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Research Article

Influence of Micronutrients on Growth, Flowering, Yield, Fruit Quality Characteristics and Profitability in Strawberry (*Fragaria* × *ananassa* Duch) cv. Chandler under Open Field Conditions

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ABSTRACT

The present investigation was conducted during the Rabi season of 2023 at the experimental farm, School of Agriculture, Sanjeev Agrawal Global Educational University, Bhopal (MP), to evaluate the impact of exogenous application of micronutrients @ 0.5%, specifically boron, Zinc, copper, and iron both individually and in combination, on the growth, flowering, yield, and quality of strawberry plants in open field conditions. The experiment was laid out in a Randomized Complete Block Design (RCBD) with three replications and fifteen treatments along with one control. Foliar applications of various micronutrients (B, Zn, Cu and Fe) were applied at 30 and 45 days after planting during the evening hours. The results indicated that both individual and combined foliar applications of various micronutrients significantly impacted strawberry growth, flowering, yield and quality characteristics. Among the various treatments, T_{13}*, the combined application of Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%, exhibited the highest values for growth characteristics, followed by treatment* T_{14}*.*

Furthermore, concerning reproductive characteristics, the shortest duration for days to key stages was recorded in treatment T_{14} *(Boric acid + Zinc Sulphate + Copper Sulphate + Ferrous Sulphate at 0.5%), followed by treatment* T_{13}*. Moreover, in terms of physical and chemical quality, yield characteristics, and B: C ratio, treatment* T_{14} *resulted in the maximum values for these characteristics, followed by treatment* T_{13}*. However, the minimum acidity was recorded under treatment* T_{14}*, followed by* T_{13}*, while the maximum acidity was observed under the* T_0 *(Control). Based on the present study's findings, it can be inferred that both individual and combined foliar applications of various micronutrients significantly enhanced the growth, flowering, yield, fruit quality, and profitability of strawberries.*

Keywords: *Fruit quality, Micronutrients, Strawberry, Fruit firmness and Yield*

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INTRODUCTION

Strawberry (*Fragaria × ananassa* Duch) is one of the world's most appealing and delectable fruits. It belongs to the Rosaceae family. This aggregative fruit is comprised of numerous achenes, with its edible component being the fleshy thalamus. Strawberries are in high demand in fresh markets and the processing industries due to their delightful flavour and nutritional benefits (Deshwal et al., 2024). The cultivated Octoploid strawberry has a chromosome number of 2n = 8x = 56 (Wang et al., 1996), and is one of the most luscious and refreshing soft fruits in the world. The fruit is rich in natural anti-oxidants (Devi et al., 2024a; Saha et al., 2019). This aggregate fruit consists of numerous achenes, with the fleshy thalamus being edible. Strawberries are very popular both in fresh markets and in processing industries because of their delicious flavour and nutritional benefits (Deshwal et al., 2024; Devi et al., 2024b; Anchal et al., 2023). Strawberry cultivation in non-traditional provinces of India has resulted in the development of new varieties adaptable to wide range of climatic conditions and standardization of new agro techniques in recent years (Sharma & Sharma, 2004; Deshwal et al., 2024; Devi et al., 2024 b). The Strawberry is grown in Himachal Pradesh, Uttarakhand, Uttar Pradesh, Maharashtra, West Bengal, Delhi, Haryana, Punjab, Rajasthan, and Madhya Pradesh.

Strawberry plants require a balanced supply of macro and micronutrients to ensure a high yield and quality. Micronutrients such as Zinc and copper are crucial for the growth and development of plants, preventing deficiencies that may lead to chlorosis (caused by zinc deficiency) and stunted growth (caused by copper deficiency) (Zewail et al., 2020). Moreover, micronutrient foliar feeding has been demonstrated to significantly enhance plant growth, yield, and fruit quality by minimizing nutrient losses and augmenting nutrient utilization efficiency (Sangeeta et al., 2019). The incorporation of micronutrients such as Zinc and iron has been demonstrated to enhance production and quality in various fruit crops (Shanker et al., 2019).

