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Using Zinc and Boron Nanoparticles to Improve the Tree Growth and Fruit Quality of Florida Prince Peach Trees [Prunus Persica (L.) Bastch]

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Abstract

Prunus persica L. Batsch is a high-value cultivar, which is valued due to its high-quality fruit, early fruit harvest, and great commercialization. In this article, the usage of zinc oxide (ZnO) and boron trioxide (B_2O_3) nanoparticles on the plants' growth, yield, and fruit quality of *Florida Prince* peach trees was investigated under semi-arid field conditions at Rashidiya, Baghdad, during the 2022 and 2023 growing seasons. The experiment was conducted on nine-year-old trees grafted onto Shar rootstock. Seven treatments were established, comprising three concentrations each of ZnO (250, 500, and 1000 ppm) and B_2O_3 nanoparticles (250, 500, and 1000 ppm), along with an untreated control. Spraying ZnO nanoparticles, particularly at 1000 ppm, markedly enhanced shoot length, number of leaves, and leaf area compared with the control. Combined application of ZnO and B_2O_3 reduced fruit drop, improved fruit set, and substantially increased yield per tree relative to untreated plants. Application of nanofertilizers also improved the physical characteristics of fruits, including their weight, size, firmness, and coloration. Spraying boron nanoparticles at 1000 ppm resulted in the lowest titratable acidity and the highest total soluble solids, while zinc nanoparticles at the same concentration significantly increased vitamin C content. Overall, the optimal usage of zinc and boron nanoparticles at appropriate concentrations and timing produced a synergistic improvement in vegetative vigor, productivity, and fruit quality of Florida Prince peach trees grown on calcareous soils under semi-arid climatic conditions. These findings show that nano-fertilization could be a possible and effective measure to enhance the efficiency of nutrients and fruitfulness of peach orchards.

Keywords:

Boron nanoparticles, foliar application, fruit quality, prunus persica, vegetative growth, yield, zinc nanoparticles.

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Introduction

One of the most valuable and widely used types of fruit trees all over the world, the peach (*Prunus persica L. Batsch*) is rich in nutrients; moreover, it has a high commercial potential (Nair & Reddy, 2024; Mihaylova et al., 2021). Essential vitamins, minerals, antioxidants, and dietary fiber contained in peaches are beneficial since they help promote human health and dietary diversity (Kumari et al., 2023; Mrázová et al., 2021; Anagnostopoulos & Varga, 2021; Jasim & Mustafa, 2022). Peaches are rich in essential vitamins, minerals, antioxidants, and dietary fiber, all of which contribute to better human health and dietary diversity, as reported by (Kumari et al., 2023; Mrázová et al. 2021; Malešević et al., 2023; Anagnostopoulos & Varga, 2021).

The key characteristics of fruits that are considered by consumers to determine their consumption and marketability include sweetness, acidity, firmness, size, and appealing coloration (Niazi, 2017). The increased consumer-based demand for high-quality fruits has shifted the agricultural activities towards a method that ensures quality and quantity (Ali et al., 2014; Anthony & Minas, 2022). Zinc (Zn) and boron (B) are examples of micronutrients that regulate the quality of fruits. They have a role in numerous physiological processes that regulate the growth of plants, reproductive development, and the formation of fruits (Malešević et al., 2023; Mosa et al., 2016; Khan et al., 2021; Daivagna et al., 2025).

More than 300 enzymes use Zinc as a cofactor, and Zinc is essential in physiological and biochemical functions, including cell division, photosynthesis, protein metabolism, and auxins (Sarhan et al., 2024; Shah et al., 2019). Boron deficiency has similar adverse effects to those presented by other micronutrient deficits and is also further affected by alkaline soils, which are also found in crops like orange trees (Ojeda-Barrios et al., 2014; Genaidy et al., 2020). The micronutrient will also aid in the development of cell walls, the transport of sugars, the extension of the pollen tube, and the efficiency of fertilization. The insufficiency of supply of boron is also associated with sandy or highly leached soils, and such soils, in turn, are related to the poor fruit set, the deformity of fruit shapes, and the overall decline of the production (Vera-Maldonado et al., 2024).

