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Evaluating the Role of Foliar-applied Micronutrients in Enhancing Quality of Broccoli

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

A field experiment was conducted during the rabi seasons of 2020–21 and 2021–22 at the Horticulture Research Farm, Department of Agriculture, Plantica Indian Academy of Rural Development (IARD), Dehradun to evaluate the influence of foliar-applied micronutrients on the growth, yield and quality of broccoli (*Brassica oleracea* L. var. *italica*). The experiment was laid out in a Randomized Complete Block Design with three replications and fourteen treatments including control. Quality parameters such as ascorbic acid, total soluble solids (TSS), crude protein and chlorophyll content were recorded and analysed statistically. The results revealed a significant effect of micronutrient sprays on all quality attributes. Treatment T_{10} recorded the highest ascorbic acid content (86.40 mg/100 g), followed by T_7 and T_5, as compared to the control (80.00 mg/100 g). Maximum TSS (7.90%) was observed in T9, while treatments T_4, T_8 and T6 also showed considerable improvement over control (6.00%). Crude protein content was highest (2.79%) in T_5 and T_8, followed closely by T_7 (2.78%). Chlorophyll content was markedly improved in T_{11} (2.15 mg g^{-1}), followed by T_{12} (2.14 mg g^{-1}) and T_9 (2.12 mg g^{-1}), whereas the lowest was recorded in control

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(1.57 mg g^{-1}). The study concludes that foliar application of specific micronutrient combinations markedly enhances the nutritional and physiological quality of broccoli. Treatments such as T_{10}, T_9, T_5, T_8, and T_{11} proved most effective and may be recommended for improving broccoli quality under similar agro-climatic conditions of the western Himalayan foothills.

Keywords: Foliar sprays; micronutrient application; quantitative traits; growth; yield; broccoli.

1. INTRODUCTION

Broccoli (*Brassica oleracea* L. var. *italica*, family Brassicaceae) is a cool-season vegetable crop cultivated worldwide for its immature green flower heads and tender stalks, which are valued as both a culinary delicacy and a functional food. The crop is characterized by a compact terminal inflorescence composed of densely arranged flower buds borne on a fleshy peduncle. Beyond its horticultural appeal, broccoli is increasingly recognized for its remarkable nutritional and phytochemical profile, positioning it as one of the most health-promoting vegetables among cole crops. Broccoli heads contain significant amounts of vitamins C, K, A, and B-complex, essential minerals such as calcium, potassium, iron, and magnesium, as well as phenolic acids, flavonoids, and glucosinolates (Vallejo et al., 2003; Domínguez-Perles et al., 2010). These bioactive constituents contribute to its antioxidant, anticarcinogenic, and cardioprotective potential, supporting its classification as a functional food in human diets (Dosz and Jeffery, 2020; Klopsch et al., 2022).

Among the bioactive metabolites, glucosinolates—particularly glucoraphanin—are precursors of sulforaphane, a potent isothiocyanate with established anticancer and detoxifying properties, and sulforaphane is generated from glucoraphanin by the action of the enzyme myrosinase in cruciferous vegetables such as broccoli. Recent comprehensive reviews highlight that sulforaphane has been shown in numerous preclinical and clinical studies to modulate carcinogen metabolism, induce phase II detoxification enzymes, and inhibit cancer cell proliferation through multiple molecular mechanisms involved in oxidative stress and epigenetic regulation (Kaiser *et al.*, 2021; Gasmi *et al.*, 2023; Abukhabta *et al.*, 2020) Broccoli also accumulates high concentrations of ascorbic acid (vitamin C), chlorophylls, and phenolic compounds that contribute to its antioxidant capacity and nutritional quality (e.g., Liu *et al.*, 2018; Podsędek *et al.*, reviews on Brassica phytonutrients), with reported vitamin C in raw broccoli often in the range of ~80–130 mg per 100 g fresh weight depending on cultivar and growing conditions. However, the expression of these nutritional attributes is strongly influenced by environmental conditions, plant genotype, and nutrient availability during growth and development.

