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Biofortification through foliar micronutrient application affects yield, nutritional quality and economic returns in cabbage (*Brassica oleracea* var. *capitata* L.)

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ABSTRACT

Cabbage though nutritionally rich, often lacks adequate micronutrient enrichment under conventional cultivation. A field experiment conducted during rabi 2020 and 2021 at the College of Horticulture, Bidar (UHS Bagalkot), evaluated foliar application of $ZnSO_4$, $FeSO_4$, $MgSO_4$ and calcium nitrate under a Randomized Complete Block Design (11 treatments, 3 replications). Micronutrients were applied individually and in combinations at 30, 45 and 60 days after transplanting along with recommended fertilizers. Results showed significant improvements in growth, yield, quality and economic returns. The combined application of $ZnSO_4$ + $FeSO_4$ + $MgSO_4$ + calcium nitrate at lower concentrations (T_9) recorded the highest head yield (32.41 t ha^{-1}), vitamin C (35.17 mg 100 g^{-1}), protein (5.57%) and net returns (₹1.27 lakh ha^{-1}). Among individual treatments, $FeSO_4$ at 1% (T_6) produced superior yield (27.13 t ha^{-1}). The study confirms that foliar-based agronomic biofortification effectively enhances productivity, nutritional quality and profitability of cabbage.

Key words: Cabbage, micronutrients, foliar nutrition, agronomic biofortification, yield, quality, economics.

INTRODUCTION

Micronutrient malnutrition, widely known as "hidden hunger," continues to be a serious public health concern worldwide. Recent estimates indicate that more than two billion people suffer from deficiencies of essential micronutrients such as iron, zinc, calcium, iodine, and vitamin A, particularly in low- and middle-income countries where diets are dominated by staple cereals and lack dietary diversity, (FAO, 8). In India, micronutrient deficiencies remain widespread, especially among women and children, with inadequate intake of iron, zinc, and calcium being major nutritional constraints. Strengthening the nutrient density of commonly consumed vegetables is therefore an important pathway for improving food and nutritional security.

Cabbage (*Brassica oleracea* var. *capitata* L.) is one of the most important cole vegetable crops cultivated globally due to its adaptability, high productivity, storability, and consumer preference. Globally, cabbage and other brassicas are grown on about 2.6 million hectares with an annual production exceeding 71 million tonnes (FAO, 9). India is among the leading producers of cabbage, cultivating approximately 0.41 million hectares with a production of about 9.6 million tonnes annually (NHB, 13). The crop is valued nutritionally for its vitamin C, provitamin A compounds, dietary fibre, minerals, and antioxidant phytochemicals, making it an ideal candidate for nutritional enhancement (Wang *et al*., 21). Despite its importance, cabbage cultivation is often managed with primary emphasis on nitrogen, phosphorus, and potassium fertilizers, while secondary and micronutrient nutrition receives comparatively less attention. Continuous cropping, imbalanced fertilizer use, and declining soil fertility have increased deficiencies of zinc, iron, calcium, and magnesium in many vegetable-growing soils, resulting not only in reduced productivity but also lower nutrient concentration in edible produce (Sharma *et al*., 18). This limits the potential of vegetables to address micronutrient deficiencies through regular diets.

Biofortification, defined as the process of increasing nutrient concentration in edible portions of crops, has emerged as an effective strategy to combat hidden hunger. Biofortification can be achieved through plant breeding, transgenic approaches, or agronomic interventions. Among these, agronomic biofortification through fertilizer management is considered the most immediate and field-applicable option for short-duration vegetable crops (Cakmak and Kutman, 5). Foliar application is especially effective because nutrients are delivered directly to plant leaves, minimizing soil fixation losses and improving nutrient use efficiency. Several studies

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have reported positive effects of foliar-applied zinc, iron, calcium, and magnesium on crop growth, yield, and quality in vegetable crops (Das *et al*., 6; Sood *et al*., 20; Ahmed and Zhang, 1).

