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RESEARCH ARTICLE

Seed yield and quality response to boron and zinc across growth stages in foxtail millet (*Setaria italica* (L.) P. Beauv.)

Kannababu N[*], Gangaiah B, Swarna R, Niveditha M, Sangappa[*], Hariprasanna K, Das I K & Tara Satyavathi C

ICAR - Indian Institute of Millets Research, Hyderabad 500 030, Telangana, India

*Correspondence email - kannababu@millets.res.in; sangappa@millets.res.in

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Abstract

A field experiment was conducted during the post-rainy seasons of 2020-21 and 2021-22 at the ICAR-Indian Institute of Millets Research, Hyderabad, using a split-plot design to evaluate the effects of boron (B) (0.5 %), zinc (Zn) (1 %) and their combination (B + Zn) applied through foliar sprays at panicle initiation (PI), 50 % flowering (FL), both stages (PI + FL) and as soil application (before sowing) on the growth, yield and seed quality of foxtail millet (cv. SiA 3156). Dual-stage foliar sprays of both B and Zn recorded maximum plant height (118 cm), productive tillers per plant (5), primary branches per panicle (119), panicle dry weight (10 g), seed yield per plot (1.40 kg), 100-seed weight (356 mg) and harvest index (48 %). The same treatment also produced superior seed quality traits with 100 % germination, 95 % field emergence and maximum seedling vigor indices indicating the synergistic effect of B and Zn. Foliar application treatments consistently outperformed soil application across both the years. Economic analysis indicated that foliar application of Zn (1 %) at both PI and FL stages recorded the highest benefit–cost ratio (1.6), while combined B (0.5 %) + Zn (1 %) application achieved the highest seed yield. The study highlighted that combining foliar applications of Zn and B at PI and FL significantly enhances plant growth, seed yield and physiological seed quality, underscoring its value as an efficient and sustainable seed production strategy in foxtail millet grown in micronutrient-deficient soils.

Keywords: boron; foliar application; foxtail millet; seed yield; seed quality; zinc

Introduction

Foxtail millet (*Setaria italica* (L.) P. Beauv.) has a rich agricultural history, with evidence of its cultivation in China dating back over 10500 years (1). Belonging to the family Poaceae, subfamily Panicoideae and tribe Paniceae, it possesses a chromosome number of 2n = 18 (AA). This millet is a short-duration crop, maturing within 60 to 90 days and is widely used for food, animal feed and fodder. It thrives in semi-arid regions with low rainfall and can be grown from sea level up to elevations of 2000 m above mean sea level. Known for its resilience, foxtail millet is notably drought-tolerant and often escapes late-season droughts due to its brief growing cycle. The de-husked grains are highly nutritious, offering a substantial protein content of 12.3 % and dietary fibre of 8 % (2). With a low glycaemic index (3), it is considered a suitable food for diabetics, as it releases glucose gradually into the bloodstream during digestion. Its high fibre content also contributes to cardiovascular health (4). Globally, foxtail millet is cultivated on approximately 1.06 million hectares, yielding around 2.29 million tonnes annually (5). China and India are the leading producers for food consumption, whereas in Europe and the United States, it is primarily grown for bird feed or as fodder for hay and silage. In India, foxtail millet is cultivated in an area of about 0.47 lakh hectares, producing around 0.30 lakh tonnes with an average productivity of 639 kg ha^{-1} (6).

With increasing food demands and evolving food choices, strategies to enhance productivity and sustainability are crucial. Small millets like foxtail millet have been proven to be essential for food and nutritional security due to their resilience to the challenging climatic conditions. Therefore, good quality seed is crucial both for preserving the genetic potential of released cultivars and for supplying farmers with reliable seeds that enhance productivity and supports sustainable food security. Micronutrient deficiencies not only hamper crop productivity but also affect the final seed quality. Micronutrient deficiency has been an escalating major issue in soil and plants worldwide (7). The raising health concerns are partly due to the foods low or lacking in micronutrients. Micronutrients majorly act as catalyst in the uptake and use of few specific macronutrients (8).