Micronutrients such as zinc (Zn), boron (B), iron (Fe), manganese (Mn), and molybdenum (Mo) are required in trace amounts but are indispensable for the regulation of enzymatic, metabolic, and redox processes in plants (Marschner, 2012). Deficiencies of these elements are widespread in intensively cultivated soils of subtropical regions due to low organic matter, soil alkalinity, and imbalanced fertilization practices (Singh et al., 2020). Micronutrient limitations can restrict photosynthesis, protein synthesis, and hormone metabolism, resulting in poor curd development and diminished nutritional quality in cole crops (Mishra et al., 2021).

Foliar application has proven to be an efficient and targeted strategy to correct micronutrient deficiencies and enhance crop performance. It ensures rapid absorption and utilization of nutrients by circumventing soil interactions, leaching, or fixation losses (Fernández and Brown, 2013). In vegetable production, foliar micronutrient sprays have been reported to improve growth, yield, and biochemical quality by stimulating photosynthetic pigments, carbohydrate metabolism, and antioxidant synthesis (Souri and Hatamian, 2019). Several recent studies have confirmed that foliar application of Zn, B, Fe, and Mo significantly enhances head weight, vitamin C concentration, and chlorophyll content in broccoli (Brassica oleracea L. var. *italica*) and other Brassica crops, improving mineral content and nutritional quality under field conditions (Sardar *et al.*, 2022; Nihar et al., 2022).

Broccoli quality attributes—particularly ascorbic acid, total soluble solids (TSS), crude protein, and chlorophyll concentration—serve as reliable biochemical indicators of physiological efficiency and nutritional value. Ascorbic acid is essential for antioxidative defense and postharvest stability; TSS reflects carbohydrate metabolism and flavor; crude protein content indicates nitrogen assimilation; and chlorophyll concentration is directly linked to photosynthetic activity and plant vigor. Optimizing these parameters through balanced micronutrient nutrition remains a major research focus in sustainable horticulture.

Considering the economic and nutritional importance of broccoli and the critical role of micronutrients in enhancing plant metabolism and quality, a field experiment was undertaken during the rabi seasons of 2020–21 and 2021–22 at the Horticulture Research Farm, Department of Agriculture, Plantica Indian Academy of Rural Development (IARD) Dehradun, India. The investigation aimed to evaluate the influence of foliar-applied micronutrients on the growth, yield, and quality of broccoli under subtropical foot-hill conditions.

This study was undertaken to generate empirical evidence for the optimization of foliar micronutrient management strategies in broccoli. It addresses the need for integrated nutrient management practices that improve both productivity and nutritional composition while maintaining environmental and economic sustainability. The findings are expected to provide a scientific basis for enhancing the functional food value of broccoli (*Brassica oleracea* L. var. *italica*) through effective micronutrient supplementation under field conditions.

2. MATERIALS AND METHODS

2.1 Experimental Site

The experiment was conducted during the rabi seasons of 2020–21 and 2021–22 at the Horticulture Research Farm, Department of Agriculture, Plantica, Indian Academy of Rural Development (IARD), Dehradun, India. The site is characterized by a subtropical climate with sandy loam to sandy clay loam soils and an average annual rainfall of approximately 2050 mm. Standard meteorological data recorded during the crop period were used for interpretation of results.

