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Eco-Nanotechnology Approach to Improve the Growth and Fruit Quality of Strawberry Through Nano Boron and Copper Applications

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ABSTRACT

Background: Strawberry is botanically a berry-like fruit in the genus Fragaria of the Rosaceae family. Strawberries are important for human health because they are a rich source of vitamin C, along with potassium, iron and comprehensive antioxidants. In order to study the effect of foliar application of nano boron and copper on vegetative growth and reproductive characteristics of strawberry c.v camarosa were investigate.

Methods: A factorial experiment in a completely randomized block design with 3 replications which the factors included Nano Boron at three levels (0, 10 and 20 ppm) and Nano Copper at three levels (0, 20 and 40 ml L^{-1}). The experiments have been done on fall season 2024.

Result: The results showed that the highest concentrations of both Nano Boron (20 $mg.L^{-1}$ and Nano Copper (40 $mg.L^{-1}$) significantly enhanced several key growth parameters, including total leaf area, chlorophyll content, number of leaves per plant and leaf dry matter percentage. Additionally, the combined application of 20 $mg.L^{-1}$ Nano Boron and 40 $mg.L^{-1}$ Nano Copper produced the most favorable outcomes in yield components, such as fruit volume (29.78 cm^3), fruit weight (21.93 g), total soluble solids (6.533%) and sugar content, while simultaneously reducing total titratable acidity. Enhanced anthocyanin accumulation was also observed in the same treatment, indicating improved fruit quality. The synergistic interaction between Nano Boron and Nano Copper appears to promote photosynthetic efficiency and metabolic activity, contributing to overall yield and fruit biochemical enhancement. These findings support the use of Nano Boron and Nano Copper as sustainable and eco-friendly agents for improving strawberry productivity and quality, particularly in cultivars grown under suboptimal conditions.

Key words: Camarosa, Foliar application, Nano boron, Nano copper, Strawberry.

INTRODUCTION

Strawberry (*Fragaria* × *ananassa* Duch) is one of the most widely consumed and cultivated fruits worldwide (Kocaman, 2024) which can be produced in many climates, are a fruit preferred by everyone because of their aromatic properties, delicious, fragrant and good view, different types of strawberries are grown around the world, especially in temperate climates. Strawberry is botanically a berry-like fruit in the genus Fragaria of the Rosaceae family (Oguz, 2021). Strawberries are important for human health because they are a rich source of vitamin C, along with potassium, iron and comprehensive antioxidants (Masoud *et al*., 2024). It also contains high amounts of dietary fiber, secondary metabolites and sugars. The high content of these compounds is beneficial to health as they could inhibit blood clotting and reduce cardiovascular disease (Mohamed *et al*., 2021).

Camarosa is an important strawberry variety that has been widely grown in Iraq in recent years. A short-day variety, the fruit is mostly conical in shape. The outside of the ripe fruits is dark red and shiny, while the inside is bright red. It has a firm, crunchy texture and excellent flavor. Increasing yield while maintaining fruit quality is an important goal, which can be achieved by foliar application of nutrients widely used to promote growth and fruit set in many crops (Rashid *et al*., 2025).

Foliar application of micronutrients is clearly an ideal method to avoid nutrient availability problems. Nanotechnology is a modern approach capable of modifying the current synthetic framework used in agricultural systems by enhancing the efficiency of agricultural chemicals and providing solutions to environmental and agricultural problems (El-Khouly *et al*., 2024). Nano fertilizers have an important effect in improving

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many aspects of strawberry plant physiology, *i.e.*, photosynthesis, reproduction, nitrogen fixation, flowering, seed production and maturation dates.

Nano boron is one of the essential micronutrients that plays a crucial role as an enzyme activator, carbohydrate transporter, ion absorber and synthesizer of nucleic acids (DNA and RNA), lignin cellulose and proteins, It also improves pollen tube growth and there is a good relationship between boron content in plant tissues and total flower number, non-aborted flower ratio and seed numbers (Wimmer and Eichert, 2013). The utilization of Nano-boron has many advantages; increasing water and nutrient absorption and low material costs which reduce the economic cost of the agricultural process (Azab *et al.*, 2024).

