

Article

Zinc Oxide and Silicone Nanoparticles to Improve the Resistance Mechanism and Annual Productivity of Salt-Stressed Mango Trees

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Abstract: Limited findings have been reported on using nanomaterials to improve tree fruit growth, development, and productivity under various stress conditions. To assess the effect of nanoparticles (NPs) like nano-zinc oxide (nZnO) and nano-silicon (nSi) on mango tree growth, yield, and fruit quality under salinity conditions, a factorial experiment was conducted using twelve treatments; three replicates each. Foliar spray of nZnO (50, 100, and 150 mg/L), nSi (150 and 300 mg/L), their combinations, and distilled water as a control was applied at full bloom and one month after of salt-stressed “Ewais” mango trees. Trees positively responded to different levels of nZnO and nSi. Plant growth, nutrients uptake, and carbon assimilation have improved with all treatments, except the higher concentration of nSi. Plant response to stress conditions was represented by a high level of proline content with all treatments, but changes in the activity of the antioxidant enzymes were positively related to the lower and medium concentrations of NPs. Flower malformation has significantly decreased, and the annual fruit yield and physiochemical characteristics have improved with all treatments. It could be recommended that a combination of 100 mg/L nZnO and 150 mg/L nSi improves mango tree resistance, annual crop load, and fruit quality under salinity conditions.

Keywords: salinity; nanoparticles; zinc; silicon; malformation; osmostimulants; antioxidants; quality

1. Introduction

Mango, *Mangifera indica* L., a member of family Anacardiaceae, order Sapindales (chromosomal number = 40), is considered to be one of the most important fruit crops grown in tropical and subtropical climates in more than 100 countries [1]. It is ranked as the second most cultivated tropical fruit, and the sixth major fruit crop worldwide [2]. It can also be successfully cultivated in all irrigated semi-arid regions around the world. Egypt is one of the semi-arid countries that has successfully grown a lot of mango cultivars in calcareous soils within a pH range of 7.5 to 8.5 [3]. The total cultivated area in Egypt is about 78,847.6 hectares, with a total annual production of 850,114.8 tonnes [4]. Although mango has high fruiting potential [5], there are several challenges facing mango production worldwide, such as micronutrients deficiency, physiological stresses, and problems related to yield and fruit quality [6]. Most of the Egyptian mango cultivars, particularly Ewais, Zebda, and Sedik, suffer from alternate

bearing, which is producing optimal yield in one year (the “on year”) and unsatisfactory yield in the following year (the “off year”) [7]. High and low temperature or humidity during flowering, pollination, fruit set, or maturation, as well as the depletion in tree reserves during the period of heavy crop load and vigorous vegetative growth with a high gibberellin content at the time of flower bud differentiation, in addition to the imbalance in the carbon: nitrogen (C/N) ratio, have been considered some of the major causes for alternate bearing in mango [8].

Abiotic stress has a crucial impact on tree fruit growth and development. Drought has the main impact on plant morphology, physiology, and biochemistry [9]. Under such conditions, xylem vessels become susceptible to embolism or dysfunction, leading to lower hydraulic conductance and carbon intake, which in turn affect plant growth characteristics and productivity [10]. Drought stress causes a reduction in root and vegetative growth, number of leaves per branch, leaf area, leaf water content, and number of malformed panicles [11]. Salinity in particular is one of the major environmental stresses that mango trees may face [12]. High levels of salts, mainly chlorides and sulfates of calcium, magnesium, and sodium, cannot be tolerated by most of the plants [13]. Mango is considered a salt-sensitive fruit crop [14]. Salinity induces cell damages and inhibits plant growth [15] through osmotic stress and ionic stress [16]. Salinity causes leaf injury [17], as well as a reduction in chlorophyll content, carbon assimilation, and nutrients uptake. It also induces the production of reactive oxygen species (ROS) that negatively affect plant metabolism through the oxidative damage of lipids, proteins, and nucleic acids [18]. Moreover, it causes a reduction in plant height and leaf area, and creates bearing problems and a reduction in fruit yield and quality [19].

Foliar fertilization is the application of nutrients, phytohormones, biostimulants, and pesticides to the aerial parts of the plant [20]. Spraying fertilizers, including micronutrients such as Zn, B, Cu, Mn, Si, and Fe, have been known to be convenient for field use, in addition to having a good effectiveness and very rapid plant response. Their application can improve the nutrient balance of the plant, resulting in increased fruit yield and quality, better disease resistance, and improved drought and salinity tolerance [21]. During the past three decades, many problems in different fields of science and industry have been resolved using nanotechnology. Materials that are smaller than 100 nm, at least in one dimension, are generally classified as nanomaterials [22]. Engineered nanoparticles (NPs) are composed of a variety of naturally occurring materials with different physical characteristics [23]. Metal and metal-oxide nanoparticles exhibit different physiochemical characteristics compared to their native bulk compounds [24]. Nanomaterials could be used for designing new fertilizers [25], to ensure the effective delivery of the required nutrients to the plant and a very rapid plant response [21] with only one-third of the required conventional counterparts added to the environment [26]. In the same context, it was reported that silicon is mostly toxic to plants in its bulk form, whereas silicon nanoparticles were beneficial for plants [27].

Zinc (Zn) is one of the essential micronutrients for plant [28], which has important roles in fruit set and retention, as well as in fruit yield and quality [29]. Zinc deficiency inhibits plant growth and reduces total yield [30]. Zinc improves the biochemistry of flowers and enhances fruit-set number per panicle and fruit retention percentage in mango [31]. It is required for the activity of different enzymes, including dehydrogenases, aldolases, isomerases, transphosphorylases, RNA, and DNA polymerases. It is also involved in cell division, maintenance of membrane structure and photosynthesis, and acts as a regulatory cofactor in the synthesis of protein and tryptophan [27]. Tryptophan is a precursor in the production of an essential growth hormone, Auxin [32], which is important to increase fruit size and total fruit yield [33]. The characteristics of the Zn nanoparticle, such as size, specific surface area, and reactivity, improve its solubility, diffusion, and availability to the plant [34]. Application of nano-ZnO positively affected seed germination, seedling vigor, leaf chlorophyll content, and stem/root growth of peanut [35]. Nano-ZnO does not pose a toxicity risk for bean and tomato crops grown in either acidic or calcareous soils [36]. Spraying nano-Zn before flowering improved total fruit yield in pomegranate [37] and mango trees that also shown increased plant resistance to floral malformation disease, and improved fruit quality [38].

Silicon (Si) is the second most abundant element in the soil; however, it is not considered as an essential element for plant growth, development, or productivity [39]. Recently, Si has gained global attention because it is safe for the environment; it induces disease and pest resistance in plants, and can reduce doses of pesticides applied for plant protection [40]. Silicon is beneficial for alleviating the nutrients imbalance stress, and improving the growth, development, and yield of various plants. It improves organogenesis, embryogenesis, growth traits, and the morphological, anatomical, and physiological characteristics of leaves; enhances tolerance to chilling, freezing, salinity, and drought; protects cells against metal toxicity; and prevents oxidative and phenolic browning [20,27,41]. Foliar application of Si is most powerful for plants under stressful conditions, such as salinity, drought, flood, heat, cold, and even biotic stress [42]. Silicon might decrease the negative effect of oxidative stress and offer slight resistance to some abiotic and biotic plant stresses. A large number of genes are activated by stress, and several Si-produced proteins that join the biochemical pathways lead to the enhancement of stress tolerance [43].

To date, only limited research findings have been reported on the effect of nanoparticles on woody plants, especially tree fruit. Some reports focused on the role of NPs to alleviate the effect of stressful conditions on tree fruit seedlings, while others focused on using NPs to improve the growth, yield, and fruit quality of tree fruit growing under non-stressful conditions. To the best of the authors' knowledge, this is considered to be one of few reports to cover both goals, and the first on mango, to estimate the role of nanoparticle (NP) fertilizers in alleviating the drastic effects of salinity and improving mango tree growth and annual productivity.

