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Influence of Selenium, Titanium, and Silicon Nanoparticles on the Growth, Yield, and Fruit Quality of Mango under Drought Conditions

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Abstract: Weather fluctuations significantly affect the growth and production of orchard crops such as mango, leading to a substantial decrease in tree growth, flowering rate, yield, and fruit quality. One of these weather factors is drought, which negatively influences multiple physiological processes in plants. It increases the transpiration rate and decreases the cell turgidity, stomatal regulation, osmoregulation, water utilization efficiency, and the development of the deep root system; consequently, it decreases the final production and fruit quality. Therefore, the present study was performed in the 2022–2023 seasons to study the role of the spraying of Selenium (Se), Titanium (Ti), and Silicon (Si) nanoparticles on the growth parameters, yielding, fruit physical and chemical characteristics, and leaf mineral composition of mango cv. Keitt. Mango trees were sprayed during the vegetative season 2022–2023 three times, starting in April with three weeks intervals, by 5, 10, and 20 mg/L Se; 40, 60, and 80 mg/L Ti; and 50, 100, and 150 mg/L Si. The results showed that the extern spray of nanoparticles from these micronutrients improved the growth attributes, yielding and fruit quality of mango trees by reducing the effect of undesirable stressful conditions. The results also indicated that the extern implementation of 150 mg/L Si, 60 mg/L Ti and 20 mg/L Se gave the best increments in the shoot number, length, thickness, leaf area, and leaf chlorophyll contrasted to the else sprayed treatments. Besides, they also improved the fruit set percentages, fruit yields, fruit physical and chemical characteristics and nutritional status of mango trees in both tested seasons.

Keywords: nutrition; mango; quality; yield; nano fertilizers

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1. Introduction

Mango (*Mangifera indica* L.) is a member of the family Anacardaceae, the cultivated area globally 5974.437 and 148.268 hectares and in Egypt, which produced 57,011,282.78 and 1,327,865 tons in the world and Egypt respectively [1]. It is an evergreen tree, and one of the highest substantial fruits in tropical or subtropical zones, and it can also be effectively grown in the irrigated semiarid regions globally [2]. Besides, it is one of the highest famous and favorite fruit in whole the world, and it is the third important crop behind citrus and grape in Egypt [3]. The mango is a fruit that is highly valued for its remarkable nutritional content and delicious taste. It is a popular fruit that is rich in fiber, carbohydrates, antioxidants, polyphenols, carotenoids, vitamins, and minerals [4,5].

Mango trees are quite sensitive to stressful climate factors; drought, salinity, and high temperatures that can passively influence their development and productivity. Besides, these stressors as well cause a great decline in flower possession and fruit set %, and photosynthesis process, however they improve the rates of respiration, and transpiration, which minimize the yearly productivity [6,7].

Drought stress is a significant environmental challenge which causes a reduction in growth attributes such as shoot and root growth, photosynthetic rates, water absorption, fruit set percentages, flower retention, and final yields across various crops, while it increases the respiration and transpiration rates [8–10].

Nanoparticles (NPs) are characterized as chemical substances whose dimensions are limited to less than 100 nm, exhibiting distinct physical, chemical, and biological characteristics compared to their larger and dissolved ionic counterparts [11,12]. Additionally, nano fertilizers are distinct by their wide surface area and small size, which allows them to pass through plant cells and boost the availability of nutrients for crop production [13–17]. They have been utilized on a large scale to reduce the deterioration of soil [18], increasing the obtained yield and the efficacy of the cultivated area [19]. Furthermore, they can also assist in reducing soil and water pollution and minimizing the emissions of carbon, as happens in conventional fertilizers that cause large climate change [20–23].

Despite Selenium (Se) is not essential for higher plants, its careful utilization can promote plant growth and enhance stress resistance [24–26]. Additionally, Se plays a crucial role in diverse plant functions, improving the crop yield by accumulating chloroplast starch, improving resilience to oxidative stress, delaying leaf senescence, and regulating water status under stressful conditions [27]. At lower concentrations, Se has been found to promote the synthesis of chlorophyll precursors [28,29]. Additionally, its application has beneficial effects on mitigating various abiotic stresses such as salt stress [30,31], heavy metals [32,33], and drought [34]. Additionally, Se can affect amino acid biosynthesis by enhancing the accumulation of nitrogen in plants [35]. Furthermore, the application of Se at 50, 100, and 150 mg/L has been shown to promote the production of soluble solids, enhance fruit growth, and increase the total chlorophyll content [36].

