



RESEARCH ARTICLE

Optimisation of zinc and boron doses for growth and seed yield traits in early cauliflower (*Brassica oleracea* var. *botrytis* L.) cv. Sabour Agrim

Baddigam Kasi Reddy^{1,2*}, Santosh Kumar Singh³, Pramila², Udit Kumar², Dumpapenchala Vijayreddy⁴,
Dumavath Srikanth Naik⁵ & Anil Kumar Singh^{2*}

¹Division of Vegetable Crops, ICAR-Indian Institute of Horticultural Research, Indian Agricultural Research Institute (New Delhi), Hessaraghatta, Bengaluru 560 089, Karnataka, India

²Department of Horticulture, Post Graduate College of Agriculture, Dr. Rajendra Prasad Central Agricultural University, Pusa, Samastipur 848 125, Bihar, India

³Department of Soil Science, Dr. Rajendra Prasad Central Agricultural University, Pusa, Samastipur 848 125, Bihar, India

⁴Division of Crop Protection, ICAR-Indian Institute of Horticultural Research, Indian Agricultural Research Institute (New Delhi), Hessaraghatta, Bengaluru 560 089, Karnataka, India

⁵Department of Vegetable Science, Dr. Y.S.R. Horticultural University, Venkataramanagudem, West Godavari 534 101, Andhra Pradesh, India

*Correspondence email - Kasireddyhorti123@gmail.com; draksingh97@gmail.com

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Abstract

The necessity to sustain and enhance crop productivity through efficient resource utilisation is paramount. In Bihar, micronutrient deficiencies are most prevalent, with zinc (Zn) being the most common, followed by boron (B). Therefore, a study was carried out to understand the interaction effects of Zn and B on the growth characteristics, seed yield attributes and quality traits of early cauliflower. The experimental design included four levels of Zn (0, 2.5, 5 and 7.5 kg ha⁻¹) and B (0, 1.0, 1.5 and 2.0 kg ha⁻¹), arranged in a factorial randomised block design (FRBD) with 16 treatments replicated 3 times. Among the treatments, the application of 2.5 kg Zn and 2 kg B per hectare (Zn_{2.5}B_{2.0}) resulted in significant improvements in growth traits, specifically plant height (64.9 cm), number of leaves per plant (25.9) and curd diameter (22.0 cm), while reducing the number of days to 50 % curd initiation (40 days) and days to 50 % flowering (121.3 days). The Zn_{2.5}B_{2.0} treatment exhibited superior performance in yield traits, including the number of pods per plant (1876.7), pod length (10.5 cm), number of seeds per pod (21.9), seed yield per plant (64.3 g plant⁻¹), total seed yield per plant (5.0 q ha⁻¹) and days to seed harvest (146.7 days). In addition, Zn_{2.5}B_{2.0} recorded the highest benefit-cost (B : C) ratio (5.8). The study demonstrated that the combined application of Zn and B at 2.5 kg Zn ha⁻¹ and 2.0 kg B ha⁻¹, respectively, significantly enhanced growth traits, yield-attributing traits and achieved the highest benefit-cost ratio compared to other treatments.

Keywords: boron; cauliflower; growth traits; seed production; yield attributing traits; zinc

Introduction

Cauliflower (*Brassica oleracea* var. *botrytis* L.) is one of the most widely cultivated cole crops in India (1). It belongs to the family Brassicaceae. It is a monogenic species with a CC genomic composition and n = 9 chromosomes (2). It grows in the plains and hills of India. West Bengal, Bihar, Odisha and Uttar Pradesh are important cauliflower-growing regions. It is also cultivated in many parts of world, including Australia, Europe, the USA and Japan (3). According to Boswell, through natural selection and mutation, cauliflower descended from the wild cabbage (*Brassica oleracea* var. *sylvestris* L.), which originated in the Mediterranean region, particularly around Cyprus (4). India ranks second in the worldwide production of cauliflowers. Cauliflower is being grown on 479.29 thousand hectares with a production of 9436.69 thousand tonnes and productivity of 19.69 tonnes per hectare. Among all states of India, Bihar is 3rd in cauliflower

production with 1031.47 thousand tonnes per hectare (5). Implementation of advanced agricultural practices such as irrigation, multiple cropping systems, intense usage of highly reactive fertilisers with a parallel reduction in the reuse of residue from crops, use of animal manure and introduction of high-yielding crop types that remove more nutrients have contributed to the widespread deficiency of micronutrient (6). Adequate micronutrient management is essential to maximise the efficiency of nitrogen (N), phosphorus (P) and potassium (K) fertilisers (7).

Among micronutrients, zinc (Zn) deficiency is the most prevalent micronutrient deficiency across the country and in Bihar, followed by boron deficiency. Zinc is required for plants to complete their life cycles. Many enzymes, including dehydrogenase, carbonic anhydrase and superoxide dismutase, require Zn as the metal component (8). Zinc facilitates

tryptophan (Indole-3-acetic acid (IAA) Precursor). Zinc required for catalytic function and carbohydrate transformation (5). It is required for plant metabolic processes such as cell division, photosynthesis, respiration and other biochemical processes (9). It helps to form chlorophyll and maintain the integrity of biological membranes, such as the ion transport system and the structural orientation of macromolecules (10). While the Zn application rate varies depending on the crop, soil type and meteorological conditions, the degree of Zn insufficiency changes enormously with soil type. Zinc deficiency is frequent in soils with a coarse texture, alkaline or calcareous PH, little or no organic matter and severe erosion. About 46 % of Indian soils have inadequate Zn levels (11). Zinc deficiency restricts plant development and causes interveinal chlorosis, rosette leaves, shortened internodes and petioles (12). It also affects auxin and protein synthesis and restricts root growth, spike sterility and harvested product quality (13). The middle leaves of Zn-deficient plants produce golden or orange tinges in the interveinal space. New leaves are still tiny and are frequently referred to as "little leaf" or "resetting" (14).