2. Materials and Methods

2.1. Experiment

This research was carried out on twenty-year-old mango trees (*Mangifera indica* L.), cultivar Ewais, in a private orchard located at Damietta Governorate (31°41'75" N, 31°81'44" E), Egypt, during the 2017 and 2018 seasons. Thirty-six "Ewais" mango trees of polyembryonic-seed origin, planted at a 4 m × 6 m spacing, similar in vigor and size, and grown in sandy loam soil were subjected to drip irrigation using salinized drainage water. Two lateral lines of irrigation pipes were provided on both sides of trees row, with two drippers on each side of the tree. Drippers were fixed at a distance of 50 cm away from the tree trunk and were set to manually operate at a slow rate to minimize water loss. Each dripper discharged about 1.5 L/day for two hours with a total of 12 L/plant/day. The soil and water characteristics are displayed in Table 1.

Table 1. Soil and water analysis.

| Soil Analysis | | Water Analysis | |
|--------------------------|------------|--------------------------------------|------|
| Texture | Sandy loam | Ca ⁺² (mg/L) | 41 |
| Sand (Coarse + Fine) (%) | 63 | Mg ⁺² (mg/L) | 13 |
| Silt | 8 | Na ⁺ (mg/L) | 75 |
| Clay | 29 | K ⁺ (mg/L) | 18 |
| Organic matter | 1.23 | Cl ⁻ (mg/L) | 147 |
| N (mg/kg) | 41.67 | SO ₄ ⁻² (mg/L) | 72.6 |
| P (mg/kg) | 16.33 | HCO ⁻³ (mg/L) | 3.2 |
| K (mg/kg) | 524 | CO ⁻³ (mg/L) | - |
| Na (mg/kg) | 426 | Na adsorption ratio | 13 |
| EC (dSm ⁻¹) | 3.67 | EC (dSm ⁻¹) | 0.96 |
| pH | 8.1 | pH | 7.9 |

Weather data of the experimental site [44] are displayed in Figure 1. Bloom date started by the last week of February in both seasons (Figure 1). Foliar spray with nanoparticle chelate fertilizers of zinc oxide (nZnO < 100 nm) at 50, 100, and 150 mg/L (Sigma Aldrich, St. Louis, MO, USA) and silicone

(nSi = 5–15 nm) at 150 and 300 mg/L (Sigma Aldrich, St. Louis, MO, USA), and their combinations, supplemented with Tween 20 as a surfactant (Sigma Aldrich, St. Louis, MO, USA), was applied two times; at full bloom (first week of April) and one month after (first week of May) (Figure 1). Control trees were also treated twice with distilled water. Trees selected for this experiment were receiving other regular agricultural practices as the entire orchard during both seasons. Season 2017 was the “off year” and 2018 was the “on year”. The experimental design was in a complete randomized system of twelve treatments with three replicates each. Each replicate was represented by one tree.

2.2. Floral Malformation Assessment (%)

Trees were inspected during full bloom for compacted, stunted, thickened, highly branched floral panicles that produce larger flowers, in terms of size and number, than normal flowers. Symptoms also included green and dwarfed floral panicles with distorted leaves growing instead of flowers. The floral malformation percentage was calculated using the following equation [45]:

$$(\text{Number of malformed panicles per tree} \div \text{Total number of panicles per tree}) \times 100 \quad (1)$$

2.3. Leaf Area (cm²)

At fruit set, the 4th leaf from ten different branches at the top of the tree was collected before noon, and leaf area was estimated according to the following formula [46]:

$$LA = 0.70 (L \times W) - 1.06 \quad (2)$$

where LA = leaf area (cm²), L = maximum leaf length (cm), W = maximum leaf width (cm), and then average leaf area was calculated.

2.4. Leaf Analysis

The same ten leaves were used for leaf analysis. Leaf NPK [nitrogen, phosphorus, and potassium] (mg/g dw), total carbohydrates (mg/g dw), and total sugars (mg/g fw) were estimated according to the methodology of Wilde et al. [47], Dubois et al. [48], and Ackerson and Krieg [49], respectively. Proline content (mg/g fw) was estimated according to Bates et al. [50]. Extraction and evaluation of the activity of superoxide dismutase (SOD, EC 1.15.1.1), peroxidase (POX, EC 1.11.1.7), and catalase (CAT, EC 1.11.1.6) (μ/min/g fw) were carried out according to the methods described by Beauchamp and Fridovich [51], Bergmeyer [52], and Herzog and Fahimi [53], respectively.

2.5. Yield and Fruit Physiochemical Characteristics

Trees designated for this experiment were harvested during the commercial harvest time by the last week of August (≈140–150 days from full bloom) in both seasons (Figure 1). Yield was recorded as total fruit number and total weight (kg) per tree. Before noon, a sample of 10 ripe fruit per tree was randomly selected from the four directions (N, E, S, and W) and three levels (top, medium, and bottom) of the tree to calculate average fruit weight, in addition to fruit length and width. Fruit weight (g) was measured using a bench-top digital scale Model PC-500 (Doran scales, Inc., Batavia, IL, USA). Fruit length and width (cm) were measured using a digital caliper (Grizzly Industrial, Bellingham, WA, USA). Total soluble solids (TSS) percentage was estimated at room temperature (≈22–23 °C) using a hand-held refractometer, Model RA-130 (KEM Kyoto Electronics Manufacturing Co. Ltd., Tokyo, Japan). Total acidity (g citric acid/100 mL juice), using phenolphthalein, and total sugars (g/100 g pulp) were estimated according to the AOAC protocol [54].

2.6. Statistical Analysis

The SPSS statistical analysis package (SPSS Inc., ver. 16, Chicago, IL, USA) was used for data analysis. Data were first run for numerical normality test using the Shapiro–Wilk test, and then

statistically analyzed using analysis of variance (ANOVA). Means of the main factors and their interaction were compared using the least significant difference (LSD) test at $P \leq 0.05$ [55].