Zinc is essential for auxin synthesis, enzyme activation, and carbohydrate metabolism; iron is involved in chlorophyll synthesis and electron transport; magnesium is the central atom of chlorophyll and regulates photosynthesis and assimilate movement; while calcium contributes to membrane stability, cell wall formation, and stress tolerance. Their balanced supply may therefore enhance growth, head formation, yield, and nutritional quality of cabbage. However, most previous studies have focused on individual micronutrients, and information on the combined use of Zn, Fe, Mg, and Ca for simultaneous improvement of productivity, nutrient enrichment, and profitability in cabbage under field conditions is limited. Considering this research gap, the present investigation was undertaken to evaluate the effect of foliar application of zinc, iron, magnesium, and calcium, applied individually and in combinations, on growth, yield, quality, nutrient enrichment, and economics of cabbage under irrigated conditions of Bidar, Karnataka. The study aims to generate scientific evidence on agronomic biofortification as a practical strategy for improving cabbage productivity, nutritional quality, and farmer returns.

MATERIALS AND METHODS

The field investigation was carried out during two consecutive *Rabi* seasons of 2020 and 2021 at the College of Horticulture, Bidar, University of Horticultural Sciences, Bagalkot, Karnataka, India. The experimental site is situated at 17°55′ N latitude, 77°32′ E longitude, with an altitude of 615 m above mean sea level, representing the Northeastern Transition Zone of Karnataka. The climate of the region is semi-arid tropical, with hot summers, moderate monsoon rainfall, and mild winters. Prior to transplanting, composite soil samples were collected from a depth of 0-15 cm, air-dried, sieved, and analyzed for physico-chemical properties using standard procedures (Jackson, 11; Piper, 14). The soil was lateritic red, sandy loam in texture, slightly acidic to neutral in reaction, with The soil of the experimental site at Bidar was low to medium in organic carbon (0.42%), available nitrogen (268 kg ha^{-1}), medium in available phosphorus (32.6 kg ha^{-1}) and potassium (285 kg ha^{-1}), and marginally deficient in available zinc (0.54 mg kg^{-1}), iron (4.21 mg kg^{-1}), calcium (1.18 cmol(p^+) kg^{-1}), and magnesium (0.62 cmol(p^+) kg^{-1}) thereby justifying the experimental objectives. The experiment was laid out in a Randomized Complete Block Design (RCBD) consisting of 11 treatments with three replications. The plot size was 4.0 × 3.0 m, accommodating 40 plants at a spacing of 60 × 45 cm. Treatments comprised foliar applications of zinc sulphate, ferrous sulphate, magnesium sulphate, and calcium either singly or in combinations at different concentrations, applied thrice at 30, 45, and 60 days after transplanting (DAT). The treatment structure included: T_1 - foliar application of zinc sulphate @ 1%; T_2 - ferrous sulphate @ 0.5%; T_3 - magnesium sulphate @ 1%; T_4 - calcium @ 0.5%; T_5 -zinc sulphate @ 1.5%; T_6 - ferrous sulphate @ 1%; T_7 - magnesium sulphate @ 1.5%; T_8 - calcium nitrate @ 1%; T_9 - combination of T_1 + T_2 + T_3 + T_4; T_{10} - combination of T_5 + T_6 + T_7 + T_8; and T_{11} - control (RDF only). A uniform Recommended Dose of Fertilizers (125:75:75 kg $N:P_2O_5:K_2O$ ha^{-1}) was applied across all treatments using urea, single superphosphate, and muriate of potash. Half of the nitrogen and the entire phosphorus and potassium were applied as basal dose at transplanting, while the remaining nitrogen was top-dressed in two equal splits at 30 and 45 DAT.