Although Titanium (Ti) is an uncommon element, it serves as a biostimulant in plant cultivation, where it exerts a positive influence on biochemical processes that accelerate and improve crop performance [37]. Ti is considered advantageous for plant growth, particularly in enhancing photosynthesis through increased iron ion activity, improving pollen vigor, and augmenting nutrient uptake by plants [38]. In addition, the application of Ti at low concentrations, whether through roots or leaves, has been shown to enhance crop performance by increasing enzyme activity, photosynthesis process, nutrient intake, and stress toleration such as for cold and drought, ultimately improving the crop yield and its quality [39]. Additionally, the utilization of Ti in plant nutrition positively affects various crop phonological processes such as root prolongation, vegetative growth, maturation, and resistance to biotic and abiotic stresses, contributing to overall crop health [40]. Moreover, Ti has been demonstrated to enhance the build up of photosynthetic pigments in strawberries [41] and supports the uptake of vital nutrients like nitrogen, potassium, calcium, magnesium, and, notably, iron [42].

Silicon (Si) occupies the second arrangement between the most plentiful nutrients in the Earth's crust, following oxygen [43,44]. It is recognized as a helpful element for plant growth and progress [45]. In addition, it contributes various positive effects such as increasing nutrient and water intake, promoting cell division and plant pigments, and enhancing plant tolerance to abiotic stresses such as lodging, nutrient imbalance, and drought [46–49]. Additionally, Si has demonstrated its ability to mitigate both abiotic and biotic stresses, such as drought in plants, by maintaining water balance, enhancing photosynthesis, facilitating the absorption of macro and micronutrients, and influencing phytohormones [50,51]. Furthermore, it impacts the organization of xylem vessels, especially during periods of high transpiration rates [47,52–54], thereby enhancing both plant growth and final yield [54,55]. Application of Si on avocado plants has been observed to reduce respiration and ethylene production rate, leading to increased growth [56,57]. Moreover, Si has been demonstrated to improve pollen fertility, increase fruit yield, enhance fruit sugar content, and prolong shelf life in strawberries [58].

Thus, the present study was assessed to evaluate the effects of administering Se, Ti, and Si nanoparticles in mitigating the negative consequences of drought stress and improving the performance of Keitt mango cultivar.

2. Materials and Methods

2.1. Experimental Site Description and Its Design

The current study was performed to test the efficiency of the foliar spraying of Selenium (Se) at 5, 10, and 20 mg/L; Titanium (Ti) was used as TiO_2 at 40, 60 and 80 mg/L; Silicon (Si), which was used as SiO_2 at 50, 100 and 150 mg/L as compared to unsprayed trees as a control. The trial was carried out on mango trees cv. Keitt, which was at eight years old in the Nubaria region, El Beheira governorate, Egypt under drip irrigation during the 2022–2023 seasons. Each treatment consisted of six trees/replicates, and the used treatments were arranged in a randomized block design (RCBD) in 60 trees that were of the same size, development, and vigor. The physical and chemical advantages of the experimental soil are shown in Table 1.

Table 1. Physical and chemical composition of the trial soil.

Parameter	**Soil Depth (cm)**	
	0–30	**30–60**
	Mechanical analysis %	
Sand	93.0	92.0
Silt	5.0	4.0
Clay	2.0	4.0
Textural class	Sandy	Sandy
$CaCO_3$ (%)	4.2	5.4
Organic matter (%)	0.35	0.20
pH	7.7	7.8
EC, dS/m (Soil extraction 1:5)	0.801	0.823
	Available nutrients (mg/kg)	
N	117.5	117.5
P	18.4	18.0
K	405	190
	Soluble cations (meq/L)	
Ca^{++}	2.30	2.15
Mg^{++}	1.70	1.30
Na^{+}	3.78	3.54
K^{+}	0.45	0.40
	Soluble anions (meq/L)	
HCO_3^{-}	3.22	3.02
CL^{-}	4.00	3.5
SO_4^{--}	4.20	4.00

The trees were sprayed three times in April, mid-April, and the start of the May 2022–2023 seasons. The impact of the above-mentioned treatments was testing by measuring their effects on the subsequent parameters.

2.2. Vegetative Growth Parameters

In mid-September and after picking the fruits in the 2022–2023 seasons, the shoot length and diameter were measured in cm and the shoot number was accounted. Leaf total chlorophyll content was measured by using a chlorophyll meter (SPAD- 502, Zhejiang Nade Scientific Instrument Co. Yuhang District, Hangzhou, Zhejiang, China) by registering 10 readings from each replicate (tree). Leaf area (cm^2) was measured in August of studying seasons, by taking twenty leaves by using the following equation [59].

$$LA = 0.70\ (L \times W) - 1.06$$

where LA = leaf area (cm^2), L = maximum length of leaf (cm), and W = maximum width of leaf (cm).

