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RESEARCH ARTICLE

Impact of foliar application of micronutrients on growth, yield, fruit quality characteristics and profitability in okra (*Abelmoschus esculentus*) cv. Ridhi

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Abstract

Okra (*Abelmoschus esculentus*) is a significant warm-season vegetable crop, renowned for its tender and nutritious fruits that are abundant in vitamins, minerals and dietary fibre. It is widely grown in tropical and subtropical regions because of its adaptability and economic importance. Despite its potential, it remains difficult to achieve higher productivity and quality due to suboptimal nutrient management practices. A field experiment was conducted at the experimental farm, School of Agriculture Sanjeev Agrawal Global Educational University, Bhopal during spring-summer season of 2024. The experiment was conducted in a Randomized Complete Block Design (RCBD) with 14 treatment combinations with three replications. Foliar applications of various micronutrients (B, Zn, Cu, Fe and Mn) were applied at 30 and 45 days after sowing during the evening hours. The foliar application of various micronutrients was found to enhance the growth, yield, fruit quality and financial viability of okra. The findings revealed that the highest values for plant height (135.39 cm), leaf area (4377.92 cm^2), leaf area index (3.86), specific leaf weight (9.85 mg/cm^2), total leaf chlorophyll (1.88 mg g^{-1}), total fruit chlorophyll (0.84 mg g^{-1}), dry matter (12.16 %), crude protein (10.29%), vitamin C (13.65 mg/100g), fruit length (10.30 cm), fruit diameter (1.42 cm), average fruit weight (9.33 g), fruit weight/plant (232.61g), number of fruits/plant (22.05) and fruit yield (172.84 q/ha) were achieved with the foliar application of treatment T_{14}. However, in term of economics the treatment T_{14} documented maximum gross return (54, 5310.20) and net return (44, 5143.59) and B: C ratio of (4.44). In conclusion, the study revealed that the foliar application of micronutrients, mostly treatment T_{14}, significantly improved the growth, yield, quality and profitability of okra cultivation. This underscores the significance of balancing micronutrient management for ensuring sustainable and economically viable crop production. The purpose of this study is to determine the most effective nutrient management strategy for optimizing okra cultivation by assessing the impact of different micronutrient treatments on plant growth, yield, quality and financial performance.

Keywords

chlorophyll; crude protein; dry matter, economics, quality parameters; vitamin C

Introduction

Okra (*Abelmoschus esculentus*), is an annual or perennial vegetable crop of the family Malvaceae, grown in the tropical and subtropical parts of the world. Okra is a rainfed crop, but it also grows well when it is irrigated during Kharif and Summer seasons. Okra originated in tropical and subtropical areas, in the north-east African centre and Asia (1). Its tender, immature fruits are mostly consumed as vegetables (2, 3). The crop is abundant in vitamins, minerals, protein, iodine, antioxidants and fibre has been reported to alleviate various diseases (4, 5). Carbohydrates are mainly present in the form of mucilage that is highly soluble in water. Potassium, sodium, magnesium and calcium are the principal elements in pods (6, 7). In India, the crop is grown during the summer months and during the rainy season. Okra is a warm season vegetable crop that requires a long warm growing season and is highly susceptible to frost. The best temperature range is between 25- 30°C. This is a tropical direct-sown vegetable that has duration of 90-100 days (8, 9). It thrives in all types of soil and thrives best in a moist, friable, well-drained soil. It is cultivated for commercial purposes in India, Nigeria, Sudan, Egypt, Pakistan, Saudi Arabia, Ghana, Mexico, Benin and Cameroon. Micronutrients play an important role in the enzymatic processes of plants, including the synthesis of chlorophyll, carbohydrate production and respiration. Furthermore, they also activate a number of biochemical processes in plants (10, 11). Even though micronutrients have such a major role in crop growth and yield, research on micronutrient application and schedule for application for various crops is limited. Foliar application has proven to be a highly effective means of supplying secondary and micronutrients for meeting plant requirements (12, 13, 14).