Seedlings of cabbage *cv*. Golden Acre were raised in a nursery and transplanted 30 days after sowing. Standard agronomic and crop protection measures were followed uniformly across treatments to ensure optimal crop growth. Irrigation was provided at regular intervals under irrigated conditions. Foliar sprays were applied using a knapsack sprayer fitted with a fine nozzle to ensure uniform coverage of the foliage. A spray volume of approximately 500 L ha^{-1} was used for each application. To improve spreading and absorption, a non-ionic surfactant (sticker) was added at 0.5 mL L^{-1} of spray solution. In the control plots, water sprays were applied at the same intervals to nullify the effect of spraying. Data were recorded on growth and yield attributes including core length, average head weight, head yield per plot, and yield per hectare (Table 1). Physiological parameters such as harvest index, dry matter content, and head compactness were measured at harvest. Quality traits including vitamin A, vitamin C, protein, and calcium content were analyzed using standard biochemical procedures, while mineral content (Mg, Fe, Zn, and Ca) was determined by atomic absorption spectrophotometry after wet digestion of plant tissue. Chlorophyll content was estimated by Arnon's (3) method. Economic analysis was carried out by calculating cost of cultivation, gross returns, net returns, and benefit-cost ratio based on prevailing market prices of cabbage (₹ 5.5 kg^{-1} in 2020 and ₹ 6.5 kg^{-1} in 2021). The experimental data were subjected to statistical analysis of variance (ANOVA) as per Gomez and Gomez (10) for RCBD, following standard biometrical procedures described by Sharma (17). Data from the two years were analyzed separately and

Table 1: Core length plant^{-1}, average head weight plant^{-1}, head yield plot^{-1} and head yield ha^{-1} as influenced by agronomic biofortification with micronutrients in cabbage.

Treatment	Core length (cm) plant^{-1}			Average head weight (kg plant^{-1})			Head yield plot^{-1} (kg)			Head yield ha^{-1} (t)		
	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled
T_1	4.16	4.22	4.19	1.10	1.12	1.11	21.61	22.27	21.94	25.01	25.77	25.39
T_2	4.13	4.19	4.16	1.11	1.13	1.12	22.57	23.24	22.91	26.13	26.90	26.52
T_3	4.21	4.27	4.24	1.15	1.17	1.16	21.81	22.45	22.13	25.24	25.99	25.61
T_4	4.16	4.21	4.18	1.09	1.11	1.10	21.44	22.08	21.76	24.82	25.55	25.19
T_5	4.19	4.25	4.22	1.13	1.15	1.14	22.28	22.95	22.62	25.79	26.57	26.18
T_6	4.13	4.18	4.15	1.18	1.20	1.19	23.10	23.79	23.44	26.74	27.53	27.13
T_7	4.24	4.30	4.27	1.16	1.18	1.17	22.60	23.27	22.93	26.15	26.93	26.54
T_8	4.15	4.21	4.18	1.12	1.14	1.13	21.89	22.53	22.21	25.33	26.08	25.71
T_9	3.99	4.04	4.02	1.33	1.36	1.34	27.58	28.42	28.00	31.92	32.90	32.41
T_{10}	4.14	4.20	4.17	1.19	1.21	1.20	23.93	24.64	24.29	27.69	28.52	28.11
T_{11}	4.60	4.66	4.63	1.09	1.10	1.10	19.34	19.91	19.63	22.39	23.04	22.71
Mean	4.19	4.25	4.22	1.15	1.17	1.16	22.56	23.23	22.90	26.11	26.89	26.50
S.Em.±	0.15	0.15	0.15	0.05	0.05	0.04	1.04	1.12	1.07	1.20	1.29	1.24
C.D. at 5%	0.44	0.45	0.44	0.14	0.14	0.14	3.06	3.30	3.17	3.54	3.82	3.67

T_1	:	Foliar application of zinc sulphate @ 1 per cent	T_7	:	Foliar application of magnesium sulphate @ 1.5 per cent
T_2	:	Foliar application of ferrous sulphate @ 0.5 per cent	T_8	:	Foliar application of calcium @ 1 per cent
T_3	:	Foliar application of magnesium sulphate @ 1 per cent	T_9	:	$T_1 + T_2 + T_3 + T_4$
T_4	:	Foliar application of calcium @ 0.5 per cent	T_{10}	:	$T_5 + T_6 + T_7 + T_8$
T_5	:	Foliar application of zinc sulphate @ 1.5 per cent	T_{11}	:	Control
T_6	:	Foliar application of ferrous sulphate @ 1 per cent			

also subjected to pooled analysis to assess treatment effects across seasons. In the pooled analysis, the effects of year, treatment, and year × treatment interaction were tested using appropriate analysis of variance. Since the year × treatment interaction was found to be non-significant for most parameters, pooled treatment means are presented and discussed. Significance of differences among treatment means was tested at 5 per cent and 1 per cent probability levels, and standard error of mean (S.Em.±) was computed to assess precision. Statistical analysis was performed using OPSTAT software.