2.3. Fruit Set Percentages, Fruit Drop Percentages and Fruit Yield

Fruit set and fruit drop percentages were calculated according to Equations (1) and (2), respectively, according to El-Hady et al. [60].

$$\text{Fruit set \%} = \frac{\text{Number of fruit setting}}{\text{Total number of flowers}} \times 100 \quad (1)$$

$$\text{Fruit drop \%} = \frac{\text{Number of fruit setting} - \text{Number of mature fruits}}{\text{Number of fruit setting}} \times 100 \quad (2)$$

Fruit yield: Assessment involved calculating the yield for each replicate/tree in kilograms, and then the yield in tons per hectare was determined by multiplying the yield of each tree* number of trees per hectare.

2.4. Fruit Quality

2.4.1. Fruit Physical Characteristics

Over the harvesting period (September 2022–2023), ten fruits were randomly selected from each replicate. The average fruit weight, size, pulp weight, and seed weight were recorded. The dimensions of the fruits, including length and thickness, were measured using a digital Vernier caliper from Cangxian Sanxing Hose Clamp Co., Ltd., China. Additionally, fruit firmness was gauged using a Magness and Taylor pressure tester equipped with a 7/18-inch plunger [61].

2.4.2. Fruit Chemical Characteristics

Total soluble solids (TSS%) were gauged using a handheld refractometer (ATAGO Co., Ltd., Tokyo, Japan). The fruit's acidity was quantified calorimetrically, relying on the estimation of citric acid. This was achieved by employing five millilitres of fruit juice, which was titrated with a known normality of 0.1 N NaOH while using phenolphthalein as an indicator [62]. The vitamin C content (mg/100 mL juice) was assessed using 3% oxalic acid and 2,6-dichlorophenol indophenols [63]. Total and reducing sugars percentages were determined through calorimetric methods involving phenol and sulfuric acid, which were extracted from 5 grams of fresh pulp [64]. Non-reducing sugar content was calculated by deducing the value of reducing sugars from the total sugar content.

2.5. Mineral Content

At the end of the season, a total of twenty leaves were collected in September 2022–2023 [65] to analyze their mineral contents, including nitrogen, potassium, and phosphorus. The collected leaves were first cleansed with tap water followed by distilled water, then dried in an oven at 70 °C until a consistent weight was achieved, and subsequently crushed. The samples were digested with a mixture of H_2SO_4 and H_2O_2. Nitrogen content was determined using the micro-Kjeldahl method described by Wang et al. [66], while phosphorus content was measured using the vanado-molybdate method as detailed by

Wieczorek et al. [67] by using a spectrophotometer (Shanghai Measuretech Instrument Co., Xujing Town, Shanghai, China) at a wavelength of 405 nm. Additionally, potassium content was assessed using a flame photometer (SKZ International Co., Ltd., Jinan Shandong, China) [68].

2.6. Statistical Analysis

The results were statistically analyzed using One-Way ANOVA in a randomized complete block design (RCBD). Duncan's test was used at 0.05 to compare between the means of the treatments [69] using CoHort Software 6.311 (Pacific Grove, CA, USA).

3. Results

3.1. Vegetative Growth Parameters

The results in Table 2 show that the foliar application of Se, Ti, and Si had a beneficial effect on vegetative growth in terms of total chlorophyll in the leaves, leaf area, shoot length, and shoot thickness, as opposed to control. Moreover, the highest significant increments in leaf chlorophyll and leaf area were as a result of the surface spraying of Si at 150 mg/L, and then by the exterior splash of 60 mg/L Ti in 2022 and 2023 seasons. Concerning the shoot length and shoot diameter, the most substantial increments were achieved through the utilization of 150 mg/L of Si, 60 of Ti, and 20 mg/L of Se through experimental seasons, surpassing the outcomes from other treatments.

Table 2. Spraying effect of Se, Ti, and Si NPs on leaf total chlorophyll, leaf area, shoot length, and shoot thickness of mango cv. Keitt during 2022–2023.