Environmental factors also play a crucial role in the growth and development of strawberries (Patil & Chetan, 2018). The quality and size of strawberries grown in Madhya Pradesh affect their marketing and profitability. The micronutrients, which are involved in virtually all metabolic and cellular processes within the plant, play an essential role in enhancing the quality and sustaining the production of strawberries (Hansch et al., 2009). These micronutrient deficiencies often affect crop productivity and quality. Given the significance of micronutrients in strawberry cultivation, the present investigation aims to evaluate the impact of exogenous application of boron, Zinc, copper, and iron, both individually and collectively, on the growth, flowering, yield, and quality of strawberry plants in open field conditions. In view of the present investigation, the dosage of micronutrients was planned to be standardized in order to overcome the problem of low yield and quality of strawberry fruits.

MATERIALS AND METHODS

The present investigation was conducted at the experimental farm of the School of Agriculture, Sanjeev Agrawal Global Educational University, Bhopal, during the Rabi season of 2023. Geographically, the experimental site is situated at altitude of 35.75º in the North and a longitude of 77.24º in the East, at an elevation of 500 m above mean sea level. The study aimed to evaluate the influence of micronutrients on growth, flowering, yield, fruit quality characteristics and profitability in strawberry (*Fragaria × ananassa* Duch) cv. Chandler under open field conditions. Raised beds, each measuring one meter in width, were prepared for the planting of runners. The cultivar Chandler was selected based on the uniformly sized and disease-free planting material. The plants were treated with a 0.1% Bavistin solution before planting. The runners were planted in the first week of November. A 300-gauge thickness black polythene mulch was applied at the time of planting. The fifteen treatments, including individual and combined applications and control (T_0), were evaluated in a Randomized Complete Block Design (RCBD) with three replications. The treatments included: T_0 (Control), T_1 (Boric acid @ 0.5%), T_2 (Zinc Sulphate @ 0.5%), T_3 (Copper Sulphate @ 0.5%), T_4 (Ferrous Sulphate @ 0.5%), T_5 (Boric acid + Zinc Sulphate @ 0.5%), T_6 (Boric acid + Copper Sulphate @ 0.5%), T_7 (Boric acid + Ferrous Sulphate @ 0.5%), T_8 (Zinc Sulphate + Copper Sulphate @ 0.5%), T_9 (Zinc Sulphate + Ferrous Sulphate @ 0.5%), T_{10} (Copper Sulphate + Ferrous Sulphate @ 0.5%), T_{11} (Boric acid + Zinc Sulphate + Copper Sulphate @ 0.5%), T_{12} (Boric acid + Zinc Sulphate + Ferrous Sulphate @ 0.5%), T_{13} (Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%) and T_{14} (Boric acid + Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%). The study implemented the recommended doses of NPK (nitrogen, phosphorus, and potassium) and maintained consistent horticultural practices throughout the cropping session. Well-decomposed farmyard manure and vermicompost, each @ 5 tonnes per hectare, were uniformly incorporated 20 days before planting. Essential agronomic practices, including regular irrigation and effective pest and disease management, were carried out as necessary throughout the investigation. Five plants per treatment were randomly marked to record the observations. The influence of micronutrients on growth, flowering, yield, fruit quality characteristics, and profitability was observed and recorded according to standard practices. Plant height, spread, and petiole length were measured using a measuring scale. The number of shoots and leaves per plant on five randomly selected plants in each treatment was counted manually. The leaf area was determined by individually collecting five leaves from five randomly tagged plants in each treatment combination using graph paper. The floral characteristics were documented during the flowering period. The number of flowers and fruits per plant was counted manually from the initial blossoming until the end of the full bloom. The number of fruits set was counted and converted into a percentage using the formula as shown below

$$Fruit\ set\ (\%) = \frac{Total\ number\ of\ fruits\ set}{Total\ number\ of\ flowers\ appeared} \times 100$$