The foliar application of micronutrients resulted in yield responses in numerous crops. It has been demonstrated that it prevents leaching into soils and prompts a quick reaction in plants (15, 16). The particular value of this technique is that it ensures that nutrients are taken up and transferred to various plant organs via the leaf tissues, so that nutrient deficiencies can be corrected quickly (17,18). Furthermore, foliar fertilization has been recommended for integrated crop production since it not only increases crop yield and quality, but it is also environmentally safe (18).

Hence, the present investigation was conducted to evaluate the impact of foliar application of micronutrients on various aspects of okra cultivation, including plant growth, yield, fruit quality characteristics and overall profitability. Furthermore, the study aimed to evaluate the economic benefits and potential for optimizing nutrient management practices in okra farming.

Materials and Methods

Experimental location

The present investigation was conducted at the experimental farm of the School of Agriculture, Sanjeev Agrawal Global Educational University, Bhopal, during the spring-summer season of 2024. Geographically, the experimental site is situated at altitude of 35.75° in the North and a longitude of 77.24° in the East, at an elevation of 500 m above mean sea level.

Planting material

The okra cultivar Ridhi was selected as the experimental material, which was sourced from a reliable, certified seed supplier. The nursery was established on the experimental farm of Sage University, Bhopal. Healthy plants, exhibiting uniform growth and free from diseases or injuries, were meticulously selected from the nursery bed for the purpose of the experiment. The trial was conducted at the experimental farm of the School of Agriculture, Sanjeev Agrawal Global Educational University, Bhopal (MP). All plants were meticulously maintained under uniform horticultural practices and guidelines during the experimentation period.

Experimental procedure

The experiment was conducted using a Randomized Complete Block Design (RCBD) with 14 treatments and three replications. Basal doses of Farmyard Manure @ 20-25 t/ha and NPK @ 120:90:60 kg/ha were given at the time of field preparation in all the treatments. Foliar applications of micronutrient solutions were done at 30, 45, and 60 days after sowing. The recommended dosages were determined by the distinct micronutrient requirements of the plants. Each application was carefully designed to ensure optimal absorption and effectiveness, promoting healthy growth and development throughout the critical stages of the okra plants. To maintain consistency, plants were treated with plain distilled water supplemented with a minimal amount of fertilizer. Healthy okra plants of the cultivar Ridhi were transplanted at a spacing of 45 cm between rows and 15 cm between plants during the first week of March 2024. The experiment included the following treatment combinations: T_1(control), T_2 (B @100ppm), T_3 (B @150ppm), T_4 (Zn @100 ppm), T_5(Zn @150 ppm), T_6(Cu @100 ppm), T_7(Cu @150 ppm), T_8(Fe @100 ppm), T_9 (Fe @150 ppm), T_{10}(Mn @100 ppm), T_{11} (Mn @150 ppm), T_{12}(B + Zn + Cu + Fe + Mn @100 ppm), T_{13}(B + Zn + Cu + Fe + Mn @150 ppm) and T_{14}(B + Zn+ Cu + Fe + Mn @ 200 ppm).

Harvesting: Picking of fruits was done at tender edible stage at an interval of 3-5 days.

Determination of plant growth characteristics

***Plant height*:** The plant height was recorded from ground level to the tip of the main stem on five tagged plants at 30, 45 and 60 days after sowing, and at harvest.

***Leaf area*:** The determination of leaf area was carried out utilizing the techniques outlined 19). For each leaf, the area was calculated using the following formula:

$$\text{Lead area} = \text{length} \times \text{Width} \times 0.62 \quad \text{(Eqn. 1)}$$

Leaf Area Index (LAI): Leaf Area Index (LAI) was calculated using the lengths and the widest section width of the first, middle, and last leaf. The LAI was calculated using the following formula:

$$LAI = \frac{\text{Area of first leaf + Area of middle leaf + Area of last leaf}}{3} \times \frac{1}{\text{Area of the ground}} \quad \text{(Eqn. 2)}$$

This calculation uses the average leaf area of the first, middle and last leaves, which is then divided by the ground area to determine the LAI. This method estimates leaf area index more accurately by combining the leaf areas of three leaves.