Among micronutrients, boron (B) plays a critical role in cauliflower growth and development. Boron has emerged as the third most deficient nutrient in Indian soils, following Zn and sulphur (S), with recent data indicating a deficiency level of 23.2 % t (15). Boron is required for the growth and development of cauliflower. It participates in cell division, which promotes root and shoot growth. It is linked to various physiological processes including protein synthesis, hormone production, sugar metabolism, solute translocation and calcium metabolism (16). In addition, it is critical for pollen elongation, fertilisation and flowering (17). The influence of B on plants results in an increase in plant stature, overall leaf count per individual plant, leaf dimensions, plant expansion, curd mass, production per plant and production per hectare (18). Boron shortages in cauliflower initially appear as wet areas on the growing head that eventually become brown and might rot. The leaves bend downward and dry. Blistering may manifest in the leaf stalk and along the central vein (19, 20). Underneath, the pith stem degenerates, forms a crack and eventually expands into an elongated hollow structure. The formation of hollow stems and browning of the curds in cauliflower due to B deficiency directly affects the market quality of cauliflower (21).

Uttar Pradesh, West Bengal, Bihar, Madhya Pradesh, Tamil Nadu and Uttarakhand are particularly affected by the lack of B (22). Limited research has been conducted on the effects of Zn and B on the quality and production of cauliflower seeds. Moreover, few studies have investigated the effects of Zn and B on early cauliflower seed production. Therefore, the present study aimed to evaluate the effect of Zn and B on growth, seed yield attributes and quality traits of early cauliflower.

Materials and Methods

A field experiment was carried out to study the interaction effect of Zn and B on the growth traits, seed yield and quality attributes of Cauliflower (*B. oleracea* var. *botrytis*) cv. Sabour Agrim," during rabi, 2022–23, at Hi-Tech Horticulture Unit, Department of Horticulture, PG College of Agriculture, Dr. RPCAU, Pusa, Samastipur. The experimental site had predominantly loamy to sandy loamy soil with an estimated 8.6–35.7 °C temperature range and 31–99 % Relative humidity during the crop period in 2022–23. The experiment was laid out in a factorial randomised block design (FRBD) with 3 replications, as detailed in Table 1. The seedlings were transplanted at a spacing of 60 × 45 cm and fertilisers were applied according to the recommended dose at a rate of 125 kg N, 80 kg P and 60 kg K, along with farmyard manure (FYM) at 20 t ha⁻¹ at the time of planting.

Five plants were randomly chosen from each plot and tagged. Growth parameters, that is, plant height (PH) (cm) at 45 DAT, number of leaves per plant (NL) at 45 DAT, day taken for 50 % of curd initiation (D50 % CI), diameter of the curd and days to 50 % flowering and yield attributing traits, that is, number of pods/plants, pod length (PL) (cm), number of seeds/pod, days to the harvest of the seed, seed yield/plant (g/plant), total yield of seed (kg/ha), calculated gross return (₹ ha⁻¹), net return (₹ ha⁻¹) and benefit : cost (B : C) ratio of all treatments. Treatment details were enlisted in Table 1.

Gross return (₹ ha⁻¹)

Gross returns were calculated by using the formula

$$\text{Gross returns} = \text{seed yield} \times \text{market price} \quad \text{Eq. 1}$$

Net return (₹ ha⁻¹)

The crop's economics were evaluated by calculating the cost of cultivation and net profit in rupees per hectare using the current costs of inputs purchased from the college farm and the local market. Net returns were calculated using the following formula:

$$\text{Net returns} = \text{Gross returns} - \text{Total cost of cultivation} \quad \text{Eq. 2}$$

Benefit-cost ratio

The benefit-cost (B : C) ratio was calculated by dividing the net return by the total cultivation cost.

$$\text{Benefit - cost ratio} = \frac{\text{Net return (₹ /ha)}}{\text{Total cost of cultivation}} \quad \text{Eq. 3}$$

Statistical analysis

The experiment was performed with 3 replications in a FRBD and the obtained data were subjected to analysis of variance (ANOVA). Duncan's multiple range test was used to determine significant differences between means with a 5 % probability level. The analysis was performed using GRAPES software (version 10.0) (23).