The application of nano-fertilizers in the modern agriculture industry has proven to be a promising technology due to nanotechnology, where the efficiency of every nutrient can be maximized through nano-fertilizers (Al-Rawi et al., 2024). Nano-fertilizers are more bioavailable to nutrients, have controlled release, and fewer environmental losses because they have an ultra-small particle size (1100 nm) than conventional fertilizers (Mohammadi et al., 2024; Kumar et al., 2024). Earlier studies have indicated that zinc and boron nanoparticles, when used as a foliar nutrient, can increase stress tolerance and physiological functioning in different fruit crops such as olive, grape, and pomegranate. These effects are supposed to be caused by the combination of the two factors in the nanoscale (Abou El-Nasr et al., 2021; Abd El et al., 2024). Although these are encouraging findings, there is very scanty information on the application of zinc and boron nanoparticles together within peach orchards, especially in calcareous soils where the micronutrient levels are naturally low (Ibrahim, 2013).

Therefore, the aim of the current study was to determine the effects of foliar application of zinc oxide (ZnO) and boron trioxide (B_2O_3) nanoparticles at various concentrations on the vegetative, yield, and fruit quality of the *Florida Prince* peach trees that were cultivated in a semi-arid environment. The hypothesis was that foliar nutritional supplementation with nano-formulated folate, iron, and thiamine would boost physiological activity, feed level, fruit retention, and fruit quality in such environmental conditions.

This paper presents the first combined analysis of nano-zinc (ZnO-NPs) and nano-boron (B_2O_3 -NPs) applied to the plant Prunus persica at semi-arid calcareous soil in Iraq. This research gives a comparative analysis of various concentrations of nanoparticles (250, 500, and 1000 ppm), their overall effects on vegetative characteristics, yield parameters, and physical and chemical characteristics of fruits. The results provide novel information on how nano-formulated micronutrients are able to enhance nutrient uptake efficiency, fruit firmness, coloration, and nutritional value, and are an environmentally friendly alternative to conventional fertilizers. The study is also relevant in creating a scientific foundation for the application of nanotechnology-based fertilization techniques in arid and semi-arid orchards that have a shortage of micronutrients.

The Florida Prince peach trees were considered in two consecutive seasons to assess the influence of ZnO and B_2O_3 nanoparticles at different concentrations (250, 500, and 1000 ppm) applied on foliage. It was observed in terms of vegetative growth parameters (shoot length, leaf count, and chlorophyll content), yield and fruiting behavior, and physical (weight, size, firmness, and color) and chemical characteristics of fruits (total soluble solids, acidity, and vitamin C). The results demonstrated that nanoparticle treatments, particularly ZnO-NPs and B_2O_3-NPs at 1000 ppm, significantly enhanced growth, yield, and overall fruit quality compared with untreated controls.

Material and Methods

Plant Material and Site Description

The field experiment was conducted on nine-year-old Shar rootstock grafted onto Florida Prince peach in the 2022 and 2023 growing seasons. This experiment was carried out in a private orchard in the Rashidiya district of Baghdad, Iraq (33.32° N, 44.23°E), with a Cold semi-arid climate (BSk). The soil on which the location was developed was a sandy loam, which had a pH and electrical conductivity (EC_{ε}) value of 7.8 and 1.2 dS/m, respectively. The trees were spaced with 3 x 4 m between them and maintained in their normal horticultural conditions, including frequent irrigation, pruning, and control of pests, to ensure that all the treatments followed grew equally and were equally vigorous.

Experimental Design and Treatments

The research aimed to determine the effects of ZnO and B_2O_3 nanoparticles when used as a foliar application on the vegetative growth, yield characteristics, and fruit quality parameters of peach trees (Anthony & Minas, 2021). The experimental design was a randomized complete block design (RCBD) in which treatment consisted of seven treatments, each with three replications, with three trees in each replication. The treatments included three concentrations of each nanoparticle type (250, 500, and 1000 ppm) and an untreated control (Table 1).

Table 1. Design of the experimental work

Study group	Details (ppm)
T0	Control (untreated)
T1	ZnO at 250
T2	ZnO at 500
T3	ZnO at 1000
T4	B_2O_3 at 250
T5	B_2O_3 at 500
T6	B_2O_3 at 1000

Three sprays per season were applied: (i) at full bloom, (ii) fifteen days after full bloom, and (iii) fifteen days before harvest. Fresh nanoparticle suspensions were prepared before each application using analytical-grade ZnO and B_2O_3 nanopowders (Sigma-Aldrich, Germany). A hand sprayer was used to apply sprays until runoff with a surfactant, Tween-20 (0.1%), to increase the absorption into the leaf.

