The Future of Horticulture

Article

Integrated Effects of Soil Sulfur and Foliar Calcium, Boron, and Sorbitol Application on Growth, Yield, and Quality of Broccoli

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https://doi.org/10.37229/fsa.fjh.2026.08.24

Future Science Association

Available online free at www.futurejournals.org

Print ISSN: 2692-5826

Online ISSN: 2692-5834

Received: 7 June 2026
Accepted: 25 July 2026
Published: 24 August 2026

Publisher's Note: FA stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Abstract: With the aim of manipulating metabolism for increasing yield and bioactive compounds in broccoli, this investigation was carried out during the two winter seasons of 2021/2022 and 2022/2023 at Shabrawish Village, Aga, Dakahila Governorate to study the effect of sulfur addition to the soil in combination with foliar spraying with calcium, boron and sorbitol, either singly or in combination, on growth, yield and bioactive compounds attributes of broccoli. The experiment was laid out as a split-plot design in a randomized complete block with three replicates. Sulfur (S) was added at the rate of 100 kg/ fed in main plots whereas sub-plots were assigned to foliar spraying treatments comprising, chelated calcium (Ca) at 0.5 %, boron (B) at 100 ppm, and sorbitol (SOB) at 0.5%, as well as their combinations. Results revealed that S soil addition, foliar spraying with Ca, B, or SOB, or their combinations increased growth attributes; head's weight, dimensions and dry matter; total head yield estimated as ton/ fed. as well as contents of N, P, K, Ca and B in both the leaf and head; chlorophyll a, b, as well as total chlorophylls; total carotenoids; ascorbic acid (ASA); total soluble solids (TSS) and total carbohydrates throughout the experimental period. The effect of the interaction between soil S addition and foliar spraying treatments was positive and significant on all tested attributes, with the combination between S, Ca, B, and SOB was the most effective in increasing these attributes. Moreover, without S addition, foliar spraying treatments increased all tested parameters, though with a lower magnitude, and the combination treatment (Ca+B+SOB) was the most effective in this respect. Based on obtained results, it could be concluded that yield of broccoli could be increased quantitatively and qualitatively by either soil addition of S at 100 kg/ fed or its combination with either individual or synergistic actions of foliar fertilization with 0.5% Ca, 100 ppm B, 0.5% SOB, and preferably by combining all the tested materials.

Keywords: Broccoli, (*Brassica oleracea* L. var. italica); Boron; Calcium; Sorbitol; Sulfur; Growth; Yield; bioactive compounds.

1. Introduction

Broccoli (Brassica Oleracea var. Italica), family Brassicaceae, is well-known by its richness with bioactive compounds which have health-promoting and chemo preventive effects. (**Nieves Baenas *et al.* 2016**). For example, glucosinolates and polyphenols in Broccoli help combat cancer and other diseases (**Ordiales *et al.* 2017**). Moreover, broccoli is rich in minerals; Fe, Zn, Ca and Mg and vitamins; E, A, B1, B2, B5 and B6 (**Weber 2017**). Successful production of broccoli depends on various factors of which fertilizer application is the most important one (**Bakhtiar *et al.*, 2018**). So, fertilizer management in broccoli is crucial for achieving maximum returns, through producing heads of high quantity and quality.

Sulfur (S) plays an essential role in the growth and development of plants, especially cruciferous crops. It is a key component of amino acids, proteins, and enzymes, influencing various physiological processes. In cruciferous vegetables, sulfur significantly contributes to the synthesis of glucosinolates, bioactive compounds that impart characteristic flavors and potential health benefits. Adequate sulfur nutrition is vital for enhancing chlorophyll formation, which is essential for efficient photosynthesis, ultimately leading to improved yield and quality (**Huang *et al.*, 2008**). Furthermore, sulfur enhances plants' disease resistance by strengthening plant tissues (**Baker *et al.*, 2018**), and contributes to soil fertility by enhancing microbial activity, thereby improving nutrient availability (**Cai *et al.*, 2019**). Sulfur is a component of cysteine and methionine, therefore, it is crucial for glucosinolate synthesis. In addition, enzymes such as myrosinase and sulfotransferases use sulfur-containing compounds during the conversion processes leading to glucosinolate formation (**Nielsen *et al.*, 2016**). So sulfur fortification has a positive effect on glucosinolates biosynthesis (**Raza *et al.*, 2016**). At the molecular level, studies indicate that sulfur supply directly influences the expression of genes involved in glucosinolate biosynthesis (**Mithen *et al.*, 2000**).

Boron (B) plays role in biochemical process in plants e.g. carbohydrates metabolism and transport of sugar through membranes, nucleic acids (DNA and RNA) synthesis, tissue development, regulation of reproductive development and formation of cell walls (**Shireen *et al.*, 2018**). Brassica vegetable crops have high boron requirements compared with other plants (**Riaz *et al.*, 2025**; **Verwaaijen *et al.*, 2023**; **Wang *et al.*, 2025**). In case of boron deficiency, broccoli plants develop characteristic deficiency symptoms including cracking of the leaf midrib, stem corkiness, necrotic lesions, and disintegration of the stem pith associated with abnormal lignification (**Kennedy *et al.*, 1992**). Boron also participates in the translocation of photosynthates and minerals to developing sinks (**Luo *et al.*, 2024**). Boron fertilization at 18 kg borax ha^{-1} substantially improves head formation, yield and quality in broccoli (**Thapa *et al.*, 2016**), and that foliar boron applications can reduce the incidence of hollow-stem formation in susceptible cultivars (**Kaymak and Kazdal, 2021**). Moreover, boron deficiency produces the so-called "flowering without fruiting" syndrome, in which flowers appear phenotypically normal but fail to set seed, ultimately causing severe sterility and yield losses (**Riaz *et al.*, 2025**; **Wang *et al.*, 2025**).