Table 1. Treatment details used in the experiment

Sl. No.	Treatment	Details	Sl. No.	Treatment	Details
1.	T ₁ -Zn ₀ B ₀	0 kg ha ⁻¹ + 0 kg ha ⁻¹	9.	T ₉ -Zn _{5.0} B ₀	5.0 kg ha ⁻¹ + 0 kg ha ⁻¹
2.	T ₂ -Zn ₀ B _{1.0}	0 kg ha ⁻¹ + 1.0 kg ha ⁻¹	10.	T ₁₀ -Zn _{5.0} B _{1.0}	5.0 kg ha ⁻¹ + 1.0 kg ha ⁻¹
3.	T ₃ -Zn ₀ B _{1.5}	0 kg ha ⁻¹ + 1.5 kg ha ⁻¹	11.	T ₁₁ -Zn _{5.0} B _{1.5}	5.0 kg ha ⁻¹ + 1.5 kg ha ⁻¹
4.	T ₄ -Zn ₀ B ₂	0 kg ha ⁻¹ + 2.0 kg ha ⁻¹	12.	T ₁₂ -Zn _{5.0} B _{2.0}	5.0 kg ha ⁻¹ + 2.0 kg ha ⁻¹
5.	T ₅ -Zn _{2.5} B ₀	2.5 kg ha ⁻¹ + 0 kg ha ⁻¹	13.	T ₁₃ -Zn _{7.5} B ₀	7.5 kg ha ⁻¹ + 0 kg ha ⁻¹
6.	T ₆ -Zn _{2.5} B _{1.0}	2.5 kg ha ⁻¹ + 1.0 kg ha ⁻¹	14.	T ₁₄ -Zn _{7.5} B _{1.0}	7.5 kg ha ⁻¹ + 1.0 kg ha ⁻¹
7.	T ₇ -Zn _{2.5} B _{1.5}	2.5 kg ha ⁻¹ + 1.5 kg ha ⁻¹	15.	T ₁₅ -Zn _{7.5} B _{1.5}	7.5 kg ha ⁻¹ + 1.5 kg ha ⁻¹
8.	T ₈ -Zn _{2.5} B _{2.0}	2.5 kg ha ⁻¹ + 2.0 kg ha ⁻¹	16.	T ₁₆ -Zn _{7.5} B _{2.0}	7.5 kg ha ⁻¹ + 2.0 kg ha ⁻¹

The results are presented as means accompanied by their corresponding standard deviations.

Results and Discussion

Effect of zinc and boron on growth traits of early cauliflower

Growth and curd development traits in cauliflower were significantly influenced by Zn and B application, both individually and in combination (Table 2). The findings highlight the critical role of these micronutrients in optimising vegetative vigour, curd initiation and earliness.

Application of Zn markedly enhanced PH and leaf production. The tallest plants (56.2 cm) and maximum NL (19.5) were recorded with Zn_{5.0}, which remained statistically comparable with Zn_{2.5} and Zn_{7.5}, while the control (Zn₀) consistently produced the lowest values. Zinc application also accelerated curd initiation, reducing the number of days to 50 % curd initiation from 52.2 days in Zn₀ to 47.3 days at Zn_{5.0}. Similarly, flowering was advanced, with days to 50 % flowering decreasing from 141.8 days (Zn₀) to 133.6 days (Zn_{7.5}). Although curd diameter showed only modest improvement, the highest value (17.9 cm) was recorded under Zn_{5.0}. The positive influence of Zn on growth traits can be attributed to its role in tryptophan synthesis, a precursor of auxin and its involvement in chlorophyll formation, cell division, cell wall synthesis and meristematic activity (24). Such physiological contributions collectively promoted enhanced vegetative growth and earliness. These findings corroborate earlier reports in, cauliflower (25, 26), broccoli (18), fenugreek (27) and mustard (28).

The B application exerted a pronounced effect on both vegetative and reproductive traits. The tallest plants (60.7 cm) and highest leaf number (22.2) were observed at B_{2.0}, significantly outperforming the control (44.1 cm height, 16.5 leaves). Boron also

markedly reduced the duration to 50 % curd initiation from 52.9 days (B₀) to 45.3 days (B_{2.0}) and advanced flowering by nearly 20 days (128.9 days vs. 149.0 days in B₀). Furthermore, curd diameter progressively increased with higher B application, peaking at 19.7 cm in B_{2.0} compared with 13.6 cm under control. The beneficial effect of B is likely associated with its role in photosynthetic efficiency, auxin and carbohydrate metabolism, meristematic activity and cell differentiation. Enhanced transport of sugars and hormonal regulation could explain the observed improvements in curd initiation and reproductive growth. These findings are consistent with previous studies (2, 29–35).

The combined application of Zn and B demonstrated a strong synergistic effect, producing the most pronounced improvements in cauliflower growth and curd traits. The treatment Zn_{2.5}B_{2.0}(T₈) recorded the maximum PH (64.9 cm), leaf number (25.9) and curd diameter (22.0 cm), while also advancing curd initiation (40.0 days) and flowering (121.3 days). In contrast, the control (Zn₀B₀, T₁) consistently produced the lowest values for these traits, including delayed curd initiation (56.4 days) and flowering (153.7 days). Several intermediate combinations such as Zn₀B_{1.5}(T₃), Zn_{2.5}B_{1.5}(T₇) and Zn_{5.0}B_{2.0}(T₁₂) also enhanced growth, but none surpassed Zn_{2.5}B_{2.0} in overall performance. The synergism between Zn and B may be explained by their complementary roles in cell division, elongation and wall formation, alongside their influence on meristematic activity and hormonal regulation. This combined effect likely enhanced photosynthetic efficiency, assimilate partitioning and internal hormone production, leading to improved vegetative growth, curd development and earliness. Similar synergistic effects of Zn and B on growth and yield traits have also been reported in cauliflower and other crops by several researchers (36–45).