RESULTS AND DISCUSSION

The pooled results across two *Rabi* seasons clearly demonstrated that foliar application of micronutrients, either individually or in combination, significantly influenced cabbage performance in terms of growth, yield, physiological efficiency, nutritional quality, mineral enrichment, chlorophyll content, and economic returns.

Cabbage growth and yield traits showed remarkable improvement with micronutrient sprays. The shortest core length (4.02 cm) was recorded with the combined treatment T_9 ($ZnSO_4$ 1% + $FeSO_4$ 0.5% + $MgSO_4$ 1% + calcium nitrate 0.5%), while the control exhibited the longest core (4.63 cm), indicating inferior head quality. Reduction in core length under micronutrient supplementation is advantageous as it enhances the proportion of edible biomass and market acceptability. Average head weight followed a similar trend, with T_9 producing the heaviest heads (1.34 kg plant^{-1}), followed by T_{10} (1.20 kg) and $FeSO_4$ @ 1% (T_6: 1.19 kg). The control produced the lightest heads (1.10 kg), underscoring the necessity of micronutrient supplementation. This translated into higher yields, with T_9 recording 32.41 t ha^{-1}, which was 43% higher than the control (22.71 t ha^{-1}). Among individual sprays, $FeSO_4$ @ 1% (T_6) achieved the highest yield (27.13 t ha^{-1}) (Table 1), confirming the pivotal role of iron in chlorophyll synthesis and assimilate partitioning. The superiority of T_9 across yield traits suggests a possible synergistic effect of multiple micronutrients in improving sink strength and assimilate translocation. Although these mechanisms were not directly measured in the present study, the response can be explained by the well-established physiological roles of these nutrients. Zinc is involved in auxin synthesis, enzyme activation, and carbohydrate metabolism; iron plays a central role in chlorophyll biosynthesis, respiration, and electron transport; magnesium is the core constituent of chlorophyll and is essential for photosynthesis and phloem loading of assimilates; while calcium contributes to cell division, membrane stability, and movement of metabolites within plant tissues. Their combined supply therefore likely enhanced photosynthetic efficiency, carbohydrate partitioning, and head development, resulting in higher yield (Jacob *et al*., 12; Sood *et al*., 20). Similar positive effects of micronutrient mixtures and foliar nutrient enrichment on cabbage and other vegetable crops have also been reported by Salehi-Arjmand *et al*. (16) and Anim *et al*. (2).

Physiological indices also reflected the positive influence of foliar-applied micronutrients. The harvest index, which indicates partitioning efficiency, was maximum in T_9 (0.68), followed by T_{10} (0.66), while the lowest was recorded in the control (0.50). Similarly, dry matter accumulation was highest in T_9 (45.87 g plant^{-1}) compared to only 29.63 g plant^{-1} in the control. Head compactness, a vital quality trait, was also improved significantly under T_9 (29.35) compared with the control (23.17). These enhancements can be attributed to improved photosynthetic efficiency, balanced nutrient supply, and stronger sink development (Table 2). Magnesium and iron, in particular, contributed to higher dry matter through their roles in chlorophyll biosynthesis and enzyme activation. The improved compactness indicates denser heads with higher storability and consumer preference, aligning with previous studies in cauliflower and broccoli (Dwivedi *et al*., 7).

Nutritional quality of cabbage was substantially enriched by micronutrient sprays. T_9 recorded the highest vitamin A content (7.29 µg 100 g^{-1}), vitamin

Table 2: Harvest index, dry matter content and head compactness as influenced by agronomic biofortification with micronutrients in cabbage.