Calcium has a nutritional as well as a signaling roles in plants that shape their biomass, harvestable yield, and the biosynthesis of health-promoting phytochemicals. As a structural component, Ca^{2+} as calcium pectate in the middle lamella physically cement cell walls and regulates membrane permeability. In addition, via cytosolic Ca^{2+} oscillations, calcium acts as a second messenger for hormonal and stress-induced responses throughout the plant (**Thor, 2019**; **Vaahtera *et al.*, 2019**). Because Ca^{2+} is an essentially immobile nutrient delivered almost exclusively in the xylem transpiration stream; the young, lightly transpiring inner leaves enclosing a developing head are prone to localized deficiency, which can damage marketable yield, and anything that disrupts the transpiration-driven ascending Ca^{2+} flux exacerbates the impact (**Hochmuth *et al.*, 2023**). Foliar application with Ca not only positively impact growth and yield of broccoli, but also reduced post-harvest degradation, and extended shelf-life of broccoli heads (**Ali and Majeed, 2023**; **Rastegar *et al.*, 2022**). Fertilization with Ca also amplifies the biosynthesis of glucosinolates. In broccoli microgreens, pre-harvest application of 10 mM $CaCl_2$ significantly increased both aliphatic glucosinolates and indolic glucosinolates (**Sun *et al.*, 2015**). Moreover, Ca signaling itself drives glucosinolate biosynthesis in broccoli sprouts (**Li *et al.*, 2023**). In addition, under abiotic stress, incorporating $CaSO_4$ into NaCl solutions increased broccoli microgreen leaf area, restored glucosinolate accumulation that was suppressed by salinity, lowered tissue nitrate by more than three-fold, and improved Ca and S uptake (**Zeng *et al.*, 2022**). At the molecular level, exogenous Ca has been linked to the up-regulation of glucosinolate biosynthetic genes and increases in total phenolic acids and anthocyanins in broccoli (**Albaladejo-Maricó *et al.*, 2024**).

Sorbitol accumulates by plant cells under abiotic stress (**Khalid *et al.*, 2023**). Plants synthesize sorbitol directly through photosynthesis in mature leaves in parallel with sucrose, where it functions both as a translocatable carbon/energy carrier between source and sink organs and as a signaling molecule that regulates stomatal behavior, sugar metabolism, and the antioxidant defense system under different abiotic stresses (**Khalid *et al.*, 2023**; **Kocaman, 2024**). When supplied exogenously as a foliar spray, sorbitol is taken up across the leaf cuticle and mesophyll, transiently raises the cellular osmotic potential, stabilizes membranes, and acts as a hydroxyl-radical scavenger (**Kocaman, 2024**; **Shehab *et al.*, 2026**). Sorbitol and sucrose share many transport and signalling routes, therefore, foliar sorbitol applications in effect elevate the leaf's "sugar status", which has direct consequences for the sulphur-rich glucosinolate pathway that determines the nutraceutical quality of broccoli and other Brassica crops (**Jeschke *et al.*, 2019**; **Liu *et al.*, 2022**). For example, foliar spraying of cauliflower with sorbitol, preferably at 32 g L^{-1}, increased leaf area, stem diameter, and root dry mass, indicating a direct positive effect on canopy expansion and source strength (**Al-Dulaimi and Mahmood, 2024**). In addition, exogenous sorbitol spraying on strawberries improved chlorophyll a, chlorophyll b, total chlorophylls, and carotenoids contents in a dose-dependent manner (**Kocaman, 2024**). Furthermore, treatment with sorbitol enhanced glucosinolate accumulation in *Arabidopsis thaliana* seedlings (**Jeschke *et al.*, 2019**). Collectively, the positive effect of sorbitol was ascribed to its roles as a readily metabolized energy source, a translocatable carbon skeleton, and an osmoprotectant that protects chloroplasts against photoinhibition and ROS accumulation under abiotic stresses.

Though application of mineral nutrients or sorbitol alone has beneficial effects on plant growth, yield, and accumulation of bioactive compounds, there are evidences that their combination would have additive positive effects. For example, combination of 40 g L^{-1} sorbitol + 50 mg L^{-1} boron delivered at vegetative, flowering and pod-set stages increased plant height, leaf area, chlorophyll content, grain protein, and 100-grain weight of Faba beans relative to control, outperforming sorbitol alone and boron alone (**Shehab *et al.*, 2026**). The authors attributed the synergism to simultaneous osmoregulation and membrane stabilization by sorbitol plus improved reproductive carbon translocation by boron. Pre-harvest sugar/polyol status has positive effects on plants, not only pre-harvest, but also affects post-harvest phytochemical retention and shelf-life of cole crops (**Tarafder *et al.*, 2023**).

Though the effect of elemental nutrition with sulfur, calcium and boron on growth, yield and bioactive compounds of broccoli have been previously investigated, the effect of sorbitol and its combined effects with either one of these mineral nutrients or all of them is less investigated and poorly understood. So, the current investigation was conducted to study the influence of sulfur soil addition and foliar application with calcium, boron, sorbitol and their interaction on growth, yield and quality of broccoli

2. Materials and methods

2.1. Experimental conditions, materials, design, and treatments

Two field experiments were carried out during the two successive seasons of 2021-2022 and 2022-2023 at Shabrawish Village, Aga District, Dakahila Governorate. The experiments were laid out in a split-plot system in a randomized complete block design with three replications.

Soil samples were collected at random before planting from the top layer (0-30 cm depth) for physical and chemical analysis, and the results are shown in Table (1). Seeds of Broccoli (*Brassica oleracea* var.

italica L.), Vicario RZ F1 hybrid, were supplied by Razan Seeds Company, Netherlands. Sulfur (99 %) was obtained from Kafr El-Zayat Co., chelated calcium (10 %) was obtained from El-Safa Chemical Co., and Boric acid (17% B) was obtained from El- Gomhoria Chem. Co., Egypt. Soil S (two levels: 0 and 100 kg/ fed.) addition was assigned to main plots, and done by thoroughly mixing with the surface soil layer (0-30 cm) during soil preparation. Foliar spraying treatments were assigned to the sub-plots as follows:

1. Control (distilled water),
2. Chelated calcium (Ca) at 0.5%,
3. Boron (B) at 100 ppm,
4. Chelated Ca at 0.5% + B at 100 ppm,
5. Chelated Ca at 0.5 % + Sorbitol (SOB) at 0.5%,
6. B at 100 ppm + SOB at 0.5%,
7. Chelated Ca at 0.5% + B at 100 ppm + SOB at 0.5%.

Foliar spraying treatments were repeated three times, at 3, 5 and 7 weeks after transplanting. Single super phosphate (12.5 % P_2O_5) was added at the rate of 60 P_2O_5 kg/ fed., during soil preparation. Potassium sulphate (50% K_2O) at the rate of 50 K_2O kg/ fed. and ammonium nitrate (33.5 %) at the rate of 80 kg/ fed., were side dressed at two equal splits, at the time of the first and the second irrigation.