Table 2. Interaction effect of zinc and boron on growth traits of early cauliflower

Treatment	Plant height (cm) at 45 DAT	Number of leaves per plant at 45 DAT	Days to taken 50 % of curd initiation	Diameter of curd (cm)	Days to 50 % of flowering
Zn ₀	50.4 ^b	18.1 ^b	52.2 ^a	15.8 ^a	141.8 ^a
Zn _{2.5}	55.8 ^a	20.0 ^a	48.3 ^b	17.8 ^a	138.9 ^b
Zn _{5.0}	56.2 ^a	19.5 ^a	47.3 ^b	17.9 ^a	138.3 ^b
Zn _{7.5}	56.1 ^a	19.2 ^{ab}	48.6 ^b	17.8 ^b	133.6 ^c
S Em (±)	1.3	0.9	0.8	0.4	2.3
CD (p = 0.05)	3.7	2.7	2.2	1.2	6.6
B ₀	44.1 ^c	16.5 ^d	52.9 ^a	13.6 ^c	149.0 ^a
B _{1.0}	53.5 ^b	18.2 ^c	49.5 ^b	17.0 ^b	141.5 ^b
B _{1.5}	60.7 ^a	20.0 ^b	48.7 ^b	19.0 ^a	133.2 ^c
B _{2.0}	60.2 ^a	22.2 ^a	45.3 ^c	19.7 ^a	128.9 ^c
S Em (±)	1.3	0.5	0.8	0.4	2.3
CD (p = 0.05)	3.7	1.4	2.2	1.2	6.6
T ₁ -Zn ₀ B ₀	36.9 ⁱ	15.7 ^h	56.4 ^a	11.0 ^h	153.7 ^a
T ₂ -Zn ₀ B _{1.0}	47.9 ^{gh}	17.7 ^{efgh}	51.4 ^{bc}	15.2 ^{efg}	143.6 ^{bcd}
T ₃ -Zn ₀ B _{1.5}	64.8 ^a	19.2 ^{cdef}	50.3 ^{bc}	18.3 ^{bc}	143.1 ^{bcd}
T ₄ -Zn ₀ B ₂	52.1 ^{efg}	19.8 ^{cde}	50.7 ^{bc}	18.8 ^{bc}	137.5 ^d
T ₅ -Zn _{2.5} B ₀	42.6 ^{hi}	16.2 ^{gh}	52.2 ^{ab}	13.0 ^{gh}	149.6 ^{ab}
T ₆ -Zn _{2.5} B _{1.0}	53.4 ^{def}	18.1 ^{defgh}	50.4 ^{bc}	17.4 ^{cde}	141.5 ^{bcd}
T ₇ -Zn _{2.5} B _{1.5}	62.3 ^{abc}	19.8 ^{cde}	48.0 ^{bc}	19.0 ^{bc}	125.2 ^e
T ₈ -Zn _{2.5} B _{2.0}	64.9 ^a	25.9 ^a	40.0 ^d	22.0 ^a	121.3 ^e
T ₉ -Zn _{5.0} B ₀	45.9 ^{gh}	16.8 ^{gh}	52.1 ^{ab}	14.9 ^{fg}	147.3 ^{abc}
T ₁₀ -Zn _{5.0} B _{1.0}	55.6 ^{bcd}	18.5 ^{cdefg}	48.7 ^{bc}	17.6 ^{bcd}	143.2 ^{bcd}
T ₁₁ -Zn _{5.0} B _{1.5}	60.5 ^{abcd}	20.3 ^{bcd}	48.3 ^{bc}	19.3 ^{bc}	141.2 ^{bcd}
T ₁₂ -Zn _{5.0} B _{2.0}	62.6 ^{ab}	22.6 ^b	42.4 ^c	19.8 ^{ab}	123.1 ^e
T ₁₃ -Zn _{7.5} B ₀	50.8 ^{efg}	17.2 ^{gh}	51.0 ^{bc}	15.4 ^{def}	145.4 ^{abcd}
T ₁₄ -Zn _{7.5} B _{1.0}	57.3 ^{bcde}	18.7 ^{cdef}	47.5 ^{bc}	18.0 ^{bc}	139.4 ^{cd}
T ₁₅ -Zn _{7.5} B _{1.5}	55.1 ^{cdef}	20.3 ^{bc}	48.0 ^{bc}	19.4 ^{bc}	126.7 ^e
T ₁₆ -Zn _{7.5} B _{2.0}	61.0 ^{abc}	20.6 ^{bcd}	48.0 ^{bc}	18.2 ^{bc}	128.3 ^e
S Em (±)	2.6	0.9	1.5	0.8	2.9
CD (p = 0.05)	7.4	2.7	4.4	2.3	8.4

Zn: zinc; B: boron; DAT: days after transplanting. Values in columns with the same letters are not significantly different.

Effect of zinc and boron on seed yield attributing traits of early cauliflower

The application of Zn and B, either individually or in combination, significantly enhanced seed yield and its contributing traits in early cauliflower (Table 3). Key parameters affected included pod number per plant, PL, number of seeds per pod (NSP), seed harvest duration, 1000-seed weight and both per-plant and per-hectare seed yield.