Specific Leaf Weight (SLW): To determine the specific leaf weight of plant leaves, which is the ratio of leaf dry weight to leaf area, was determined using the methods described by (19) SLW (leaf dry weight per leaf area) was calculated for each leaf using the measured leaf area and dry weight with the following formula:

$$SLA = \frac{\text{Leaf Dry Weight (g)}}{\text{Leaf Area } (M^2)} \quad \text{(Eqn. 3)}$$

The total chlorophyll content of leaf and fruit (mg g $^{-1}$): The total chlorophyll content of leaf and fruit was determined spectrophotometrically using dimethyl sulfoxide (DMSO) as the extractant. The total chlorophyll content in leaves and fruit was estimated using the method described by (20). The chlorophyll content in both leaves and fruit was determined using the following formula

$$\text{Total chlorophyll (mg/g)} = \frac{(20.2\,(A_{645}) + 8.02\,(A_{663}) \times v)}{1000 \times W} \quad \text{(Eqn. 4)}$$

Where,

A= Absorbance at specific wave length (nm), V= Volume of chlorophyll extract in 80% acetone, W= Fresh weight of tissue extracted (g).

Determination of physico-chemical quality characteristics of the fruit

Dry matter content (%): The dry matter content of fruits was determined by drying the samples in a hot air oven, initially at 80 ±5°C for two hours and then at 60±5°C until a consistent weight was obtained. The dry matter content was determined using the following formula:

$$\text{Dry matter content} = \frac{\text{Dry weight}}{\text{Fresh weight}} \times 100 \quad \text{(Eqn. 5)}$$

***Crude protein content (%)*:** The protein content was determined by multiplying the total nitrogen content of the fruits by a factor of 6.25 (the protein factor). The total nitrogen content in the fruits was determined using the Kjeldahl method as outlined by (21).

***Vitamin C content (mg/100g)*:** The determination of vitamin C content (mg/100g) was carried out by titrating a known weight of the sample with 2, 6-dichlorophenol indophenols dye, employing metaphosphoric acid as a stabilizing agent (22).

Fruit length and fruit diameter (mm): Fruit length and fruit diameter (mm) were measured separately for five fruits collected from five randomly marked plants for each treatment combination. The fruit length was recorded from the stalk end to the floral end, and the fruit diameter was measured at the center of the fruit using a Vernier calliper.

Determination of yield characteristics

The average fruit weight and the fruit weight per plant (g): The average fruit weight and the fruit weight per plant (g) were measured for five fruits collected from five randomly tagged plants for each treatment combination. The weight of each fruit was determined individually using an electronic balance. The average fruit weight was calculated by dividing the total weight of the fruits by the number of fruits, and the fruit weight per plant was calculated by adding the weights of all the fruits from each plant.

Number of fruits per plant: The number of fruits produced by five randomly tagged plants in each treatment combination was calculated at each harvest.

Fruit yield per ha (q): The total fruit yield per hectare for each treatment was recorded from five randomly selected plants per plot from five randomly selected plants per plot. Yield per hectare (q) was calculated by multiplying the yield per plot (kg) by the number of plots per hectare, then dividing by 1,000

Economic analysis of crop treatments

A tabular analysis was conducted to evaluate the crop's economics. The gross returns were determined by multiplying the yield by the average market price. Net profit was obtained by subtracting the production cost from the gross returns. The cost-benefit ratio for each treatment was also determined to assess economic viability.

Statistical analysis

The data collected on different traits was statistically analyzed using the standard procedure as given in (23). Statistical analysis of the data for various fruit characteristics was conducted using SAS software version 9.3 (SAS Institute Inc., Cary, NC, USA). The results were tested at $P \leq 0.05$. significance. The critical difference was used to compare treatment means.