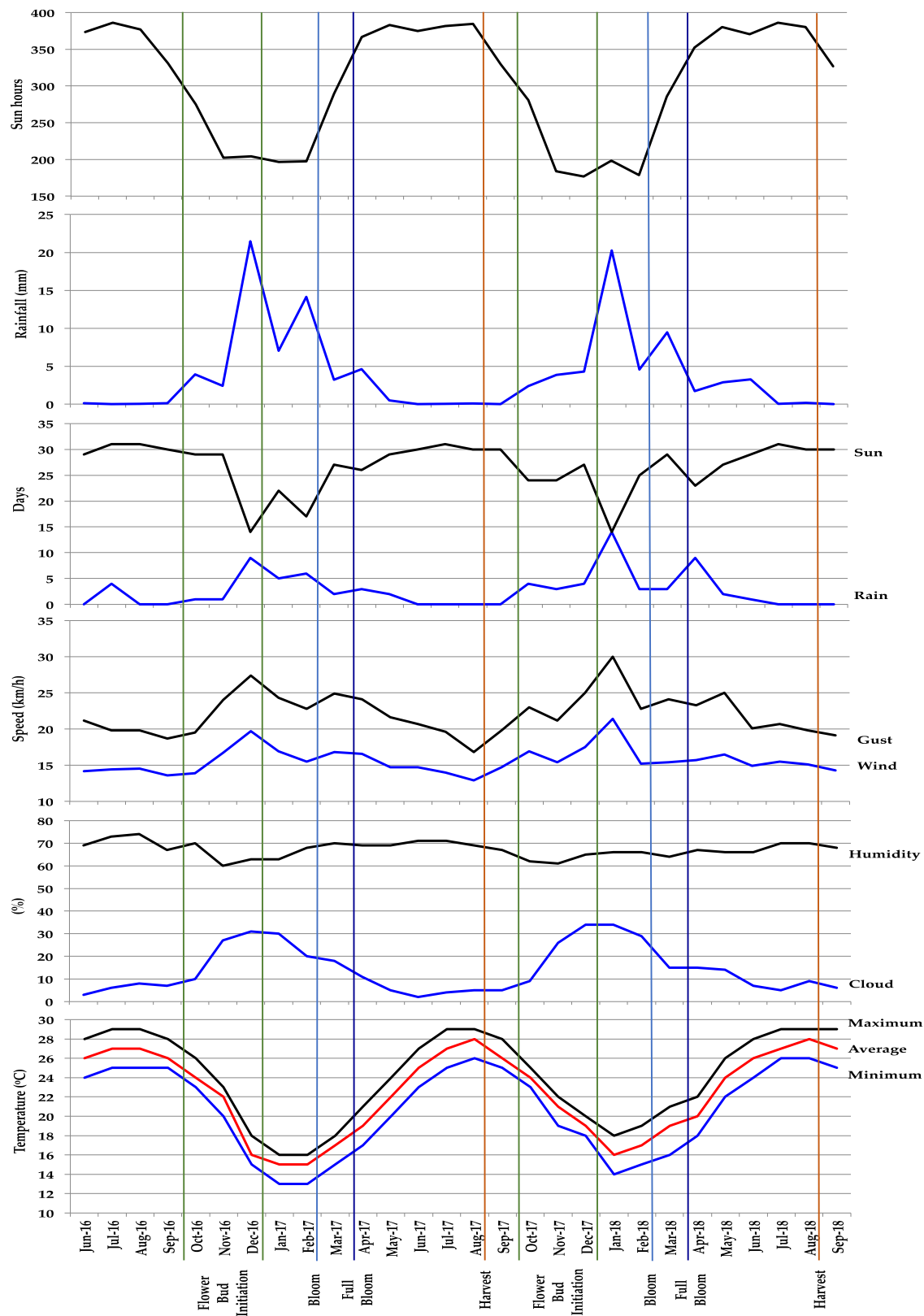


Figure 1. Fruiting phenology of “Ewais” mango trees in relation to weather of Damietta, Egypt.

3. Results and Discussion

3.1. Leaf Area

As an indication of plant growth and development, leaf area has increased with all NP treatments compared to the control in both seasons (Table 2). This effect was only significant with the application of 300 mg/L nSi during the first season. The most conspicuous effect was referred to the application of 100 mg/L nZnO + 150 mg/L nSi, followed by 150 mg/L nZnO + 150 mg/L nSi, then 150 mg/L nZnO. The main effect of the nZnO was a significant increase in leaf area with the application of 100 and 150 mg/L in comparison to 50 mg/L; however, the increase in leaf area with 150 mg/L was very small and insignificantly different from that of 100 mg/L. This might be due to the inefficient or inhibitive effect of higher concentrations of nZnO [56]. It should be mentioned that 150 mg/L nZnO is just inhibiting plant growth, while higher concentrations (e.g., 500 mg/L) caused complete plant damage in soybean [57], because excess Zn could be toxic to the plant [58]. The addition of 150 nSi has vitalized the role of nZnO and significantly increased leaf area, particularly at 100 mg/L nZnO, but increasing nSi concentration to 300 mg/L significantly reduced leaf area even when compared to the sole application of either 100 or 150 nZnO. This could be attributed to the inefficiency of the higher Si concentrations on the nutrient balance, which may affect plant growth and leaf area [59,60]. Results also indicated that the main effect of seasons was a significant increase in leaf area from one season to another; this may be due to the accumulation of Zn and Si NPs in plant tissue after the subsequent spray of the NPs [61]. The control showed a reduction in leaf area for the 2018 “on year” in comparison to the 2017 “off year”; this may be due to the competition between fruit growth and vegetative growth during the “on year” [62].

Table 2. Effect of foliar spray with ZnO and Si nanoparticles (NPs) (mg/L) on leaf area (cm²) of “Ewais” mango trees during the 2017 and 2018 seasons.

| Treatment (T) | Leaf Area | | Mean |
|-----------------------|------------|-----------|--------------|
| | Season (S) | | |
| | 2017 | 2018 | |
| 0 nZnO + 0 nSi | 39.8 | 38.5 | 39.15 |
| 0 nZnO + 150 nSi | 45.5 | 46.3 | 45.9 |
| 0 nZnO + 300 nSi | 36.7 | 38.6 | 37.65 |
| 50 nZnO + 0 nSi | 48.3 | 49.7 | 49 |
| 50 nZnO + 150 nSi | 52.7 | 54.7 | 53.7 |
| 50 nZnO + 300 nSi | 49.3 | 51.8 | 50.55 |
| 100 nZnO + 0 nSi | 59.6 | 60.5 | 60.05 |
| 100 nZnO + 150 nSi | 63.4 | 65.8 | 64.6 |
| 100 nZnO + 300 nSi | 52.3 | 53.7 | 53 |
| 150 nZnO + 0 nSi | 60.1 | 61.6 | 60.85 |
| 150 nZnO + 150 nSi | 61.2 | 62.7 | 61.95 |
| 150 nZnO + 300 nSi | 43.3 | 45.6 | 44.45 |
| Mean | 51.02 | 52.46 | |
| LSD ($P \leq 0.05$) | S = 0.62 | T = 1.534 | S × T = 2.16 |

Previous reports showed the effect of Zn (non-NP) on plant growth and development. Foliar spray of 50 µm zinc sulphate increased leaf area in bean plant [63]. Foliar application of Zn compounds improved leaf area in cashew [64]. It is suggested that nZnO has improved leaf area, because zinc is helpful for protein synthesis, membrane function, and cell elongation [30]. Zinc plays a fundamental role in regulating osmotic activities, as well as protecting and maintaining the cell water balance and the structural stability of the cell membrane under stressful conditions [65]. The nanoparticle form ensures the effective delivery of Zn to the plant with a very rapid plant response [21]; reflected in enhanced plant growth and development [35].

The application of Si is also beneficial for growth and development of various plants and to alleviate various stresses, such as chilling, freezing, salinity, and drought. Drought reduces the morphological and physiological characteristics of the plant and alternates the xylem anatomical features, leading to a reduction in growth rate [66]. Silicon was reported to improve organogenesis, embryogenesis, growth traits, and the morphological, anatomical, and physiological characteristics of leaves [38]. Le et al. [67] reported an impact of Si NPs on IAA, which is responsible of cell division and improves leaf growth [59]. Previous reports showed the role of silicon in increasing the leaf area of banana [68], grapes [69], and potato [70]. Kleiber [71] reported that Si increased leaf fresh weight, relative water content, and the number of leaves per plant, while reducing the dry matter content of salt-stressed lettuce.

3.2. Leaf NPK Content

Under salinity conditions, an adverse effect on the uptake of N, P, K, Ca, Mg, and Fe was noticed in mango trees [13]. Results in Table 3 revealed that leaf NPK content has predominately increased in both seasons with spraying a mixture of 100 mg/L nZnO and 150 mg/L nSi. Treatments of 150 mg/L nZnO + 150 mg/L nSi and 100 mg/L nZnO, respectively, were ranked the second and the third with regard to increasing the P content, but their effect on the N and K content was almost the same. The control recorded the lowest values of NPK in both seasons. It can also be noticed that the high concentration of nZnO (150 mg/L) as well as nSi (300 mg/L) significantly reduced the P content when compared to 100 mg/L nZnO and 150 mg/L nSi, respectively, but the reduction in N and K content was insignificant. It is also clear that 100 nZnO + 150 nSi significantly increased the P content in comparison to 100 nZnO. This could be justified as lower concentrations of zinc enhanced phosphorus uptake [72], and this effect has improved with silicon addition [73]. No differences in N, P, and K content were noticed between the 2017 and 2018 seasons.