Treatments		Total Chlorophyll (SPAD)		Leaf Area (cm^2)		Shoot Length (cm)		Shoot Thickness (mm)	
		2022	2023	2022	2023	2022	2023	2022	2023
Control	0	40.706 g	43.37 e	71.47 g	73.47 h	37.12 f	41.25 e	6.22 f	6.58 f
Se	5 mg/L	41.60 fg	43.68 e	74.52 f	75.92 g	39.73	43.45 de	6.45 e	6.85 e
	10 mg/L	44.05 e	46.20 d	80.01 d	83.47 d	40.49 e	44.05 d	7.07 c	7.31 d
	20 mg/L	53.16 c	55.02 c	82.12 c	87.60 c	46.57 c	49.46 b	8.04 a	8.37 a
Ti	40 mg/L	43.39 ef	43.20 e	77.07 e	77.87 f	39.69 e	41.76 de	6.83 d	6.90 e
	60 mg/L	55.70 b	57.49 b	85.85 b	90.28 b	49.11 b	51.82 a	8.16 a	8.53 a
	80 mg/L	48.11 d	45.96 d	79.65 d	83.54 d	43.87 d	46.66 c	7.40 b	7.64 c
Si	50 mg/L	42.13 fg	44.80 de	77.80 e	80.68 e	41.24 e	43.77 d	6.91 cd	7.28 d
	100 mg/L	51.832 c	54.31 c	82.10 c	84.01 d	44.47 d	47.37 bc	7.59 b	7.98 b
	150 mg/L	58.76 a	61.92 a	88.22 a	92.32 a	52.02 a	52.82 a	8.12 a	8.42 a
$LSD_{0.05}$		1.83	2.00	1.84	1.40	1.71	2.16	0.21	0.17

When comparing treatments with identical letters in the same column, there are not any obvious differences.

3.2. Shoot Number, Fruit Set and Drop Percentage, and Yield

Table 3 showed that, in comparison to unsprayed trees, spraying nanoparticles from each of the Si, Ti, and Se had a significant impact on increasing the shoots numbers, fruit set percentage, and the productivity even in kg or in ton. The results indicate that the most substantial increases in shoot number and fruit set percentages were notably attained through foliar splash of 60 mg of Ti and 20 mg/L of Se, while the most significant enhancements were observed with the spraying of 150 mg/L of Si in the 2022–2023 period. Additionally, the final fruit yields in the two seasons were resulted from the surface spraying of 150 mg/L Si, and then by the spraying of 60 mg/L Ti, and the difference between them were insignificant in 2022 and 2023 seasons. Besides, the fruit drop percentages were markedly minimized by the enforcement of nanoparticles from the three applied micronutrients. The least remarkable and significant values for the fruit drop percentages in the two seasons were noticed with the external spray of 150 mg/L Si and also with 60 mg/L Ti and 20 mg/L Se.

Table 3. Spraying effect of Se, Ti, and Si NPs on shoot number, fruit set %, and fruit yields of mango cv. Keitt during 2022–2023.

Treatments		**Shoot Number**		**Fruit Set %**		**Fruit Drop %**		**Fruit Yield (kg/Tree)**		**Fruit Yield (ton/h)**	
		2022	**2023**	**2022**	**2023**	**2022**	**2023**	**2022**	**2023**	**2022**	**2023**
Control	Control	38.55 h	38.24 f	7.87 h	8.65 f	82.97 a	80.90 a	32.07 d	35.70 d	51.35 d	57.15 d
Se	5 mg/L	40.58 g	44.29 de	8.35 g	8.79 ef	81.59 b	79.12 b	32.88 d	37.03 cd	52.64 d	59.28 cd
	10 mg/L	45.08 e	46.08 d	9.71 de	10.20 c	76.87 d	73.59 d	34.90 bc	37.66 c	55.87 bc	60.29 c
	20 mg/L	49.58 c	52.88 b	10.37 c	10.69 b	73.31 f	68.75 f	36.56 b	40.85 b	58.53 b	65.39 b
Ti	40 mg/L	42.83 f	44.48 de	9.18 f	9.07 e	80.50 b	76.64 c	32.69 d	36.79 cd	52.32 d	58.89 cd
	60 mg/L	53.44 b	55.67 a	10.66 b	11.19 a	70.32 g	65.75 g	39.88 a	43.90 a	63.84 a	70.27 a
	80 mg/L	44.62 e	48.47 c	9.91 d	10.28 c	75.59 e	72.94 d	34.97 bc	38.33 c	55.97 bc	61.50 c
Si	50 mg/L	43.62 ef	43.22 e	9.52 e	9.64 d	78.22 c	75.52 c	33.11 cd	37.71 c	53.00 cd	60.37 c
	100 mg/L	47.08 d	48.85 c	10.23 c	10.52 bc	74.43 ef	70.67 e	36.38 b	40.19 b	58.23 b	64.33 b
	150 mg/L	56.04 a	57.76 a	10.96 a	11.42 a	65.68 h	62.50 h	41.66 a	44.70 a	66.66 a	71.52 a
$LSD_{0.05}$		1.58	2.32	0.25	0.32	1.26	1.50	1.80	1.55	2.89	2.48

When comparing treatments with identical letters in the same column, there are not any obvious differences.