Results

Plant growth characteristics

During the present investigation, data on various plant growth characteristics, including plant height (cm), leaf area (cm^2), leaf area index, specific leaf weight (mg/cm^2), total leaf chlorophyll content (mg g^{-1}), and total fruit chlorophyll content (mg/g) were documented and presented in Table 1. The results indicated that foliar application of various micronutrients at different concentrations had a significant effect on the growth characteristics of okra plants. Among the various treatments, the treatment T_{14} (B + Zn + Cu + Fe + Mn @ 200 ppm) exhibited the highest plant height (135.39 cm), leaf area (4377.92 cm^2), leaf area index (3.86), specific leaf weight (9.85 mg/cm^2) total leaf chlorophyll content (1.88 mg g^{-1}), and total fruit chlorophyll content (0.84 mg g^{-1}), while the lowest values were observed under treatment T_1 (Control).

Table 1. The impact of foliar application of various micronutrients on the plant growth characteristics of okra cv. Ridhi

Treatment notations	Treatments combinations	Plant height (cm)	Leaf area (cm²)	Leaf area index	Specific leaf weight (mg/cm²)	Total leaf chlorophyll content (mg g⁻¹)	Total fruit chlorophyll content (mg g⁻¹)
T_1	(Control)	125.17	3943.14	1.93	6.69	1.61	0.50
T_2	(B @100ppm)	127.61	3976.40	1.96	6.84	1.72	0.54
T_3	(B @150ppm)	128.51	4075.74	1.97	6.79	1.76	0.59
T_4	(Zn @100 ppm)	127.67	4144.59	1.98	7.11	1.76	0.63
T_5	(Zn@150 ppm)	128.00	4146.42	2.00	7.44	1.77	0.66
T_6	(Cu @100 ppm)	127.40	4148.82	2.01	7.75	1.79	0.71
T_7	(Cu @150 ppm)	127.04	4149.40	2.04	8.01	1.78	0.73
T_8	(Fe @100 ppm)	128.59	4182.98	2.06	8.35	1.77	0.75
T_9	(Fe @150 ppm)	128.87	4285.70	2.08	8.45	1.76	0.77
T_{10}	(Mn @100 ppm)	129.82	4303.43	2.56	8.69	1.79	0.75
T_{11}	(Mn @150 ppm)	130.89	4301.73	2.89	8.81	1.81	0.76
T_{12}	(B+ Zn+ Cu + Fe + Mn @100 ppm)	131.91	4308.96	3.55	8.97	1.82	0.79
T_{13}	B + Zn + Cu + Fe + Mn @150 ppm)	133.82	4310.54	3.77	9.47	1.84	0.83
T_{14}	(B + Zn+ Cu + Fe + Mn @ 200 ppm)	135.39	4377.92	3.86	9.85	1.88	0.84
CD (P=0.05)	-	0.76	61.32	0.07	0.15	0.12	0.02
SE(m)	-	0.26	20.98	0.02	0.05	0.04	0.01

Physico-chemical quality characteristics of the fruit

During the study period, data on various physico-chemical quality characteristics of the fruit such as dry matter content (%), crude protein content (%), vitamin C content (mg/100g), fruit length (cm) and fruit diameter (cm) were noted and exhibited in Table 2. The findings revealed that the foliar application of different micronutrients at varying concentrations significantly influenced the physicochemical quality characteristics of okra fruit. Among the various treatments, the treatment T_{14} (B + Zn + Cu + Fe + Mn @ 200 ppm) showed the highest values for dry matter content (12.16 %), crude protein content (10.29%), vitamin C content (13.65 mg/100g), fruit length (10.30 cm) and fruit diameter (1.42 cm), whereas the lowest values were recorded in treatment T_1 (Control).