Nanoparticles Preparation

Boron Nanoparticles

Boron trioxide (B_2O_3) nanoparticles were produced using the ball-milling technique. In this process, boric acid was thermally decomposed at approximately 300°C to form boron trioxide. Heating to around 170°C produces water vapor (H_2O) to form metaboric acid (HBO_2). At temperatures greater than 300°C, further dehydration takes place to form boron trioxide (B_2O_3) and even more water vapor. Boron trioxide powder becomes a nanosized scale between 24 and 95 nm when it is cooled with the help of a ball mill for 5 hours. In order to make a solution that has a concentration of 1000 ppm (Alizadeh et al., 2015; Genaidy et al., 2024; Long & Peng, 2023; Maded et al., 2024).

Zinc Nanoparticles

The precipitation technique applied in the development of ZnO-NPs is the microwave-assisted precipitation technique as described by (Abdulhadi et al., 2022). The $ZnSO_4$ (0.1 M) was mixed with both ethylene glycol and NaOH solution, and allowed 2 hours to mix. The precipitated white material was then subjected to 3 minutes of microwave irradiation, dried for 3 minutes, washed, filtered, and dried in the oven at 75°C. This powder was then heated to 350°C to obtain ZnO nanoparticles, where the particle size of the material was 22.2- 27.8 nm. A 1000 ppm stock solution was then made, and consequent dilutions of 500 and 250 ppm were prepared.

Analytical Methods

Vegetative Growth

At the end of the vegetative growth phase, several growth parameters were recorded, including shoot length (cm) and the number of leaves per shoot. Leaf area (cm^2) was determined using a formula that incorporated leaf length (L) and width (W), both expressed in centimeters.

$$Leaf\ Area = L \times W \times 0.75$$

The total chlorophyll content was quantified spectrophotometrically using a Jenway 6800 UV/Vis (Bibby Scientific Ltd., England) in 80% acetone.

Fruiting and Yield

Four branches, each one year old and representing a cardinal direction of the canopy, were marked at the balloon stage. The following additional parameters were then determined according to the methods described by (Hifny et al., 2013):

$$Fruit\ set(\%) = \frac{No.\ Of\ set\ fruit\ per\ shoot}{No.\ of\ flowers} x100$$

$$Fruit\ drop\ (\%) = \frac{No.\ Fruits\ at\ fruit\ set\text{-}Fruits\ retained\ at\ \text{h}arvest}{Fruits\ at\ fruit\ set} \text{ x } 100$$

Yield (Kg tree-1) was collected; the percentage increase in yield compared to the control was determined using the formula (Abd El-Naby et al., 2019):

$$Yield\ increase\ (\%) = \frac{Treatment\ yield\ (kg)\text{-}Control\ \ yield\ (kg)}{Control\ \ yield\ (kg)} x100$$

Fruit Physical Properties

To evaluate fruit characteristics, twenty fruits from each treatment were randomly sampled at full maturity. Measurements included fruit weight (g), fruit volume (cm^3), fruit length and width (cm), firmness (N/cm^2), and peel color expressed as hue angle using a Chroma Meter (CR-400/410, Minolta Corp., Osaka, Japan).

Fruit Chemical Properties

The total soluble solids (TSS) percentage was determined using a digital refractometer, whereas titratable acidity (TA) was measured as malic acid equivalents and presented as g/100 mL of juice. Vitamin C concentration was quantified using the 2,6-dichlorophenol indophenol titration method and expressed in mg/100 mL of juice.

Statistical Analysis

All statistical analyses were performed using two-way ANOVA in GraphPad Prism software (version 10.4). Treatment means were compared using Tukey's post hoc test at a significance level of $p \leq 0.05$.

Results

Vegetative Growth

The Florida Prince peach trees showed a significant increase in vegetative growth when foliar treated with zinc and boron nanoparticles (ZnO-NPs and B_2O_3-NPs) than when they were not treated (control) in both seasons of study (2022 and 2023).

The length of shoots was also impressive, with the treatment of zinc nanoparticles, in that the mean values were the highest in zinc nanoparticles, especially at 1000 ppm of zinc oxide nanoparticles in both years (Figure 1A). Boron applications at 500 and 1000 ppm also induced significant increments, though the effects were comparatively lower than zinc treatments.

Peach tree samples with levels of 500 and 1000 ppm of ZnO nanoparticles and 1000 ppm of B_2O_3 nanoparticles had a significant positive impact on the number of leaves per shoot compared to the control (Figure 1B). On the same note, the leaf area of all trees treated with nanoparticles showed statistically significant growth (Figure 1C), which suggests a higher level of vegetative vigor.

