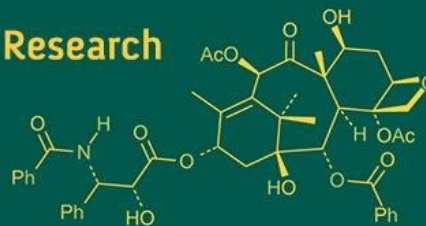


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Influence of nano zinc and nano boron on growth and development of strawberry (*Fragaria × ananassa* Duch.) under Prayagraj agro-climatic conditions

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Abstract

The present experiment was conducted at the Department of Horticulture, Naini Agricultural Institute, Sam Higginbottom University of Agriculture, Technology and Sciences, Prayagraj, during the 2024-2025 session. The experiment was laid out in a randomized block design with three replications and included 8 treatment combinations, including a control. The best treatment was T₇ Nano Zinc @ 10 ppm + Nano Boron @ 10 ppm, which showed the highest values across all parameters, including plant height (35.37 cm), plant spread (36.93 cm), number of leaves per plant (44.24), petiole length (13.54 cm), number of flowers per plant (32.94), number of fruits per plant (17.69), fruit weight (23.84 g), fruit length (3.79 cm), fruit diameter (2.80 cm), fruit yield per plant (421.67 g), fruit yield per plot (2.53 kg), fruit yield (25.30 t/ha), TSS (9.46 °Brix), acidity (1.25%), ascorbic acid (57.57 mg/100g), specific gravity (1.53), juice content (95.42%), and pH (3.61). The maximum benefit-cost ratio (1:6.41) was also observed in treatment T₇ Nano Zinc @ 10 ppm + Nano Boron @ 10 ppm.

Keywords: Strawberry, Nano zinc, Nano boron, fruit quality, yield, Nano fertilizers

Introduction

Strawberry (*Fragaria × ananassa* Duch, Rosaceae) is a globally prized soft fruit crop, renowned for its bright red color, distinctive aroma, juicy texture, and sweet flavor. As an octoploid species (2n = 8x = 56), the strawberry produces an aggregate accessory fruit in which the edible portion arises from the floral receptacle rather than the ovaries. Beyond its culinary appeal, strawberry is celebrated for its rich content of vitamin C, anthocyanins, flavonoids, and phenolic acids, all of which contribute to antioxidant activity and health promotion (Davarpanah *et al.*, 2016) ^[14].

Today, more than 14.5 million tons of strawberries are harvested annually across over 76 countries, with China and the United States leading global production. In India, commercial strawberry cultivation is a relatively recent phenomenon concentrated in regions such as Mahabaleshwar (Maharashtra), the mid-hill zones of Himachal Pradesh, and parts of Punjab, Haryana, and Uttar Pradesh. The 'Winter Dawn' cultivar has gained traction in subtropical and tropical plains due to its adaptability and early fruiting habit.

Optimal strawberry growth and fruit quality hinge on balanced micronutrient nutrition. Zinc is vital for auxin synthesis, chlorophyll production, enzyme activation, and protein metabolism, while boron is indispensable for cell wall formation, carbohydrate transport, pollen germination, and membrane integrity. Conventional bulk applications of zinc and boron—whether as sulfates or chelates—often suffer from leaching, fixation, and low uptake efficiency, especially in alkaline or coarse-textured soils.

Nanotechnology offers a promising alternative by delivering nutrients in nano-scale formulations (1-100 nm), thereby increasing surface area, reactivity, and enabling controlled release. Nano zinc and nano boron fertilizers have shown enhanced plant uptake, reduced application rates, and lower environmental losses. Research in various horticultural crops indicates that nano zinc boosts photosynthetic performance and stress tolerance, whereas nano boron enhances reproductive development, sugar accumulation, and overall fruit quality. Despite these advances, the response of the strawberry to nano zinc and nano boron under the unique soil, temperature, and moisture regimes of the Prayagraj agro-climatic zone remains underexplored.

This study was undertaken to evaluate the effects of different concentrations and combinations of nano zinc and nano boron on strawberry’s vegetative growth (plant height, spread, leaf number), flowering and fruiting behavior, yield, key quality parameters (total soluble solids, acidity, juice content, ascorbic acid), and the economic returns from these treatments under local field conditions.