2.2 Experimental Design and Treatments

The study was laid out in a Randomized Complete Block Design (RCBD) with fourteen treatments and three replications. The experiment comprised fourteen foliar micronutrient treatments including a control. T_0 served as untreated control without spray. Individual micronutrient applications included boric acid (T_1), manganese sulphate (T_2), zinc sulphate (T_3), ammonium molybdate (T_4), copper sulphate (T_5) and ferrous sulphate (T_6) each at 100 ppm. Binary combinations were prepared by adding boric acid @100 ppm with manganese sulphate (T_7), zinc sulphate (T_8), ammonium molybdate @50 ppm (T_9), copper sulphate (T_{10}) and ferrous sulphate (T_{11}). A mixed formulation comprising all six micronutrient salt solutions used individually in T_1–T_6 was applied as T_{12}. A commercial foliar micronutrient formulation 'Multiplex' @100 ppm constituted T_{13}. All foliar applications were made at critical vegetative stages using distilled water as solvent, and solutions were sprayed uniformly to ensure complete coverage of the crop canopy.

2.3 Crop Establishment and Management

Broccoli seedlings (35 days old) were transplanted at a spacing of 45 × 45 cm on ridges prepared after uniform basal application of 15 t ha^{-1} compost and 120:60:45 kg N:P:K ha^{-1}. All cultural, irrigation, weed and pest-management practices were carried out uniformly across treatments as per recommended agronomic standards for the region.

2.4 Observations Recorded

Five tagged plants per plot were used for recording observations on quality parameters and Ascorbic acid, total soluble solids, crude protein content and chlorophyll content were observed.

a) Estimation of Ascorbic acid

Ascorbic acid content (mg 100 g^{-1}) was determined by dye titration using 2,6-dichlorophenol indophenol (AOAC, 1960).

b) Estimation of Total Soluble Solids

Total soluble solids were measured with a digital refractometer and expressed in °Brix.

c) Estimation of Crude protein content

Crude protein content was estimated from nitrogen concentration (colorimetric method) using a conversion factor of 6.25.

d) Estimation of Chlorophyll Content

Chlorophyll content was quantified spectrophotometrically following DMSO extraction using the formula of Arnon (1949).

2.5 Statistical Analysis

Data from both seasons were subjected to analysis of variance (ANOVA) applicable to RCBD as described by Fisher (1950). Treatment means were compared using the critical difference (CD) at 5% and 1% levels where the F-test indicated significance.

3. RESULTS AND DISCUSSION

3.1 Ascorbic Acid

Foliar supplementation of micronutrients exerted a significant ($p < 0.05$) influence on ascorbic acid content in broccoli across both experimental years as well as in the pooled analysis (Table 1). The pooled data (Table 2; Fig. 1) showed that the untreated control consistently recorded the lowest ascorbic acid concentration (80.00 mg 100 g^{-1}), representing the baseline nutritional level in the absence of external micronutrient supply. In contrast, the foliar application of boric acid in combination with copper sulphate (@ 100 ppm each) resulted in the highest pooled ascorbic acid content (86.40 mg 100 g^{-1}), demonstrating its pronounced efficacy in enhancing vitamin C accumulation. This was closely followed by the combination of boric acid with manganese sulphate (86.20 mg 100 g^{-1}) and the sole application of copper sulphate (85.50 mg 100 g^{-1}), both of which also exhibited a statistically significant increase over the control. The remaining micronutrient treatments likewise showed appreciable improvement over the untreated check, indicating a consistent and positive response of broccoli antioxidant quality to micronutrient foliar interventions.

Table 1. Analysis of variance for the effect of foliar spray of micronutrients at different quality traits in Broccoli

S.V.	d.f.	Mean of squares			
		Ascorbic acid	Total Soluble Solid	Crude Protein Content	Chlorophyll content
Replication	2	0.97	0.004	0.01	0.0004
Treatment	13	11.17**	0.64**	0.002	0.13**
Error	26	3.67	0.03	0.01	0.00
SEm±		1.107	0.105	0.046	0.021
CD (at 5%)		3.236	0.307	0.13	0.061
CV (%)		2.301	2.472	2.89	1.958

Table 2. Effect of different micronutrient application on ascorbic acid in broccoli