Table (1). Some physical and chemical properties of the experimental soil (average of the two experimental seasons)

Physical characteristics	
Texture	Clayey
sand (%)	23.05
Silt (%)	17.43
Clay (%)	59.52
Chemical characteristics	
$CaCO_3$(%)	1.74
Organic matter (%)	1.45
Electrical conductivity ($dS.m^{-1}$)	1.62
pH (1:2.5 soil: water)	7.9
Available nutrients (ppm)	
N (ppm)	72.10
P (ppm)	14.60
K (ppm)	68.40
Anion exchange capacity (meq 100 g^{-1} soil)	
HCO_3^-	0.53
CL^-	0.41
SO_4^-	1.35
Cation exchange capacity (meq 100 g^{-1} soil)	
Ca^{2+}	1.13
Mg^{2+}	0.88
K^+	0.85
Na^+	1.06

Seeds of broccoli were sown in the nursery on 6^{th} and 12^{th} of September in the first and season, respectively. Uniform transplants (40 d after seed sowing, DAS), were transplanted at 50 cm distance on one side of the ridge. Each plot consisted of 5 ridges, 75 cm in width and 5 m in length, with a plot area of 18.75 m^2. Other normal agricultural practices were carried out according to the Ministry of Agriculture's recommendations for broccoli cultivation.

2.2. Data recorded

Vegetative growth characters

Ten plants were taken randomly from each plot at 75 d after transplanting (DAT) to determine plant height, number of leaves per plant, fresh as well as dry weight per leaf after drying the in an oven at 80 °C until it reaches a constant weight, and leaf area per plant using weight-area ratio.

Yield and its components

At harvest time (90 DAT), a sample of 8 plants were randomly collected from each plot to record the following attributes: head fresh weight, head length, head diameter, head dry matter, and head yield as per plant and as ton / fed. (Feddan = 4200 m2 = 0.42 hectare).

Estimation of mineral composition and head quality attributes

For assessing the mineral composition and head quality, the following attributes were estimated at harvest time. Total carbohydrates content was determined according to **Herbert et al. (1971)**. Chlorophyll a, b and total chlorophylls in the flowering buds were determined calorimetrically according to **Lichtenthaler (1987)**. Total carotenoids content was determined according to the method adopted in **Ellong et al. (2015)**. In addition, the contents of N, P, K, Ca and B were determined in leaves, 10 wk DAT, as well as in the head at harvest. Total nitrogen, phosphorus and potassium were determined according to the methods described by **Bremner and Mulvaney (1982)**. Total calcium was estimated Flame photometrically using Jenway Flame photometer model corning 400 according to the modified method of **Peters *et al.* (2003)**. Boron was determined by Carmine method as described by **Sarkar *et al.* (2014)**. Total soluble solids (TSS) in the flowering buds' extract was determined by hand refractometer. Ascorbic acid content in fresh flowering buds was estimated by titration with 2,6 dichlorophenol indophenol according to **Rao and Deshpande (2006)**.

2.3. Statistical analysis

Data were statistically analyzed using the technique of analysis of variance according to **Snedecor and Cochran (1989)**, and means were compared using L.S.D at 5% level.

3. Results

3.1. Vegetative growth characters

The effect of sulfur soil addition, foliar spraying with Ca, B and SOB, and their combinations on vegetative growth attributes are shown in Table (2). Data show that S soil addition increased plant height, fresh as well as dry weight of leaves per plant, and leaf area per plant throughout the experimental period. In addition, number of leaves per plant was also increased, but only in the second season. All the aforementioned growth traits were increased in response to foliar spraying with Ca, B, their combination, and their combination with SOB. The maximum values of leaf number per plant, leaves fresh as well as dry weight per plant, and leaf area per plant were obtained in response to the treatment in which Ca, B and SOB were combined (Table 2).

The effect of the interaction between soil application of S and foliar spraying with Ca, B, and SOB was significant regarding all estimated growth traits. The tallest plants were recorded in response to Ca+B combination. On the other hand, number of leaves per plant, leaf fresh as well as dry weight and leaf area per plant were maximum in plants received the combination of S soil application with the foliar application of the Ca+B+SOB mixture.

Table (2). Influence of sulfur soil addition and foliar application with calcium, B, SOB and their interactions on vegetative characters of broccoli plants during 2021/2022 and 2022/2023 seasons.

Characters / Treatments	Plant height (cm)		Number of leaves/plants		Fresh weight of leaves (g)		Dry weight of leaves (%)		Leaf area (cm^2)	
	21/2022	22/2023	21/2022	22/2023	21/2022	22/2023	21/2022	22/2023	21/2022	22/2023
Sulfur										
Without	62.64	60.42	19.02	17.73	1215.00	1127.95	9.25	9.11	6648.86	6409.29
With	68.11	65.76	19.26	18.71	1314.33	1242.62	11.57	11.05	6956.52	6696.24
F. Test	**	**	N. S	**	*	**	**	*	**	*
Foliar application										
Control	58.84	57.57	18.48	17.24	1145.00	1075.83	8.39	8.10	6164.17	5882.83
Ca chelated 0.5%	65.65	63.86	19.15	18.01	1225.83	1126.67	9.83	9.69	6453.33	6160.83
B 100 ppm	63.34	61.08	18.69	17.74	1200.83	1089.33	9.56	9.35	6651.67	6303.33
Ca chelated 0.5%+ B 100 ppm	71.09	68.03	19.63	18.36	1206.00	1158.33	10.64	10.37	6832.50	6580.83
Ca 0.5% + SOB 0.5%	66.32	63.86	19.22	18.51	1240.83	1191.67	11.12	10.97	7052.50	6789.00
B 100 ppm + SOB 0.5%	64.57	63.29	19.29	18.85	1325.00	1268.50	10.63	10.25	7141.83	6979.17
Ca 0.5% +B 100 ppm+0.5% SOB 0.5%	67.84	63.95	19.53	18.86	1509.17	1386.67	12.70	11.85	7322.83	7173.33
LSD at 5%	0.81	1.14	0.45	0.43	31.37	42.51	0.23	0.29	59.41	70.44
Interaction between soil applied sulfur and foliar spraying with calcium, B, sorbitol										
Without sulfur										
Control	57.48	56.37	18.20	16.54	1076.67	1000.00	6.97	6.83	6071.67	5760.33
Ca chelated 0.5%	62.67	61.28	19.10	17.73	1185.00	1083.33	8.37	8.27	6393.33	5961.67
B 100 ppm	61.67	59.40	18.17	17.03	1165.00	1052.00	8.33	8.05	6547.00	6316.67
Ca chelated 0.5% + B 100 ppm	67.45	64.10	19.93	17.43	1133.33	1056.67	9.37	9.18	6720.00	6553.33
Ca 0.5%+SOB 0.5%	63.30	60.71	19.00	18.29	1183.33	1121.67	10.24	10.05	6906.67	6659.67
B 100 ppm + SOB 0.5%	61.20	59.10	19.12	18.84	1266.67	1227.00	9.65	9.86	6905.00	6726.67
Ca 0.5%+B 100 ppm + SOB 0.5%	64.73	61.96	19.65	18.25	1495.00	1355.00	11.80	11.53	6998.33	6886.67
With sulfur										
Control	60.20	58.77	18.77	17.93	1213.33	1151.67	9.80	9.37	6256.67	6005.33
Ca chelated 0.5%	68.63	66.43	19.20	18.28	1266.67	1170.00	11.30	11.10	6513.33	6360.00
B 100 ppm	65.02	62.77	19.22	18.45	1236.67	1126.67	10.78	10.66	6756.33	6290.00
Ca chelated 0.5% + B 100 ppm	74.73	71.95	19.32	19.28	1278.67	1260.00	11.92	11.55	6945.00	6608.33
Ca 0.5% +SOB 0.5%	69.33	67.00	19.43	18.73	1298.33	1261.67	12.00	11.88	7198.33	6918.33
B 100 ppm + SOB 0.5%	67.93	67.48	19.47	18.85	1383.33	1310.00	11.60	10.63	7378.67	7231.67
Ca 0.5% +B 100 ppm + SOB 0.5%	70.94	65.93	19.40	19.46	1523.33	1418.33	13.60	12.17	7647.33	7460.00
LSD at 5%	1.15	1.62	0.63	0.61	44.37	60.12	0.32	0.40	84.03	99.61