3.3. Fruit Quality

3.3.1. Physical Fruit Characteristics

Data in Table 4 indicated that fruit weight, size, length and diameter were markedly ameliorated by the surface spray of nanoparticles from Se, Ti and Si contrasted to untreated trees in the 2022–2023 period. Moreover, the results indicated that the positive impact of Si and Se increased proportionally with the rising concentration. Specifically, the highest values were observed at concentrations of 20 mg/L form Se and 150 mg/L form Si, surpassing the performance of untreated trees. In the case of Ti application, the most favorable results were noticed with the exterior spray of 60 mg/L of Ti during experimental time.

Table 4. Spraying effect of Se, Ti, and Si NPs on fruit weight, size, length, and diameter of mango cv. Keitt during 2022–2023.

Treatments		**Fruit Weight (g)**		**Fruit Size (cm^3)**		**Fruit Length (cm)**		**Fruit Diameter (cm)**	
		2022	**2023**	**2022**	**2023**	**2022**	**2023**	**2022**	**2023**
Control	0	449.01 f	458.63 h	460.21 f	477.63 h	9.85 f	10.12 f	8.22 f	8.26 f
Se	5 mg/L	467.83 e	477.33 g	486.03 e	497.53 g	10.39 e	10.44 ef	8.28 f	8.47 e
	10 mg/L	493.80 d	513.42 e	514.20 d	532.42 e	11.28 d	11.70 d	8.70 e	9.32 d
	20 mg/L	539.69 b	542.09 c	560.29 b	562.09 c	12.38 c	12.47 c	9.86 c	10.37 b
Ti	40 mg/L	468.42 e	488.49 f	488.42 e	510.87 f	10.50 e	10.76 e	8.44 ef	8.63 e
	60 mg/L	566.53 a	566.10 b	586.73 a	584.50 b	13.26 b	13.43 b	10.26 b	10.96 a
	80 mg/L	513.47 c	516.46 e	533.47 c	536.86 e	12.05 c	12.05 cd	9.15 d	9.46 d
Si	50 mg/L	476.93 e	495.53 f	497.13 e	514.33 f	10.78 e	10.78 e	8.64 e	8.66 e
	100 mg/L	530.22 b	525.08 d	550.62 b	551.68 d	12.31 c	12.31 c	9.60 c	9.81 c
	150 mg/L	571.00 a	584 a	589.10 a	603.00 a	14.59 a	15.12 a	10.82 a	11.10 a
$LSD_{0.05}$		13.23	8.57	14.62	9.116	0.47	0.43	0.28	0.20

When comparing treatments with identical letters in the same column, there are not any obvious differences.

Fruit physical attributes such as fruit firmness, and pulp and seed weights were positively improved by the spraying of nanoparticles from Si, Ti and Se compared with not sprayed trees in the 2022–2023 seasons (Table 5). Furthermore, the use of 150 mg/L of Si gave the most notable increases in seed weight compared to other applied treatments. It was observed that the variations between the foliar splash effects of 150 mg/L Si and 60 mg/L Ti were minimal and not significant concerning fruit firmness and pulp weight.

Additionally, the influence of Si or Se was increased in parallel to increasing the used doses in both experimental time.

Table 5. Spraying effect of Se, Ti, and Si NPs on fruit firmness, pulp weight, and seed weight of mango cv. Keitt during 2022–2023.

Treatments		Fruit Firmness (kg/cm^2)		Pulp Weight (g)		Seed Weight (g)	
		2022	2023	2022	2023	2022	2023
Control	0	1.21 e	1.22 e	363.03 e	367.22 f	42.07 f	43.23 g
Se	5 mg/L	1.30 d	1.30 d	379.94 cd	382.26 e	42.91 ef	44.70 fg
	10 mg/L	1.40 c	1.47 c	394.24 c	406.42 c	44.55 ef	49.31 e
	20 mg/L	1.55 b	1.59 b	428.48 ab	422.54 b	53.67 c	54.94 c
Ti	40 mg/L	1.26 de	1.31 d	377.22 d	391.25 d	43.79 ef	44.86 fg
	60 mg/L	1.73 a	1.70 a	442.96 a	437.22 a	60.34 b	62.26 b
	80 mg/L	1.51 b	1.48 c	416.13 b	408.76 c	45.22 de	50.54 de
Si	50 mg/L	1.31 d	1.38 d	384.93 cd	396.47 d	42.93 ef	46.44 f
	100 mg/L	1.55 b	1.49 c	428.29 ab	412.99 c	47.17 d	52.25 d
	150 mg/L	1.77 a	1.69 a	438.04 a	443.74 a	65.80 a	69.32 a
$LSD_{0.05}$		0.07	0.08	13.82	8.81	2.33	2.11

When comparing treatments with identical letters in the same column, there are not any obvious differences.