Conversely, the amount of chlorophyll was relatively constant across treatments, and the numerical differences were statistically insignificant (Figure 1D). The overall appearance of trees treated with Zinc and boron indicated accelerated vegetative development relative to the control (Figure 1E).

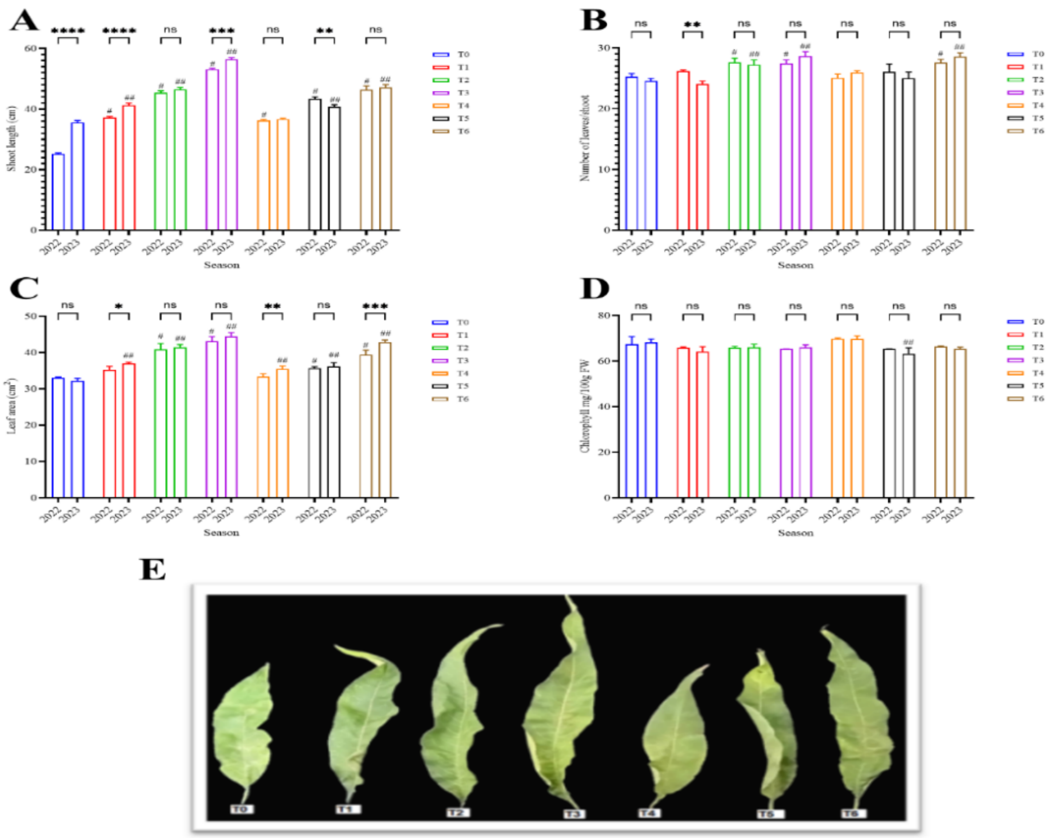

Figure 1. Effect of foliar application of zinc and boron nanoparticles on the vegetative growth of florida prince peach trees. (A) shoot length, (B) number of leaves per shoot, (C) leaf area, (D) chlorophyll content (mg/100 g fresh weight), and (E) general vegetative appearance of treated trees. significance levels are indicated as follows: $p < 0.05$ (), $p < 0.01$ (), $p < 0.001$ (), and $p < 0.0001$ (****). symbols # and ## denote $p < 0.05$ compared with the control during the first and second seasons, respectively

Fruiting and Yield

Treatments with nanoparticles also had a significant effect on fruiting and yield-related characteristics. Zinc/boron nanoparticle applications to the foliage greatly increased the fruit set percentage and lessened fruit drop, as compared to the trees that were not treated (Figures 2A and 2B). The highest increase in fruit retention was observed in treatment with 1000 ppm of ZnO-NPs and B_2O_3-NPs, which indicates that they have a positive effect on maintaining fruit yield.

Nanoparticle foliar sprays were very influential on yield per tree (Figure 2C). The highest yield values were obtained under treatments with 500 and 1000 ppm of both nanoparticles, with the 1000 ppm ZnO-NP treatment showing the most significant improvement in yield compared with the control (Figure 2D).