Treatment	Harvest index			Dry matter content (g) plant^{-1}			Head compactness		
	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled
T_1	0.53	0.54	0.54	33.33	34.42	33.88	23.41	23.96	23.69
T_2	0.56	0.57	0.57	34.41	35.57	34.99	23.54	24.08	23.81
T_3	0.55	0.56	0.56	33.33	34.47	33.90	24.91	25.49	25.20
T_4	0.51	0.51	0.51	34.75	35.93	35.34	23.05	23.59	23.32
T_5	0.55	0.55	0.55	34.33	35.45	34.89	23.88	24.43	24.16
T_6	0.58	0.59	0.58	35.06	36.24	35.65	24.31	24.88	24.60
T_7	0.58	0.58	0.58	34.50	35.68	35.09	24.98	25.56	25.27
T_8	0.54	0.54	0.54	34.85	36.14	35.50	23.56	24.11	23.84
T_9	0.67	0.68	0.68	45.12	46.63	45.87	29.04	29.67	29.35
T_{10}	0.65	0.66	0.66	35.66	36.87	36.26	26.17	26.79	26.48
T_{11}	0.49	0.50	0.50	29.11	30.15	29.63	22.91	23.43	23.17
Mean	0.56	0.57	0.57	34.95	36.14	35.55	24.52	25.09	24.81
S.Em.±	0.03	0.03	0.03	1.52	1.76	1.62	0.95	0.96	0.96
C.D. at 5%	0.10	0.10	0.10	4.48	5.20	4.79	2.81	2.84	2.82

T_1	:	Foliar application of zinc sulphate @ 1 per cent	T_7	:	Foliar application of magnesium sulphate @ 1.5 per cent
T_2	:	Foliar application of ferrous sulphate @ 0.5 per cent	T_8	:	Foliar application of calcium @ 1 per cent
T_3	:	Foliar application of magnesium sulphate @ 1 per cent	T_9	:	$T_1 + T_2 + T_3 + T_4$
T_4	:	Foliar application of calcium @ 0.5 per cent	T_{10}	:	$T_5 + T_6 + T_7 + T_8$
T_5	:	Foliar application of zinc sulphate @ 1.5 per cent	T_{11}	:	Control
T_6	:	Foliar application of ferrous sulphate @ 1 per cent			

C (35.17 mg 100 g^{-1}), protein (5.57%), and calcium (1.76%), compared with only 4.08 µg, 27.95 mg, 2.99%, and 1.26%, respectively, in the control (Table 3). T_{10} also performed significantly better than individual sprays, while among single nutrients, calcium sprays (T_8) enriched tissue Ca, and Fe sprays (T_6) contributed to higher vitamin C and protein content. The enhanced vitamin and protein levels observed under micronutrient supplementation may be associated with improved metabolic activity and better nutrient utilization. However, since enzymatic activity, oxidative metabolism, and related biochemical pathways were not directly measured in the present study, these explanations should be considered as probable interpretations rather than confirmed mechanisms. Micronutrients are widely recognized for their role as cofactors in enzymatic reactions, photosynthesis, protein synthesis, and antioxidant metabolism, which can indirectly influence the accumulation of quality constituents in vegetables (Ahmed and Zhang, 1; Behera *et al*., 4). Similar improvements in nutritional quality following micronutrient enrichment have also been reported in biofortification studies of horticultural crops (Rehman *et al*., 15). Further investigations involving enzyme assays and detailed biochemical analyses are needed to validate the exact mechanisms responsible for increased vitamin and protein content.

Mineral accumulation and chlorophyll content were also significantly improved by foliar feeding. T_9 exhibited the highest magnesium (1.00%), iron (688 ppm), and zinc (58.96 ppm) content, as well as chlorophyll concentration (82.09 mg 100 g^{-1}). For micronutrient estimation, samples were analyzed using Atomic Absorption Spectrophotometry (AAS) after wet digestion following standard analytical procedures. The instrument was calibrated using certified standard solutions for each element, and quality control was maintained through reagent blanks, duplicate samples, and periodic recalibration during analysis. Where available, standard reference materials were used to verify analytical accuracy and precision. Among individual sprays, $FeSO_4$ @ 1% (T_6) enhanced iron accumulation (545 ppm), Ca

Table 3: Vitamin-A, vitamin-C, protein and calcium content as influenced by agronomic biofortification with micronutrients in cabbage.