Zn is one of the key metallic components and activators of numerous enzymes involved in biochemical pathways and metabolic activities. It plays a vital role in various physiological functions acting as a functional, structural and regulatory co-factor for many enzymes. Hence it is essential for various enzymatic reactions as well as DNA transcription (9). Zn catalyzes oxidation processes, participates in carbohydrate metabolism and is involved in chlorophyll formation and auxin synthesis (10). Zn is unique in being the only metal found across all 6 major classes of enzymes oxidoreductases, transferases, hydrolases, lyases, isomerases and ligases (11). It additionally influences nitrogen, phosphorous and potassium uptake and its metabolism in the crop growth (12). B is one of the micronutrients that chiefly influences the yield and quality of the crops (13). It is involved in at least 16 functions in plants that include cell wall formation, membrane integrity, cell wall lignification, RNA, carbohydrate, phenol and indole acetic acid metabolism, respiration, flowering, pollination and may help in the translocation of sugar (14). Micronutrients such as Zn and B are essential as they have a pronounced effect on physiological functions such as pollen tube formation, enzyme activation and nutrients assimilation (15).

The comparison of soil and foliar application at panicle initiation (PI) and 50 % flowering (FL) is particularly important in foxtail millet owing to its short growth period, shallow root system and limited nutrient uptake window. Under post-rainy season conditions, where high evapotranspiration and low residual moisture prevail, soil-applied micronutrients often become less effective (16). Foliar nutrition at critical stages such as PI and FL can ensure timely nutrient availability, enhancing reproductive efficiency, yield and seed quality. Despite its potential, systematic evaluation of B and Zn application methods and timings in foxtail millet remains limited, necessitating the present investigation. Hence, this study was undertaken to evaluate the response of foxtail millet to B and Zn applications through different methods (soil and foliar) and at different growth stages (PI and FL) with an anticipated outcome to offer meaningful insights for enhancing both seed productivity and seedling vigor in foxtail millet.

Materials and Methods

Treatment details

Field trials were conducted during 2 consecutive post-rainy seasons (October-March) of 2020-21 (Year-1) and 2021-22 (Year-2) at ICAR-Indian Institute of Millets Research (ICAR-IIMR), Hyderabad located at 17.3850°N, 78.4867°E and altitude of 505 m (India). The aim of the experiment was to investigate the influence of 2 modes (foliar spray and soil application) of B and Zn fertilization on growth, yield attributes, seed yield and seedling vigor of foxtail millet. The study was conducted using the cultivar SiA 3156, a high-yielding, semi-erect, medium-duration (85-90 days) variety characterized by compact panicles and notable responsiveness to nitrogenous fertilizers. Initial soil analysis revealed that the soils were low in organic carbon and available N, with a moderate level of available P and K. The soils were found to be deficient for both Zn and B (Table 1). The experimental layout followed a split plot design with 3 replications. The main plot treatments (M) comprised of 4 foliar spray regimes: B applied at 0.5 % in the form of borax ($Na_2[B_4O_5(OH)_4]·8H_2O$) with trade name Borosol containing 20 % B (M_1), Zn applied at 1 % in the form of zinc sulphate ($ZnSO_4·7H_2O$) containing 21 % Zn (M_2), a combination of B (0.5 %) and Zn (1 %) (M_3) and a control with water spray only without soil application (M_4). The sub-plot treatments consisted of 4 application stages (S): foliar spray at PI (PI) (S_1), foliar spray at 50 % flowering (FL) (S_2), foliar spray at both PI and FL (S_3) and soil application (SA) before sowing (S_4).

For the SA treatment (S_4), 1 kg/ha borax and 15 kg/ha Zinc sulphate were applied basally before sowing along with the recommended NPK fertilizers. All phosphorus and potassium fertilizers, in the form of single super phosphate and muriate of potash, along with 50 % nitrogen through urea granules, were applied to the soil as a basal dose during the final ploughing.