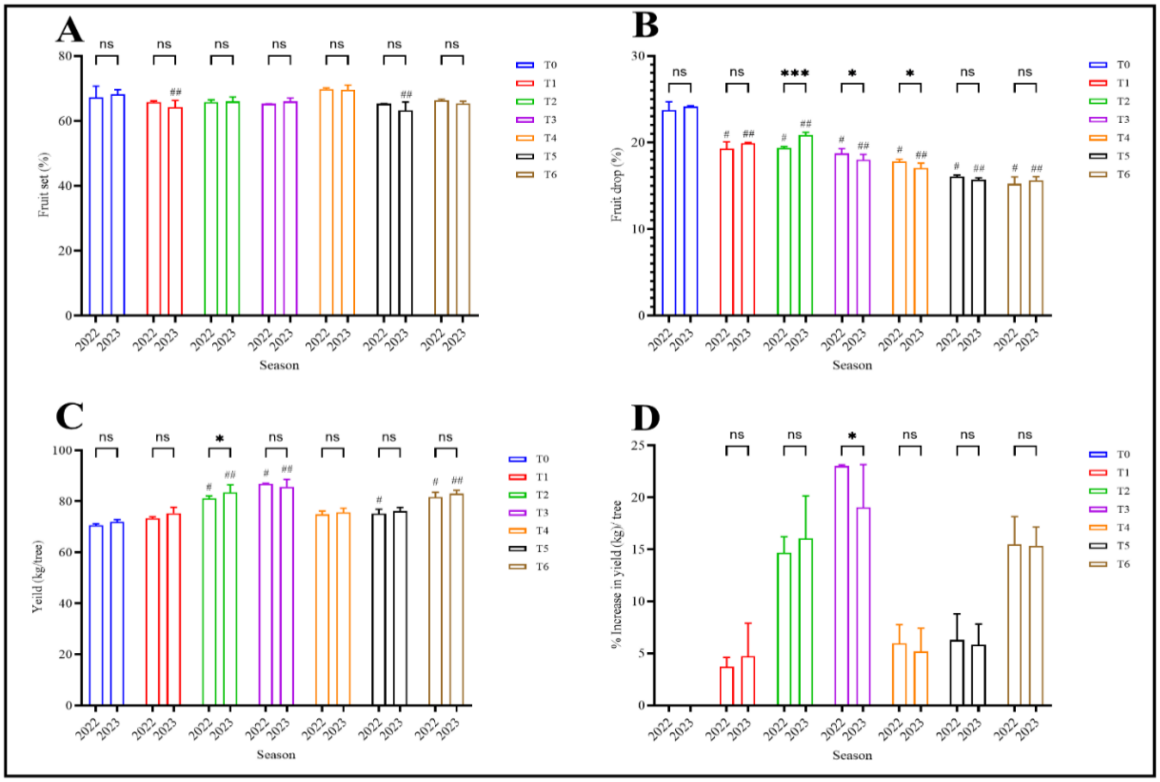

Figure 2. Influence of boron and zinc nanoparticles as foliar spraying on fruiting and yield of florida prince peach trees. A) fruit set, B) fruit drop, C) yield, D) percentage increase in yield.* p-value <0.05 appears as *, ** p-value <0.01 appears as **, *** p-value <0.001 appears as ***, **** p-value <0.0001 appears as ****. # P-value <0.05 between the control group in the first season. ## signify p-value <0.05 vs. control group in second season

Fruit Physical Properties

The use of ZnO-NPs and B_2O_3-NPs had a great effect on the physical characteristics of fruits as compared to trees that had not been treated.

At concentrations below 500 ppm for Zinc and 1000 ppm for boron, there was a notable enhancement in fruit weight and dimensions. The 1000 ppm ZnO-NP treatment produced the heaviest and largest fruits among all treatments (Figures 3A–3C).

Boron nanoparticle sprays (Figure 3D) most improved the fruit firmness at 500 and 1000 ppm. Skin color (hue angle) values decreased significantly in all nanoparticle treatments relative to the control (Figures 3E–3F), indicating improved fruit coloration and ripening uniformity.