Materials and Methods

Study Area and Experimental Conditions

The experiment titled “Influence of Nano Zinc and Nano Boron on Growth and Development of Strawberry (*Fragaria × ananassa* Duch.) under Prayagraj Agro-Climatic Conditions” was conducted at the Horticultural Research Farm, Department of Horticulture, Sam Higginbottom University of Agriculture, Technology and Sciences (SHUATS), Prayagraj, Uttar Pradesh (25°26’N, 81°50’E; 98 m above mean sea level). Trials ran during the 2024-2025 Rabi season from November 2024 to March 2025 under open-field conditions, following standard cultural practices for strawberry.

Climatic and Meteorological Data

Prayagraj falls in a subtropical climate zone with hot summers (maximum up to 49 °C), cool winters (minimum 2-5 °C), and average annual rainfall of 850-1100 mm. Daily records of maximum and minimum temperature, relative humidity, and rainfall were obtained from the university’s agro-meteorological observatory throughout the experimental period.

Soil Sampling and Analysis

Prior to transplanting, composite soil samples were collected from 0-30 cm depth for physicochemical characterization. Analyses were performed following standard protocols (Piper, 1966; Jackson, 1973; Walkley and Black, 1934; Subbiah and Asija, 1956). Results are presented below:

- **Mechanical composition:** Sand 48%, silt 22%, clay 30%
- **pH (1:2.5 soil-water):** 6.5
- **Organic carbon:** 0.34%
- **Available nitrogen:** 0.016%
- **Available phosphorus:** 0.022%
- **Available potassium:** 0.018%

Plant Material and Establishment: Strawberry runners of cv. ‘Winter Dawn’-a high-yielding, early-maturing cultivar-were procured from Green Light Nursery, Pune (Maharashtra). Healthy, uniform runners with intact root balls were transplanted on 15 November 2024. Beds were prepared in advance, and runners were placed at uniform spacing to ensure consistent establishment. Throughout the crop cycle, recommended irrigation, mulching, weeding, and plant protection measures were employed.

Field Preparation and Planting

The field was ploughed and harrowed to a fine tilth, then shaped into raised beds with irrigation and drainage channels. Strawberry runners of uniform size were transplanted in the evening to reduce shock, followed by immediate light irrigation. Gap filling was completed within 15 days after transplanting to ensure consistent plant density.

Crop Maintenance

- Manual weeding and hoeing every 15-20 days to control weeds and improve aeration
- Irrigation was scheduled frequently, adjusting for weather and soil moisture to avoid waterlogging or drought stress
- Basal application of the recommended dose of fertilizers incorporated before transplanting
- Foliar sprays of nano zinc and nano boron (5 ppm and 10 ppm) applied at 30, 60, and 75 days after transplanting using a hand atomizer in the evening

Pest, Disease Control, and Harvest

- Neem cake and chlorpyrifos used at the first sign of red termites
- Alternating Blitox (0.2%) and Bavistin (0.2%) sprays for fungal disease prevention
- Additional Endosulfan (0.2%) applications against insect pests as needed
- Manual harvesting in the morning when fruits reached over 75% red surface, taking care to avoid damage

Result and Discussion

Plant height

The results demonstrated significant effects of planting dated and cultivar on all measure parameters the highest plant height was observed in T₇ (Nano Zinc @ 10 ppm + Nano Boron @ 10 ppm) with a mean value of 35.37 cm, was followed by T₆ (Nano Zinc @ 5 ppm + Nano Boron @ 5 ppm) with a mean value of 31.77cm and T₅ (Nano Zinc @ 5 ppm + Nano Boron @ 10 ppm) with a mean value of 33.22cm, while the minimum value was observed in T₀, which had only 24.60 cm plant height.

The increased plant height can be attributed to zinc’s role in promoting auxin production and boron’s involvement in cell division and elongation. Similar findings were reported by Bagali *et al.* (1993) ^[7] in guava, Singh *et al.* (2023) in strawberry, and Raliya & Tarafdar (2013) in cucumber and tomato. Elizabeth *et al.* (2017) ^[16] also confirmed that nano Zn and B improve photosynthetic activity and carbohydrate metabolism, ultimately enhancing vegetative growth.