Treatment	Vitamin-A (µg/100 g)			Vitamin-C (mg/100 g)			Protein content (%)			Calcium (%)		
	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled
T_1	6.96	6.98	6.97	30.40	30.81	30.60	4.24	4.27	4.26	1.48	1.50	1.49
T_2	6.60	6.63	6.61	31.21	31.63	31.42	3.84	3.86	3.85	1.58	1.60	1.59
T_3	6.97	6.99	6.98	31.11	31.52	31.32	3.94	3.97	3.95	1.59	1.61	1.60
T_4	6.63	6.66	6.64	31.61	32.03	31.82	4.55	4.58	4.56	1.71	1.73	1.72
T_5	6.90	6.92	6.91	32.42	32.85	32.64	4.34	4.37	4.36	1.45	1.49	1.47
T_6	7.04	7.06	7.05	32.93	33.37	33.15	3.99	4.02	4.00	1.59	1.61	1.60
T_7	7.15	7.17	7.16	31.82	32.24	32.03	4.00	4.03	4.01	1.68	1.70	1.69
T_8	6.67	6.70	6.69	31.92	32.34	32.13	4.65	4.68	4.66	1.74	1.76	1.75
T_9	7.27	7.30	7.29	34.94	35.40	35.17	5.56	5.59	5.57	1.75	1.77	1.76
T_{10}	7.26	7.28	7.27	34.57	35.03	34.80	5.35	5.39	5.37	1.79	1.82	1.80
T_{11}	4.08	4.09	4.08	27.50	28.39	27.95	2.98	3.00	2.99	1.25	1.27	1.26
Mean	6.68	6.77	6.70	31.86	32.33	32.09	4.31	4.34	4.33	1.60	1.62	1.61
S.Em.±	0.13	0.13	0.13	0.55	0.57	0.56	0.09	0.10	0.09	0.02	0.02	0.02
C.D. at 1%	0.37	0.38	0.37	2.23	2.29	2.25	0.37	0.39	0.38	0.06	0.06	0.06

T_1 : Foliar application of zinc sulphate @ 1 per cent
T_2 : Foliar application of ferrous sulphate @ 0.5 per cent
T_3 : Foliar application of magnesium sulphate @ 1 per cent
T_4 : Foliar application of calcium @ 0.5 per cent
T_5 : Foliar application of zinc sulphate @ 1.5 per cent
T_6 : Foliar application of ferrous sulphate @ 1 per cent
T_7 : Foliar application of magnesium sulphate @ 1.5 per cent
T_8 : Foliar application of calcium @ 1 per cent
T_9 : $T_1 + T_2 + T_3 + T_4$
T_{10} : $T_5 + T_6 + T_7 + T_8$
T_{11} : Control

sprays (T_8) improved Ca (1.75%), and Mg sprays (T_7) enriched Mg (0.94%). The increased chlorophyll under Fe and Mg treatments substantiates their vital roles in chlorophyll biosynthesis and stability, while Zn contributed indirectly by promoting auxin metabolism and leaf expansion. The synergistic improvement under T_9 indicates that balanced micronutrient application not only boosts yield but also ensures nutritional biofortification of cabbage (Table 4).