Table 3. Effect of foliar spray with ZnO and Si NPs (mg/L) on leaf NPK content (mg/g dw) of “Ewais” mango trees during the 2017 and 2018 seasons.

| Treatment (T) | Nitrogen (N) | | | Phosphorus (P) | | | Potassium (K) | | |
|-----------------------|--------------|----------|--------------|----------------|-----------|---------------|---------------|----------|---------------|
| | Season (S) | | Mean | Season (S) | | Mean | Season (S) | | Mean |
| | 2017 | 2018 | | 2017 | 2018 | | 2017 | 2018 | |
| 0 nZnO + 0 nSi | 1.31 | 1.34 | 1.325 | 0.136 | 0.137 | 0.1365 | 0.74 | 0.74 | 0.74 |
| 0 nZnO + 150 nSi | 1.48 | 1.41 | 1.445 | 0.159 | 0.164 | 0.1615 | 0.86 | 0.82 | 0.84 |
| 0 nZnO + 300 nSi | 1.44 | 1.37 | 1.405 | 0.146 | 0.148 | 0.147 | 0.77 | 0.77 | 0.77 |
| 50 nZnO + 0 nSi | 1.52 | 1.58 | 1.55 | 0.173 | 0.189 | 0.181 | 0.87 | 0.88 | 0.875 |
| 50 nZnO + 150 nSi | 1.67 | 1.62 | 1.645 | 0.182 | 0.197 | 0.1895 | 0.99 | 0.93 | 0.96 |
| 50 nZnO + 300 nSi | 1.58 | 1.58 | 1.58 | 0.166 | 0.174 | 0.17 | 0.83 | 0.89 | 0.86 |
| 100 nZnO + 0 nSi | 1.78 | 1.72 | 1.75 | 0.204 | 0.217 | 0.2105 | 0.98 | 1.07 | 1.025 |
| 100 nZnO + 150 nSi | 1.92 | 1.97 | 1.945 | 0.247 | 0.268 | 0.2575 | 1.17 | 1.21 | 1.19 |
| 100 nZnO + 300 nSi | 1.62 | 1.66 | 1.64 | 0.193 | 0.197 | 0.195 | 0.95 | 0.98 | 0.965 |
| 150 nZnO + 0 nSi | 1.74 | 1.68 | 1.71 | 0.184 | 0.193 | 0.1885 | 0.94 | 0.95 | 0.945 |
| 150 nZnO + 150 nSi | 1.81 | 1.86 | 1.835 | 0.226 | 0.232 | 0.229 | 1.03 | 1.05 | 1.04 |
| 150 nZnO + 300 nSi | 1.59 | 1.62 | 1.605 | 0.177 | 0.185 | 0.181 | 0.88 | 0.91 | 0.895 |
| Mean | 1.62 | 1.62 | | 0.183 | 0.192 | | 0.917 | 0.933 | |
| LSD ($P \leq 0.05$) | S = 0.35 | T = 0.09 | S × T = 0.12 | S = 0.05 | T = 0.011 | S × T = 0.015 | S = 0.54 | T = 0.13 | S × T = 0.187 |

Nair and Chung [74] noticed a reduction in P, K, S, and Cu content after treating *Arabidopsis thaliana* seedlings with 200 mg/L nZnO. An overall significant increase in leaf NPK content was observed in response to Zn application in mandarin [75] and mango [31]. Salt-stressed wheat plants showed higher accumulation of water and nutrients with nZnO treatment [76]. Exogenous application of nSi improved nutrients uptake in plant [77]. Al-Wasfy [78] reported that Si improved plant growth and increased levels of N, P, K, and Mg in date palm leaves. The application of Si is beneficial to alleviate drought stress and nutrients imbalance, protect cells against metal toxicity, and improve the anatomical and physiological characteristics of mango leaves [27]. Silicon alleviates heavy metal toxicity through reducing Na^+ uptake and increase the $\text{K}^+ : \text{Na}^+$ ratio [79].

3.3. Carbohydrates and Osmostimulants

Salinity poses two major threats to plant growth: osmotic stress and ionic stress [16]. The uptake of high amounts of salt increases the osmotic pressure in the cytosol. Under such conditions, cell homeostasis is maintained by an osmotic adjustment mechanism, which leads to the synthesis of organic osmolytes [80], such as proline and soluble sugars to protect cells against the adverse effects of salt stress [81]. An increase in the proline level is an osmotic stress response, because it is contributing to osmotic adjustment in plant cells [82]. Accumulation of sugars and proline as osmoprotectants, and ascorbic acid (ABA) and glutathione (GSH) as antioxidants, protect plant cells under salt stress conditions by balancing the osmotic pressure of the cytosol and the vacuole with that of the external environment [83].

Data in Table 4 revealed that spraying mango trees with a mixture of 100 mg/L nZnO and 150 mg/L nSi has the most pronounced effect on increasing total carbohydrates, total sugars, and proline content under salinity conditions. Application of 150 mg/L nZnO + 150 mg/L nSi was insignificantly ranked the second in this regard. In comparison to the control, lower concentration of nZnO (50 mg/L) was not that effective on all three parameters, unless it was combined with 150 or 300 mg/L nSi. However, the increase in proline content with 50 mg/L nZnO + 300 mg/L nSi was insignificant. The control recorded the lowest in terms of proline (both seasons) and sugars (first season only). No significant effect was noticed between seasons.

Table 4. Effect of foliar spray with ZnO and Si NPs (mg/L) on leaf total carbohydrates (mg/g dw), total sugars, and proline (mg/g fw) content of “Ewais” mango trees during the 2017 and 2018 seasons.

| Treatment (T) | Total Carbohydrates | | | Total Sugars | | | Proline | | |
|-----------------------|---------------------|---------|-------------|--------------|----------|-------------|------------|----------|-------------|
| | Season (S) | | Mean | Season (S) | | Mean | Season (S) | | Mean |
| | 2017 | 2018 | | 2017 | 2018 | | 2017 | 2018 | |
| 0 nZnO + 0 nSi | 39.6 | 39.6 | 39.6 | 5.3 | 6.3 | 5.8 | 5.4 | 5.4 | 5.4 |
| 0 nZnO + 150 nSi | 39.8 | 40.2 | 40 | 5.8 | 5.8 | 5.8 | 5.9 | 5.9 | 5.9 |
| 0 nZnO + 300 nSi | 39.1 | 39.3 | 39.2 | 6.1 | 5.3 | 5.7 | 5.8 | 5.7 | 5.75 |
| 50 nZnO + 0 nSi | 40.4 | 41.2 | 40.8 | 6.3 | 6.8 | 6.55 | 5.9 | 6.1 | 6 |
| 50 nZnO + 150 nSi | 43.2 | 45.8 | 44.5 | 8.1 | 8.4 | 8.25 | 6.7 | 6.9 | 6.8 |
| 50 nZnO + 300 nSi | 42.7 | 43.5 | 43.1 | 7.2 | 7.5 | 7.35 | 6.2 | 5.9 | 6.05 |
| 100 nZnO + 0 nSi | 44.4 | 45.1 | 44.75 | 8.3 | 8.4 | 8.35 | 6.5 | 6.7 | 6.6 |
| 100 nZnO + 150 nSi | 46.6 | 47.2 | 46.9 | 9.6 | 9.7 | 9.65 | 7.3 | 7.4 | 7.35 |
| 100 nZnO + 300 nSi | 43.8 | 45.1 | 44.45 | 7.6 | 7.7 | 7.65 | 6.1 | 6.4 | 6.25 |
| 150 nZnO + 0 nSi | 42.8 | 41.3 | 42.05 | 7.9 | 7.9 | 7.9 | 7 | 7.1 | 7.05 |
| 150 nZnO + 150 nSi | 45.8 | 45.5 | 45.65 | 8.8 | 9.2 | 9 | 7.1 | 7.3 | 7.2 |
| 150 nZnO + 300 nSi | 40.5 | 40.6 | 40.55 | 5.7 | 6.2 | 5.95 | 6 | 6.2 | 6.1 |
| Mean | 42.39 | 42.87 | | 7.22 | 7.43 | | 6.32 | 6.42 | |
| LSD ($P \leq 0.05$) | S = 0.86 | T = 2.1 | S × T = 2.9 | S = 0.48 | T = 1.18 | S × T = 1.7 | S = 0.46 | T = 1.14 | S × T = 1.6 |