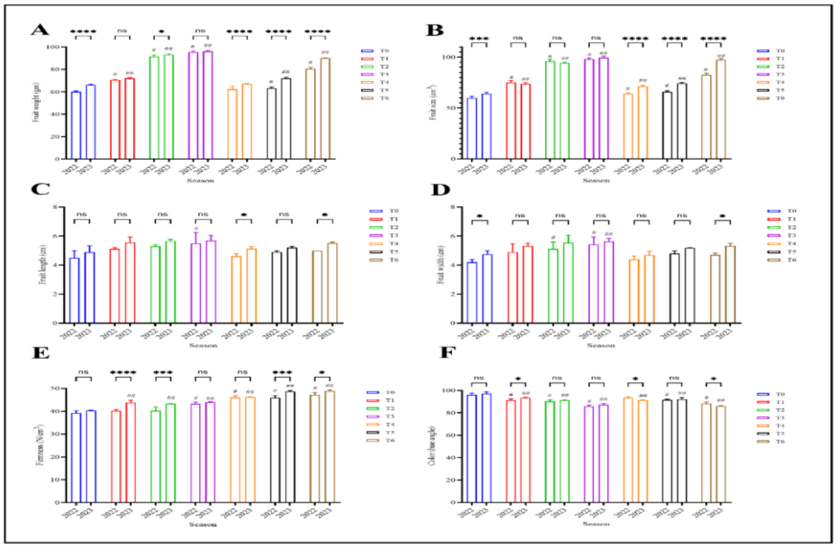

Figure 3. Effect of foliar application of boron and zinc nanoparticles on the physical characteristics of florida prince peach fruits: (A) fruit weight, (B) fruit size, (C) fruit length, (D) fruit width, (E) firmness, and (F) color. statistical significance levels are indicated as follows: $p < 0.05$ (), $p < 0.01$ (), $p < 0.001$ (), and $p < 0.0001$ (****). the symbols # and ## indicate $p < 0.05$ compared with the control group during the first and second seasons, respectively

Fruit Chemical Properties

Chemical attributes of peach fruits were markedly influenced by nanoparticle foliar treatments (Figure 4).

TSS showed a significant increase in the B_2O_3 NP at 1000ppm of B_2O_3, indicating a better accumulation of sugar. Titratable acidity (TA) was found to have an inverse correlation, increasing downwards in all the treatments of the nanoparticles, with the lowest values of titratable acidity being the boron 1000 ppm (Figure 4A-4D).

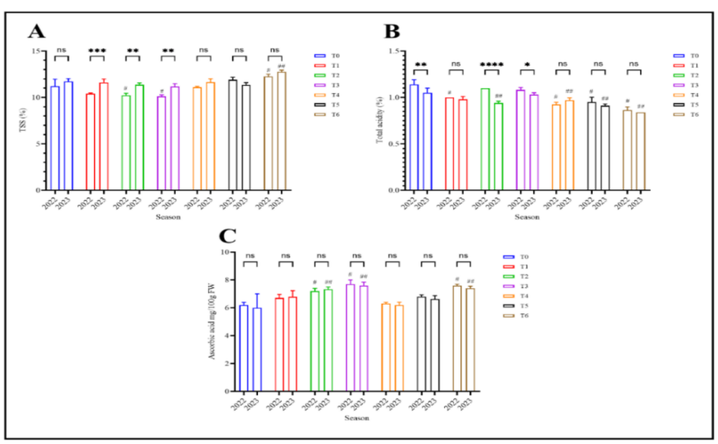

Figure 4. Influence of foliar Boron and zinc nanoparticles on chemical properties of florida prince peach fruits: (A) total soluble solids (TSS), (B) total acidity, and (C) ascorbic acid level. the levels of statistical significance are presented as follows: $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***), and $p < 0.0001$ (****). The signs, # and ##, refer to $p <0.05$ than the control group in the first and second seasons, respectively

Discussion

The results of this investigation clearly indicate that foliar application of zinc oxide (ZnO) and boron trioxide (B_2O_3) nanoparticles (NPs) markedly improved the vegetative growth, fruit yield, and overall fruit quality of Florida Prince peach trees cultivated under semi-arid conditions. The findings point out the potential of nanoparticle-based fertilizer to cope with the shortages of micronutrients that are normally encountered in the calcareous soils, such as those in Iraq and other arid regions, hence providing a practical solution to the agricultural output and quality.