Economic analysis further validated the superiority of combined micronutrient application. The highest gross returns (₹ 1.95 lakh ha^{-1}), net returns (₹ 1.27 lakh ha^{-1}), and benefit cost ratio (2.88) were achieved under T_9, followed by T_6 and T_2. In contrast, the control yielded the lowest net returns (₹ 77,821 ha^{-1}) with a BC ratio of 2.33 (Table 5). The improved profitability under T_9 was due to higher yields coupled with better-quality produce, which fetched premium prices. These results are in agreement with Singh *et al*. (19), who reported enhanced profitability in broccoli with foliar application of Fe and Zn. Taken together, the superior performance of T9 across the studied parameters indicates that balanced supplementation of Zn, Fe, Mg, and Ca was more effective than individual nutrient application. The combined treatment likely improved physiological efficiency, nutrient utilization, and metabolic activity, resulting in better growth, higher yield, enhanced quality, and greater nutrient accumulation. This response highlights the advantage of integrated micronutrient management over single-nutrient approaches in cabbage cultivation. Zinc enhanced auxin metabolism and enzyme regulation, iron facilitated chlorophyll biosynthesis and respiration, magnesium improved photosynthesis and carbon fixation, while calcium contributed to cell wall integrity and stress resistance. When applied together, these nutrients acted synergistically to maximize photosynthetic efficiency, assimilate partitioning, nutritional quality, and economic returns. The findings confirm that agronomic biofortification through foliar sprays of multiple micronutrients is a practical, cost-effective, and field-ready strategy to address

Table 4: Magnesium, iron, zinc, and chlorophyll content as influenced by agronomic biofortification with micronutrients in cabbage.

Treatment	Magnesium (%)			Iron (ppm)			Zinc (ppm)			Chlorophyll (mg/100 g)		
	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled
T_1	0.73	0.74	0.74	430.19	438.67	434.43	56.12	56.12	56.12	63.00	64.04	63.52
T_2	0.67	0.68	0.67	526.12	536.57	531.34	24.42	24.44	24.43	70.85	72.02	71.43
T_3	0.91	0.93	0.92	412.79	421.00	416.89	22.27	22.27	22.27	72.78	73.98	73.38
T_4	0.70	0.71	0.71	316.20	322.48	319.34	26.74	26.74	26.74	53.57	54.46	54.01
T_5	0.76	0.77	0.77	455.69	464.74	460.21	57.44	57.48	57.46	64.71	65.77	65.24
T_6	0.72	0.73	0.73	539.78	550.51	545.15	26.43	26.43	26.43	71.64	72.83	72.24
T_7	0.94	0.95	0.94	434.07	442.70	438.38	22.94	22.94	22.94	74.05	75.27	74.66
T_8	0.74	0.75	0.75	342.29	349.00	345.65	28.21	28.21	28.21	54.49	55.39	54.94
T_9	0.98	1.01	1.00	681.36	694.90	688.13	58.95	58.98	58.96	81.42	82.76	82.09
T_{10}	0.97	0.99	0.98	653.00	665.91	659.45	58.14	58.24	58.19	72.20	73.42	72.81
T_{11}	0.48	0.49	0.48	261.53	266.72	264.13	20.55	20.57	20.56	50.69	51.50	51.10
Mean	0.78	0.79	0.79	459.37	468.47	463.92	36.56	36.57	36.57	66.31	67.40	66.86
S.Em.±	0.01	0.01	0.01	6.12	6.13	6.11	0.63	0.64	0.63	1.25	1.30	1.27
C.D. at 1%	0.05	0.05	0.05	24.63	24.65	24.59	2.55	2.56	2.55	5.02	5.22	5.12

T_1	:	Foliar application of zinc sulphate @ 1 per cent	T_7	:	Foliar application of magnesium sulphate @ 1.5 per cent
T_2	:	Foliar application of ferrous sulphate @ 0.5 per cent	T_8	:	Foliar application of calcium @ 1 per cent
T_3	:	Foliar application of magnesium sulphate @ 1 per cent	T_9	:	$T_1 + T_2 + T_3 + T_4$
T_4	:	Foliar application of calcium @ 0.5 per cent	T_{10}	:	$T_5 + T_6 + T_7 + T_8$
T_5	:	Foliar application of zinc sulphate @ 1.5 per cent	T_{11}	:	Control
T_6	:	Foliar application of ferrous sulphate @ 1 per cent			

Table 5: Cabbage yield cost of cultivation, gross returns, net returns and BC ratio as influenced agronomic biofortification with micronutrients.