Treatments	Ascorbic acid (mg/100g)		
	2020-21	2021-22	Pooled
T_0	79.24	80.76	80.00
T_1	83.61	80.39	82.00
T_2	81.17	80.83	81.00
T_3	82.09	83.91	83.00
T_4	82.98	83.82	83.40
T_5	84.47	86.53	85.50
T_6	84.26	84.34	84.30
T_7	85.86	86.54	86.20
T_8	84.69	82.51	83.60
T_9	83.64	81.16	82.40
T_{10}	86.29	86.51	86.40
T_{11}	84.96	83.84	84.40
T_{12}	83.56	82.64	83.10
T_{13}	80.49	81.91	81.20
SEm±	0.936	1.361	1.107
CD (at 5%)	2.888	3.115	3.236

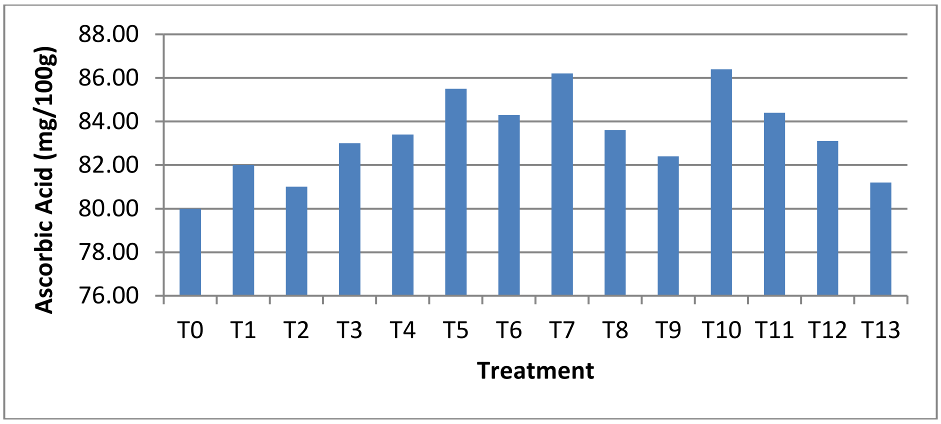

Fig. 1. Graph showing effect of different micronutrient application on ascorbic acid in broccoli

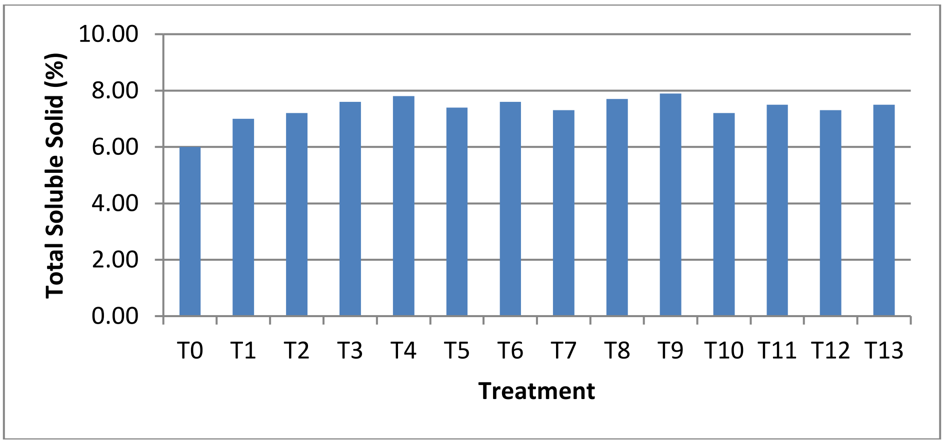

Fig. 2. Graph showing effect of different micronutrient application on total soluble solid in broccoli