Application of ZnO and B_2O_3 NPs stimulated vigorous vegetative growth, as evidenced by significant increases in shoot length, leaf number, and leaf area compared with the untreated control. Among the tested concentrations, the 1000 ppm ZnO-NP treatment produced the most substantial enhancements in these parameters, reflecting its superior effectiveness in promoting vegetative development. The results have been close with other researchers who have already studied other fruits, such as olive and guava, in which the use of Zinc has also been linked to enhancing vegetative development as a cofactor in photosynthetic enzymes, protein synthesis, and auxin metabolism enzymes (Parmar et al., 2014; Ibrahim, 2013). Cell division and cell growth need Zinc to counteract their occurrence, and the bioavailability of Zinc in the form of a nanoparticle is likely to enhance its absorption in plant tissues, thus enhancing the rate at which plants grow. Boron treatment also had a positive influence on vegetative growth, but to a lesser extent than Zinc. Boron plays a pivotal role in plant physiological processes, especially in carbohydrate metabolism and maintaining the structural stability of cell walls. Boron sufficiency enhances sugar translocation across the membrane and cell wall production, which results in an increase in fruit maturity and fruit quality characteristics. Although the effect of the boron on growth was not as high as that of Zinc, there was a general positive response of the plants, implying the role played by boron in cell maintenance that facilitates the growth processes. This may be because the increased vegetative growth with the nanoparticle treatments is probably attributed to the high absorption and efficient nutrient uptake offered by the uncommon features of the nanoparticles, which are their high surface area and low size. The aforementioned properties make the nanoparticles a competent material for plant tissue penetration, which will, in turn, lead to a quicker response during growth compared to conventional fertilizers.

Additionally, fruiting and yield parts were also greatly affected by nanoparticle treatments. ZnO-NPs and B_2O_3-NPs foliar application at a concentration of 500 and 1000 ppm significantly enhanced the fruit set and fruit drop, and the most significant impacts of the two nanoparticles were at 1000 ppm. The results can be attributed to previous studies of other fruit crops, where zinc and boron foliar sprays increased fruit retention and yield (Saadati et al., 2016; Abd El et al., 2024). Zinc is involved in the formation of fruit by activating auxin synthesis, and boron facilitates pollen tube length and fertilization, which are factors of fruit setting and reduction of early fruit abscission (Hussain et al., 2015; Rudani et al., 2018). The most promising outcomes were achieved in the scenario when 1000 ppm of ZnO-NP were applied, since the highest yield was received per tree. The yield advantages observed in the presence of nanoparticles can be explained by the fact that these particles increase the fruit retention and photosynthetic rate because of active vegetative growth and fertilization rate. All these physiological improvements contribute to the high performance of trees treated with ZnO and B_2O_3 nanoparticles over the untreated controls.

ZnO-NPs and B_2O_3 -NPs were also used to put in place far-reaching effects on the physical characteristics of the fruit. Weight growth, size growth, and firmness increase of fruits were experienced in the 500 and 1000 ppm treatments of the two nanoparticles. It is necessary to say that conditioning using 1000 ppm ZnO-NP was observed to produce the highest and heaviest fruits. The reported growth of the fruit size and weight is consistent with the previous findings, indicating that Zinc enhances cell division and expansion of various fruits, such as grapes and date palms (Okatan et al., 2018). The growth in the quality of these characteristics is likely due to Zinc, since it has an effect on Zinc, inducing cell division and general development. In addition, association with the boron treatments was rather noticeable because the firmness of the fruits was markedly increased under the conditions of 500 and 1000 ppm concentration of the substance, which is possibly caused by the cross-linking of the boron molecules with the pectin molecules in the cell wall that strengthens the structural integrity and increases the fruit firmness (Khalifa et al., 2016). Besides this, the color of the fruit of all the nanoparticle treatments was found to have a significantly low value of hue angle, which is a measure of increased coloration and uniformity of the ripening cycle of fruit. Zinc nanoparticles also played a significant role in coloring fruits. According to the previous reports, Zinc controls anthocyanin biosynthesis and pigment development during the ripening process, which enhances the color intensity of fruits (Wadhwa et al., 2014; Medda et al., 2020).

Another clear change in the chemical composition of fruits in response to the use of nanoparticles was also observed. The content of the total soluble solids (TSS) was the greatest in fruits subjected to 1000 ppm B_2O_3 nanoparticles, indicating increased sugar accumulation, and titratable acidity (TA) declined significantly in all the treatments of the nanoparticles. The lowest acidity was recorded when used under 1000 ppm B_2O_3, and this is consistent with the previous research showing that zinc ascorbic acid synthesis (asgary) and sugar storage are enhanced through the use of zinc nanoparticles (Hafeez et al., 2013; Khan et al., 2015). Zinc is a cofactor of enzyme L-galactono-1,4-lactone dehydrogenase, which is one of the important constituents of ascorbic acid production, and a sufficient supply of Zinc increases vitamin C content in the tissues of fruit.