Copper is crucial for pollen production and seed formation and its deficiency can result in reduced grain and seed production. Therefore, "It plays a significant role in improving agricultural crop production" (Pramanik *et al.*, 2020). The use of nano copper fertilizer in fertilization presents an effective alternative to traditional fertilizers, as it offers several advantages such as requiring smaller quantities and displaying high stability under different conditions. Nano fertilizers are known for their extremely small size. This means they do not require large spaces and are rapidly absorbed by plants, allowing for their use at the required times based on the actual needs of the plant. They can be applied as sprays on the green group, enabling plants to benefit from them more quickly. This provides a larger area for various metabolic reactions in the plant, enhancing the activity of photosynthesis and increasing the production of dry matter and crop productivity (Thakur *et al.*, 2018).

Copper nanoparticles play role in plants enhanced photosynthetic activity by modulating fluorescence emission, photophosphorylation, electron transport chain and carbon assimilatory pathway, uses of metal particles as fertilizers have potential to increase crop growth and productivity, with minimize environmental hazards (Uddin *et al.*, 2022).

It seems that the combination of Boron, Copper Nano as safe and environmental friendly stress mediating phytochemicals, may have more positive effects in improving tolerance mechanisms against decreased nutrient levels. Since there is no report regarding the combination effects of these two phytochemicals on strawberry yield and fruit quality parameters, then this study was conducted to determine if Nano Boron, Copper are able to mitigate the probable adverse effects of deficit fertigation on strawberry fruit quality and yield or not. Therefore, aspects present study was conducted to find out the effect of boron and copper nanoparticles concentration in enhancing growth and increasing yield of Strawberry.

MATERIALS AND METHODS

Material and design

The experiment was carried out at the research station of the Department of Horticulture and Landscape Engineering, College of Agriculture, University of Diyala, during the 2025 agricultural season. The study aimed to evaluate the effects of spraying Nano Boron and Nano Copper on the characteristics of vegetative growth, Physical and Chemical characteristics of fruits. The soil was sandy and prepared by plowing, sowing and fertilizer application. A drip irrigation system was used in the experiment. The area of each experimental plot was 12.80 m^2 and included one bed 8.0 m long and 1.6 m wide. Each bed consisted of four rows and plants were transplanted at 0.25 m inter-row spacing and 0.15 m within one row. Transplanting was carried out on September 20 (60 days after sowing) when plants reached 3-4 true leaves. The treatments were done in a completely randomized block design with four replications, with each experimental plot consisting of five 2 m rows. The experiments have been done on fall season 2024. The experiment has started on 1/11/2024 till 10/5/2025.

1. Characteristics of vegetative growth

Ten flowering plants were randomly selected from each plot; the average of ten plants was taken as one replicate. The following characteristics were recorded for each plant:

- Total leaf area (cm^2).
- Total chlorophyll (SAPD).
- Number of leaves per plant.
- Percentage dry matter of leave.

2. Physical and Chemical characteristics of fruits

20 fruits from each replicate were randomly collected at harvest time and the following traits were measured

- Fruit volume (cm^3).
- Fruit weight (g).
- Total yield (g).
- Total soluble solids % (TSS): Measured with a hand refractometer.
- Total sugars % and reducing sugars%: Determined according to the Lane and Eynon method described in AOAC (1990).
- Total titratable acidity%: Determined by titration of pure fruit juice with 0.1 N NaOH with phenolphthalein as indicator (AOAC, 1990). The acid content was calculated as g citric acid/100 ml of juice.
- Anthocyanin content, method described in (AOAC, 1990).