3.2 Total Soluble Solids (TSS)

Micronutrient foliar application also produced a significant ($p < 0.05$) response in total soluble solids of broccoli curds during both seasons as well as in the pooled mean (Table 3). As depicted in Table 4 and Fig. 2, the control treatment recorded the lowest pooled TSS value (6.00%), indicating limited sugar accumulation in the absence of micronutrient supplementation. The combined application of boric acid with ammonium molybdate resulted in the highest pooled TSS value (7.90%), reflecting the strongest improvement among all treatments. This superior treatment was followed by the application of ammonium molybdate alone (7.80%) and the combination of boric acid with zinc sulphate (7.70%). Several other micronutrient treatments, including the combinations with manganese, iron and copper, also recorded appreciable increases over the control. The overall trend indicates a clear enhancement of TSS in broccoli in response to foliar micronutrient supply.

3.3 Crude Protein

The effect of foliar micronutrient application on crude protein content in broccoli heads was also statistically significant at $p < 0.05$ (Table 4). As shown in Table 5 and Fig. 3, the lowest pooled protein value was recorded in the control (2.71%), whereas the highest pooled protein content (2.79%) was obtained under the foliar application of copper sulphate alone. This treatment was followed by boric acid combined with zinc sulphate (2.79%, slightly lower in the second year but at par numerically) and boric acid combined with manganese sulphate (2.78%). Most micronutrient treatments outperformed the untreated control, confirming that exogenous micronutrient supply consistently promoted higher crude protein accumulation in broccoli inflorescences under field conditions.

Table 3. Effect of different micronutrient application on Total Soluble Solid in Broccoli

Treatments	Total soluble solid (%)		
	2020-21	**2021-22**	**Pooled**
T_0	5.98	6.02	6.00
T_1	6.93	7.07	7.00
T_2	7.13	7.27	7.20
T_3	7.52	7.68	7.60
T_4	7.92	7.68	7.80
T_5	7.46	7.34	7.40
T_6	7.62	7.58	7.60
T_7	7.20	7.40	7.30
T_8	7.61	7.79	7.70
T_9	7.87	7.93	7.90
T_{10}	7.13	7.28	7.20
T_{11}	7.46	7.54	7.50
T_{12}	7.30	7.30	7.30
T_{13}	7.54	7.46	7.50
SEm±	0.121	0.073	0.105
CD (at 5%)	0.375	0.225	0.307

Table 4. Effect of different micronutrient application on crude protein content in broccoli

Treatments	Crude protein content (%)		
	2020-21	2021-22	Pooled
T_0	2.72	2.70	2.71
T_1	2.74	2.70	2.72
T_2	2.70	2.76	2.73
T_3	2.77	2.75	2.76
T_4	2.76	2.72	2.74
T_5	2.81	2.77	2.79
T_6	2.74	2.78	2.76
T_7	2.76	2.80	2.78
T_8	2.83	2.75	2.79
T_9	2.70	2.76	2.73
T_{10}	2.76	2.72	2.74
T_{11}	2.70	2.76	2.73
T_{12}	2.77	2.73	2.75
T_{13}	2.73	2.77	2.75
SEm±	0.037	0.043	0.046
CD (at 5%)	0.096	0.105	0.13

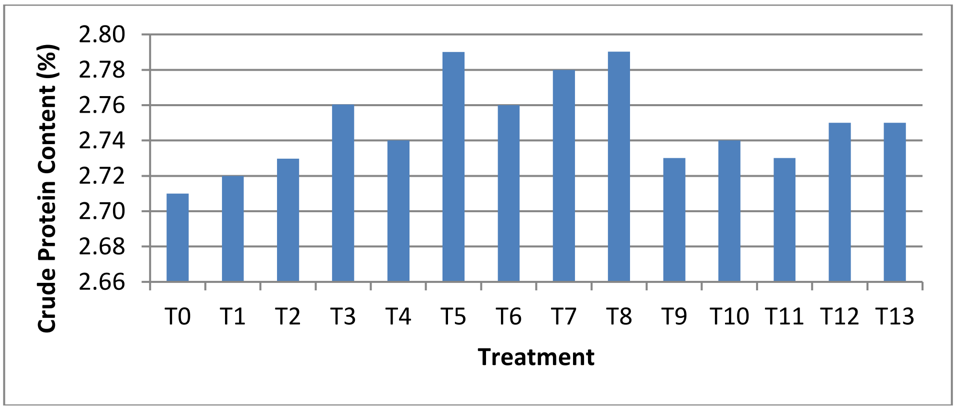

Fig. 3. Graph showing effect of different micronutrient application on crude protein content in broccoli