Plant spread

The highest plant spread was observed in T₇ (Nano Zinc @ 10 ppm + Nano Boron @ 10 ppm) with a mean value of 36.93cm, was followed by T₆ (Nano Zinc @ 5 ppm + Nano Boron @ 5 ppm) with a mean value of 35.85cm and T₅ (Nano Zinc @ 5 ppm + Nano Boron @ 10 ppm) with a mean value of 34.38cm, while the minimum value was observed in T₀, which had only 26.00 cm plant spread. These results are supported by Rout and Sahoo (2015) who highlighted the role of Zn in promoting shoot development and leaf expansion.

Table 1: Treatment details

Symbols	Treatment Combination
T ₀	Control spray
T ₁	Nano Zinc @ 10 ppm
T ₂	Nano Boron @ 10 ppm
T ₃	Nano Zinc @ 5ppm
T ₄	Nano Boron @ 5ppm
T ₅	Nano Boron @ 10 ppm + Nano Zinc @ 5ppm
T ₆	Nano Zinc @ 5ppm + Nano Boron @ 5ppm
T ₇	Nano Zinc @ 10 ppm + Nano Boron @ 10 ppm

Number of leaves per plant

The highest number of leaves was observed in T₇ (Nano Zinc @ 10 ppm + Nano Boron @ 10 ppm) with a mean value of 44.24, was followed by T₆ (Nano Zinc @ 5 ppm + Nano Boron @ 5 ppm) with a mean value of 43.37 and T₅ (Nano Zinc @ 5 ppm + Nano Boron @ 10 ppm) with a mean value of 42.74, while the minimum value was observed in T₀, which had only 26.73 number of leaves per plant. Similar observations were made by Singh *et al.* (2017) in strawberry and El-Morsy *et al.* (2022) [17] in vegetable crops.

Petiole Length (cm)

The highest petiole length was observed in T₇ (Nano Zinc @ 10 ppm + Nano Boron @ 10 ppm) with a mean value of 13.54, was followed by T₆ (Nano Zinc @ 5 ppm + Nano Boron @ 5 ppm) with a mean value of 13.35 and T₅ (Nano Zinc @ 5 ppm + Nano Boron @ 10 ppm) with a mean value of 12.98, while the minimum value was observed in T₀, which had only 9.49 petiole length. Improved petiole elongation may be attributed to zinc's impact on enzyme activation and boron's role in cell wall flexibility. Taheri *et al.* (2015) reported similar results in studies involving nano nutrient applications.

Number of flowers per plant

The highest number of flowers per plant was observed in T₇ (Nano Zinc @ 10 ppm + Nano Boron @ 10 ppm) with a mean value of 32.94, was followed by T₆ (Nano Zinc @ 5 ppm + Nano Boron @ 5 ppm) with a mean value of 31.77 and T₅ (Nano Zinc @ 5 ppm + Nano Boron @ 10 ppm) with a mean value of 30.54, while the minimum value was observed in T₀, which had only 24.32 number of flowers per plant. The increase in flowering may be due to boron's critical role in pollen development and zinc's involvement in hormone regulation. These findings align with those of Yadav *et al.* (2017), who reported that combined nano nutrient applications promote reproductive success in strawberries and other horticultural crops.

Number of fruits per plant

The highest number of fruits per plant was observed in T₇ (Nano Zinc @ 10 ppm + Nano Boron @ 10 ppm) with a mean value of 17.69, was followed by T₆ (Nano Zinc @ 5 ppm + Nano Boron @ 5 ppm) with a mean value of 17.37 and T₅ (Nano Zinc @ 5 ppm + Nano Boron @ 10 ppm) with a mean value of 17.15, while the minimum value was observed in T₀, which had only 9.17 number of fruits per plant. The improvement in fruit set is associated with enhanced flowering and successful pollination, supported by adequate micronutrient availability. This is consistent with the work of Lakshya *et al.* (2024) in strawberry and pomegranate.

Fruit Weight (g)

The highest fruit weight was observed in T₇ (Nano Zinc @ 10 ppm + Nano Boron @ 10 ppm) with a mean value of 23.84g, was followed by T₆ (Nano Zinc @ 5 ppm + Nano Boron @ 5 ppm) with a mean value of 23.43g and T₅ (Nano Zinc @ 5 ppm + Nano Boron @ 10 ppm) with a mean value of 23.35g, while the minimum value was observed in T₀, which had only 19.11g fruit weight. The increase in weight can be attributed to improved nutrient uptake and

translocation, which enhance cell enlargement. These results are in line with the findings of Patel *et al.* (2019).