Zinc application markedly improved pod development and seed productivity. The highest pod number per plant (1767.7), longest pods (8.3 cm), greatest NSP (18.6) and earliest seed harvest (165.9 days) were observed with Zn_{7.5}. This treatment also produced the highest seed yield per plant (SYP) (54.5 g) and seed yield per hectare (SYH) (3.6 q), remaining statistically comparable with Zn_{5.0} for most traits. In contrast, Zn₀ consistently recorded the lowest values across all parameters, emphasising the pivotal role of Zn in seed development. The beneficial impact of Zn can be attributed to its involvement in protein synthesis, enzymatic activity and N metabolism, all of which contribute to reproductive efficiency and improved seed set.

Boron application also had a profound effect on reproductive traits. The treatment B_{2.0} produced the maximum number of pods (1825.7), longest pods (9.6 cm), highest seed number per pod (19.6) and superior seed yields both per plant (57.1 g) and per hectare (4.6 q). Seed maturity was also advanced, with harvest occurring in 160.5 days compared with significantly delayed harvest in the control (B₀). Boron's role in efficient sugar translocation, pollen viability and prevention of blossom drop likely explains the observed improvements in pod set and seed yield. These results corroborate earlier reports in other crops, where B enhanced reproductive success through improved carbohydrate metabolism and hormonal regulation.

The Zn × B interaction was highly significant, demonstrating a synergistic effect on seed yield traits. The treatment Zn_{2.5}B_{2.0} (T₈) was most effective, producing the maximum number of pods per plant (1876.7), longest PL (10.5 cm), highest seed number per pod (21.9) and superior seed yields (64.3 g plant⁻¹ and 5.0 q ha⁻¹). Moreover, this treatment advanced seed harvest to 146.6 days, considerably earlier than the control (T₁, Zn₀B₀), which exhibited the lowest performance for all parameters. Other combinations, such as Zn_{5.0}B_{2.0} (T₁₂) and Zn_{7.5}B_{2.0} (T₁₆), were statistically on par with T₈, indicating that higher levels of Zn in combination with B can also sustain superior productivity. The synergistic effect of Zn and B may be attributed to their complementary roles in physiological processes: while Zn supports protein synthesis, enzymatic activity and N fixation, B enhances reproductive growth by facilitating pod initiation, flower retention and assimilate transport. Together, these nutrients improved pod set, seed filling and earliness, ultimately resulting in higher yields. These findings are consistent with previous studies in mustard (46), radish (47), carrot (48) and faba bean (49), highlighting the universal importance of Zn and B in reproductive success and seed productivity across crops.

Effect of zinc, boron on the economics of early cauliflower

Economic analysis revealed wide variation among treatments with respect to cost of cultivation, gross and net returns and B : C ratio (Table 4). The highest net income (₹640145 ha⁻¹) and B : C ratio (5.8) were achieved with Zn_{2.5}B_{2.0} (T₈), closely followed by Zn_{5.0}B_{2.0} (T₁₂; net income ₹623026 ha⁻¹, B : C 5.6) and Zn_{5.0}B_{1.5} (T₁₁; net income ₹578550 ha⁻¹, B : C 5.2). These results demonstrate that higher levels of Zn and B, especially in combination, markedly enhanced profitability.

Table 3. Interaction effect of zinc and boron on yield attributing traits of early cauliflower