Table 5. Effect of different micronutrient application on chlorophyll content in broccoli

Treatments	Chlorophyll content (mg/g)		
	2020-21	2021-22	Pooled
T_0	1.58	1.56	1.57
T_1	1.58	1.60	1.59
T_2	1.63	1.61	1.62
T_3	1.65	1.63	1.64
T_4	1.75	1.69	1.72
T_5	1.83	1.81	1.82
T_6	1.86	1.80	1.83
T_7	1.97	1.93	1.95
T_8	1.99	1.95	1.97
T_9	2.09	2.15	2.12
T_{10}	1.98	1.94	1.96
T_{11}	2.17	2.13	2.15
T_{12}	2.14	2.14	2.14
T_{13}	1.80	1.76	1.78
SEm±	0.023	0.026	0.021
CD (at 5%)	0.071	0.081	0.061

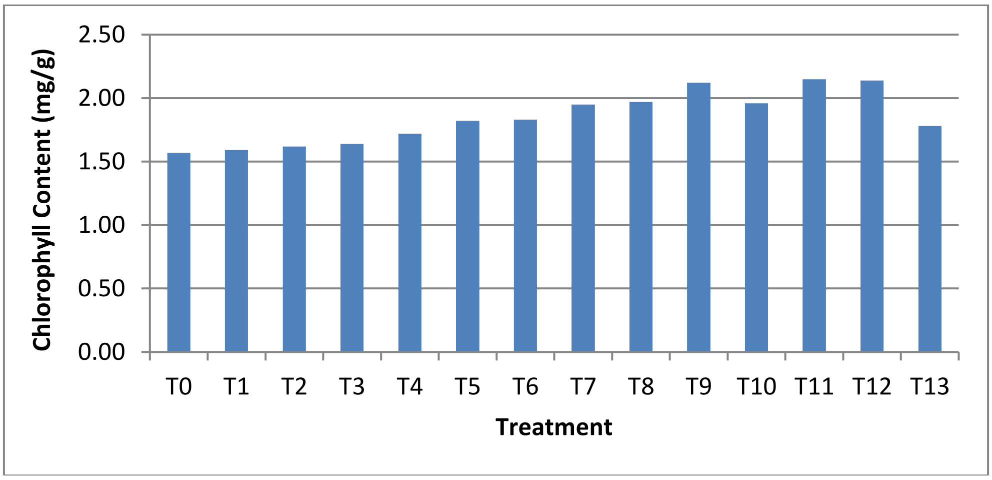

Fig. 4. Graph showing effect of different micronutrient application on chlorophyll content in broccoli

3.4 Chlorophyll Content

Foliar supplementation of micronutrients exerted a marked and statistically significant influence ($p < 0.05$) on total chlorophyll content in broccoli leaves in both seasons and in the pooled analysis (Table 5). According to the pooled means presented in Table 5 and Fig. 4, the minimum chlorophyll content was observed in the untreated control (1.57 mg g^{-1}), whereas the combination of boric acid with ferrous sulphate resulted in the highest pooled chlorophyll concentration (2.15 mg g^{-1}). This treatment was closely followed by the mixed micronutrient formulation (2.14 mg g^{-1}) and the combination of boric acid with ammonium molybdate (2.12 mg g^{-1}). All effective micronutrient treatments exhibited higher chlorophyll values compared to the control, indicating a consistent improvement in the photosynthetic pigment profile of broccoli leaves in response to foliar micronutrient nutrition.