Fruit Length (cm)

The highest fruit length was observed in T₇ (Nano Zinc @ 10 ppm + Nano Boron @ 10 ppm) with a mean value of 3.79cm, was followed by T₆ (Nano Zinc @ 5 ppm + Nano Boron @ 5 ppm) with a mean value of 3.37cm and T₅ (Nano Zinc @ 5 ppm + Nano Boron @ 10 ppm) with a mean value of 3.63cm, while the minimum value was observed in T₀, which had only 2.09cm fruit length. A comprehensive study explored the impact of nano zinc and nano boron on the fruit length (cm) of strawberries. Increase in fruit length and diameter and is attributed to the role of Zn in cell division and cell elongation which resulted in synthesis of tryptophan and auxin (Alloway, 2008; Boettcher *et al.*, 2010) [1, 11].

Fruit diameter (cm)

The highest fruit diameter was observed in T₇ (Nano Zinc @ 10 ppm + Nano Boron @ 10 ppm) with a mean value of 2.80 cm, was followed by T₆ (Nano Zinc @ 5 ppm + Nano Boron @ 5 ppm) with a mean value of 3.69cm and T₅ (Nano Zinc @ 5 ppm + Nano Boron @ 10 ppm) with a mean value of 2.56cm, while the minimum value was observed in T₀, which had only 1.81 cm fruit diameter. A comprehensive study explored the impact of nano zinc and nano boron on the fruit diameter (cm) of strawberries. Increase in fruit length and diameter and is attributed to the role of Zn in cell division and cell elongation which resulted in synthesis of tryptophan and auxin (Alloway, 2008; Boettcher *et al.*, 2010) [1, 11].

Fruit Yield per Plant (g)

The highest fruit yield per plant was observed in T₇ (Nano Zinc @ 10 ppm + Nano Boron @ 10 ppm) with a mean value of 421.67g, was followed by T₆ (Nano Zinc @ 5 ppm + Nano Boron @ 5 ppm) with a mean value of 407.11g and T₅ (Nano Zinc @ 5 ppm + Nano Boron @ 10 ppm) with a mean value of 400.31g, while the minimum value was observed in T₀, which had only 175.29g fruit yield per plant. A positive influence on fruit yield with nano ZnO application have also been reported in strawberry, pomegranate (Davarpanah *et al.*, 2016) [14], mango and grapes (El-Said *et al.*, 2019) [18].

Vegetative Growth

Treatments combining nano zinc and nano boron markedly enhanced vegetative vigor. The T₇ treatment (Zn 10 ppm + B 10 ppm) produced the tallest plants (35.37 cm), widest spread (36.93 cm), most leaves (44.24 leaves/plant), and longest petioles (13.54 cm), compared with the unfertilized control (T₀: 24.60 cm height; 26.00 cm spread; 26.73 leaves; 9.49 cm petiole). The intermediate treatments, T₆ (Zn 5 ppm + B 5 ppm) and T₅ (Zn 5 ppm + B 10 ppm), ranked second and third for all parameters. Enhanced auxin synthesis (Zn) and improved cell division and wall flexibility (B) likely drove these gains, echoing findings in strawberry, cucumber, and tomato (Elizabeth *et al.*, 2017) [16].

Reproductive Performance

Flowering and fruit set followed the same pattern: T₇ yielded the most flowers (32.94 flowers/plant) and fruits (17.69 fruits/plant), versus T₀'s 24.32 flowers and 9.17 fruits. Boron's role in pollen viability and zinc's hormonal

regulation underpinned superior reproductive success, consistent with reports by Yadav *et al.* (2017)".

Fruit Attributes and Yield

Individual fruit weight, size, and overall yield per plant peaked under T₇ (23.84 g; 3.79 cm length; 2.80 cm diameter; 421.67 g/plant), with T₆ and T₅ again trailing. Control plants produced the lightest and smallest fruits (19.11 g; 2.09 cm × 1.81 cm) and lowest yield (175.29 g). Improved nutrient uptake and carbohydrate partitioning-driven by nanoscale Zn and B-promoted cell enlargement and sugar accumulation, mirroring observations in pomegranate, mango, and grapes (Davarpanah *et al.*, 2016; El-Said *et al.*, 2019)^[14, 18].