Treatments	No. of pods per plant	Pod length (cm)	Number of seeds/ pod	Days to the harvest of the seed	Seed yield/plant (g/plant)	Seed yield/hectare (q/ha)
Zn ₀	1516.4 ^c	5.9 ^c	15.5 ^c	178.3 ^a	45.3 ^c	3.1 ^b
Zn _{2.5}	1643.2 ^b	7.2 ^b	17.0 ^b	168.6 ^b	51.4 ^{ab}	3.2 ^b
Zn _{5.0}	1678.2 ^{ab}	7.9 ^a	18.0 ^{ab}	166.8 ^b	50.5 ^b	3.6 ^a
Zn _{7.5}	1767.7 ^a	8.3 ^a	18.6 ^a	165.9 ^b	54.5 ^a	3.6 ^a
S Em (±)	39.8	0.2	0.4	3.3	2.4	0.2
CD (p = 0.05)	114.9	0.5	1.1	9.6	7.0	0.5
B ₀	1424.0 ^c	4.8 ^d	14.2 ^d	183.1 ^a	43.2 ^c	2.1 ^d
B _{1.0}	1620.0 ^b	6.6 ^c	16.9 ^c	169.5 ^b	47.1 ^b	2.8 ^c
B _{1.5}	1735.7 ^a	8.4 ^b	18.3 ^b	166.4 ^b	54.3 ^a	4.1 ^b
B _{2.0}	1825.7 ^a	9.6 ^a	19.6 ^a	160.5 ^b	57.1 ^a	4.6 ^a
S Em (±)	39.8	0.2	0.4	3.3	1.2	0.1
CD (p = 0.05)	114.9	0.5	1.1	9.6	3.5	0.2
T ₁ -Zn ₀ B ₀	1072.1 ^g	3.7 ⁱ	10.3 ^h	188.7 ^a	40.9 ^f	1.9 ⁱ
T ₂ -Zn ₀ B _{1.0}	1516.7 ^{ef}	5.9 ^{gh}	15.8 ^{efg}	182.1 ^{abc}	44.7 ^{ef}	2.4 ^{gh}
T ₃ -Zn ₀ B _{1.5}	1600.0 ^{cdef}	6.2 ^{gh}	17.2 ^{cdef}	173.7 ^{abcd}	47.3 ^{def}	3.6 ^{de}
T ₄ -Zn ₀ B ₂	1792.8 ^{abc}	7.9 ^{de}	18.4 ^{bcd}	168.7 ^{bcd}	48.1 ^{de}	4.7 ^a
T ₅ -Zn _{2.5} B ₀	1400.0 ^f	4.4 ^{ij}	14.4 ^g	184.4 ^{ab}	42.8 ^{ef}	2.0 ^{hi}
T ₆ -Zn _{2.5} B _{1.0}	1638.3 ^{bcd}	6.5 ^{fg}	17.1 ^{cdef}	173.3 ^{abcde}	47.4 ^{def}	2.8 ^{fg}
T ₇ -Zn _{2.5} B _{1.5}	1767.7 ^{abcd}	8.3 ^{cd}	18.3 ^{bcd}	168.0 ^{bcd}	52.5 ^{cd}	4.0 ^{cd}
T ₈ -Zn _{2.5} B _{2.0}	1876.7 ^a	10.5 ^a	21.9 ^a	146.6 ^f	64.3 ^a	5.0 ^a
T ₉ -Zn _{5.0} B ₀	1553.3 ^{def}	5.2 ^{hi}	15.6 ^{fg}	180.1 ^{abc}	43.9 ^{ef}	2.1 ^{hi}
T ₁₀ -Zn _{5.0} B _{1.0}	1616.7 ^{cdef}	7.0 ^{ef}	17.1 ^{cdef}	175.7 ^{abcd}	47.6 ^{def}	3.0 ^f
T ₁₁ -Zn _{5.0} B _{1.5}	1750.0 ^{abcd}	9.0 ^{bc}	19.0 ^{bc}	164.7 ^{cdef}	60.0 ^{ab}	4.6 ^{ab}
T ₁₂ -Zn _{5.0} B _{2.0}	1866.7 ^{ab}	10.3 ^a	20.1 ^{ab}	148.7 ^f	63.0 ^{ab}	4.9 ^{ab}
T ₁₃ -Zn _{7.5} B ₀	1670.7 ^{abcde}	5.8 ^{gh}	16.3 ^{defg}	179.4 ^{abc}	45.0 ^{ef}	2.3 ^{hi}
T ₁₄ -Zn _{7.5} B _{1.0}	1708.3 ^{abcde}	7.0 ^{ef}	17.5 ^{cdef}	171.7 ^{abcde}	48.7 ^{de}	3.1 ^{ef}
T ₁₅ -Zn _{7.5} B _{1.5}	1766.7 ^{abcd}	9.7 ^{ab}	18.0 ^{bcd}	153.3 ^{ef}	53.0 ^{cd}	4.0 ^a
T ₁₆ -Zn _{7.5} B _{2.0}	1825.0 ^{abc}	10.0 ^a	18.9 ^{bc}	159.1 ^{def}	54.3 ^{bc}	4.2 ^{bc}
S Em (±)	79.6	0.3	0.8	6.6	2.4	0.2
CD (P = 0.05)	230.9	1.0	2.2	N/A	7.0	0.5

Zn: zinc; B: boron. Values in columns with the same letters are not significantly different.

Table 4. Effect of zinc and boron on economics of early cauliflower

Treatments	Total cost of cultivation (₹ ha ⁻¹)	Total seed yield (q ha ⁻¹)	Selling price (₹ q ⁻¹)	Gross income (₹ ha ⁻¹)	Net income (₹ ha ⁻¹)	B : C ratio
T ₁ -Zn ₀ B ₀	105641.2	1.9	150000	285000.0	179358.9	1.7
T ₂ -Zn ₀ B _{1.0}	106688.4	2.4	150000	360000.0	253311.7	2.4
T ₃ -Zn ₀ B _{1.5}	107149.0	3.6	150000	540000.0	432851.1	4.0
T ₄ -Zn ₀ B ₂	107735.6	4.3	150000	645000.0	537264.5	5.0
T ₅ -Zn _{2.5} B ₀	107760.3	2.0	150000	300000.0	192239.7	1.8
T ₆ -Zn _{2.5} B _{1.0}	108807.5	2.8	150000	420000.0	311192.5	2.9
T ₇ -Zn _{2.5} B _{1.5}	109331.1	4.0	150000	600000.0	490668.9	4.5
T ₈ -Zn _{2.5} B _{2.0}	109854.7	5.0	150000	750000.0	640145.3	5.8
T ₉ -Zn _{5.0} B ₀	109879.6	2.1	150000	315000.0	205120.5	1.9
T ₁₀ -Zn _{5.0} B _{1.0}	110926.8	3.0	150000	450000.0	339073.3	3.1
T ₁₁ -Zn _{5.0} B _{1.5}	111450.4	4.6	150000	690000.0	578549.7	5.2
T ₁₂ -Zn _{5.0} B _{2.0}	111974.0	4.9	150000	735000.0	623026.1	5.6
T ₁₃ -Zn _{7.5} B ₀	111998.7	2.3	150000	345000.0	233001.3	2.1
T ₁₄ -Zn _{7.5} B _{1.0}	113045.9	3.1	150000	465000.0	351954.1	3.1
T ₁₅ -Zn _{7.5} B _{1.5}	113506.5	4.2	150000	630000.0	516493.5	4.6
T ₁₆ -Zn _{7.5} B _{2.0}	114093.1	4.0	150000	600000.0	485906.9	4.3

Zn: zinc; B: boron. Values in columns with the same letters are not significantly different.