Yield characteristics

During the investigation, data on various yield characteristics, including average fruit weight (g), fruit weight/plant (g), number of fruits/plant and fruit yield (q/ha) were recorded and presented in Table 3. The results show that the foliar application of different micronutrients at varying concentrations significantly influenced the yield characteristics of okra. Among the various treatments, the treatment T_{14} (B + Zn + Cu + Fe + Mn @ 200 ppm) exhibited the highest values for average fruit weight (9.33 g), fruit weight/plant (232.61 g), number of fruits/plant (22.05) and fruit yield (172.84 q/ha), however the lowest values were documented under treatment T_1 (Control).

Economics of okra

The results indicated that capital investment varied across different treatments for okra cultivation. The benefit-cost ratio for each treatment was calculated and is presented in Table 4. Maximum cost of cultivation (10, 0166.61) was calculated for treatment T_{14} (B + Zn + Cu + Fe + Mn @ 200 ppm), while minimum cost of cultivation (98,450.4) was calculated in treatment T_1 (Control). Maximum gross return (54, 5310.20) was also observed in treatment in T_{14} (B + Zn + Cu + Fe + Mn @ 200 ppm), whereas minimum gross return (40, 7878.40) was calculated in treatment T_1 (Control). Similarly, the maximum net return (44, 5143.59) was documented for treatment T_{14} (B + Zn + Cu + Fe + Mn @ 200 ppm) while, minimum net return (30, 9428.00) was recorded in treatment T_1 (Control). However, maximum B: C ratio (4.44) was calculated in the treatment T_{14} (B + Zn + Cu + Fe + Mn @ 200 ppm), whereas minimum B: C ratio (3.14) was calculated in treatment T_1 (Control).

Table 2. The impact of foliar application of various micronutrients on physico-chemical quality characteristics of the fruit of okra cv. Ridhi

Treatment notations	Treatments combinations	Dry matter content (%)	Crude protein content (%)	Vitamin C content (mg/100g)	Fruit length (cm)	Fruit diameter (cm)
T_1	(Control)	9.64	7.48	12.12	9.43	0.99
T_2	(B @100ppm)	9.79	7.99	12.30	9.47	1.09
T_3	(B @150ppm)	9.78	7.95	12.36	9.50	1.14
T_4	(Zn @100 ppm)	10.17	8.26	12.43	9.53	1.16
T_5	(Zn@150 ppm)	10.29	8.43	12.47	9.56	1.18
T_6	(Cu @100 ppm)	10.48	8.73	12.57	9.59	1.22
T_7	(Cu @150 ppm)	10.55	8.80	12.59	9.63	1.25
T_8	(Fe @100 ppm)	10.67	8.93	12.68	9.66	1.28
T_9	(Fe @150 ppm)	10.50	9.10	12.97	9.70	1.32
T_{10}	(Mn @100 ppm)	10.83	9.25	13.18	9.73	1.33
T_{11}	(Mn @150 ppm)	10.75	9.38	13.28	9.76	1.34
T_{12}	(B+ Zn+ Cu + Fe + Mn @100 ppm)	10.68	9.48	13.40	9.80	1.37
T_{13}	(B + Zn + Cu + Fe + Mn @150 ppm)	11.46	10.03	13.47	9.96	1.39
T_{14}	(B + Zn+ Cu + Fe + Mn @ 200 ppm)	12.16	10.29	13.65	10.30	1.42
CD (P=0.05)	-	0.13	0.02	0.01	0.13	0.02
SE(m)	-	0.05	0.01	0.002	0.05	0.01

Table 3. The impact of foliar application of different micronutrients on yield characteristics of okra cv. Ridhi