The volume of every strawberry fruit was measured using the water displacement method. Every fruit was immersed in a container filled with water. The volume of water displaced was measured directly using a 250 cm³ graduated cylinder, and the volume was expressed in cubic centimetres (cm^3). The fruit firmness was measured using a TA-Plus Texture Analyzer (Texture Technologies Corp., NY) to determine the maximum penetration force (N) during tissue breakage. A 10 mm diameter cylindrical probe with a penetration depth of 3 mm was used with a crosshead speed of 1 mm/s and a penetration depth of 3 mm. Each Strawberry was divided into half, and the firmness was measured in the central region. The firmness scores were calculated by averaging three fruits from each sample. The specific gravity of the strawberry fruits was determined by dividing the weight of each fruit by its volume. The results were expressed in g per cubic centimetre (g/cc). The weight of fifteen fruits, collected from five randomly chosen plants for each treatment combination, was measured separately, and the average fruit weight was calculated. The fruit yield of each treatment was recorded from five randomly selected plants. During each harvest, the yield was determined using a digital analytical balance. The average yield per plant was calculated by summing the total yield of all marked plants and expressing it in grams per plant. The yield per hectare (tonnes) was calculated by multiplying the yield per plot (kg) by the total number of plots per hectare and dividing the product by 1,000. Total soluble solids were determined using the standard AOAC (2012) method. The measurements were conducted using a hand-refractometer (ATAGO Pocket Refractometer). The total sugar content, reduced sugar content, and non-reducing sugar content were determined using the AOAC (2012) methodology. The sugar content was expressed as a percentage (%). The volumetric method outlined in AOAC (2012) determined the acidity. TSS: acidity ratio was determined by dividing the total soluble solids (TSS) value by the acidity. The results were expressed as the TSS: acidity ratio. The following equation was used to calculate the TSS: acid ratio:

$$\text{TSS: Acid ratio} = \frac{TSS}{Acidity}$$

Economic analysis of crop treatments:

A tabular analysis was conducted to evaluate the crop's economics. The gross returns were calculated by multiplying the yield by the average market price. Net profit was obtained by subtracting the production cost from the gross returns. Each treatment is B: C ratio was calculated using the following formula.

$$The\ B{:}\ C\ ratio = \frac{Net\ return}{total\ cost\ of\ cultivation}$$

Statistical analysis

Statistical analysis of the data on growth, flowering, yield, and fruit quality characteristics was performed using SAS software version 9.3 (SAS Institute 1989) Inc., Cary, NC, USA), with significance determined at $p \leq 0.05$.

RESULTS AND DISCUSSION

Growth characteristics:

During the present investigation, data on various growth characteristics, including plant height (cm), plant spreads (cm), petiole length (cm), number of shoots per plant, number of leaves per plant and leaf area (cm²) were documented and presented in (Table 1). The findings indicated that both individual and combined foliar applications of various micronutrients significantly impacted the growth characteristics of strawberry plants. Among the various treatments, the treatment T_{13} (Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%) exhibited the highest values for plant height (18.96 cm), plant spreads (38.43 cm), petiole length (15.31cm), number of shoots/plant (19.81), number of leaves per plant (22.48) and leaf area (91.45 cm²), followed by treatment $T_{14.}$ The lowest values were observed under treatment T_0 (Control). The significant improvement in these growth characteristics is attributed to the critical role of micronutrients, which are required in relatively small quantities, but are vital for plant growth and development. These nutrients are essential for numerous processes, such as cell wall synthesis, enzyme activation, regulation of cell division, cell differentiation, cell elongation, sugar transport, chloroplast development, and hormonal regulation. The present findings are in agreement with the findings of Deshwal et al. (2024), Devi et al. (2024b), Anchal et al. (2023) and Saha et al. (2019) in Strawberry. Furthermore, iron is essential for electron transport chains, enhancing energy utilization and supporting various physiological functions in plants. The results are in agreement with the findings of Mohamed et al. (2011), Singh et al. (2015) and Saha et al. (2019) in Strawberry.

Table 1: Influence of micronutrients on vegetative growth characteristics of Strawberry