Fertilizers that are produced using nanotechnology, such as ZnO-NPs and (B_2O_3) -NPs, have some benefits over the regular fertilizers. The better performance of treated trees can be explained by the greater efficiency of nutrient use, regulated nutrient release, and loss of nutrients, which is normally characteristic of nanoparticle formulations. The solubility of nanoparticles rises due to high surface-volume ratio which is more readily absorbed by leave tissues due to high surface to volume ratio which enhances increased nutrient uptake and decreased wastage. It is more so in the areas that use calcareous soils, where the traditional fertilizers have never stopped experiencing problems with the inaccessibility of nutrients and leaching. Moreover, the nanoparticles are more sustainable than conventional fertilizers as they allow the plants to grow at their best instead of using small volumes of fertilizer. Nanoparticle-based fertilizers are also aligned with sustainable agriculture in that they lead to reduced downstream nutrient loss and improved environmental effects of the application of fertilizers.

But, when the desired effects are sustained, the question is whether nanoparticles can be considered in terms of their long-term impact on the body following repeated exposure. Despite the high influence of nanoparticles on the efficiency of nutrient delivery and crop productivity, their retention in the soil and possible accumulation in the plants and soil biota should also be taken into consideration to prevent ecological risks. The possible outcomes of the accretion of nanoparticles on the well-being of soil, microbial community, and the ecosystems, in general, are a topic of investigation. Also, cumulative effects caused by repetitive use of nanoparticles in the field can change the soil fertility and crop performance in the long run.

Further research is to be done to discover different areas where ZnO-NPs and B_2O_3 -NPs can be applied to their maximum potential in the agricultural field. To a great degree, the soil quality, the presence of the plants, and environmental friendliness that will be enhanced by the constant use of nanoparticles will be the result of the test of soil with nanoparticle treatment that will happen in the long term. Also, one can address the implementation of nanoparticle treatment, as well as organic additions like compost or biochar, as a more substantial nutrient management strategy. Organic change may result in soil structure, water-binding capacity, and enhanced microbial activity, which would also be facilitated by the effect of fertilization using nanoparticles. In addition, the reaction of such nanoparticles to environmental challenges like drought, heat, and salinity should also be known, as this knowledge can be a good indicator in the instance of crops becoming more resilient to climatic extremes with the assistance of nanoparticles. In addition to that, the most timely period to use the nanoparticles and the potential synergistic effect of their use with other micronutrients can result in an even more sophisticated and effective method of application.

Conclusion

Overall, the outcomes of this investigation confirm that foliar supplementation with zinc oxide (ZnO) and boron trioxide (B_2O_3) nanoparticles markedly enhanced vegetative growth, fruit retention, yield, and the physical and biochemical quality of Florida Prince peach fruits cultivated under semi-arid conditions. This shows that ZnO-NPs and B_2O_3-NPs can be effectively used as an environmentally friendly alternative to traditional fertilizers. Arguably, the surface area and bioavailability of nanoparticles are so immense that they can augment the effectiveness of micronutrients and plants get the entirety, therefore enhancing the uptake and application by plants.

The results indicate that the solution to the issue of the micronutrient deficit in the limestone soils in the semi-arid areas, such as Iraq, may lie in the application of the nanotechnology-based fertilizers. The nanoparticle fertilizers are able to offer sustainable agriculture with methods of loss reduction, enhancement of nutrient absorption, and crop yield. Nevertheless, the duration of the potential impact of nanoparticle application to soil health, on environmental sustainability, and on plant physiology should be studied further. The possible future research studies should concentrate on the possible cumulative effects of the repetitive use of nanoparticles and the mixture of nanoparticles with organic amendments and other micronutrients. In addition, the evaluation of the effect of the nanoparticles on the tolerance of plants against environmental conditions (such as drought, heat, and salinity) can provide more information on how such materials can be used in harsh climatic conditions. Although the application of nanofertilizers presents a promising pathway toward sustainable agriculture, it remains essential to establish systematic monitoring frameworks and conduct in-depth assessments of their environmental behavior. This ensures that nanoparticle-based fertilizers are both safe and effective for long-term agricultural use. ZnO-NPs and B_2O_3-NPs provide the capability to enhance agricultural productivity in nutrient-deficient regions by replenishing essential nutrients and providing sustainability benefits linked to the nanoparticles.

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Conflicts of Interest

The authors declare that they have no conflicts of interest related to this study.

Author Contribution

All the work, the study, methodology design, the experiments, data analysis, and writing of the manuscript were conceptualized by the single author. The author is responsible for all aspects of the research and publication.

Data Availability Statement

The dataset generated and analyzed in this study is publicly available on Zenodo at https://doi.org/10.5281/zenodo.15105053 (Reference No. 15105053).

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