Among all treatments, Zn_{7.5}B₀ (T₁₃) and Zn_{2.5}B₀ (T₅) recorded lower net incomes (₹233001 and ₹192240 ha⁻¹, respectively) and B : C ratios (≤ 2.1), reflecting limited economic returns under imbalanced nutrition. The lowest profitability was observed in the absolute control (Zn₀B₀; T₁) with a net return of ₹179359 ha⁻¹ and B : C ratio of 1.7. Overall, combined Zn and B application, particularly Zn_{2.5}B_{2.0}, proved most effective in enhancing seed yield and economic viability of cauliflower seed production under nutrient-deficient conditions. The favourable B : C ratio can be primarily attributed to the combined application of Zn and B, which produced the highest possible yield. The present study demonstrated that early cauliflower seed production can be highly profitable with the combined application of Zn and B. These results (Table 4) are consistent with the findings of previous researchers in cauliflower (36, 38, 43, 50).

Correlation analysis among growth and seed yield traits of early cauliflower

Correlation analysis, as presented in Table 5, demonstrated that SYP and SYH exhibited strong positive correlations with the NL ($r = 0.929^{***}$, 0.910^{***}), PL ($r = 0.919^{***}$, 0.936^{***}) and NSP ($r = 0.858^{***}$, 0.874^{***}). Conversely, both SYP and SYH were strongly negatively correlated with days to curd initiation ($r = -0.907^{***}$, -0.811^{***}), days to flowering ($r = -0.835^{***}$, -0.847^{***}) and days to harvest ($r = -0.926^{***}$, -0.912^{***}). Notably, curd diameter exhibited the highest positive correlation with seeds per pod ($r = 0.962^{***}$) and seed yield ($r = 0.845^{***}$, 0.911^{***}), underscoring its pivotal role in yield determination. These findings are consistent with those reported by previous researchers (38). The correlation matrix of growth and seed

yield-contributing traits in cauliflower is depicted in Fig. 1. This matrix illustrates the strength and direction of correlations between various plant characteristics, with green indicating positive correlations and pink indicating negative correlations. The intensity of the colour reflects the magnitude of the correlation coefficient, ranging from -1 to 1.

Conclusion

Among the various boron levels, B_{2.0} (2 kg ha⁻¹) showed the most significant improvement in growth characteristics, yield-contributing traits, seed quality attributes and the boron (B) and zinc (Zn) content in the roots, stems, leaves, curds and seeds of early cauliflower, compared to other treatments. This was followed by B_{1.5} (1.5 kg ha⁻¹) and B_{1.0} (1 kg ha⁻¹). Regarding Zn treatments, Zn_{7.5} (7.5 kg ha⁻¹) was the most advantageous in terms of growth and yield-contributing traits, followed by Zn_{5.0} (5.0 kg ha⁻¹) and Zn_{2.5} (2.5 kg ha⁻¹). Among the interaction treatments, the combination Zn_{2.5}B_{2.0} (2.5 kg Zn ha⁻¹ with 2.0 kg B ha⁻¹) proved to be the most beneficial for growth traits, yield-contributing traits and seed quality attributes of early cauliflower, compared to other treatments, followed by Zn_{5.0}B_{2.0} (5 kg Zn ha⁻¹ with 2.0 kg B ha⁻¹). The highest gross income (750000 Rs. ha⁻¹) net income (640145.3 ₹ ha⁻¹) and maximum benefit-cost ratio (5.6) were achieved with the soil application of 2.5 kg zinc ha⁻¹ along with 2.0 kg B ha⁻¹ (Zn_{2.5}B_{2.0}), followed by Zn_{5.0}B_{2.0}. The lowest benefit-cost (B : C) ratio was observed in the control (Zn₀B₀). Therefore, soil application of Zn at 2.5 kg ha⁻¹ along with B at 2.0 kg ha⁻¹ may be recommended for profitable and quality seed production of early cauliflower under the experimental conditions.

Table 5. Correlation between growth and yield attributing traits in cauliflower

	PH	NL	D50 %CI	DC	D50 % F	NPP	PL	NSP	DHS	SYP	SYH
PH	1										
NL	0.798***	1									
D50 %CI	-0.803***	-0.934***	1								
DC	0.914***	0.893***	-0.869***	1							
D50 % F	-0.759***	-0.877***	0.86***	-0.842***	1						
NPP	0.841***	0.785***	-0.824***	0.921***	-0.824***	1					
PL	0.802***	0.9***	-0.858***	0.902***	-0.923***	0.881***	1				
NSP	0.881***	0.89***	-0.902***	0.962***	-0.834***	0.965***	0.896***	1			
DHS	-0.768***	-0.933***	0.897***	-0.883***	0.928***	-0.833***	-0.965***	-0.871***	1		
SYP	0.784***	0.929***	-0.907***	0.845***	-0.835***	0.774***	0.919***	0.858***	-0.926***	1	
SYH	0.836***	0.91***	-0.811***	0.911***	-0.847***	0.817***	0.936***	0.874***	-0.912***	0.914***	1

