photosynthetic electron transport (Mahmoud *et al.*, 2022). The current study demonstrated that the application of Ca, K, and Si significantly increased the activity levels of superoxide dismutase (SOD) and catalase (CAT) in cucumber leaves (Table 5). The higher activity levels of these

antioxidant enzymes (CAT and SOD) and the lower lipid peroxidation (MDA) associated with Ca application suggest that Ca mitigates the structural and functional deterioration of cell membranes (Rajput *et al.*, 2021). Recent publications indicate that the application of calcium, potassium, and silicon fertilizers effectively enhances plant tolerance to water stress by boosting the antioxidant system (Siddiqui *et al.*, 2012).

The enhanced yield quality and quantity of drought-stressed plants treated with Ca, K, and Si nanoparticles may be attributed to improved growth, increased fresh biomass, enhanced photosynthesis efficiency, nutrient translocation, antioxidant enzyme activity, and carbohydrate accumulation (Li *et al.*, 2016; Mahmoud *et al.*, 2022; Akhtar *et al.*, 2022). The matrix correlation in the current study demonstrated that total yield correlated with leaf area (LA), fresh weight, number of branches, fruit weight, endogenous nutrient content, antioxidant levels, water use efficiency, and chlorophyll content. The accumulation of carbohydrates, ascorbic acid (AsA), and total phenol content significantly increased in the fruits of water-stressed plants sprayed with Ca, K, and Si compared to untreated plants. The increase in these biomolecules in fruits may be linked to enhanced photosynthesis rates and the activation of various enzymes involved in carbohydrate metabolism, as well as the synthesis of AsA and total phenolic content (Li *et al.*, 2016; Akhtar *et al.*, 2022).

Enhancing the levels of ascorbic acid (AsA) and total phenolic compounds (TPC) in the fruits of drought-stressed plants may be associated with increased activity of enzymes such as monodehydroascorbate reductase (MDHAR) and phenylalanine ammonia lyase (PAL) (Ahmad *et al.*, 2016). Additionally, water stress elevates the osmotic potential in plants, resulting in decreased water uptake and reduced flow of water into the fruit (El-Bauome *et al.*, 2022; Shehata *et al.*, 2022). This condition leads to an increase in total soluble solids (TSS) concentration and the accumulation of solutes and organic molecules typically produced in plants during periods of drought stress (El-Bauome *et al.*, 2022; Mahmoud and Swaefy, 2020). In cucumbers subjected to drought conditions, fruits with lower water content and higher dry weight demonstrated greater firmness, as water stress significantly increased the firmness of the affected fruits (Shehata *et al.*, 2022).

Cucurbitacin refers to triterpenoid compounds that found in the *Cucurbitaceae* plant family and are responsible for the bitter taste (Mkhize *et al.*, 2023). The primary enzyme involved in the biosynthesis of cucurbitacin in cucurbit crops is cucurbitadienol synthase. The activity of cucurbitadienol is regulated by the gene CYP450s. In bottle gourd, the genes QBt.1 and QBt.2 are responsible for controlling cucurbitacin production, which differs from the bitterness-regulating genes present in other cucurbit species, such as watermelon, melon, and cucumber (Mkhize *et al.*, 2023). Therefore, the biosynthesis of cucurbitacin is dependent on the specific cucurbit species. The genes QBt.1 and QBt.2 may enhance the content of cucurbitacins in the leaves and root tissues of bottle gourd (Mashilo *et al.*, 2018) when subjected to water stress, aligning with the findings of this research. Generally, the cucurbitacin content in cucumber fruit increases under drought, poor nutrition, and cold conditions due to the upregulation of relevant genes (Mkhize *et al.*, 2023). In contrast, the current study indicates that foliar supplementation of calcium (Ca), potassium (K), and silicon (Si) enhances water use efficiency and reduces water loss, which alleviates drought stress and decreases the concentration of cucurbitacin in cucumber fruit. Overall, foliar application of Ca, K, and Si—whether individually or in combination—significantly mitigated the negative effects of drought stress by regulating osmolyte content, the activity level of enzymatic antioxidants, malondialdehyde (MDA), the photosynthesis rate, and phytohormones in drought-stressed cucumber plants. This leads to improvements in plant growth performance as well as fruit quantity and quality (Figure 6).



**Figure 6.** Show ameliorative impact of Ca, K and Si nanoparticles on growth performance, yield traits and fruit quality. Fv/Fm= chlorophyll fluorescence, ABA = abscisic acid, SOD= superoxide dismutase, WUE= water use efficiency, Tr= transpiration rate, Pn= photosynthesis rate, IAA = indole-3-acetic acid, CAT= catalase, and MDA= malondialdehyde

## Conclusions

The findings of the current study suggest that foliar supplementation of Ca, Si, and K nanoparticles, individually or in combination, may be an effective strategy to enhance plant growth, yield quantity, and fruit quality of cucumber plants under drought stress conditions. The exogenous application of these nanoparticles alleviates the adverse effects of drought stress on cucumber plants by improving the concentration of osmolytes (such as protein and proline), photosynthetic pigments (measured by SPAD), photosynthesis rate ( $P_n$ ), water use efficiency (WUE), and indole-3-acetic acid (IAA). Additionally, this treatment boosts the activity levels of antioxidant enzymes (catalase—CAT and superoxide dismutase—SOD) and enhances the accumulation of essential nutrients in the leaves and fruits of cucumber plants. Conversely, the use of Ca, K, and Si nanoparticles reduces the transpiration rate (Tr), malondialdehyde (MDA), and abscisic acid (ABA). The exogenous application of these nanoparticles is a promising technique for improving fruit quality by increasing total antioxidant compounds (TPC and ascorbic acid—AsA), enhancing total soluble solids (TSS), and decreasing the levels of cucurbitacin compounds, which are responsible for the bitter taste. Further molecular experiments are needed to better understand the impact of Ca, K, and Si nanoparticles on aquaporin genes, which play a role in modulating plant water homeostasis.

## Author contribution statement

M.M.El-M.: conceptualization, investigation, and drafted the manuscript. E.A.A.: field work. S.A.A.: Laboratory work and manuscript editing. N.M.A.: data analysis and manuscript review and editing. A.W.M.M.: samples analysis, review and editing. S.A.M.: Review and editing. All authors have read and agreed to the published version of the manuscript.

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## Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request

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