Treatment notations	Treatments combinations	Average fruit weight (g)	Fruit weight/plant (g)	Number of fruits/plant	Fruit yield (q/ha)
T_1	(Control)	8.90	119.95	21.23	129.28
T_2	(B @100ppm)	8.95	129.27	21.34	138.44
T_3	(B @150ppm)	9.13	134.48	21.37	139.68
T_4	(Zn @100 ppm)	9.14	149.70	21.51	141.00
T_5	(Zn@150 ppm)	9.15	171.22	21.59	142.05
T_6	(Cu @100 ppm)	9.16	187.99	21.67	142.96
T_7	(Cu @150 ppm)	9.19	196.83	21.48	144.87
T_8	(Fe @100 ppm)	9.21	205.32	21.73	150.06
T_9	(Fe @150 ppm)	9.24	214.38	21.78	153.99
T_{10}	(Mn @100 ppm)	9.26	218.34	21.81	156.54
T_{11}	(Mn @150 ppm)	9.27	224.22	21.84	159.24
T_{12}	(B+ Zn+ Cu + Fe + Mn @100 ppm)	9.28	227.56	21.86	165.39
T_{13}	B + Zn + Cu + Fe + Mn @150 ppm)	9.31	230.73	21.89	168.08
T_{14}	(B + Zn+ Cu + Fe + Mn @ 200 ppm)	9.33	232.61	22.05	172.84
CD (P=0.05)	-	0.01	2.75	0.12	1.07
SE(m)	-	0.002	0.94	0.04	0.36

Table 4. The impact of foliar application of different micronutrients on economics of cultivation of okra.

Treatment notations	Treatments combinations	Total cost of cultivation (Rs. ha^{-1})	Fruit yield (q/ha)	Gross returns (Rs. ha^{-1})	Net returns (Rs. ha^{-1})	B: C ratio
T_1	(Control)	98450.4	129.28	407878.40	309428.00	3.14
T_2	(B@100ppm)	98566.23	138.44	436778.20	338211.97	3.43
T_3	(B @150ppm)	98676.25	139.68	440690.40	342014.15	3.47
T_4	(Zn @100 ppm)	98466.23	141.00	444855.00	346388.77	3.52
T_5	(Zn@150 ppm)	98566.23	142.05	448167.75	349601.52	3.55
T_6	(Cu @100 ppm)	98595.24	142.96	451038.80	352443.56	3.57
T_7	(Cu @150 ppm)	98711.69	144.87	457064.85	358353.16	3.63
T_8	(Fe @100 ppm)	98666.23	150.06	473439.30	374773.07	3.80
T_9	(Fe @150 ppm)	98707.58	153.99	485838.45	387130.87	3.92
T_{10}	(Mn @100 ppm)	98723.02	156.54	493883.70	395160.68	4.00
T_{11}	(Mn @150 ppm)	98895.24	159.24	502402.20	403506.96	4.08
T_{12}	(B+ Zn+ Cu + Fe + Mn @100 ppm)	98811.69	165.39	521805.45	422993.76	4.28
T_{13}	B + Zn + Cu + Fe + Mn @150 ppm)	99953.96	168.08	530292.40	430338.44	4.31
T_{14}	(B + Zn+ Cu + Fe + Mn @ 200 ppm)	100166.61	172.84	545310.20	445143.59	4.44

Discussion

Okra (*Abelmoschus esculentus*), also known as lady's finger, is a widely cultivated and nutritionally significant vegetable crop known for its high dietary fibre, vitamins, and minerals. Okra is important for its economic and nutritional value, but it is often hindered by micronutrient deficiencies in the soil, which affect plant metabolism and productivity. The foliar application of micronutrients has emerged as an efficient approach to overcome these deficiencies, as it ensures the direct and effective delivery of vital nutrients to the plant's foliage, thereby enhancing nutrient uptake and utilization. The aim of this study is to evaluate the impact of foliar application of micronutrients on the growth, yield, fruit quality characteristics, and profitability of Okra cv. Ridhi. The findings will contribute to improving nutrient management practices for sustainable and profitable okra production. The present study indicated that the foliar application of different micronutrients at various concentrations had a significantly influenced on the growth characteristics of okra plants compared to other treatments, including the control, during the 2024. The significant variation in the growth characteristics of okra cv. Ridhi was attributed to the substantial influence of various micronutrients applied at different concentrations. The findings indicate that among the various treatment combination, the treatment T_{14} (B + Zn + Cu + Fe + Mn @ 200 ppm) exhibited the highest values for plant height (cm), leaf area (cm^2), leaf area index, specific leaf weight (mg/cm^2). In contrast, the lowest values were observed under treatment T_1 (Control). The significant improvement in these parameters is attributed to the critical role of micronutrients, which, although required in relatively small quantities, are vital for plant growth and development. These nutrients are essential for various processes such as cell wall synthesis, enzyme activation, regulation of cell division, cell differentiation, cell elongation, sugar transport, chloroplast development, and hormonal regulation. Micronutrients contribute to overall plant growth and are involved in flower, fruit, and seed development. They are also involved in plant growth. However, the application of micronutrients through foliar application has been documented in other studies (8, 24, 25). Furthermore, in the present study, a significant increase in plant height (cm), leaf area (cm^2), leaf area index, and specific leaf weight (mg/cm^2) was recorded in terms of both area and thickness. These results confirm the findings from the above studies and are consistent with the fundamental roles of micronutrients in promoting plant growth and development (10, 12).