3.3.2. Fruit Chemical Characteristics

Concerning the chemical characteristics of the fruit, total soluble solids content and vitamin C, there was a notable increase through foliar application of nanoparticles from Si, Ti, and Se compared to untreated trees in the 2022–2023 period (Table 6). The optimal results in terms of TSS percentage and VC were achieved with the extern splash of 150 mg/L Si, 60 mg/L Ti, and 20 mg/L Se, surpassing the effectiveness of other applied treatments, and 100 mg/L Si was as the upper treatment. Additionally, the TSS-acidity ratio was saliently ameliorated as a result of the spraying of 20 mg/L Se, and 80 mg/L Ti, while at the same time, the most notable increment was obtained by the exterior spraying of 150 mg/L Si in both trial seasons. The fruit acidity content was raised with control treatment compared with sprayed mango trees in the 2022–2023 seasons. Additionally, the least significant values from fruit acidity were noticed by the extern implementation of 150 mg/L Si as compared to the other sprayed treatments.

Table 6. Spraying effect of Se, Ti, and Si NPs on fruit content from TSS and acidity percentages, TSS-Acidity ratio, and fruit content from vitamin C of mango cv. Keitt during 2022–2023.

Treatments		TSS%		Acidity%		TSS-Acidity		VC (mg/100 mL Juice)	
		2022	2023	2022	2023	2022	2023	2022	2023
Control	0	12.88 f	13.65 e	1.41 a	1.40 a	9.13 g	9.72 f	33.80 e	35.18 d
Se	5 mg/L	13.30 ef	13.60 e	1.38 b	1.37 b	9.67 f	9.94 f	34.85 de	36.10 d
	10 mg/L	14.51 c	15.63 c	1.32 cd	1.30 c	10.98 d	11.99 d	36.62 c	37.86 bc
	20 mg/L	15.62 b	16.26 b	1.29 de	1.25 e	12.10 b	12.97 b	37.24 c	38.67 b
Ti	40 mg/L	13.48 de	14.19 e	1.40 ab	1.34 b	9.62 f	10.57 e	34.54 e	36.10 d
	60 mg/L	15.88 b	16.36 b	1.27 e	1.30 cd	11.64 bc	12.42 cd	39.91 b	41.71 a
	80 mg/L	14.73 c	16.12 bc	1.32 cd	1.22 f	12.07 b	13.37 b	36.92 c	38.758 b
Si	50 mg/L	13.82 d	14.84 d	1.33 c	1.35 b	10.39 e	11.01 e	36.07 cd	36.64 cd
	100 mg/L	14.96 c	16.36 b	1.31 cd	1.27 de	11.44 c	12.87 bc	36.76 c	39.33 b
	150 mg/L	16.42 a	17.28 a	1.23 f	1.19 g	13.37 a	14.58 a	41.54 a	42.12 a
$LSD_{0.05}$		0.44	0.58	0.03	0.03	0.44	0.52	1.32	1.36

When comparing treatments with identical letters in the same column, there are not any obvious differences.

Total, reduced and non-reduced sugars and carotene content were highly enhanced by the extern spray of Si, Ti and Se nanoparticles in mango fruits as compared to the unsprayed trees (Table 7). Additionally, the highest fruit content from total, reduced and non-reduced sugars and carotene was accompanied by the splash of 150 mg/L Si and then by the exogenous applying of 60 mg/L Ti and then 20 mg/L Se in the two seasons. Additionally, the higher influences from the applied nanoparticles from the three nutrients were more effective than the lower concentrations.

Table 7. Spraying effect of Se, Ti, and Si NPs on fruit content from total, reduced, and non-reduced sugars percentages and carotene of mango cv. Keitt during 2022–2023.

Treatments		Total Sugars %		Reduced Sugars %		Non Reduced Sugars %		Carotene (mg/100 g)	
		2022–2023		2022–2023		2022–2023		2022–2023	
Control	0	9.32 e	9.64 h	5.34 e	5.25 f	3.98 d	4.39 e	1.26 c	1.28 e
Se	5 mg/L	9.45 e	9.66 h	5.52 de	5.22 f	3.93 d	4.44 e	1.27 c	1.294 e
	10 mg/L	10.37 d	10.49 e	5.80 cd	5.86 de	4.58 bc	4.63 de	1.35 b	1.37 c
	20 mg/L	11.16 c	12.07 c	6.32 b	6.79 b	4.84 b	5.28 c	1.36 b	1.44 b
Ti	40 mg/L	9.36 e	9.92 gh	5.41 e	5.54 ef	3.95 d	4.37 e	1.27 c	1.31 de
	60 mg/L	12.22 b	12.77 b	6.59 b	7.12 a	5.63 a	5.65 b	1.42 a	1.44 b
	80 mg/L	10.57 d	10.44 ef	5.83 c	5.96 d	4.74 b	4.48 e	1.35 b	1.43 b
Si	50 mg/L	9.62 e	10.17 fg	5.37 e	5.65 de	4.24 cd	4.52 e	1.28 c	1.34 d
	100 mg/L	11.04 c	11.39 d	6.32 b	6.47 c	4.72 b	4.92 d	1.40 a	1.45 ab
	150 mg/L	13.02 a	14.06 a	7.10 a	7.14 a	5.92 a	6.92 a	1.44 a	1.48 a
$LSD_{0.05}$		0.38	0.29	0.29	0.31	0.39	0.33	0.04	0.03