Statistical analysis

The experiment was set up with three repeats (10 plants in each repeat), three nano boron levels (0, 10 and 20 ppm) and Nano Copper at three levels (0, 20 and 40 ml L^{-1}). For Nano Boron and Nano Copper treatment, the powders were dissolved in hot water, allowed to cool and then applied to the plant material. Three spraying applications of each treatment were applied with one-month intervals. The first application was carried out 6 weeks after transplanting. The results were statistically evaluated by analysis of variance (ANOVA) using statistical analysis system software (SAS) version 20. Significant differences were evaluated using the least significant difference (Duncan) and differences were considered statistically significant when $P<0.05$.

RESULTS AND DISCUSSION

Characteristics of vegetative growth

Total leaf area

Table 1 has indicated that the level 20 ml L^{-1} of nano boron and 40 ml L^{-1} nano copper has been realized a significant differences in total leave area recorded 179.0 and 176.1 cm^2 respectively, the combination of 20 mg l^{-1} nano boron and 20 mg l^{-1} of nano copper have achieved the highest values as for total leave area recorded 190.4 cm^2, while control treatment had the lowest leave area at 165.5 cm^2.

Total chlorophyll

The results in Table 2 showed that application of nano boron significantly increased total chlorophyll compared to water spraying (control) 40.37 and 39.48 SPAD respectively, while the control treatment recorded 34.66 SPAD. Table 1 has indicated significant differences in total chlorophyll content during spraying nano copper at 40 and 20 ml L^{-1} which record 41.96 and 38.56 SPAD respectively. The combination of 20 mg l^{-1} nano boron and 40 mg l^{-1} of nano copper have achieved the highest values as for chlorophyll content 44.73 SPAD, while control treatment had the lowest chlorophyll content at 30.60 SPAD.

Number of leaves per plant

The results in Table 3 indicated that the 20 mg l^{-1} of nano boron has given best value to leaves number 15.69 and 14.80 leaf, while application of nano copper significantly increased leaves number compared to water spraying 16.10 and 14.82 leaf respectively. The combination 20 mg l^{-1} of nano boron and 40 mg l^{-1} of nano copper achieved significant differences of leaves number recorded 17.53 leaf, while control treatment had the lowest leaves number recording 12.10 leaf.

Percentage dry matter of leave

The data in Table 4 showed that sprayed with nano boron at 20 mgl^{-1} had the best significant values in percentage

Table 1: Effect of nano boron and nano copper spraying and the interaction between them on total leaf area (cm^2) of strawberry c.v camarosa.

Nano boron rate	Nano copper ml L^{-1}			Nano boron ml L^{-1}
	40	20	0	
0	144.0e	150.4e	165.5cd	153.4A
10	153.9de	164.1cd	172.3bc	163.4B
20	166.0cd	180.6ab	190.4a	179.0C
Nano copper rate	176.1A	165.0B	154.6C	

Table 2: Effect of nano boron and nano copper spraying and the interaction between them on relative content of chlorophyll in leaves (SPAD) of strawberry c.v camarosa.

Nano boron rate	Nano copper ml L^{-1}			Nano boron ppm
	40	20	0	
0	30.60f	33.83ef	39.53bcd	34.66B
10	36.33cde	40.47abc	41.63ab	39.48A
20	35.00def	41.37ab	44.73a	40.37A
Nano copper rate	33.98C	38.56C	41.96A	

Table 3: Effect of nano boron and nano copper spraying and the interaction between them on leaves number plant-1 of strawberry c.v camarosa.

Nano boron ppm	Nano copper ml L^{-1}			Nano boron rate
	0	20	40	
0	12.10c	14.40b	15.27b	13.92C
10	14.23b	14.67b	15.50b	14.80B
20	14.13b	15.40b	17.53a	15.69A
Nano copper rate	13.48C	14.82B	16.10A	

Table 4: Effect of nano boron and nano copper spraying and the interaction between them on percentage dry matter of leave strawberry c.v Camarosa.