Furthermore, Chlorophyll is a critical photosynthetic parameter for evaluating the synthesis of metabolites during photosynthesis. The highest total leaf and fruit chlorophyll content (mg/g) was observed in treatment T_{14} (B + Zn + Cu + Fe + Mn @ 200 ppm). However, the lowest chlorophyll content (mg/g) was recorded in treatment T_1 (control). It was apparent from the present investigation that chlorophyll, a crucial pigment for enhancing light capture during photosynthesis, is significantly influenced by the foliar application of micronutrients. Chlorophyll synthesis relies on adequate mineral nutrition, and an increase in chlorophyll content is attributed to the optimal availability of micronutrients. These nutrients are essential for cell division and the formation of active photosynthetic pigments, including chlorophyll. They are also essential for the formation of active photosynthetic pigments, including chlorophyll. The uptake of sufficient micronutrient levels is closely related to the facilitation of biochemical processes and the biosynthesis of pigment molecules, particularly chlorophyll. Micronutrients, such as Cu, Mn, Zn, and Fe, act as cofactors for NAD and NADP, participating in various oxidation-reduction reactions (26). Mn and Fe, which are integral components of chlorophyll molecules, contribute to photosynthesis by supporting chloroplast development and function (27). Our results also revealed that the foliar application of a combination of micronutrients (B, Zn, Cu, Fe, and Mn) significantly enhanced the leaf and fruit chlorophyll content in okra. These findings are supported by the findings of (6, 28, 29).

The study further revealed that the foliar application of micronutrients had a significant impact on the physico-chemical quality characteristics of the fruit in comparison to other treatments as well as the control. The significant variation in the physical and chemical quality characteristics of okra fruit was attributed to the significant impact of various micronutrients applied at varying concentrations. Among the various treatment combination, the treatment T_{14} (B + Zn + Cu + Fe + Mn @ 200 ppm) exhibited the maximum values for dry matter content (%), crude protein content (%), vitamin C content (mg/100g), fruit length (cm) and fruit diameter (cm) while the minimum values were recorded under treatment T_1 (Control).

Dry matter is a significant attribute that provides valuable insights into photosynthetic ability and food accumulation in edible fruits. In the present investigation, treatment T_{14} (B + Zn + Cu + Fe + Mn @ 200 ppm) exhibited the maximum values for dry matter content (%), while the minimum values were recorded under treatment T_1 (Control). The optimal application of micronutrients at regular intervals increases the availability of essential micronutrients, which in turn supports efficient physiological and biochemical processes. The incorporation of micronutrients plays a significant role in facilitating the production of active photosynthetic pigments by augmenting the levels of stomatal and thylakoid proteins in leaves. This promotes root biomass and ensures a continuous release of nutrients, which are adequately absorbed by the plants. This process helps produce valuable biochemical components, as evidenced by the increased dry matter content (6). (30) Also reported variations in dry matter concentration in tomatoes due to different micronutrients levels, with content increasing as nutrient levels increased.