Similar results were reported and proved the vital role of zinc in carbohydrate and protein metabolism [35]. Application of nZnO increased photosynthetic activity, enhanced carbohydrate and by-products metabolism, and stimulated plant tolerance under salt stress conditions [84]. On the other hand, growth inhibition and reduction in photosynthetic activity of *Datura* plants exposed to Zn products have been noticed [85]. This might be another explanation to support the role of nSi (either 150 or 300 mg/L) when added to 50 mg/L nZnO, causing an increase in carbohydrates and osmostimulants content (Table 4). The vital role of Si has been previously reported [86], although 300 mg/L nSi induced less carbohydrates, sugars, and proline compared to 150 mg/L; this might be due to the inhibition effect of high Si concentrations [87].

Foliar spray with silicon fertilizers increased leaf area, chlorophyll and carotenoid content, and photosynthesis and transpiration rates of potato plants [70]. Previous findings revealed that exogenous application of silicon and nano-silicon on stressed plants enhanced plant growth and development by increasing proline, free amino acids, and auxin content, as well as nutrient uptake, antioxidant enzyme activity, gas exchange, and the efficiency of the photosynthetic apparatus [76,82,88]. Silicon application increased proline, soluble sugars, ascorbic acid, and glutathione content in drought- and salt-stressed plants [87]. High accumulation of proline and soluble sugars are associated with plant tolerance

to stress. In contrast, polysaccharide content decreased significantly with high salt concentration in pistachio leaves [89]. Foliar spray with a combined application of nSiO₂ and nZnO significantly improved the chlorophyll and carotenoid content, photochemical efficiency, and gas exchange of chilling-stressed sugarcane [90].

3.4. Antioxidant Enzymes Activity

The balance between production and removal of reactive oxygen species (ROS) is controlled by cellular osmoprotectants [91] and antioxidant enzyme systems [92]. In order to prevent oxidative damages under stress conditions, plants evolve complex antioxidant system, including enzymatic (scavenger enzymes) and non-enzymatic (mainly ascorbate and glutathione) components [93]. Enzymatic components include superoxide dismutase (SOD), the most effective intracellular metalloenzyme that plays a fundamental role in the antioxidant defense system [78], and catalyzes the dismutation of superoxide anions to dioxygen (O₂) and hydrogen peroxide (H₂O₂). The decline in SOD activity revealed that the antioxidant defense system was low (compromised) [94]. Catalase (CAT), the primary antioxidant enzyme that was first discovered and characterized, plays an important role with ascorbate peroxidase (APX) and peroxidase (POX) in ROS detoxification under stress by converting H₂O₂ into H₂O and O [95]. Plants respond to oxidative stress through changing the expression level of these enzymes [96]. Salt-stressed mango seedlings have shown higher SOD, CAT, and POX activity than non-stressed plants [97]. Several strategies have been used to artificially over-express these enzymes and improve their activity to regulate the translocation and accumulation of ions in salt-stressed mango trees [18]. Among these strategies is using NP materials to improve plant tolerance to salinity [76].

Data in Table 5 show that spraying salt-stressed “Ewais” mango trees with 100 mg/L nZnO + 150 mg/L nSi significantly increased the activity of SOD, POX, and CAT over the control and all other treatments during the 2017 and 2018 seasons. The activity of SOD and POX had also increased with the application of 100 mg/L nZnO and 50 mg/L nZnO + 150 mg/L nSi during both seasons. The control showed more SOD activity over the rest of the eight treatments. The activity of CAT had also increased with the application of 50 mg/L nZnO + 150 mg/L nSi and 50 mg/L nZnO, but 100 mg/L nZnO showed less CAT activity than the control. These results also indicated that a lower enzyme activity was always achieved with the application of 300 mg/L nSi, either alone or in combination with any level of nZnO; this may be because excess Si might cause a nutrient imbalance [71,85], affecting the enzymatic component of the antioxidant system, or due to the inhibition effect of high Si concentrations [87]. A significant reduction in SOD activity, associated with significant increase in POX and CAT activity from one season to another, may infer a less compromised antioxidant system in the 2018 season [94].

Table 5. Effect of foliar spray with ZnO and Si NPs (mg/L) on the superoxide dismutase (SOD), peroxidase (POX), and Catalase (CAT) activity (μ/min/g fw) of “Ewais” mango trees during the 2017 and 2018 seasons.

| Treatment (T) | SOD | | | POX | | | CAT | | |
|-----------------------|------------|----------|-------------|------------|----------|--------------|------------|----------|-------------|
| | Season (S) | | Mean | Season (S) | | Mean | Season (S) | | Mean |
| | 2017 | 2018 | | 2017 | 2018 | | 2017 | 2018 | |
| 0 nZnO + 0 nSi | 83.5 | 84.9 | 84.2 | 74.6 | 74.6 | 74.6 | 16.8 | 16.8 | 16.8 |
| 0 nZnO + 150 nSi | 72.4 | 73.7 | 73.05 | 75.2 | 76.4 | 75.8 | 17.1 | 17.8 | 17.45 |
| 0 nZnO + 300 nSi | 63.6 | 43.9 | 53.75 | 46.7 | 47.5 | 47.1 | 11.6 | 12.3 | 11.95 |
| 50 nZnO + 0 nSi | 81.2 | 81.8 | 81.5 | 76.3 | 77.3 | 76.8 | 18.4 | 19.7 | 19.05 |
| 50 nZnO + 150 nSi | 86.2 | 87.8 | 87 | 76.8 | 77.8 | 77.3 | 20.4 | 21.6 | 21 |
| 50 nZnO + 300 nSi | 74.3 | 52.5 | 63.4 | 56.8 | 57.4 | 57.1 | 15.8 | 16.2 | 16 |
| 100 nZnO + 0 nSi | 91.2 | 94.6 | 92.9 | 78.4 | 78.7 | 78.55 | 15.7 | 16.2 | 15.95 |
| 100 nZnO + 150 nSi | 97.5 | 98.2 | 97.85 | 84.6 | 86.6 | 85.6 | 24.2 | 25.7 | 24.95 |
| 100 nZnO + 300 nSi | 78.3 | 56.3 | 67.3 | 63.4 | 65.2 | 64.3 | 16.2 | 16.6 | 16.4 |
| 150 nZnO + 0 nSi | 55.5 | 59.5 | 57.5 | 52.5 | 53.8 | 53.15 | 12.5 | 13.4 | 12.95 |
| 150 nZnO + 150 nSi | 58.6 | 49.7 | 54.15 | 74.8 | 75.1 | 74.95 | 14.6 | 15.4 | 15 |
| 150 nZnO + 300 nSi | 52.7 | 32.7 | 42.7 | 42.3 | 42.8 | 42.55 | 11.2 | 11.5 | 11.35 |
| Mean | 74.58 | 67.97 | | 66.87 | 67.77 | | 16.21 | 16.93 | |
| LSD ($P \leq 0.05$) | S = 0.8 | T = 1.95 | S × T = 2.7 | S = 0.48 | T = 1.17 | S × T = 1.66 | S = 0.48 | T = 1.19 | S × T = 1.7 |