Fruit Yield per Plot (kg)

The highest fruit yield per plot was observed in T₇ (Nano Zinc @ 10 ppm + Nano Boron @ 10 ppm) with a mean value of 2.53kg, was followed by T₆ (Nano Zinc @ 5 ppm + Nano Boron @ 5 ppm) with a mean value of 2.44kg and T₅ (Nano Zinc @ 5 ppm + Nano Boron @ 10 ppm) with a mean value of 2.40kg, while the minimum value was observed in T₀, which had only 1.05kg fruit yield per plot. This positive influence on fruit yield is attributed to the role of Zn in formation of flower primordia due to synthesis of tryptophan (Davarpanah *et al.*, 2016)^[14].

Fruit Yield (ha-1)

The highest fruit yield per hectare was observed in T₇ (Nano Zinc @ 10 ppm + Nano Boron @ 10 ppm) with a mean value of 25.30 ha⁻¹ was followed by T₆ (Nano Zinc @ 5 ppm + Nano Boron @ 5 ppm) with a mean value of 24.43 ha⁻¹ and T₅ (Nano Zinc @ 5 ppm + Nano Boron @ 10 ppm) with a mean value of 24.02 ha⁻¹, while the minimum value was observed in T₀, which had only 10.52 ha⁻¹ fruit yield per hectare. This positive influence on fruit yield is attributed to the role of Zn in formation of flower primordia due to synthesis of tryptophan (Davarpanah *et al.* (2016)^[14].

Total Soluble Solids (°Brix)

Treatment T₇ (10 ppm nano-Zn + 10 ppm nano-B) produced the highest TSS (9.46 °Brix), followed by T₆ (5 ppm + 5 ppm; 9.32 °Brix) and T₅ (5 ppm Zn + 10 ppm B; 9.15 °Brix). The unfertilized control (T₀) registered just 7.66 °Brix. Enhanced leaf photosynthetic efficiency under ZnO nanoparticles sustained carbon assimilation, while boron improved phloem loading and sugar translocation-together driving the rise in fruit sweetness.

Acidity (%)

Treatment T₇ (10 ppm nano-Zn + 10 ppm nano-B) exhibited the highest acidity at 1.25%, followed by T₆ (5 ppm + 5 ppm; 1.19%) and T₅ (5 ppm Zn + 10 ppm B; 1.15%). The unfertilized control (T₀) recorded the lowest acidity of 0.65%. The synergistic action of zinc and boron likely underpins this increase: zinc serves as a cofactor for key enzymes in organic acid biosynthesis, boosting malate and citrate accumulation, while boron stabilizes cell membranes and improves proton transport, enhancing acid retention in fruit tissues. Similar trends have been observed in apples, where zinc application stimulated carbohydrate metabolism and organic acid synthesis (Davarpanah *et al.*, 2016)^[14].

Ascorbic Acid (mg/100g pulp)

The highest ascorbic acid was observed in T₇ (Nano Zinc @ 10 ppm + Nano Boron @ 10 ppm), with a mean value of 57.57 mg/100g, followed by T₆ (Nano Zinc @ 5 ppm + Nano Boron @ 5 ppm) with a mean value of 57.30 mg/100g, and T₅ (Nano Zinc @ 5 ppm + Nano Boron @ 10 ppm) with a mean value of 56.41 mg/100g. The lowest value was observed in T₀, which had only 50.69 mg/100g of ascorbic acid. A comprehensive study explored the impact of nano zinc and nano boron on the ascorbic acid (mg/100g) of strawberries. Similar findings have been reported in apples, where an increase in TSS is attributed to the effect of Zn on carbohydrate synthesis and translocation (Davarpanah *et al.*, 2016)^[14].

pH

The lowest pH was observed in T₇ (Nano Zinc @ 10 ppm + Nano Boron @ 10 ppm), with a mean value of 3.61 pH, followed by T₆ (Nano Zinc @ 5 ppm + Nano Boron @ 5 ppm), with a mean value of 3.65 pH, and T₅ (Nano Zinc @ 5 ppm + Nano Boron @ 10 ppm), with a mean value of 3.71 pH. The highest pH value was observed in T₀, which had 3.93 pH. Similar findings have been reported in apple, where an increase in TSS is attributed to the effect of Zn on carbohydrate synthesis and translocation (Davarpanah *et al.*, 2016)^[14].