The highest values for crude protein content were recorded under treatment T_{14} (B + Zn + Cu + Fe + Mn @200 ppm), whereas the lowest values were observed under treatment T_1 (Control). The maximum protein content was observed with treatment T_{14} may be attributed to the application of optimum levels of micronutrients, which improved nutrient availability and uptake. The improved physiological activities and source-sink relationships led to greater assimilation and translocation of primary and secondary metabolites in plant tissues (6, 31).

Maximum vitamin C content was documented under treatment T_{14} (B + Zn + Cu + Fe + Mn @200 ppm), whereas the minimum values were observed under treatment T_1 (Control). The increase in ascorbic acid content is attributed to the continuous availability of nutrients at shorter, more frequent intervals, which kept the plants photosynthetically active and led to higher assimilation of primary and secondary metabolites such as ascorbic acid and sugars. Furthermore, the increase in ascorbic acid was due to an enhanced activity of the enzyme ascorbic acid oxidase, which further boosts ascorbic acid levels in the fruit. Treatments that received micronutrients exhibited a significantly higher level of ascorbic acid content (mg/100g) in comparison to the control. These results are in agreement with the findings of (6) in okra and (32) in tomato.

The present findings indicate that the foliar application of different micronutrients at varying concentrations significantly influenced the yield characteristics of okra. The observed variation in yield characteristics was attributed to the substantial impact of micronutrients applied at various concentrations. Higher values for fruit length (cm), fruit diameter (cm), average fruit (g), fruit weight/plant (g), number of fruit/plant and fruit yield/ha (q) were recorded under treatment T_{14} (B + Zn + Cu + Fe + Mn @ 200 ppm), whereas the lowest values were observed under treatment T_1 (Control). This may be due to the progressive enhance in the absolute quantities of inorganic elements and the accumulation of appropriate food reserves, which promoted early bud differentiation into flower buds, leading to increases in fruit length (cm), fruit diameter (cm), average fruit weight (g), fruit weight per plant (g), number of fruits per plant, and fruit yield per hectare (q). These findings are consistent with the findings of (10, 11) in okra and (33) and (34) in tomato.

Furthermore, the highest number of fruits per plant, along with the highest fruit length, fruit diameter, and fruit weight were recorded in treatment (T_{14}) compared to all other treatments, with the lowest values observed in the control (T_1). The increased fruit length and diameter is attributed to improved photosynthetic characteristics, including greater leaf area, leaf thickness, and chlorophyll content. These characteristics contributed to a higher individual fruit weight and overall yield per plant (35). These results align with the findings of (6, 12, 34) in okra.

Economics of okra

The outcomes of this investigation revealed a variation in capital expenditure across diverse micronutrient treatment combinations in okra cultivation. Based on the findings of the study, it can be concluded that the foliar application of micronutrients such as (B, Zn, Cu, Fe, and Mn at 200 ppm) is the most effective approach for achieving the highest yield and generating substantial gross returns, net returns, and the highest benefit-cost (B:C) ratio for every rupee expended. This treatment is recommended for commercial cultivation of okra in open field conditions. These results are in agreement with the findings of (12) in okra, (28) in strawberry, (36) in cauliflower and (37) in bitter gourd.

Conclusion

The study concluded that the foliar application of micronutrients had a significant positive impact on the growth, yield, fruit quality, and profitability of okra (*Abelmoschus esculentus*) cv. Ridhi. The combined application of micronutrients in treatment T_{14} resulted in improved plant growth, enhanced physico-chemical quality characteristics of the fruit, and increased overall yield per hectare. Furthermore, the higher yield, coupled with higher gross returns, net returns, and an improved benefit-cost ratio, demonstrated the economic viability of this treatment. Therefore, it is highly recommended for the commercial cultivation of okra for commercial purposes.

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Authors' contributions

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Compliance with ethical standards

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

Ethical issues: None.

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