Nano boron ppm	Nano copper ml L^{-1}			Nano boron rate
	0	20	40	
0	25.01c	25.76bc	29.60a	26.79B
10	25.78bc	27.19abc	29.00ab	27.33B
20	27.49abc	29.29a	30.62a	29.13A
Nano copper rate	26.10B	27.41B	29.74A	

dry matter leave of strawberry c.v camarosa recording 29.13%, while the level 40 mg l^{-1} of nano copper has been realized a significant differences recording 29.74%. The combination of nano boron 20 mg l^{-1} and nano copper spraying at 40 mg l^{-1} significantly achieved the highest value compared to other study combination treatments in percentage dry matter of leave parameter recording 30.62%, while control treatment had the lowest dry matter recording 25.01%.

Physical and chemical characteristics of fruits

Fruit volume

The data in Table 5 showed that application of nano boron significantly increased fruit volume compared to water spraying recording 24.66 and 22.96 cm^3 respectively, while the level 40 and 20 mg l^{-1} of nano copper has been realized a significant differences recording 27.34 and 22.36 cm^3 respectively. The combination of nano boron 20 mg l^{-1} and nano copper spraying at 40 mg l^{-1} significantly achieved the highest value compared to other study combination treatments in fruit volume recording 29.78 cm^3, while control treatment had the lowest fruit volume recording 15.09 cm^3.

Fruit weight

The data in Table 6 showed that application of nano boron significantly increased fruit weight compared to water spraying recording 20.59 and 19.05 g, while the level 40 mg l^{-1} of nano copper has been realized a significant differences recording 20.29 g. The combination of nano boron 20 mg l^{-1} and nano copper spraying at 40 mg l^{-1} significantly achieved the highest value compared to other study combination treatments in fruit weight recording 21.93 g, while control treatment had the lowest recording 16.76 g.

Total yield

The data in Table 7 showed that application of nano boron significantly increased total yield compared to water spraying recording 528.2 and 461.7 g, while the level 40 mg l^{-1} of nano copper has been non-significant differences. The combination of nano boron 20 mg l^{-1} and nano copper spraying at 40 mg l^{-1} significantly achieved the highest value compared to other study combination treatments in total yield recording 541.0 g, while control treatment had the lowest total yield recording 341.0 g.

Total soluble solids

The results in Table 8 showed that application of nano boron 10 and 20 mg l^{-1} significantly increased TSS compared to water spraying (control) recording 5.911 and 5.533% respectively, while the control treatment recorded 5.056%, while the level 40 and 20 mg l^{-1} of nano copper has been realized a significant differences recording 6.144 and 5.544% respectively. The combination of 20 mg l^{-1} nano boron and 20 mg l^{-1} of nano copper have achieved the highest values as for TSS 6.533%, while control treatment had the lowest TSS at 4.467%.

Table 5: Effect of nano boron and nano copper spraying and the interaction between them on fruit volume (cm3) strawberry c.v camarosa.

Nano boron	Nano copper ml L^{-1}			Nano boron rate
	0	20	40	
0	15.09d	17.82cd	25.62b	19.51C
10	18.12cd	24.13b	26.63b	22.96B
20	19.09c	25.12b	29.78a	24.66A
Nano copper rate	17.43C	22.36B	27.34A	

Table 6: Effect of nano boron and nano copper spraying and the interaction between them on fruit weight (g) strawberry c.v camarosa.

Nano boron	Nano copper ml L^{-1}			Nano boron rate
	0	20	40	
0	16.76d	17.67cd	18.55bcd	17.66C
10	18.24bcd	18.50bcd	20.39ab	19.05B
20	19.63abc	20.22ab	21.93a	20.59A
Nano copper rate	18.21B	18.80B	20.29A	

Table 7: Effect of nano boron and nano copper spraying and the interaction between them on total yield (g) strawberry c.v camarosa.