3.2. Yield and its components

The effect of S soil addition, foliar spraying with Ca, B and SOB, and their combinations on yield attributes are shown in Table (3). Data show that S soil addition increased head weight, head length, head diameter, head dry matter, and total head yield estimated as ton/fed throughout the experimental period. In addition, foliar spraying with Ca, B, their combination, and their combination with SOB increased all the aforementioned yield attributes, and the treatment in which plants received the combination of Ca, B, and SOB (Ca+B+SOB) was the most effective in this respect, with the treatment comprised the combination between Ca and SOB (Ca+SOB) ranked second in this respect. The effect of the interaction between Soil S addition and foliar spraying of Ca, B, their additive effect, and their combination with SOB on all tested yield attributes is significant. Head weight, length, diameter, dry matter and total yield (ton/fed) were significantly higher in all treatments with compared with without S. Compared with other interaction treatments, the interaction between S soil addition and foliar spraying with the combination of Ca, B and SOB resulted in the highest values for all tested yield traits. This interaction treatment increased head weight by 51.4 and 53.9 %, in the experimental season of 2021/22 and 22/23, respectively, compared with the same combination without S. Compared with control untreated plants, The interaction between S soil addition with the combination Ca+B+SOB increased head weight by 74.6 and 78.3 in 21/22 and 22/23, respectively. The corresponding increases in total yield of heads estimated as ton/fed were 33.4 and 31.5% over S-untreated, and 45.6 and 44.9 % over control untreated plants in 21/22 and 22/23 season, respectively.

3.3. N, P,K, Ca, and B contents in both the leaf and the curd

The effects of S soil addition, foliar spraying with Ca, B and SOB, and their combinations on N, P,K, Ca, and B contents in the leaf are presented in Table (4,a), whereas those in the curd are presented in Table (4, b). Data illustrate that S soil addition, Foliar spraying with Ca, B, their combination, and their combination with SOB, and their interactions increased N, P,K, Ca, and B contents in both the leaf and curd . Within foliar spraying treatments, the treatment in which plants received the combination of Ca, B, and SOB (Ca+B+SOB) was the most effective in this respect, and ranked second in this context the combination between Ca and SOB (Ca+SOB) with regard to N, P,K, and Ca contents, whereas the combination between Ca and B (Ca+B) with regard to B content. The effects of the interaction between Soil S addition and foliar spraying of Ca, B, their additive effect, and their combination with SOB on all estimated nutrients contents were significant. The interaction between S soil addition and foliar spraying with the combination of Ca, B and SOB surpassed all other interactions effects in this respect. In addition, all foliar spraying combination treatments were more effective in enhancing nutrients contents when interacted with soil S addition.

Table (3). Influence of sulfur soil addition and foliar application with calcium, B, SOB and their interactions on head yield attributes of broccoli plants during 2021/2022 and 2022/2023 seasons