PH: plant height; NL: number of leaves; D50 % CI: days to 50 % curd initiation; DC: days to curd maturity; D50 % F: days to 50% flowering; NPP: number of plants per plot; PL: pod length; NSP: number of seed per plant; DHS: days to harvest maturity; SYP: seed yield per plant; SYH: seed yield per hectare. *** Correlation is significant at 0.001 level (two tailed) ** Correlation is significant at 0.01 level (two tailed) * Correlation is significant at 0.05 level (two tailed)

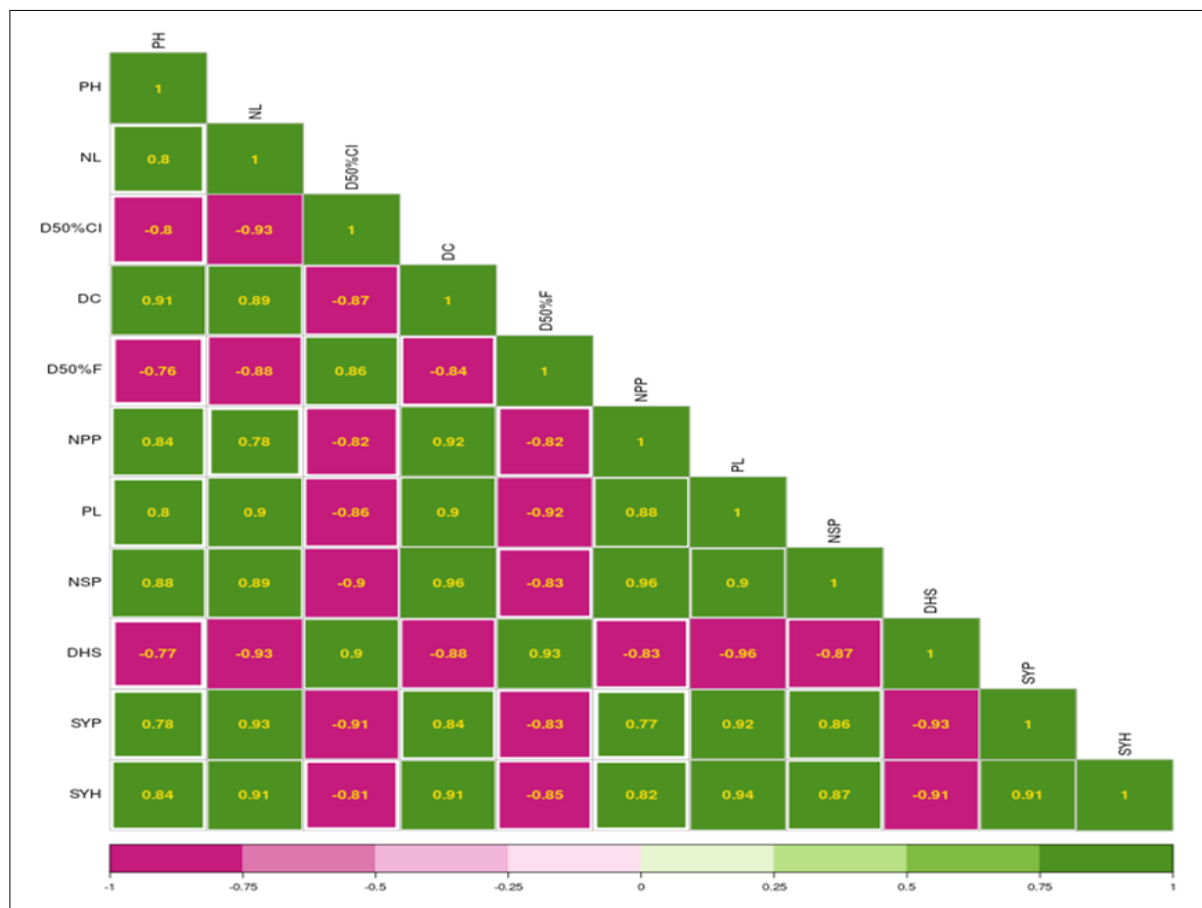


Fig. 1. Correlation matrix of growth and seed yield attributing traits in cauliflower. PH: plant height at 45 DAT; NL: number of leaves per plant at 45 DAT; D50 % CI: days taken to 50 % curd initiation; DC: diameter of curd (cm); D50 % F: days to 50 % flowering; NPP: number of pods per plant; PL: pod length (cm); NSP: number of seeds per pod; DHS: days to harvest of seed; SYP: seed yield per plant (g plant^{-1}); SYH: seed yield per hectare (q ha^{-1}).

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Authors' contributions

BKR contributed to writing the original draft, visualisation, methodology, investigation, formal analysis and data curation. SKS contributed to resources, supervision and methodology. P contributed to writing review and editing, data curation and conceptualisation. UK contributed to methodology. DV contributed to formal analysis and writing review and editing. DSN contributed to writing review and editing. AKS contributed to writing review and editing, resources, supervision, methodology and data curation. All authors have read and approved the final manuscript.

Compliance with ethical standards

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During preparation of this work, the authors used ChatGPT to correct the language of the manuscript. After using this tool, authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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