Treatment notation	Treatment combination	Plant height (cm)	Plant spread (cm)	Petiole length (cm)	Number of shoots plant^{-1}	Number of leaves plant^{-1}	Leaf area (cm^2)
T_0	Control	13.10	25.36	11.49	11.83	13.07	85.17
T_1	(Boric acid @ 0.5%)	14.96	27.96	12.69	13.48	15.48	86.81
T_2	(Zinc Sulphate @ 0.5%)	14.73	27.91	12.71	14.86	18.73	86.68
T_3	(Copper Sulphate @ 0.5%)	14.44	28.47	12.63	15.17	18.76	86.66
T_4	(Ferrous Sulphate @ 0.5%)	14.82	28.19	12.34	15.58	18.53	86.38
T_5	(Boric acid + Zinc Sulphate @ 0.5%)	16.68	30.78	13.60	16.50	20.60	89.07
T_6	(Boric acid + Copper Sulphate @ 0.5%)	17.68	32.54	13.67	16.63	20.10	88.23
T_7	(Boric acid + Ferrous Sulphate @ 0.5%)	16.84	30.85	13.82	16.83	19.84	88.13
T_8	(Zinc Sulphate + Copper Sulphate @ 0.5%)	16.69	32.08	13.78	16.67	19.49	88.73
T_9	(Zinc Sulphate + Ferrous Sulphate @ 0.5%)	16.78	32.87	13.80	16.63	19.97	89.03
T_{10}	(Copper Sulphate + Ferrous Sulphate @ 0.5%)	17.19	34.80	13.47	16.90	20.23	88.89
T_{11}	(Boric acid + Zinc Sulphate + Copper Sulphate @ 0.5%)	18.56	36.05	14.22	17.84	21.17	90.15
T_{12}	(Boric acid + Zinc Sulphate + Ferrous Sulphate @ 0.5%)	18.68	36.88	14.61	18.13	21.66	90.11
T_{13}	(Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%)	18.96	38.43	15.31	19.81	22.48	91.45
T_{14}	(Boric acid + Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%)	18.86	37.84	14.86	19.32	21.98	90.60
-	CD (P=0.05)	0.26	1.10	0.31	0.72	0.75	1.18
-	SE m (±)	0.09	0.38	0.11	0.25	0.26	0.41

Reproductive characteristics:

The data on reproductive characteristics of strawberries, such as days to first flowering, days from flowering to fruit set, days from fruit set to maturity, number of flowers per plant, number of fruits per plant, and fruit set percentage, were recorded and exhibited in (Table 2), showing significant variation. The results showed that both individual and combined foliar applications of different micronutrients significantly influenced the reproductive characteristics of Strawberries. Among the various treatments, the treatment T_{14} (Boric acid + Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%) exhibited the minimum values for days to first flowering (46.77), days from flowering to fruit set (4.85), days from fruit set to maturity (18.22), followed by treatment T_{13}. At the same time, the maximum values for days to first flowering (59.11), days from flowering to fruit set (8.92), and days from fruit set to maturity (27.55) were observed under treatment T_0 (Control). Foliar sprays of micronutrients, particularly iron and Zinc, significantly enhanced flowering characteristics by reducing the number of days to first flowering and fruit maturity. This enhancement can be attributed to Zinc's role in the biosynthesis of the plant hormone IAA, which promotes cell division and growth. It is also involved in nucleic acid and protein synthesis. Iron, on the other hand, plays a pivotal role in the production of chlorophyll and the activation of various enzymes, thereby expediting the processes of flowering and fruit development. Similarly, the application of iron reduced the time required for flowering and fruit development, as it is essential for forming numerous enzymes and deleting chlorophyll. These findings are in agreement with the findings of Nawaz et al. (2012), who reported a significant impact of Zinc on reducing the duration of first flowering in tomatoes. These results are in agreement with the findings of Singh et al. (2015), Yadav et al. (2021), and Deshwal et al. (2024) in strawberries. Furthermore, an improved source-sink relationship enhances the effectiveness of carbohydrate transfer to the developing fruits, resulting in a shorter period between flowering and fruit set and the minimum days until fruit maturity. These findings are in line with those reported by Nawaz et al. (2012) and Mehraj et al. (2015) in Strawberry.

However, the highest values for the number of flowers per plant (24.72), number of fruits per plant (21.66) and fruit set