Characters / Treatments	Head weight (g)		Head length (cm)		Head diameter (cm)		Dry matter (%)		Total yield of heads (ton/fed.)	
	21/2022	22/2023	21/2022	22/2023	21/2022	22/2023	21/2022	22/2023	21/2022	22/2023
Sulfur										
Without	897.57	804.76	10.08	9.63	23.23	21.97	11.74	11.58	7.95	7.71
With	1040.33	983.14	11.54	11.83	24.86	23.71	12.59	12.44	9.19	8.76
F. Test	**	**	**	**	**	**	**	**	**	**
Foliar application										
Control	806.00	728.17	9.61	9.33	21.06	20.20	11.28	11.18	7.52	7.11
Ca chelated 0.5%	890.83	816.00	10.81	10.45	22.79	21.08	11.69	11.52	8.32	7.99
B 100 ppm	860.50	790.00	10.59	10.18	23.34	22.02	11.73	11.56	8.10	7.83
Ca chelated 0.5% + B 100 ppm	931.67	872.50	10.91	10.98	24.69	23.03	12.14	11.88	8.70	8.35
Ca 0.5% + SOB 0.5%	1047.83	1011.67	11.25	11.31	25.30	24.01	12.49	12.30	9.00	8.68
B 100 ppm + SOB 0.5%	1045.67	949.00	11.16	11.10	25.38	24.58	12.68	12.54	8.77	8.52
Ca 0.5%+B 100 ppm + SOB 0.5%	1200.17	1090.33	11.33	11.79	25.75	24.96	13.15	13.10	9.57	9.16
LSD at 5%	29.10	26.13	0.27	0.11	0.55	0.35	0.13	0.14	0.10	0.09
Interaction between soil applied sulfur and foliar spraying with calcium, B, sorbitol										
Without sulfur										
Control	748.67	674.67	9.43	9.03	20.32	19.70	11.08	10.96	7.19	6.77
Ca chelated 0.5%	841.67	746.67	9.87	9.32	22.55	20.95	11.47	11.32	7.75	7.36
B 100 ppm	817.00	731.67	9.71	9.12	22.50	21.75	11.32	11.12	7.45	7.24
Ca chelated 0.5%+ B 100 ppm	890.33	818.33	10.30	9.67	24.07	22.30	11.86	11.55	8.07	7.85
Ca 0.5% + SOB 0.5%	953.33	850.00	10.41	10.10	24.43	22.63	12.12	11.97	8.37	8.22
B 100 ppm + SOB 0.5%	938.67	834.67	10.22	9.98	24.25	23.07	12.02	11.93	8.15	8.02
Ca 0.5% +B 100 ppm + SOB 0.5%	1093.33	977.33	10.60	10.22	24.46	23.40	12.32	12.23	8.66	8.50
With sulfur										
Control	863.33	781.67	9.78	9.62	21.80	20.70	11.48	11.40	7.85	7.46
Ca chelated 0.5%	940.00	885.33	11.75	11.58	23.03	21.20	11.90	11.72	8.90	8.62
B 100 ppm	904.00	848.33	11.47	11.25	24.18	22.28	12.15	12.00	8.75	8.42
Ca chelated 0.5% + B 100 ppm	973.00	926.67	11.52	12.28	25.30	23.77	12.42	12.22	9.32	8.85
Ca 0.5%+SOB 0.5%	1142.33	1173.33	12.08	12.52	26.17	25.38	12.85	12.64	9.62	9.15
B 100 ppm + SOB 0.5%	1152.67	1063.33	12.10	12.22	26.50	26.10	13.35	13.15	9.39	9.02
Ca 0.5% + B 100 ppm+ SOB 0.5%	1307.00	1203.33	12.05	13.35	27.03	26.52	13.97	13.97	10.47	9.81
LSD at 5%	41.15	36.95	0.38	0.16	0.78	0.50	0.50	0.19	0.15	0.12

Table (4, a). Influence of sulfur soil addition and foliar application with calcium, B, SOB and their interactions on mineral content of leaves of broccoli plants during 2021/2022 and 2022/2023 seasons

Characters / Treatments	Leaves									
	N%		P%		K%		Ca%		B (ppm)	
	21/2022	22/2023	21/2022	22/2023	21/2022	22/2023	21/2022	22/2023	21/2022	22/2023
Sulfur										
Without	2.91	3.03	0.281	0.291	2.20	2.34	1.28	1.36	43.23	45.98
With	3.11	3.23	0.302	0.313	2.46	2.60	1.38	1.47	47.11	49.90
F. Test	**	**	**	**	**	**	**	**	**	**
Foliar application										
Control	2.59	2.69	0.242	0.251	1.77	1.87	1.15	1.22	37.23	39.33
Ca chelated 0.5%	2.88	2.99	0.275	0.285	2.12	2.26	1.25	1.34	40.62	43.19
B 100 ppm	2.79	2.90	0.267	0.277	2.02	2.14	1.21	1.29	41.67	44.02
Ca chelated 0.5%+ B 100 ppm	3.17	3.30	0.311	0.323	2.55	2.72	1.42	1.50	49.77	52.95
Ca 0.5%+SOB 0.5%	3.24	3.37	0.316	0.328	2.64	2.81	1.43	1.53	47.35	50.49
B 100 ppm + SOB 0.5%	3.10	3.22	0.304	0.315	2.47	2.62	1.37	1.46	48.47	51.33
Ca 0.5%+B 100 ppm + SOB 0.5%	3.31	3.44	0.325	0.337	2.72	2.89	1.47	1.57	51.08	54.26
LSD at 5%	0.05	0.05	0.005	0.005	0.04	0.04	0.02	0.03	0.76	0.59
Interaction between soil applied sulfur and foliar spraying with calcium, B, sorbitol										
Without sulfur										
Control	2.54	2.65	0.241	0.250	1.72	1.83	1.13	1.20	36.75	38.91
Ca chelated 0.5%	2.81	2.92	0.265	0.274	2.04	2.17	1.21	1.30	39.19	41.66
B 100 ppm	2.72	2.83	0.257	0.267	1.92	2.03	1.18	1.25	40.37	42.76
Ca chelated 0.5%+ B 100 ppm	3.03	3.15	0.298	0.309	2.38	2.55	1.35	1.43	46.98	50.25
Ca 0.5%+SOB 0.5%	3.12	3.24	0.302	0.313	2.48	2.65	1.37	1.46	44.66	47.86
B 100 ppm + SOB 0.5%	2.98	3.10	0.293	0.304	2.30	2.44	1.30	1.39	46.00	48.87
Ca 0.5%+B 100 ppm+ SOB 0.5%	3.18	3.30	0.310	0.321	2.56	2.71	1.41	1.51	48.65	51.54
With sulfur										
Control	2.64	2.74	0.243	0.252	1.81	1.90	1.16	1.24	37.72	39.76
Ca chelated 0.5%	2.94	3.06	0.285	0.296	2.21	2.35	1.28	1.37	42.05	44.71
B 100 ppm	2.86	2.97	0.276	0.286	2.13	2.25	1.25	1.32	42.97	45.27
Ca chelated 0.5% + B 100 ppm	3.31	3.44	0.324	0.336	2.72	2.88	1.48	1.58	52.55	55.65
Ca 0.5% + SOB 0.5%	3.36	3.50	0.331	0.343	2.81	2.98	1.50	1.60	50.03	53.11
B 100 ppm + SOB 0.5%	3.22	3.35	0.315	0.327	2.65	2.80	1.44	1.54	50.94	53.79
Ca 0.5% +B 100 ppm + SOB 0.5%	3.44	3.58	0.339	0.352	2.89	3.07	1.53	1.63	53.51	56.98
LSD at 5%	0.07	0.07	0.007	0.007	0.06	0.06	0.03	0.03	1.07	0.83

Table (4,b). Influence of sulfur soil addition and foliar application with calcium, B, SOB and their interactions on mineral content of head of broccoli plants during 2021/2022 and 2022/2023 seasons.