Zinc is an essential micronutrient and co-factor for many plant transcription factors, membrane stabilization, and enzymes involved in the antioxidant defense system [98]. Fang and Kao [99] found that Zn enhanced POX activity, which was related to defense functions and stress-induced lignification in rice leaves. Marreiro et al. [100] reported that Zn protects cells against oxidative stress, because it is a structural component of SOD. Zinc also inhibits the transport of calcium from the extracellular environment to the cytosol alleviating the effect of salinity stress. It also minimizes the activity of NADPH oxidase and reduces the production of ROS. Maret [101] reported that zinc induces copper deficiency, and activates copper-dependent enzymes, such as SOD. A low concentration of Zn promotes ROS production causing cell death [102]. Application of 100 mg/L nZnO reduced oxidative stress in cadmium-stressed wheat, and led to higher water and nutrient uptake, as well as improved SOD and POX activity [76]. Silicon also improved the activity of SOD and CAT in salt-stressed wheat plants [103]. Le et al. [60] reported an impact of Si NPs on the IAA concentration, as well as on CAT and SOD activity. Silicon stimulates plant's antioxidant system and decreases membrane-lipid peroxidation [104] through the activation of SOD, CAT, and POX [87].

3.5. Floral Malformation

Spraying mango with ZnO and Si NPs significantly reduced the percentage of floral malformation. This is clearly noticed with all treatments compared to the control during both seasons of study (Table 6). The most pronounced effect was noticed with the combination of 100 mg/L nZnO and 150 mg/L nSi, which significantly differed from all other treatments in both seasons. Treatments with 150 mg/L nZnO + 150 mg/L nSi and 100 mg/L nZnO were ranked second and third in this regard, respectively. Mango malformation is the major constraint to mango production in the world [105]. It has been reported early in Egypt by Attiah [106] and various times been attributed to biotic stress (e.g., acarological, viral, and fungal diseases) or abiotic stress (e.g., salinity, drought, oxidative, low temperature, metal toxicity, etc.) [19]. Multiple reports related malformation to the increase in endogenous ethylene [107,108], which is usually associated with an increase in abscisic acid and a reduction in auxins, gibberellins, and cytokinins [27].

In the current study, under salinity stress conditions, the great reduction in malformation percentage with the application of ZnO and Si NPs is believed to be related to the role of zinc that improves the biochemistry of the flowers and enhances the fruit-set number per panicle, as well as fruit retention percentage [31]. Zagzog and Gad [38] reported that spraying nano-Zn before flowering increased plant resistance to floral malformation. Rymbai and Rajesh [109] reported that Zn^{+2} chelates could restore the biochemical functions and reduce ethylene in the infected tissue, and hence reduce malformation. It is well documented that zinc plays a vital role in the synthesis of tryptophan [29]; a precursor of auxin synthesis [32], which leads to the formation of healthy panicles [110]. An impact of Si NPs on auxin synthesis was also documented by Le et al. [67].

Silicon generally improves plant growth and development [36] and enhances plant tolerance to salinity and nutritional imbalance [20]. This might explain the prominent role of nSi (150 mg/L) when added to nZnO, resulting in a big reduction in malformation percentage; this may be because Si vitalized the role of Zn in plants [86]. However, a higher concentration of nSi (300 mg/L) was not that effective, even when compared to the application of nZnO alone; this may be because excess Si may cause a nutritional imbalance and affect plant growth [74,87]. On the other hand, it seems that the continuous use of NPs from one season to another was efficient in reducing the percentage of malformed flowers, as clearly indicated by comparing the main effect of both seasons (Table 6). This could be considered a possible application to minimize the incidence of alternate bearing in "Ewais" mango trees [7], especially those grown under salinity stress conditions [19].

3.6. Yield and Fruit Quality

Spraying "Ewais" mango with Zn and Si NPs improved the total yield (fruit number and weight per tree) and fruit physiochemical characteristics compared to the untreated trees. Trees that received

the combined application of 100 mg/L nZnO + 150 mg/L nSi had the highest fruit yield, average fruit weight, length, width, TSS, sugars, and the lowest acidity percentage compared to all other treatments and the control in both seasons of study (Tables 6–8).

Total fruit number and weight of the control in the “off year” was about 56% and 57%, respectively, of that in the “on year”. Results indicated an impressive significant role of NPs improving tree productivity compared to the control in the “off year”. The same role was noticed in the “on-year”, except with the effect of 300 mg/L nSi and 150 mg/L nZnO + 300 mg/L nSi on fruit number and weight, respectively (Table 6). Results also indicated that a higher concentration of nSi was not that effective, compared to the lower one; either alone or in combination with nZnO. This may be due to the negative effect on nutrient balance, which thereby affects plant growth and productivity [59,83]. The second-best treatment that increased the total fruit yield was the application of 150 mg/L nZnO + 150 mg/L nSi. Both 100 mg/L nZnO + 150 mg/L nSi and 150 mg/L nZnO + 150 mg/L nSi were the first- and the second-best treatments in reducing floral malformation percentage, and hence showed the highest fruit yield in the same order (Table 6).

Data of average fruit weight, length, and width (Table 7) also showed that trees treated with 50 mg/L nZnO + 150 mg/L nSi and those that received 150 mg/L nZnO + 150 mg/L nSi were the second and the third, respectively, in this regard, whereas they were the third and the second, respectively, in terms of total yield (Table 6). This is might be because of a higher yield that was associated with smaller fruit [111], despite the differences among all three treatments only being significant with regard to fruit weight (Table 7). Mango plants treated with 150 mg/L nZnO + 300 mg/L nSi, as well as the control, recorded the lowest values of fruit weight, height, width, but the difference was only significant with regard to fruit weight (Table 7). Similarly, control trees, as well as those that received 100 mg/L nZnO + 300 mg/L nSi, 300 mg/L nSi, and 50 mg/L nZnO + 300 mg/L nSi, recorded the lowest TSS and sugars, but the highest acidity values, respectively, with no significant differences in all cases (Table 8). This reduction in the fruit physiochemical characteristics with the application of 300 mg/L nSi might be due to the inhibition effect of a high nSi concentration [60], and less water availability for plant and fruit growth due to salinity [112]. The significant reduction in TSS from “off-year” to “on-year” might be related to increased fruit competition due to the higher yield in the “on-year” [111].

Table 6. Effect of foliar spray with ZnO and Si NPs (mg/L) on floral malformation (%), total fruit number, and fruit weight (kg) of “Ewais” mango trees during the 2017 and 2018 seasons.