Treat-ment	Cabbage yield (t ha^{-1})			Cost of cultivation (₹ ha^{-1})			Gross returns (₹ ha^{-1})			Net returns (₹ ha^{-1})			BC ratio		
	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled
T_1	25.01	25.77	25.39	60821	61921	61371	137567	167525	152546	76747	105605	91176	2.26	2.71	2.48
T_2	26.13	26.90	26.52	60847	61947	61397	143702	174868	159285	82856	112921	97888	2.36	2.82	2.59
T_3	25.24	25.99	25.61	60183	61283	60733	138814	168917	153866	78631	107634	93133	2.31	2.76	2.53
T_4	24.82	25.55	25.19	59396	60496	59946	136504	166105	151305	77109	105610	91359	2.30	2.75	2.52
T_5	25.79	26.57	26.18	62189	63289	62739	141821	172686	157254	79632	109397	94514	2.28	2.73	2.50
T_6	26.74	27.53	27.13	59658	60758	60208	147055	178950	163002	87397	118192	102794	2.46	2.95	2.71
T_7	26.15	26.93	26.54	61233	62333	61783	143849	175047	159448	82616	112714	97665	2.35	2.81	2.58
T_8	25.33	26.08	25.71	60708	61808	61258	139332	169505	154418	78624	107697	93160	2.30	2.74	2.52
T_9	31.92	32.90	32.41	66997	68097	67547	175585	213820	194702	108588	145723	127155	2.62	3.14	2.88
T_{10}	27.69	28.52	28.11	69539	70639	70089	152304	185407	168856	82765	114768	98766	2.19	2.62	2.41
T_{11}	22.39	23.04	22.71	58083	59183	58633	123119	149788	136454	65036	90605	77821	2.12	2.53	2.33
Mean	26.11	26.89	26.50	-	-	-	-	-	-	-	-	-	2.32	2.78	2.55
S.Em.±	1.20	1.29	1.24	-	-	-	-	-	-	-	-	-	0.10	0.13	0.12
C.D. at 5%	3.54	3.82	3.67	-	-	-	-	-	-	-	-	-	0.30	0.38	0.34

Price of cabbage: ₹ 5.5 kg^{-1} (2020) and ₹ 6.5 kg^{-1} (2021).

T_1	:	Foliar application of zinc sulphate @ 1 per cent	T_7	:	Foliar application of magnesium sulphate @ 1.5 per cent
T_2	:	Foliar application of ferrous sulphate @ 0.5 per cent	T_8	:	Foliar application of calcium @ 1 per cent
T_3	:	Foliar application of magnesium sulphate @ 1 per cent	T_9	:	$T_1 + T_2 + T_3 + T_4$
T_4	:	Foliar application of calcium @ 0.5 per cent	T_{10}	:	$T_5 + T_6 + T_7 + T_8$
T_5	:	Foliar application of zinc sulphate @ 1.5 per cent	T_{11}	:	Control
T_6	:	Foliar application of ferrous sulphate @ 1 per cent			

both yield enhancement and nutritional enrichment in cabbage.

The present investigation demonstrated that foliar application of micronutrients significantly improved growth, yield, physiological traits, nutritional quality, mineral enrichment, and economic returns in cabbage. Among the treatments, the combined application of $ZnSO_4$, $FeSO_4$, $MgSO_4$, and calcium nitrate at lower concentrations (T_9) consistently performed best, indicating the advantage of balanced multi-micronutrient supplementation over individual nutrient sprays. This treatment enhanced head development, yield, quality attributes, vitamin and mineral content, chlorophyll concentration, and profitability. Among the single nutrient treatments, $FeSO_4$ @ 1% was the most effective, highlighting the important role of iron in cabbage productivity. Overall, the findings suggest that agronomic biofortification through foliar application of multiple micronutrients is a practical and cost-effective approach for improving cabbage productivity, nutritional quality, and farmer returns. The improved nutrient composition of cabbage may also contribute to better dietary micronutrient intake when included as part of a diversified diet.

AUTHOR'S CONTRIBUTION

Conceptualization of research (ISJ); Designing of the experiments (RSJ); Contribution of experimental materials (HCN); Execution of experiments and data collection (PAG); Analysis of data and interpretation (HCN, PAG); Preparation of manuscript and literature review (ISJ, RSJ); Supervision and critical review (PAG).

DECLARATION

The authors declare no competing interests.

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