Nano boron	Nano copper ml L^{-1}			Nano boron rate
	0	20	40	
0	341.0d	366.0cd	379.3cd	362.1C
10	429.7bc	466.3ab	489.0ab	461.7B
20	513.0ab	530.7a	541.0a	528.2A
Nano copper rate	427.9A	454.3A	469.8A	

Total sugars %

The results in Table 9 showed that application of nano boron 10 and 20 mg l^{-1} significantly increased total sugars compared to water spraying (control) recording 7.539 and 6.301% respectively, while the control treatment recorded 5.131%, while the level 40 and 20 mg l^{-1} of nano copper has been realized a significant differences recording 7.508 and 6.687% respectively. The combination of 20 mg l^{-1} nano boron and 20 mg l^{-1} of nano copper have achieved the highest values as for total sugars 9.024%, while control treatment had the lowest total sugars at 3.937%.

Reducing sugars%

The results in Table 10 showed that application of nano boron 10 and 20 mg l^{-1} significantly increased reducing sugars compared to water spraying (control) recording 5.367 and 4.328% respectively, while the control treatment recorded 3.156%, while the level 40 and 20 mg l^{-1} of nano copper has been realized a significant differences recording 5.111 and 4.774% respectively. The combination of 20 mg l^{-1} nano boron and 20 mg l^{-1} of nano copper have achieved the highest values as for reducing sugars 6.482%, while control treatment had the lowest reducing sugars at 2.330%.

Total titratable acidity

The results in Table 11 showed that application of nano boron 10 and 20 mg l^{-1} significantly decreased reducing total acidity compared to water spraying recording 0.472 and 0.539% respectively, while the control treatment recorded 0.570%, while the level 40 and 20 mg l^{-1} of nano copper has been realized a significant differences recording 0.468 and 0.516% respectively. The combination of 20 mg l^{-1} nano boron and without spraying of nano copper have achieved the lowest values for total acidity 0.426%, while control treatment had the highest total titratable acidity at 0.653%.

Table 8: Effect of nano boron and nano copper spraying and the interaction between them on TSS% strawberry c.v camarosa.

Nano boron ppm	Nano copper ml L^{-1}			Nano boron rate
	0	20	40	
0	4.467f	5.133de	5.566cd	5.056C
10	4.7000ef	5.5667cd	6.333ab	5.533B
20	5.267d	5.933bc	6.533a	5.911A
Nano copper rate	4.811C	5.544B	6.144A	

Table 9: Effect of nano boron and nano copper spraying and the interaction between them on total sugar% strawberry c.v camarosa.

Nano boron ppm	Nano copper ml L^{-1}			Nano boron rate
	0	2	4	
0	3.937f	5.374de	6.081cd	5.131C
10	4.682ef	6.803bc	7.418b	6.301B
20	5.709cde	7.884b	9.024a	7.539A
Nano copper rate	4.776C	6.687B	7.508A	

Table 10: Effect of nano boron and nano copper spraying and the interaction between them on reducing sugar% strawberry c.v camarosa.

Nano boron ppm	Nano copper ml L^{-1}			Nano boron rate
	0	20	40	
0	2.330e	3.335de	3.802d	3.156C
10	2.999de	4.937c	5.048bc	4.328B
20	3.568d	6.049ab	6.482a	5.367A
Nano copper rate	2.966B	4.774A	5.111A	

Table 11: Effect of nano boron and nano copper spraying and the interaction between them on total titratable acidity% strawberry c.v camarosa.

Nano boron ppm	Nano copper ml L^{-1}			Nano boron rate
	0	20	40	
0	0.653a	0.560bc	0.497de	0.570A
10	0.606ab	0.530cd	0.480def	0.539B
20	0.533cd	0.457ef	0.426f	0.472C
Nano copper rate	0.598A	0.516B	0.468C	

Table 12: Effect of nano boron and nano copper spraying and the interaction between them on anthocyanin content (mg 100 g wet weight^{-1}) strawberry c.v camarosa.