| Treatment (T) | Floral Malformation | | | Fruit Number/Tree | | | Fruit Weight/Tree | | |
|-----------------------|---------------------|----------|--------------|-------------------|----------|--------------|-------------------|----------|-------------|
| | Season (S) | | Mean | Season (S) | | Mean | Season (S) | | Mean |
| | 2017 | 2018 | | 2017 | 2018 | | 2017 | 2018 | |
| 0 nZnO + 0 nSi | 39.6 | 39.6 | 39.6 | 71 | 127 | 99 | 21.5 | 37.6 | 29.5 |
| 0 nZnO + 150 nSi | 31.3 | 30 | 30.65 | 159 | 173 | 166 | 41.3 | 41.8 | 41.55 |
| 0 nZnO + 300 nSi | 32.9 | 31.2 | 32.05 | 127 | 138 | 132.5 | 40.6 | 41.6 | 41.1 |
| 50 nZnO + 0 nSi | 29.4 | 27.5 | 28.45 | 168 | 176 | 172 | 41.8 | 44.2 | 43 |
| 50 nZnO + 150 nSi | 24.2 | 22.8 | 23.5 | 184 | 206 | 195 | 47.2 | 51.2 | 49.2 |
| 50 nZnO + 300 nSi | 27.8 | 25.5 | 26.65 | 154 | 167 | 160.5 | 42.5 | 43.5 | 43 |
| 100 nZnO + 0 nSi | 20.8 | 20.5 | 20.65 | 186 | 202 | 194 | 46.7 | 48.9 | 47.8 |
| 100 nZnO + 150 nSi | 15.2 | 14.4 | 14.8 | 217 | 232 | 224.5 | 55.4 | 63.4 | 59.4 |
| 100 nZnO + 300 nSi | 25.9 | 23.4 | 24.65 | 172 | 189 | 180.5 | 46.4 | 47.6 | 47 |
| 150 nZnO + 0 nSi | 23.5 | 21.5 | 22.5 | 178 | 186 | 182 | 45.3 | 46.3 | 45.8 |
| 150 nZnO + 150 nSi | 18.5 | 18 | 18.25 | 202 | 207 | 204.5 | 51.8 | 52.8 | 52.3 |
| 150 nZnO + 300 nSi | 31.8 | 30.5 | 31.15 | 162 | 179 | 170.5 | 37.2 | 39.5 | 38.3 |
| Mean | 26.74 | 25.41 | | 165.00 | 181.83 | | 43.14 | 46.53 | |
| LSD ($P \leq 0.05$) | S = 0.4 | T = 1.02 | S × T = 1.44 | S = 5.4 | T = 13.4 | S × T = 18.9 | S = 0.75 | T = 1.84 | S × T = 2.6 |

Table 7. Effect of foliar spray with ZnO and Si NPs (mg/L) on the average fruit weight (g), length, and width (cm) of “Ewais” mango trees during the 2017 and 2018 seasons.

| Treatment (T) | Fruit Weight | | | Fruit Length | | | Fruit Width | | |
|-----------------------|--------------|----------|-------------|--------------|----------|-------------|-------------|----------|--------------|
| | Season (S) | | Mean | Season (S) | | Mean | Season (S) | | Mean |
| | 2017 | 2018 | | 2017 | 2018 | | 2017 | 2018 | |
| 0 nZnO + 0 nSi | 246.4 | 247.4 | 246.9 | 9.5 | 9.7 | 9.6 | 6.6 | 6.9 | 6.75 |
| 0 nZnO + 150 nSi | 269.4 | 283.1 | 276.25 | 10.2 | 10.4 | 10.3 | 7.1 | 7.3 | 7.2 |
| 0 nZnO + 300 nSi | 261.5 | 271.5 | 266.5 | 9.7 | 9.8 | 9.75 | 6.9 | 7.1 | 7 |
| 50 nZnO + 0 nSi | 287.5 | 286.8 | 287.15 | 9.9 | 10.5 | 10.2 | 7.3 | 7.4 | 7.35 |
| 50 nZnO + 150 nSi | 318.7 | 316.4 | 317.55 | 10.6 | 10.8 | 10.7 | 7.8 | 7.9 | 7.85 |
| 50 nZnO + 300 nSi | 279.4 | 256.5 | 267.95 | 10.1 | 10.3 | 10.2 | 7.2 | 7.3 | 7.25 |
| 100 nZnO + 0 nSi | 285.7 | 299.7 | 292.7 | 10.4 | 10.7 | 10.55 | 7.6 | 7.8 | 7.7 |
| 100 nZnO + 150 nSi | 336.6 | 348.6 | 342.6 | 11.2 | 11.6 | 11.4 | 8.1 | 8.3 | 8.2 |
| 100 nZnO + 300 nSi | 244.6 | 267.4 | 256 | 10.3 | 10.8 | 10.55 | 7.1 | 7.4 | 7.25 |
| 150 nZnO + 0 nSi | 288.5 | 298.7 | 293.6 | 10.1 | 10.6 | 10.35 | 6.9 | 7.2 | 7.05 |
| 150 nZnO + 150 nSi | 308.3 | 304.5 | 306.4 | 10.5 | 10.8 | 10.65 | 7.6 | 7.8 | 7.7 |
| 150 nZnO + 300 nSi | 239.3 | 231.7 | 235.5 | 9.7 | 9.9 | 9.8 | 6.8 | 6.8 | 6.8 |
| Mean | 280.49 | 284.36 | | 10.18 | 10.49 | | 7.25 | 7.43 | |
| LSD ($P \leq 0.05$) | S = 0.75 | T = 1.02 | S × T = 2.6 | S = 0.47 | T = 1.17 | S × T = 1.6 | S = 0.3 | T = 0.75 | S × T = 1.06 |

Table 8. Effect of foliar spray with ZnO and Si NPs (mg/L) on the fruit total soluble solids (TSS) (%), total acidity (g citric acid/100 mL juice), and total sugars (g/100 g pulp) of “Ewais” mango trees during the 2017 and 2018 seasons.

| Treatment (T) | TSS | | | Total Acidity | | | Total Sugars | | |
|-----------------------|------------|----------|--------------|---------------|----------|-------------|--------------|----------|--------------|
| | Season (S) | | Mean | Season (S) | | Mean | Season (S) | | Mean |
| | 2017 | 2018 | | 2017 | 2018 | | 2017 | 2018 | |
| 0 nZnO + 0 nSi | 21.7 | 21.9 | 21.8 | 1.42 | 1.42 | 1.42 | 14.4 | 14.8 | 14.6 |
| 0 nZnO + 150 nSi | 24.6 | 25.3 | 24.95 | 1.29 | 1.26 | 1.275 | 15.5 | 15.8 | 15.65 |
| 0 nZnO + 300 nSi | 24.3 | 24.7 | 24.5 | 1.37 | 1.35 | 1.36 | 15 | 15.3 | 15.15 |
| 50 nZnO + 0 nSi | 24.8 | 25.1 | 24.95 | 1.28 | 1.27 | 1.275 | 15.8 | 16.4 | 16.1 |
| 50 nZnO + 150 nSi | 25.6 | 25.8 | 25.7 | 1.15 | 1.16 | 1.155 | 17.1 | 17.7 | 17.4 |
| 50 nZnO + 300 nSi | 22.6 | 23.2 | 22.9 | 1.48 | 1.38 | 1.43 | 16.2 | 16.8 | 16.5 |
| 100 nZnO + 0 nSi | 25.8 | 25.9 | 25.85 | 1.22 | 1.21 | 1.215 | 17.2 | 17.7 | 17.45 |
| 100 nZnO + 150 nSi | 26.2 | 26.7 | 26.45 | 1.12 | 1.12 | 1.12 | 17.4 | 17.6 | 17.5 |
| 100 nZnO + 300 nSi | 22.2 | 22.7 | 22.45 | 1.41 | 1.41 | 1.41 | 15.7 | 16.1 | 15.9 |
| 150 nZnO + 0 nSi | 23.1 | 24.4 | 23.75 | 1.26 | 1.29 | 1.275 | 16.3 | 16.7 | 16.5 |
| 150 nZnO + 150 nSi | 23.3 | 23.7 | 23.5 | 1.29 | 1.24 | 1.265 | 16.3 | 16.8 | 16.55 |
| 150 nZnO + 300 nSi | 22.1 | 23.4 | 22.75 | 1.38 | 1.33 | 1.355 | 14.9 | 15.7 | 15.3 |
| Mean | 32.86 | 24.40 | | 1.31 | 1.29 | | 15.98 | 16.45 | |
| LSD ($P \leq 0.05$) | S = 0.042 | T = 1.04 | S × T = 1.47 | S = 0.047 | T = 0.17 | S × T = 1.6 | S = 0.42 | T = 1.05 | S × T = 1.48 |