The results of the present investigation clearly indicated that foliar application of micronutrients exerted a pronounced influence on the biochemical quality of broccoli. A marked increase in ascorbic acid content was observed in plants receiving a combined foliar application of boric acid and copper sulphate compared with the untreated control. Comparable enhancement of ascorbic acid content in broccoli and other cole crops following micronutrient supplementation has been reported earlier, where zinc, boron, and copper were shown to stimulate antioxidant metabolism and ascorbate biosynthesis through improved redox regulation and enzymatic activation (Singh et al., 2018; Souri & Hatamian, 2019). This response may be attributed to improved availability of micronutrients as enzymatic cofactors involved in oxidative metabolism and carbohydrate turnover under optimal nutritional status, as extensively documented in mineral nutrition literature (Marschner, 2012; Souri & Hatamian, 2019). Total soluble solids increased significantly when boric acid was combined with ammonium molybdate at the foliar level. Similar improvements in soluble solids have been reported in Brassica vegetables following foliar micronutrient application, where enhanced carbohydrate synthesis, phloem loading, and assimilate partitioning were observed (Fernández & Brown, 2013; Singh et al., 2018). Increased TSS under micronutrient nutrition aligns with the physiological roles of boron and molybdenum in sugar translocation, nitrate reduction, and metabolic efficiency (Marschner, 2012; Kaiser et al., 2015) Crude protein content was highest in broccoli heads treated with copper sulphate alone. Copper is known to function as a catalytic or structural component of enzymes involved in nitrogen metabolism, including amine oxidases and nitrate reductase (Marschner, 2012). Previous studies in Brassica crops have similarly demonstrated that copper-based foliar sprays enhance nitrogen assimilation and protein accumulation in edible tissues (Ali et al., 2014; Singh et al., 2018). The present findings are consistent with these reports.

Leaf chlorophyll content reached its maximum under the combined application of boric acid and ferrous sulphate. Iron plays a critical role in chlorophyll biosynthesis and photosynthetic electron transport, while boron contributes to membrane integrity and nutrient translocation (Fernández & Brown, 2013; Kaiser et al., 2015). Enhanced chlorophyll concentration under micronutrient supplementation has been repeatedly documented in broccoli and other Brassica vegetables (Dosz & Jeffery, 2013). Taken together, the differential responses of ascorbic acid, total soluble solids, crude protein, and chlorophyll to various micronutrient combinations underscore the functional importance of targeted foliar nutrition in modulating the biochemical quality of broccoli. The present results are in close agreement with established literature demonstrating that trait-specific biochemical enrichment in broccoli can be effectively achieved through strategic foliar micronutrient management under field conditions.

5. CONCLUSION

The findings of the present investigation demonstrate that foliar application of micronutrients is an effective strategy for improving the biochemical quality of broccoli (*Brassica oleracea* L. var. *italica*) under field conditions. Significant enhancement in ascorbic acid content was achieved with the combined application of boric acid and copper sulphate, whereas the highest total soluble solids were recorded under combined application of boric acid and ammonium molybdate. Copper sulphate alone produced the maximum crude protein content, and the combined application of boric acid and ferrous sulphate resulted in the highest chlorophyll concentration.

These results confirm that specific micronutrient combinations act on distinct biochemical pathways, resulting in targeted improvement of nutritional attributes. The overall pattern indicates that foliar supplementation enables rapid nutrient assimilation, metabolic activation, and quality enhancement compared to the untreated control. The study establishes that precise formulation and timing of foliar micronutrient application can serve as a practical and agronomically viable method to enhance the functional food value of broccoli without altering the production system.

The results provide a scientific basis for recommending foliar micronutrient strategies for quality enrichment of broccoli, and they support further integration of micronutrient foliar feeding into sustainable nutrient management programs for high-value vegetable crops.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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