Nano boron ppm	Nano copper ml L^{-1}			Nano boron rate
	0	20	40	
0	18.57d	19.21cd	19.30cd	19.03C
10	18.98cd	20.35bc	21.37ab	20.24B
20	19.40cd	21.14b	22.55a	21.03A
Nano copper rate	18.99C	20.23B	21.07A	

Anthocyanin content

The results in Table 12 showed that application of nano boron 10 and 20 mg l^{-1} significantly increased fruit content of anthocyanin compared to water spraying (control) recording 21.03 and 20.24 mg 100 g wet weight^{-1} respectively, while the control treatment recorded 19.03 mg 100 g wet weight^{-1}, while the level 40 and 20 mg l^{-1} of nano copper has been realized a significant differences recording 21.07 and 20.23 mg 100 g wet weight^{-1} respectively. The combination of 20 mg l^{-1} nano boron and 40 mg l^{-1} of nano copper have achieved the highest values as for leaf content of anthocyanin 22.55 mg 100 g wet weight^{-1}, while control treatment had the lowest content at 18.57 mg 100 g wet weight^{-1}.

The results of this study indicated the effects of nano boron and nano copper on plant growth and fruit quality. It is suggested that foliar application of or nano boron could significantly improve plant growth and fruit quality of camarosa strawberry. This may be due to the physiological role of boron and its involvement in protein metabolism, pectin synthesis, maintenance of proper water relations in the plant, adenosine triphosphate (ATP) resynthesize and sugar translocation during flowering and fruiting (Masoud *et al.*, 2024; Gogoi *et al.*, 2023). Boron has effects on cell wall structure, cell elongation and root elongation. It is also believed to be a nutrient that increases phloem carbohydrate translocation, which may increase the soluble solids content of fruit (Marschner, 2012). Boron application was very beneficial in the photosynthesis process, promoting carbohydrate accumulation and ultimately improving fruit quality (Mohamed *et al.*, 2021; Sorate *et al.*, 2025).

The strawberry's growth, yield and quality were significantly improved by increasing the amount of spraying the crop with nano copper, the best results in the plant traits studied were achieved with the treatment involving the foliar feeding with (20,40 ml L^{-1}) of nano copper can be explained by achieving a better nutritional balance for these nutrients within the plant. This balanced nutrition encouraged better growth and production by enhancing the plant's ability to effectively utilize growth factors. It seems that when foliar nutritionals were used, the photosynthetic activity was stimulated, leading to enhancement of chemical constituents as total sugars and reducing sugars, anthocyanin content and T.S.S in strawberry's fruit. Copper has an influential role in the biological processes in plants by activating some enzymes, likewise the oxidizing enzymes of the polyphenol oxidase and the role of transferring electrons in photosynthesis. Several studies revealed that about 70% of the total copper in the leaf tissues is present in the chloroplasts and this confirms its bioactivity in the process of photosynthesis. Copper has long been used with other constituents as a mixture to tackle fungal diseases (Al-Janabi *et al.*, 2021; Muttulani *et al.*, 2025).

CONCLUSION

The current results indicate that foliar application of nano boron and nano copper, not only individually but also in combination, notably improves biochemical attributes of strawberry (*Fragaria* × *ananassa*) cv. Camarosa fruit. Significant, improvements in total soluble solids (TSS), sugar content, anthocyanin content and relative chlorophyll (SPAD) were recorded, especially, plants treated with combination of nano boron and nano copper. These findings indicate that nano boron and nano copper positively affect physiological and metabolic pathways associated with fruit quality. The synergistic effect recorded in combination may be linked to improved regulation of photosynthetic activity, biosynthesis of secondary metabolite and mitigation of stress. Such responses are important for enhancing fruit colour, sweetness and nutritional quality. Importantly, improvements were achieved without compromising titratable acidity, indicating a balanced impact on organoleptic traits. These findings highlight potential of integrating biostimulants based approaches into modern horticultural practices for quality improvement and stress resilience in strawberry production.

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Author's contribution

Conceptualization, Zeina Sami Rashid, Methodology and Writing-Original Draft; Preparation, Ahmed Thamer Homed; Software, Data Curation, Mohammed Dhahir Abdulhadi; Investigation, Writing-Review and Editing and F.F.I.

Data availability

The data related to current study is presented in the manuscript.

Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Conflict of interest

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