Characters	N%		P %		K %		Ca %		B ppm	
	21/2022	22/2023	21/2022	22/2023	21/2022	22/2023	21/2022	22/2023	21/2022	22/2023
Sulfur										
Without	3.22	3.48	0.334	0.346	3.14	3.34	1.61	1.72	69.65	74.09
With	3.50	3.78	0.358	0.370	3.41	3.64	1.74	1.85	72.23	76.49
F. Test	**	**	**	**	**	**	**	**	**	**
Foliar application										
Control	2.82	3.05	0.295	0.306	2.74	2.92	1.47	1.57	65.72	69.47
Ca chelated 0.5%	3.13	3.38	0.323	0.334	3.04	3.25	1.56	1.67	67.86	72.17
B 100 ppm	3.05	3.29	0.314	0.325	2.96	3.13	1.53	1.63	68.64	72.54
Ca chelated 0.5%+ B 100 ppm	3.59	3.88	0.370	0.382	3.49	3.71	1.77	1.88	74.04	78.83
Ca 0.5%+SOB 0.5%	3.66	3.95	0.378	0.391	3.60	3.85	1.81	1.93	72.24	76.98
B 100 ppm+ SOB 0.5%	3.51	3.79	0.356	0.368	3.41	3.64	1.73	1.85	73.15	77.47
Ca 0.5% + B 100 ppm + SOB 0.5%	3.77	4.07	0.386	0.400	3.69	3.93	1.86	1.98	74.91	79.56
LSD at 5%	0.06	0.06	0.007	0.008	0.05	0.06	0.03	0.03	0.35	1.31
Interaction between soil applied sulfur and foliar spraying with calcium, B, sorbitol										
Without sulfur										
Control	2.78	3.01	0.293	0.303	2.68	2.85	1.45	1.54	65.34	69.34
Ca chelated 0.5%	3.04	3.28	0.313	0.323	2.96	3.16	1.53	1.64	67.05	71.26
B 100 ppm	2.97	3.21	0.306	0.316	2.86	3.04	1.51	1.61	67.72	71.72
Ca chelated 0.5%+ B 100 ppm	3.39	3.66	0.352	0.364	3.32	3.52	1.67	1.77	72.32	77.43
Ca 0.5%+SOB 0.5%	3.47	3.75	0.362	0.375	3.43	3.65	1.72	1.83	70.47	75.40
B 100 ppm + SOB 0.5%	3.33	3.59	0.343	0.355	3.23	3.44	1.65	1.77	71.47	75.92
Ca 0.5%+B 100 ppm+ SOB 0.5%	3.57	3.86	0.370	0.382	3.50	3.74	1.78	1.90	73.15	77.53
With sulfur										
Control	2.86	3.09	0.297	0.308	2.79	2.99	1.49	1.60	66.09	69.59
Ca chelated 0.5%	3.23	3.48	0.334	0.345	3.13	3.34	1.60	1.71	68.67	73.08
B 100 ppm	3.13	3.38	0.322	0.333	3.05	3.23	1.56	1.65	69.55	73.35
Ca chelated 0.5%+ B 100 ppm	3.79	4.09	0.388	0.401	3.67	3.90	1.87	1.99	75.76	80.23
Ca 0.5%+SOB 0.5%	3.85	4.16	0.394	0.408	3.78	4.05	1.90	2.03	74.02	78.56
B 100 ppm+ SOB 0.5%	3.69	3.99	0.369	0.382	3.59	3.83	1.81	1.94	74.84	79.01
Ca 0.5%+B 100 ppm+ SOB 0.5%	3.96	4.28	0.403	0.417	3.87	4.12	1.94	2.06	76.67	81.59
LSD at 5%	0.08	0.09	0.10	0.011	0.08	0.08	0.04	0.04	0.50	1.85

3.4. Biochemical head quality attributes

The effects of S soil addition, foliar spraying with Ca, B and SOB, and their combinations on Biochemical head quality attributes represented by contents from chlorophylls, carotenoids, ascorbic acid (AsA), TSS, and carbohydrates are presented in Tables (5, 6). Data illustrate that S soil addition, Foliar spraying with Ca, B, their combination, and their combination with SOB, and their interactions increased chlorophyll a, b, and total chlorophylls as well as total carotenoids contents (Table 5), as well as AsA, TSS and carbohydrates contents (Table 6). Within foliar spraying treatments, the treatment in which plants received the combination of Ca, B, and SOB (Ca+B+SOB) was the most effective in this respect, with the treatment comprised the combination between Ca and SOB (Ca+SOB) ranked second in this respect. The treatment (Ca+B+SOB) increased AsA content by 6.3, 6.6 % in the experimental season 21/22, 22/23, respectively. The effects of the interaction between Soil S addition and foliar spraying of Ca, B, their additive effect, and their combination with SOB on all tested head biochemical quality attributes were significant. The interaction between S soil addition and foliar spraying with the combination of Ca, B and SOB resulted in the highest values for all head biochemical quality attributes. However, the second higher AsA content was recorded in the head of the plants in which their leaves were sprayed with the combination of Ca and SOB, but untreated with soil S addition.

Table (5). Influence of sulfur soil addition and foliar application with calcium, B, SOB and their interactions on chlorohyll a, b, total chlorophylls and carotenoids in head's flowering buds of broccoli plants during 2021/2022 and 2022/2023 seasons