(87.55%) were documented under the treatment T_{14} (Boric acid + Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%) followed by treatment T_{13}, while lowest values were observed under treatment T_0 (Control). The significant enhancement in these reproductive characteristics, such as the number of flowering and the number of fruit and fruit sets, can be attributed to the pivotal role of micronutrients, which, although required in modest quantities, are crucial for plant growth and development. These micronutrients play a crucial role in several physiological processes, including cell wall synthesis, enzyme activation, cell division and differentiation regulation, cell elongation, sugar transport, chloroplast development, hormonal balance, and pollen germination. Their participation in these processes ultimately enhances flower initiation, fruit emergence, and the number of fruits per plant. The findings are consistent with those of Deshwal et al. (2024 a), Devi et al. (2024 b), Anchal et al. (2023), and Saha et al. (2019) in Strawberry. Furthermore, these micronutrients have an essential role in various physiological activities. For example, Zinc is essential for pollination and fruit set, while boron is critical for flower formation and pollen germination, thereby promoting vigorous flowering in crops like strawberries. Copper is essential for enzymatic processes and nutrient uptake, which are vital for overall plant health and fruit development. The results of this study are consistent with those reported by Saha et al. (2019), Deshwal et al. (2024 b), Yadav et al. (2021), Priya et al. (2022) and Mehraj et al. (2015) in Strawberry.

Table 2: Influence of micronutrients on reproductive characteristics of strawberry plants

Treatment notation	Treatment combination	Days to first flowering	Days from flowering to fruit set	Days from fruit set to maturity	Number of flowers per plant	Number of fruits per plant	Fruit set (%)
T_0	Control	59.11	8.92	27.55	15.60	12.19	78.49
T_1	(Boric acid @ 0.5%)	57.33	7.78	25.89	17.55	14.44	82.21
T_2	(Zinc Sulphate @ 0.5%)	57.55	7.72	25.22	17.55	14.55	82.79
T_3	(Copper Sulphate @ 0.5%)	57.89	7.84	24.55	17.88	14.56	81.32
T_4	(Ferrous Sulphate @ 0.5%)	58.53	7.92	24.78	18.22	15.22	83.42
T_5	(Boric acid + Zinc Sulphate @ 0.5%)	54.44	6.78	23.77	19.22	16.01	83.27
T_6	(Boric acid + Copper Sulphate @ 0.5%)	54.55	6.88	23.55	19.23	15.89	82.48
T_7	(Boric acid + Ferrous Sulphate @ 0.5%)	55.55	6.97	22.89	20.22	16.50	81.56
T_8	(Zinc Sulphate + Copper Sulphate @ 0.5%)	55.33	6.85	22.55	19.66	16.33	83.21
T_9	(Zinc Sulphate + Ferrous Sulphate @ 0.5%)	55.37	6.61	21.33	20.44	16.66	81.55
T_{10}	(Copper Sulphate + Ferrous Sulphate @ 0.5%)	55.88	6.76	20.55	20.22	16.88	83.31
T_{11}	(Boric acid + Zinc Sulphate + Copper Sulphate @ 0.5%)	51.23	5.95	19.55	21.12	17.77	84.24
T_{12}	(Boric acid + Zinc Sulphate + Ferrous Sulphate @ 0.5%)	52.23	5.74	19.22	22.22	18.77	84.40
T_{13}	(Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%)	49.56	5.44	18.94	24.01	20.32	84.54
T_{14}	(Boric acid + Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%)	46.77	4.85	18.22	24.72	21.66	87.55
-	CD (P=0.05)	0.86	0.68	1.17	1.08	1.35	5.13
-	SE m (±)	0.30	0.23	0.40	0.37	0.46	1.76

Physical quality and yield characteristics:

During the investigation, data were collected on the physical quality and yield characteristics of strawberries, including fruit volume (cm³), fruit firmness (kg/cm²), specific gravity (g/cc), fruit weight (g), fruit yield per plant (g), and total yield (t/ha). These data, exhibited in (Table 3), revealed significant variation. The findings indicated that both individual and combined foliar applications of various micronutrients significantly impacted the physical quality and yield characteristics of

Strawberries. Among the various treatments, the treatment T_{14} (Boric acid + Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%) resulted in the highest values for fruit volume (14.26 cm^3), fruit firmness (1.42 kg/cm^2), specific gravity (1.14 g/cc), fruit weight (23.29 g), fruit yield per plant (507.39 g) and total yield (27.40 t/ha) followed by treatment T_{13}. At the same time, the lowest values were observed under treatment T_0 (Control). The phenomenon may be attributed to increased uptake of nutrients and their efficient transfer to the fruits, along with increased metabolite production, which ultimately improves fruit volume, weight, and firmness, as reported by Anchal et al. (2023) and Priya et al., (2022) in Strawberry. However, according to Graham et al. (2000), Zinc plays a crucial role in enhancing photosynthetic activity and the translocation of photosynthates, increasing fruit volume, specific gravity, and weight.