Economics Parameter

The total cost of strawberry cultivation ranged from 648500.6 to 648478.1 per hectare. Treatment T₇ recorded the highest benefit-cost ratio, followed by T₆ and T₅, indicating greater profitability. The lowest benefit-cost ratio was observed in T₀. Overall, T₇ emerged as the most economically viable option for the conditions in Prayagraj.

Table 2: Effect of treatments on growth and yield parameters of the crop, showing significant improvement in all traits with T₇ and lowest values in T₀.

Treatments	Plant Height	Plant spread	No of leaves	Petiole length	No of flowers	Number of fruits per plant	Fruit weight (g)	Fruit length (cm)	Fruit Diameter (cm)
T ₀	24.60	26.00	26.73	9.49	24.32	9.17	19.11	2.09	1.81
T ₁	30.15	33.04	30.47	12.31	30.10	16.39	21.10	3.44	2.53
T ₂	28.78	31.43	35.33	11.37	28.42	16.30	20.70	3.37	2.64
T ₃	30.11	30.54	34.38	12.11	27.25	16.50	22.10	3.21	2.48
T ₄	31.57	30.95	39.17	12.60	28.43	15.70	21.51	3.16	2.56
T ₅	33.22	34.38	42.74	12.98	30.54	17.15	23.35	3.63	2.69
T ₆	34.30	35.85	43.37	13.35	31.77	17.37	23.43	3.73	2.73
T ₇	35.37	36.93	44.24	13.54	32.94	17.69	23.84	3.79	2.80
F-Test	S	S	S	S	S	S	S	S	S
S.EM+-	1.203	1.161	1.270	0.590	1.116	0.709	0.641	0.102	0.075
C.D@ 5%	0.393	0.379	0.415	0.193	0.364	0.232	0.209	0.033	0.025
C.v	2.195	2.027	1.938	2.729	2.160	2.541	1.656	1.746	1.683

Table 3: Effect of treatments on fruit yield and quality parameters, with T₇ recording the highest yield and superior quality attributes, while T₀ showed the lowest values

Treatments	Fruit per plant (g)	Fruit yield per plot (kg)	Fruit yield t ha ⁻¹	TSS °Brix	Acidity (%)	Ascorbic acid (mg/100g)	Specific gravity	Juice content (%)	pH
T ₀	175.29	1.05	10.52	7.66	0.65	50.69	1.06	80.05	3.93
T ₁	345.69	2.07	20.74	8.30	0.82	56.42	1.32	93.27	3.81
T ₂	337.30	2.02	20.24	8.44	1.06	56.18	1.29	92.08	3.74
T ₃	364.72	2.19	21.88	9.04	0.84	54.44	1.26	90.65	3.74
T ₄	337.89	2.03	20.27	8.59	1.06	55.30	1.21	90.17	3.85
T ₅	400.31	2.40	24.02	9.15	1.14	56.41	1.35	94.34	3.71
T ₆	407.11	2.44	24.43	9.32	1.19	57.30	1.42	94.54	3.65
T ₇	421.67	2.53	25.30	9.46	1.25	57.57	1.53	95.42	3.61
F-Test	S	S	S	S	S	S	S	S	S
S.E.M+/-	16.033	0.095	0.962	0.310	0.052	0.484	0.052	0.693	0.043
C.D@ 5%	5.235	0.031	0.314	0.101	0.017	0.158	0.017	0.226	0.014
C.v	2.600	2.570	2.600	2.004	2.917	0.493	2.233	0.429	0.644

Conclusion

This study examined the effects of foliar applications of Nano Zinc and Nano Boron, both individually and in combination, on the growth, yield, quality, and economics of the Winter Dawn strawberry variety (*Fragaria × ananassa* Duch.) in Prayagraj.

The findings revealed that the combination of nano micronutrients, particularly at 10 ppm (T₇), significantly enhanced vegetative parameters like plant height, leaf count, and overall yield. T₇ also produced the highest numbers of flowers and fruits, as well as improvements in quality parameters such as Total Soluble Solids (TSS) and ascorbic acid.

Economically, T₇ achieved the highest gross and net returns with a Benefit: Cost ratio of 6.41, illustrating its profitability.

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