Characters / Treatments	Chlorophyll a (mg/gFW)		Chlorophyll b (mg/g FW)		Total chlorophylls (mg/g FW)		Carotenoids (mg/100 g)	
	21/2022	22/2023	21/2022	22/2023	21/2022	22/2023	21/2022	22/2023
Sulfur								
Without	0.627	0.636	0.453	0.468	1.080	1.103	15.86	16.87
With	0.661	0.672	0.493	0.509	1.155	1.181	17.85	18.91
F. Test	**	**	**	**	**	**	**	**
Foliar application								
Control	0.577	0.585	0.391	0.404	0.968	0.989	12.96	13.70
Ca chelated 0.5%	0.617	0.627	0.441	0.456	1.058	1.083	15.14	16.10
B 100 ppm	0.605	0.615	0.426	0.440	1.031	1.055	14.54	15.37
Ca chelated 0.5%+ B 100 ppm	0.673	0.682	0.507	0.524	1.179	1.206	18.54	19.73
Ca 0.5%+ SOB 0.5%	0.682	0.690	0.519	0.534	1.201	1.224	19.12	20.37
B 100 ppm+ SOB 0.5%	0.661	0.670	0.493	0.509	1.154	1.179	17.83	18.88
Ca 0.5%+B100 ppm + SOB 0.5%	0.695	0.706	0.535	0.552	1.230	1.258	19.86	21.09
LSD at 5%	0.008	0.003	0.008	0.009	0.014	0.009	0.027	0.31
Interaction between soil applied sulfur and foliar spraying with calcium, B, sorbitol								
Without sulfur								
Control	0.569	0.577	0.384	0.396	0.953	0.973	12.59	13.36
Ca chelated 0.5%	0.606	0.615	0.426	0.440	1.032	1.055	14.50	15.41
B 100 ppm	0.593	0.601	0.413	0.425	1.006	1.027	13.89	14.71
Ca chelated 0.5%+ B 100 ppm	0.650	0.660	0.481	0.498	1.131	1.158	17.20	18.42
Ca 0.5%+SOB 0.5%	0.661	0.669	0.494	0.507	1.155	1.176	17.76	19.01
B 100 ppm + SOB 0.5%	0.637	0.647	0.466	0.481	1.104	1.128	16.50	17.53
Ca 0.5%+B100 ppm+ SOB 0.5%	0.671	0.680	0.509	0.526	1.179	1.206	18.55	19.66
With sulfur								
Control	0.584	0.594	0.398	0.412	0.982	1.006	13.32	14.04
Ca chelated 0.5%	0.629	0.639	0.456	0.472	1.085	1.111	15.77	16.78
B 100 ppm	0.617	0.628	0.440	0.455	1.056	1.083	15.19	16.02
Ca chelated 0.5%+ B 100 ppm	0.695	0.704	0.532	0.549	1.228	1.254	19.87	21.04
Ca0.5%+SOB 0.5%	0.702	0.711	0.545	0.561	1.247	1.271	20.48	21.73
B 100 ppm+ SOB 0.5%	0.684	0.693	0.520	0.537	1.204	1.230	19.16	20.23
Ca 0.5%+B 100 ppm+ SOB 0.5%	0.720	0.732	0.561	0.578	1.281	1.310	21.16	22.51
LSD at 5%	0.012	0.004	0.011	0.012	0.020	0.013	0.39	0.45

Table (6). Influence of sulfur soil addition and foliar application with calcium, B, SOB and their interactions on head quality of broccoli plants during 2021/2022 and 2022/2023 seasons

Characters / Treatments	V.C		TSS %		Carbohydrates %		Total sugar %	
	21/2022	22/2023	21/2022	22/2023	21/2022	22/2023	21/2022	22/2023
Sulfur								
Without	90.80	90.30	8.33	8.13	28.23	30.03	4.49	4.79
With	92.74	92.42	8.94	8.78	30.66	32.47	4.80	5.12
F. Test	*	**	**	**	**	**	**	**
Foliar application								
Control	88.91	88.33	7.43	7.30	24.58	25.96	4.00	4.26
Ca chelated 0.5%	90.50	89.85	8.53	8.39	27.44	29.23	4.38	4.69
B 100 ppm	90.78	90.65	7.95	7.74	26.56	28.05	4.26	4.53
Ca chelated 0.5%+ B100 ppm	92.04	91.64	8.74	8.58	31.56	33.58	4.92	5.23
Ca 0.5%+SOB 0.5%	93.28	92.69	9.28	8.93	32.26	34.37	5.03	5.37
B 100 ppm+ SOB 0.5%	92.43	92.22	8.93	8.80	30.63	32.42	4.81	5.14
Ca 0.5%+B 100 ppm+ SOB 0.5%	94.48	94.15	9.60	9.44	33.08	35.12	5.15	5.48
LSD at 5%	0.42	0.38	0.08	0.16	0.16	0.52	0.06	0.03
Interaction between soil applied sulfur and foliar spraying with calcium, B, sorbitol								
Without sulfur								
Control	89.60	88.92	7.70	7.60	24.30	25.74	3.97	4.21
Ca chelated 0.5%	91.48	91.17	8.73	8.60	26.66	28.39	4.28	4.58
B 100 ppm	90.77	90.88	8.17	8.10	25.74	27.25	4.16	4.43
Ca chelated 0.5%+ B 100 ppm	92.53	92.18	8.88	8.68	29.98	32.02	4.70	4.98
Ca 0.5%+SOB 0.5%	94.77	94.05	9.67	9.22	30.59	32.77	4.82	5.13
B 100 ppm+ SOB 0.5%	93.48	93.42	9.24	9.17	29.02	30.83	4.60	4.93
Ca 0.5%+B 100 ppm+ SOB 0.5%	92.40	91.95	8.98	8.78	31.34	33.18	4.93	5.26
With sulfur								
Control	88.22	87.75	7.15	7.00	24.85	26.18	4.02	4.30
Ca chelated 0.5%	89.52	88.53	8.33	8.18	28.22	30.07	4.48	4.79
B 100 ppm	90.80	90.42	7.73	7.38	27.38	28.85	4.37	4.63
Ca chelated 0.5%+ B 100 ppm	91.55	91.10	8.60	8.47	33.15	35.13	5.14	5.48
Ca 0.5%+SOB 0.5%	91.78	91.33	8.90	8.63	33.94	35.98	5.24	5.61
B 100 ppm+ SOB 0.5%	91.37	91.02	8.63	8.43	32.23	34.02	5.01	5.35
Ca 0.5%+B 100 ppm+ SOB 0.5%	96.55	96.35	10.22	10.10	34.82	37.05	5.36	5.71
LSD at 5%	0.59	0.55	0.11	0.23	0.23	0.74	0.09	0.04

4. Discussion

The current investigation was conducted to study the influence of sulfur soil addition and its combination with foliar application of calcium, boron, sorbitol as well as their combinations on growth, yield and quality-related bioactive compounds of broccoli. The obtained results indicated that soil addition of S at 100 kg/ fed. or its combination with foliar fertilization of either 0.5% Ca, 100 ppm B, their combination, their mixture with 0.5% SOB [(Ca+SOB) and (B + SOB)], and preferably by combining all the tested materials boosted growth and increased, as well as enhanced the yield of broccoli. The underlying effect of the tested materials that led to obtained results could be discussed as follows:

4.1. The effect of sulfur

Sulfur nutrition is essential, generally to all plants and specifically to cruciferous plants. Generally, S is required for the plant’s physiological functions, growth, and development. Sulfur enhances cell multiplication, elongation, expansion and imparts a deep green colour to leaves due to better chlorophyll synthesis, which in turn increases photosynthesis and augments the translocation of photosynthate to sink site, resulting in relatively greater amount of dry matter accumulation **Mehriya and Khangarot, 2000**. Specifically, S influences the metabolic pathways in the cruciferous crops as it is a constituent of the sulfur-containing amino acids, methionine and cysteine, besides gutathione, vitamins (biotin and thiamine), phytochelatins, chlorophyll, coenzyme A, and S-adenosyl-methionine (**Lee *et al*, 2020**). Through glutathione and its derivatives, S offers protection from oxidative damage, and it is also involved in disulfide bond formation in proteins and enzymes’ regulation, particularly in redox control (**Narayan *et al.*, 2023**). In addition, Sulfur-containing compounds such as Fe–S clusters-containing proteins are required in multiple biological processes, such as photosynthesis, energy generation, photoprotection, and metabolic reactions (**Yadav *et al.*, 2021**).

4.2. The effect of boron

Boron (B) influences various physiological and structural functions important for growth and development of plants. It is involved in cell division and elongation; stabilization and regulation of ion transport across membranes; formation of plant cell walls through its cross linking with rhamnogalacturonan II (RG-II) chains, enhancing mechanical strength and maintaining cell wall integrity; and germination as well as growth of pollen tube, thereby ensuring fertility and seed formation (**Mahious *et al.*, 2025**).

4.3. The effect of calcium

For plants, Ca is a component of the cell wall as calcium pectate, maintaining the physical strength of cell wall and the integrity and permeability of the plasma membrane and other cellular membranes. In addition, Ca acts as a secondary messenger in various metabolic pathways, regulating how plants metabolize and respond to environmental stressors (**Chandan *et al.*, 2024**). In photosynthesis, Ca ions regulate stomatal movement, which controls gas exchange, and also interact with proteins in the chloroplast membranes to maintain photosynthetic efficiency (**Tadevosyan *et al.*, 2023**). For cruciferous plants, Ca is critical for the formation of healthy heads and for biosynthesis of their characteristic bioactive compounds. **Tadevosyan *et al.* (2023)** found that pre-harvest application of CaCl2 at 10 mM not only significantly increased the total glucosinolate content in broccoli microgreens and indolic glucosinolates in Chinese kale, but also enhanced the accumulation of phenolic compounds and increased the Ferric Reducing Antioxidant Power (FRAP), improving the plant's overall antioxidant profile.

4.4. The effect of sorbitol

Application of sorbitol, a potent plant biostimulant and osmoprotectant, has been reported to trigger a series of physiological and biochemical adaptations that enhance growth, yield, and accumulation of health-promoting bioactive compounds in plants. As a compatible solute, sorbitol helps maintain cell turgor, which is essential for cell expansion and leaf area development, as well as protects chlorophyll and the enzyme Rubisco while reduces the oxidative damage, thereby maintains the photosynthetic machinery (**Godoy *et al.*, 2021**). In addition, Sorbitol treatment stimulates the biosynthesis of bioactive compounds, such as polyphenols, carotenoids, and glucosinolates through its action as a stress signal molecule, which triggers the synthesis of antioxidants, including polyphenols and flavonoids (**Chen *et al.*, 2022**).

4.5. The effect of integrated action of S, Ca, B and Sorbitol

Results of the present investigation indicated that broccoli plants cultivated in S-added soil, and co-treated with foliar application of Ca, B, and sorbitol combination recorded higher growth traits (Table 2); yield attributes (Table 3), higher concentrations of N, P, K, Ca, and B (Tables 4a, b) and their heads were of higher quality due to higher concentrations of ascorbic acid, carotenoids, TSS, and total carbohydrates (Table 6). This superior effect of the integrated action of the tested materials may be due to their integrated positive effects on plant growth and flowering traits contributing to yield, as well as on plant metabolic pathways contributing to the biosynthesis of the plant's characteristic bioactive compounds.

The integration of soil-applied sulfur (S) with foliar spraying of calcium (Ca), boron (B), or sorbitol exerts a profoundly positive synergistic effect on broccoli (*Brassica oleracea* var. *italica*) growth, head yield, and the accumulation of vital bioactive compounds. As a heavy sulfur-demanding crop, broccoli relies on soil S as a key constituent for the synthesis of sulfur-containing amino acids (methionine and cysteine), which elevate chlorophyll content and establish a robust photosynthetic capacity (**Moniruzzaman *et al.*, 2008**). When combined with foliar applications of Ca or B, which play critical, complementary roles in cell wall structural integrity and meristematic cell division, the plant achieves superior biomass accumulation and higher yield of more compact curds (**Patel *et al.*, 2017**). In addition, incorporating sorbitol, as an efficient metabolic carrier and osmo-protectant, accelerates phloem mobility, thereby, enhancing translocation of photosynthates to developing floral heads (**Radhi and Hussein, 2024**). Furthermore, the combination effect surpasses those of individual treatments because soil-applied S builds a powerful primary metabolic framework, maximizing nitrogen use efficiency and source capacity, while the foliar spraying treatments optimize carbohydrate distribution and sink strength. In addition, this multi-channel nutrient delivery system circumvents individual nutrient deficiencies and triggers a simultaneous up-regulation of multiple structural and metabolic developmental pathways. This ultimately leads to a cooperative surge in growth, yield, and contents of health-promoting secondary metabolites, compared to applying either factor alone.

5. Conclusion

Yield of broccoli could be increased quantitatively and qualitatively by either soil addition of S at 100 kg/ fed. or its combination with foliar fertilization of either 0.5% Ca, 100 ppm B, their combination, their mixture with 0.5% SOB [(Ca+SOB) and (B + SOB)], and preferably by combining all the tested materials. Over the experimental period, the interaction between S soil addition with the combination Ca+B+SOB increased head weight and total yield (t/ fed) by an average of 76.5 and 31.0%, respectively, compared with control, untreated plants. As this combination also resulted in the highest contents from AsA and other head quality-related metabolites, applying this treatment regime not only increases yield and its quality of broccoli, but also increases net revenues for the producer and a healthier produce for the consumer.

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