Furthermore, the increased fruit weight, yield per plant, and ultimately higher yield per hectare can be attributed to Zinc's role as a key component of enzymes like carbonic anhydrase and various dehydrogenases, along with its involvement in auxin production, which collectively enhance plant growth (Anchal et al., 2023; Devi et al., 2024 a). Moreover, iron is vital for the production of chlorophyll and cytochromes, resulting in enhanced production of vital biomolecules and overall plant development, thereby enhancing fruit weight and overall yield. Abdollahi et al. (2012) also reported that the application of $ZnSO_4$ enhanced inflorescence and fruit size in the strawberry cultivar 'Selva' due to its significant role in enhancing pollination and fruit set. Copper supports enzymatic processes and nutrient uptake, which is vital for plant vigour and fruit development, thereby enhancing overall yield (Singh et al., 2015). The results of this study are consistent with the results reported by Saha et al. (2019), Deshwal et al. (2024 b), Yadav et al. (2021), Priya et al. (2022) and Mehraj et al. (2015) in Strawberry.

Table 3: Influence of micronutrients on physical quality and yield characteristics of strawberry plants

Treatment notation	Treatment combination	Fruit volume (cm^3)	Fruit firmness (kg/cm^2)	Specific gravity (g/cc)	Fruit weight (g)	Fruit yield (g $plant^{-1}$)	Total yield (t ha^{-1})
T_0	Control	12.60	1.28	0.71	16.75	204.09	11.02
T_1	(Boric acid @ 0.5%)	13.27	1.30	0.81	18.46	266.88	14.41
T_2	(Zinc Sulphate @ 0.5%)	13.23	1.31	0.82	18.60	270.97	14.63
T_3	(Copper Sulphate @ 0.5%)	13.14	1.30	0.85	18.76	273.81	14.79
T_4	(Ferrous Sulphate @ 0.5%)	13.10	1.31	0.86	18.73	285.55	15.42
T_5	(Boric acid + Zinc Sulphate @ 0.5%)	13.57	1.33	0.91	20.27	325.71	17.59
T_6	(Boric acid + Copper Sulphate @ 0.5%)	13.59	1.33	0.94	20.43	325.90	17.60
T_7	(Boric acid + Ferrous Sulphate @ 0.5%)	13.61	1.34	0.96	20.47	338.58	18.28
T_8	(Zinc Sulphate + Copper Sulphate @ 0.5%)	13.52	1.35	0.98	20.67	338.24	18.26
T_9	(Zinc Sulphate + Ferrous Sulphate @ 0.5%)	13.54	1.36	1.01	21.49	359.16	19.39
T_{10}	(Copper Sulphate + Ferrous Sulphate @ 0.5%)	13.57	1.35	1.03	21.43	364.97	19.71
T_{11}	(Boric acid + Zinc Sulphate + Copper Sulphate @ 0.5%)	13.92	1.37	1.08	22.07	393.56	21.25
T_{12}	(Boric acid + Zinc Sulphate + Ferrous Sulphate @ 0.5%)	14.03	1.38	1.10	22.35	422.68	22.82
T_{13}	(Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%)	14.13	1.39	1.12	22.79	466.10	25.17
T_{14}	(Boric acid + Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%)	14.26	1.42	1.14	23.29	507.38	27.40
-	CD (P=0.05)	0.31	0.02	0.04	1.01	9.13	2.40
-	SE m **(±)**	0.11	0.01	0.01	0.35	4.76	0.82

Chemical quality characteristics:

During the investigation, data were collected on the chemical quality characteristics of strawberries, including total soluble solids (ºBrix), total sugars (%), reducing sugars (%), non-reducing sugars (%), acidity (%) and TSS: acidity ratio. These data, presented in (Table 4), revealed significant variation. The findings indicated that both individual and combined foliar applications of various micronutrients significantly impacted Strawberry's chemical quality characteristics. Among the various treatments, the treatment T_{14} (Boric acid + Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%) resulted in the maximum values for total soluble solids (11.51 ºBrix), total sugars (8.06 %), reducing sugars (5.64 %), non-reducing sugars (2.30 %), TSS: acidity ratio (18.78), followed by treatment T_{13} and minimum values were observed under treatment T_0 (Control). Whereas the minimum value for acidity (0.61%) was recorded under the T_{14} (Boric acid + Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%), while the maximum value for acidity (0.92%) was observed under treatment T_0 (Control). The enhancement in the chemical quality characteristics of strawberry fruit can be attributed to the direct influence of micronutrients in plant metabolism. Zinc is essential for enzymatic reactions, such as those involving hexokinase, as well as in the formation of carbohydrate and protein synthesis. Boron enhances sugar transport by forming boron-sugar complexes and enhances the hydrolysis of saccharides into simple sugars. Furthermore, iron plays a crucial role in increasing photosynthetic efficiency, which results in a higher photosynthetic rate. Since the primary product of photosynthesis is sugar, enhanced photosynthesis results in an increase in sugar content, thereby raising the levels of soluble solids in fruit juice (Hasani et al., 2012). These results were in agreement with those obtained by Ramezanian et al. (2009), Trivedi et al. (2012), and Yadav et al. (2022) in Strawberry. Korkmaz et al. (2015) found that foliar application of micronutrients significantly increased total soluble solids (TSS), total sugars, reducing sugars, and non-reducing sugars in pomegranate. However, the lower acidity of fruits may have been caused by the accumulation of sugars, the better distribution of sugars into fruit tissues, and the transformation of organic acids into sugars (Kumar et al., 2015).

Table 4: Influence of micronutrients on chemical quality characteristics of strawberry fruits

Treatment notation	Treatment combination	Total soluble solids (ºBrix)	Total sugars (%)	Reducing sugars	Non-reducing sugars (%)	Acidity (%)	TSS: acidity ratio
T_0	Control	7.87	5.51	3.85	1.57	0.92	8.57
T_1	(Boric acid @ 0.5%)	8.71	6.10	4.27	1.74	0.81	10.80
T_2	(Zinc Sulphate @ 0.5%)	8.76	6.13	4.29	1.75	0.79	11.09
T_3	(Copper Sulphate @ 0.5%)	8.79	6.16	4.31	1.75	0.81	10.82
T_4	(Ferrous Sulphate @ 0.5%)	8.82	6.17	4.32	1.76	0.82	10.76
T_5	(Boric acid + Zinc Sulphate @ 0.5%)	9.42	6.59	4.61	1.88	0.77	12.20
T_6	(Boric acid + Copper Sulphate @ 0.5%)	9.44	6.61	4.63	1.88	0.76	12.37
T_7	(Boric acid + Ferrous Sulphate @ 0.5%)	9.53	6.67	4.67	1.90	0.77	12.34
T_8	(Zinc Sulphate + Copper Sulphate @ 0.5%)	9.60	6.72	4.70	1.92	0.75	12.73
T_9	(Zinc Sulphate + Ferrous Sulphate @ 0.5%)	9.80	6.86	4.80	1.96	0.74	13.26
T_{10}	(Copper Sulphate + Ferrous Sulphate @ 0.5%)	9.94	6.96	4.87	1.98	0.73	13.70
T_{11}	(Boric acid + Zinc Sulphate + Copper Sulphate @ 0.5%)	10.60	7.42	5.20	2.12	0.70	15.23
T_{12}	(Boric acid + Zinc Sulphate + Ferrous Sulphate @ 0.5%)	10.69	7.49	5.24	2.13	0.67	15.96
T_{13}	(Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%)	11.14	7.80	5.46	2.22	0.63	17.59
T_{14}	(Boric acid + Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%)	11.51	8.06	5.64	2.30	0.61	18.78
-	CD (P=0.05)	0.51	0.36	0.25	0.10	0.03	0.83
-	SE m (±)	0.18	0.12	0.09	0.04	0.01	0.28

Economics of Strawberry:

The results indicated that the capital investment for strawberry cultivation varied across different treatments. The benefit-cost ratio analysis for each treatment was conducted and presented in (Table 5). Based on experimental findings, the highest cost of cultivation (₹ 5, 83,095.34) was determined for treatment T_{14} (Boric acid + Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%), while the lowest cost of cultivation (₹ 5, 58, 754.54) was recorded in treatment T_0 (Control). Furthermore, maximum gross return (₹ 45, 21, 000) was observed under the treatment T_{14} (Boric acid + Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%), while minimum gross return (₹ 18, 18, 300) was calculated in the treatment T_0 (Control). Similarly, the highest net return (₹ 39, 37, 904.66) was documented in the treatment T_{14} (Boric acid + Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%), while the lowest net return (₹ 12, 59, 545.46) was documented under treatment T_0 (Control). However, the maximum B: C ratio (₹ 6.75) was calculated in the treatment T_{14} (Boric acid + Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%), whereas the minimum B: C ratio (₹ 2.25) was calculated in treatment T_0 (Control). This outcome may be attributed to the foliar application of micronutrients, specifically Boric Acid, Zinc Sulphate, Copper Sulphate, and Ferrous Sulphate at 0.5%, which proved to be the most effective strategy for maximizing yield. This treatment produced substantial gross and net returns and resulted in the highest benefit-cost ratio, ensuring optimal returns for every rupee invested. These findings are in line with the findings of Singh et al. (2023), Anchal et al. (2023), Kumar et al. (2021) in Strawberries, Narayan et al. (2021) in okra, Kumar et al. (2010) in cauliflower and Bharati et al., (2018) in bitter gourd.

Table 5: Influence of micronutrients on the economics of strawberry cultivation

Treatment notation	Treatment combination	Cost of cultivation (Rs $ha^{1)}$)	Fruit Yield (t ha^{-1})	Selling Rate (Rs t^{-1})	Gross return (Rs ha^{-1})	Net return (Rs ha^{-1})	B:C Ratio
T_0	Control	558754.54	11.02	165000	1818300	1259545.46	2.25
T_1	(Boric acid @ 0.5%)	561229.53	14.41	165000	2377650	1816420.47	3.24
T_2	(Zinc Sulphate @ 0.5%)	561714.36	14.63	165000	2413950	1852235.64	3.30
T_3	(Copper Sulphate @ 0.5%)	561875.45	14.79	165000	2440350	1878474.55	3.34
T_4	(Ferrous Sulphate @ 0.5%)	561879.78	15.42	165000	2544300	1982420.22	3.53
T_5	(Boric acid + Zinc Sulphate @ 0.5%)	571972.79	17.59	165000	2902350	2330377.21	4.07
T_6	(Boric acid + Copper Sulphate @ 0.5%)	571968.67	17.60	165000	2904000	2332031.33	4.08
T_7	(Boric acid + Ferrous Sulphate @ 0.5%)	571956.75	18.28	165000	3016200	2444243.25	4.27
T_8	(Zinc Sulphate + Copper Sulphate @ 0.5%)	571965.64	18.26	165000	3012900	2440934.36	4.27
T_9	(Zinc Sulphate + Ferrous Sulphate @ 0.5%)	571985.42	19.39	165000	3199350	2627364.58	4.59
T_{10}	(Copper Sulphate + Ferrous Sulphate @ 0.5%)	571995.68	19.71	165000	3252150	2680154.32	4.69
T_{11}	(Boric acid + Zinc Sulphate + Copper Sulphate @ 0.5%)	582045.75	21.25	165000	3506250	2924204.25	5.02
T_{12}	(Boric acid + Zinc Sulphate + Ferrous Sulphate @ 0.5%)	582075.65	22.82	165000	3765300	3183224.35	5.47
T_{13}	(Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%)	582089.73	25.17	165000	4153050	3570960.27	6.13
T_{14}	(Boric acid + Zinc Sulphate + Copper Sulphate + Ferrous Sulphate @ 0.5%)	583095.34	27.40	165000	4521000	3937904.66	6.75

CONCLUSION

The study concluded that the foliar application of micronutrients significantly influenced the growth, flowering, yield, fruit quality, and profitability of strawberry (*Fragaria* × *ananassa* Duch) cv. Chandler under open field conditions. The combined application of micronutrients under the treatment T_{14} resulted in improved plant growth, improved physico-chemical quality of the fruit, and augmented overall yield per hectare. Moreover, the higher yield, along with greater gross returns, net returns, and an enhanced benefit-cost ratio, demonstrated the economic viability of this treatment. Therefore, it is highly recommended that the commercial cultivation of strawberries be done for improved productivity and profitability.

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Authors' contributions

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Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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