When comparing treatments with identical letters in the same column, there are not any obvious differences.

3.4. Mineral Content from Macronutrients

Comparing to unsprayed trees, the data displayed in Table 8 clearly demonstrated an increase in the nitrogen, phosphorus, and potassium content of the leaves as a result of the application of nanoparticles from Se, Ti, and Si. Notably, spraying with 150 mg/L Si resulted in distinct increments in the leaf content of these macronutrients, outperforming other applied treatments. Furthermore, the exterior applying of 60 mg/L Ti and 20 mg/L Se also contributed to an improvement in the nutritional status of mango trees in terms of nitrogen, phosphorus, and potassium, surpassing the impact of other applied concentrations in the 2022–2023 period.

Table 8. Spraying effect of Se, Ti, and Si NPs on leaf mineral content from nitrogen, phosphorous and potassium of mango cv. Keitt during 2022–2023.

Treatments		N%		P%		K%	
		2022	2023	2022	2023	2022	2023
Control	0	1.29 g	1.39 g	0.45 f	0.50 f	2.25 f	2.30 g
Se	5 mg/L	1.33 g	1.44 f	0.48 ef	0.52 ef	2.27 f	2.32 g
	10 mg/L	1.46 ef	1.49 e	0.51 d	0.58 d	2.41 d	2.36 f
	20 mg/L	1.57 c	1.61 c	0.55 c	0.62 c	2.38 d	2.41 e
Ti	40 mg/L	1.41 f	1.44 f	0.48 def	0.52 ef	2.33 e	2.35 f
	60 mg/L	1.64 b	1.67 b	0.62 b	0.64 b	2.47 c	2.49 c
	80 mg/L	1.50 de	1.53 d	0.54 c	0.60 cd	2.45 c	2.43 de
Si	50 mg/L	1.426 f	1.47 ef	0.51 de	0.54 e	2.46 c	2.46 cd
	100 mg/L	1.54 cd	1.57 cd	0.54 c	0.61 c	2.52 b	2.56 b
	150 mg/L	1.75 a	1.80 a	0.70 a	0.71 a	2.63 a	2.66 a
$LSD_{0.05}$		0.05	0.04	0.03	0.02	0.04	0.03

When comparing treatments with identical letters in the same column, there are not any obvious differences.

4. Discussion

It is clear from the results of the present study that the extern spraying of Se enhanced vegetative growth, yield, physical and chemical measurements of fruits, and nutrient content from N, K, and P of Keitt mango cultivar.

This was interpreted by the previous studies of many authors, who reported that Se could increase the uptake and balance of essential nutrient elements [70,71]. Yu et al. [72] that Se has a beneficial effect in increasing the growth of crops, stress resistance, photosynthesis, and antagonistic effects against heavy metals. The role of Se in increasing leaf pigments by delaying the tissue senescence and raising the leaf chlorophyll content [73]. Moreover, the leafy spraying of Se markedly raised the iron concentration in roots [74], and absorption of different elements [75]. Additionally, it has been shown that Se can organize the water balance in the plants under drought [76]. The foliar spraying of Se on orange trees increased the leaf area, growth parameters, nutritional status, productivity, and the advantages of fruit quality [71,77,78]. When applied via foliar spraying on apple trees, Se has demonstrated the capacity to elevate both leaf and fruit Se concentrations, resulting in enhanced flesh firmness, and soluble solid content in the fruit [79]. The utilization of Se has demonstrated positive impacts on the nutritional quality of table grapes, contributing to heightened levels of soluble solids, sugars, vitamin C, protein, and leaf mineral content, specifically potassium and calcium. This application has also been effective in diminishing organic acid levels and reducing the accumulation of heavy metals [80]. The surface spray of Se on pomegranate at 0.025, 0.05, and 0.1 mg/L, led to enhancements in shoot length, leaf chlorophyll, fruit set, and fruit yield contrasted to not treated trees. Additionally, this treatment also improved the fruit weight, and length, along with increased the soluble solids as well as total, reduced, and non-reduced sugars in fruits. Simultaneously, it resulted in a reduction in juice acidity on opposite to not sprayed trees [81]. Additionally, the extern application of Se on blueberry at a complete flowering time and one month later, has been found to significantly enhance fruit quality, as well as the nutritional content of the trees [82].