The impact of NPs on total fruit yield was suggested to be due to the essential role of Zn and Si on fruit set, pollen grain germination, and pollen tube elongation [113]. Zinc is rapidly absorbed by flowers, and affects fruit set and development, as well as carbohydrate metabolism and nutrient uptake. Increase in yield of mango trees due to zinc application may be attributed to its role in flower bud differentiation [26]. Usenik and Stampar [114] reported that Zn plays an important role in auxin synthesis and improves metabolite translocation to the site of bud initiation or to the bud itself. Spraying a mixture of Zn and B improves nut yield in cashew [64]. This combination has also improved plant tolerance to nutrient imbalances; increased fruit set and retention, total yield, and TSS; and reduced acidity and early fruit shedding. Additionally, it has improved the fruit taste, flavor, texture, and aroma of mango fruit [31]. Spraying nano-Zn before flowering improved the total fruit yield and quality of pomegranate [37] and mango [38]. Rizwan et al. [76] reported that the application of 100 mg/L nZnO improved grains weight in cadmium-stressed wheat plants. Adding silicon to the spray solution can precipitate Cd as Cd-silicate, which could also restrict Cd translocation to shoots and fruit [115]. Cadmium is a heavy metal that could cause toxicity to humans even at very low concentrations [116]; another aspect of fruit nutritional quality. Generally, plants possess metal homeostasis in response to toxic heavy metals through the chelation and sequestration of essential metals, such as Fe and Zn, to some specific cellular destination and removal of toxic metals from sensitive sites in the plant [117]. Silicon improved the plant growth, yield, and fruit quality of date palm [78] and tomato [118]. The application of Si is beneficial for yield and fruit quality, because it prevents oxidative stress and phenolic browning in fruit [119]. Nanoparticle fertilizers generally

improve the nutritional value of the fruit, because they enhance nutrients and sugar accumulation in fruit [120]. An increase in fruit sugar content is usually associated with an increase in TSS, because sugars are the main constituent of TSS [121].

In this context, it is worthy to mention that flowering in mango is an important and complex physiological event that determines the amount of annual fruit production [122]. Although mango has high fruiting potential [5], it has a tendency of alternate bearing (bienniality) due to erratic flowering in most cultivars [7]. Complex interactions between the shoot developmental stage and environmental conditions resulted in floral initiation in mango. Initiation is the first event that takes place for mango to flower. Flower bud initiation starts at 5 to 6 months (October–December period) before the actual spring flowering [123]. This process occurs before the onset of the coolest months of the year, which is the period of December to January in Egypt (Figure 1). Flowering requires 4–6 weeks of cool night temperatures (19 °C day/13 °C night) [124] to trigger the hormonal regulation and metabolites translocation from source to sink, and then floral induction [121]. This process is generally influenced by the previous crop load [125], bearing habit, genetic characteristics [126], age and size of the reproductive shoots, as well as other plant factors [127].

Climatic factors and environmental stresses are associated with alternate bearing of mango trees in two ways: either by damaging the crop directly through destroying buds, flowers, and fruits; or by creating conditions that indirectly affect the formation of flowers or fruits on the tree. Under tropical and subtropical conditions, early spring frost, photoperiod, cloudy weather, and rains during the flowering period reduce the crop indirectly by creating favorable conditions for disease spread like powdery mildew and anthracnose, and this could convert an “on year” into an “off year” [123]. Temperature generally affects mango fruit set. The optimum temperature is about 24–30 °C (Figure 1); however, mango trees can tolerate temperatures up to 48 °C for short periods and are sensitive to temperatures below 10 °C [128]. Moreover, it has been reported that at an optimum growth temperature, sufficient moisture increases fruit TSS [129]. Mango is a highly heterozygous tropical tree; this means the genotype \times environment interaction is very high and, hence, it is stable enough to perform well under different climatic conditions like the Mediterranean weather of Egypt [130].

The increase in carbohydrate availability is required for a high C/N ratio, which is an important attribute for floral initiation in mango [131]. The C/N ratio also differs with the environmental conditions and prevailing metabolic balance. The increase in carbohydrates is concomitant with changes in phytohormones, especially with the decline in gibberellin levels [132]. Zinc plays an important role in hormonal balance [27]. It should be noticed that even in the regular-bearing tree fruit types, if they carry a heavy load of the crop in one year, they show a tendency towards reduced yield in the following year. Hence, the basic tendency of bienniality exists even in regular-bearing varieties of mango. In other words, the potential of shoots to form flower buds will depend on the nutritional condition of the tree, which in turn will be determined by the amount of fruit load carried by the tree in the previous year. Generally, moderate flowering is one of the major conditions of annual fruit bearing in fruit trees. Apparently, in mango the fruiting is an exhausting process. For instance, the maximum available number of leaves (≈ 30) on a single shoot could not support the growth of a single fruit to normal size in the “on year”. Therefore, fruit development depends not only on the current year assimilates, but also to a great extent on the tree reserve. The utilization of reserve metabolites from vegetative organs during the “on year” could contribute to alternate bearing [133].

In the current study, under the Mediterranean conditions of Egypt, it is suggested that alternate bearing of salt-stressed “Ewais” mango trees was mainly dependent upon the annual tree reserve and metabolite availability, and to a lesser extent on weather conditions, since weather conditions were almost alike in both seasons (Figure 1) and hence have minimal or no effect on bienniality. This was also confirmed with the 5-year yield and weather data [44] that showed an alternate bearing tendency at almost-alike weather conditions (Table 9). However, the tendency to alternate bearing has been improved in the 2017 “off year” with the application of NPs (Table 6). Therefore, results of this

study confirmed the significant role of NPs in improving the plant's nutritional status, growth, and productivity under salinity conditions.

Table 9. Yield of untreated “Ewais” mango trees during five years, associated with average weather data per year calculated from September to August of each season. Yield LSD = 3.5 ($P \leq 0.05$).

| Season | 2014/2015 | 2015/2016 | 2016/2017 | 2017/2018 | 2018/2019 |
|-----------------------|-----------|-----------|-----------|-----------|-----------|
| Yield (kg/tree) | 19.9 | 35.5 | 21.5 | 39.5 | 19.6 |
| Alternate bearing | Off | On | Off | On | Off |
| Temperature (°C) | 21.2 | 22 | 21.3 | 22.2 | 22.6 |
| Humidity (%) | 67.5 | 67.7 | 67.5 | 65.8 | 64.3 |
| Cloud (%) | 13.7 | 16.2 | 14.2 | 16.8 | 18.1 |
| Rainfall (mm/month) | 6.9 | 11.1 | 4.8 | 4.4 | 17.4 |
| Rainfall (days/month) | 4.7 | 6.5 | 2.4 | 3.6 | 7.6 |
| Wind speed (km/h) | 15.5 | 15.8 | 15.5 | 16.2 | 15.1 |
| Gust speed (km/h) | 22.2 | 22.9 | 22.0 | 22.9 | 23.2 |
| Sun (hours/month) | 296.8 | 295.9 | 298.9 | 291.9 | 284.9 |
| Sun (days/month) | 24.3 | 23.4 | 26.2 | 26.1 | 22.8 |

4. Conclusions

The findings of this study demonstrated the impact of nanoparticles on plant morphology, physiology, and biochemistry. Mango trees have positively responded to NPs and showed promising results under salinity stress conditions. Nutrient uptake and carbon assimilation were positively improved with the combined application of 100 mg/L nZnO and 150 mg/L nSi. As a result, the plant's defense mechanisms under such conditions were improved, and thus overall plant growth, productivity, and fruit quality was positively changed, with indication of a possible reduction in alternate bearing incidence. More research on using NPs to improve woody plant stress tolerance and productivity is required, particularly under drought and salinity conditions, which became chief problems in most of the cultivated lands of arid-climate countries. The future prospective of this research may extend to the biotechnology field, which aims to explore the molecular bases of plant defense mechanisms. Implementing nanoparticle-mediated targeting of biomolecules [134] in such research would be useful for developing new cultivars resistant to various environmental stresses.

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