Regarding the result of the present study, Ti remarkably ameliorated the mango growth, yield, fruit quality advantages and its content from elements. These results were earlier illustrated by Grenda [83], who stated that Ti promotes the activity of iron ions, the synthesis of pigments, and leaf chlorophyll content, vegetative growth and the resistance to stressful environmental conditions. Furthermore, Bacilieri et al. [40] reported that Ti can improve the absorption of both macro and micronutrients, which ultimately leads to increased yield. Additionally, it can improve fruit pollination, fertilization, and growth [84]. Moreover, Ti may raise the role of iron, copper, and zinc in leaf cell chloroplasts and cytoplasm [85], so it increases chlorophyll biosynthesis and enzymatic effectiveness, as well as photosynthesis and nutrient uptake rates, and frequently it can raise plant growth and yield [86]. Additionally, the surface spraying of TiO_2 NPs increased nitrogen assimilation, thereby boosting amino acids and protein production and growth [87]. Mustafa et al. [88] demonstrated that TiO_2 NPs raised IAA and GA, proline, and carbohydrate rates under drought stress conditions. Doklega et al. [89] documented that the spraying of TiO_2 at 2.0 and 4.0 mg/L on red cabbage plants led to enhancement of plant growth and yield contrasted to trees that were not sprayed. Additionally, the application of 1 mg Ti L^{-1} on tomato markedly raised the nitrogen uptake, the weights of shoots and roots, flowering level, number of flowers, chlorophyll content, and photosynthetic rate [90]. The extern spraying of Ti on apple trees led to an extreme increase in fruit yield of around 10–20% [91].

The results show the beneficial role of Si in improving the performance of Keitt mango cultivar under the experimental conditions, and this was previously explained by many authors, who reported that Si can enhance the uptake and transport of water and nutrients by stimulating root system development [92,93]. Further, Kleiber et al. [94] documented that the application of Si fertilizer led to a simultaneous increase in both leaf water content and the fresh weight of plant organs. Additionally, it was reported that Si can alleviate water stress by reducing transpiration [95], improving water retention, and raising photosynthetic rates [96–99] and chlorophyll content, thereby increasing both crop yield and quality [100,101]. In addition, Si plays a beneficial role in preserving the stability of plant cell membranes, increasing the cellular structure, regulating the intake of the plant elements, and promoting overall growth attributes under abiotic stresses like drought, salinity, and acidity [96,102,103]. The application of SiO_2 NPs enhanced the growth and yield of strawberry under water stress [8]. Moreover, applying Si increased fig fruit content from N, K, P, and Ca [104] and Ca content in apple leaves [105]. Additionally, the extern spraying of SiO_2 at 100, 200, and 300 mg on apple cvs. Gala Schniga, Ligol, and Topaz markedly raised the fruit yield, fruit weight and size, red blush percentage, and fruit content from silicon, zinc, and copper, as well as leaf content from iron and copper [106]. Al-Hamadani and Joody [107] reported that the application of Si at 50 mL L^{-1} on peach remarkably increased the number of lateral shoots. The leafy spray of Si increased the content from various micronutrients and fruit weight in mango, pomegranate, and strawberry [81,108,109]. Spraying of K_2SiO_3 at 0.2% on mango cv. Kesar greatly raised the fruit number and fruit set percentages, and consequently increased the fruit number, while it minimized the fruit drop percentages [110]. In another study, it was documented that the leafy spraying of Si NPs on mango at 50, 100, and 150 mg L^{-1} throughout the complete flowering time and one month later raised the leaf NPK content, total carbohydrates, and proline under salinized drainage water [111]. The leafy application of K_2SiO_3 NPs on mango trees markedly increased the flowering rate, chlorophyll content, fruit set percentages, panicle length, and the fruit yield, while it decreased the floral malformation in mango [112].

5. Conclusions

The results of this study cleared that under stressful conditions as drought, it was found that the surface spraying of Se, Ti, and Si NPs effectively improved the performance of mango trees under drought conditions. They increased the shoot length, diameter, number, leaf chlorophyll content, and leaf area; increased the fruit set percentages; and reduced the fruit drop percentages, which consequently ameliorated the final yield and fruit quality parameters in contrast to the unsprayed trees during the experimental seasons. Besides, the application of 150 mg/L Si, gave the highest and significant values in growth, yielding, and fruit quality, and after that was 60 mg/L Ti and 20 mg/L Se in both experimental seasons.

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