Table 1. Physiochemical properties of experimental soil (mean of two years)

Particulars	Value	Method employed
A. Mechanical analysis		
Sand (%)	78 %	Bouyoucos hydrometer (17)
Silt (%)	12 %	
Clay (%)	10 %	
Soil texture	Sandy loam	
B. Physical analysis		
Soil pH (1:2 soil suspension)	8.14	pH meter (18)
E.C (dSm^{-1} at 25°C)	0.11	Conductivity bridge method (18)
C. Chemical analysis		
Organic carbon (%)	0.36	Walkley and Black's method (19 & 18)
Available N (kg ha^{-1})	174.7	Alkaline permanganate method (20)
Available P (kg ha^{-1})	13.5	Olsen's method (21)
Available K (kg ha^{-1})	273.7	Flame photometry (18)
DTPA extractable Zn	0.42	Lindsay and Norvell's method (22)
0.02M hot $CaCl_2$ –B	0.38	Parker and Gardner's method (23)

Remaining half N in the form of urea was top-dressed 30 days after sowing.

Methodology

Observations recorded

Data on plant height (PHT), productive tillers per plant (PTL), panicle dry weight (PCW), primary branches per panicle (PBR), hundred seed weight (HSW), seed yield per plant (YPN), seed yield per plot (YPT), stover dry weight (STV), seed germination (SG) and field emergence (FE) were recorded, while seedling vigor index-1 (SVI.1) and seedling vigor index-2 (SVI.2) were estimated.

Growth and yield traits

Measurements for PHT (cm), PTL, PCW (g), PBR, YPN (g) and STV (g) were taken from 5 randomly selected plants in each treatment and average values were computed. The seed yield (g) per net plot (6 sq. m for 100 plants) was computed from the bulk yield of total number of plants harvested per plot. The hundred seed weight (mg) with 4 replicates was recorded after threshing and drying of seeds.

Seed quality traits

Seed germination tests were conducted in petri plates, following top of the paper method in accordance with procedures of the International Seed Testing Association (24). Germination counts were taken on the 10th day and expressed in percentage (%), after which 10 randomly selected seedlings were measured for root length (cm), shoot length (cm) and seedling dry weight (mg). The seedlings were oven-dried at 80 °C for 24 hr to record dry weight. Seedling vigor indices were calculated following formulae (25):

Seedling vigor index-1 = Seed germination (%) x Seedling length (cm)

Seedling vigor index-2 = Germination (%) x Seedling dry weight (g)

Field emergence

Field emergence (%) of seeds was assessed by sowing 4 replicates each of 50 seeds in cement pots (45 cm diameter) filled with a mixture of red and black soils. After 20 days, seedlings with leaves above the soil surface were counted and expressed in percentage.

Economic analysis

An economic analysis was conducted to assess the feasibility of applying micronutrients (B and Zn) during the entire crop growth period. The total cost accounted for the standard package of practices adopted for foxtail millet cultivation, in addition to the expenses incurred from micronutrient application through soil and foliar methods. Gross income was calculated based on the prevailing 'breeder seeds' class price, while net income was derived by subtracting the total expenditure from the gross returns. The benefit-cost (BC) ratio was then estimated as the proportion of gross income to the overall production cost.

$$\text{Benefit - Cost (BC) ratio} = \frac{\text{Gross returns (₹/ha)}}{\text{Total cost of cultivation (₹/ha)}}$$

Statistical analysis

Percentage data were transformed wherever necessary and analysis of variance (ANOVA) was carried out using split plot design (SPD). All statistical analyses were performed using statistix software, version 8.1 and figures were drawn in MS excel sheets.

Results and Discussion

Plant growth and panicle traits

Foliar application of B at 0.5 % (M_1) and Zn at 1 % (M_2), either individually or in combination (M_3), significantly improved the growth and yield parameters of foxtail millet compared to the control (M_4). Pooled data over two years revealed that the treatment M_3 produced taller plants over M_4 by 20.6 %. PTL and PBR were markedly higher under M_3 during both years of study (Fig. 1). Although PCW was higher under M_3in both years, statistical

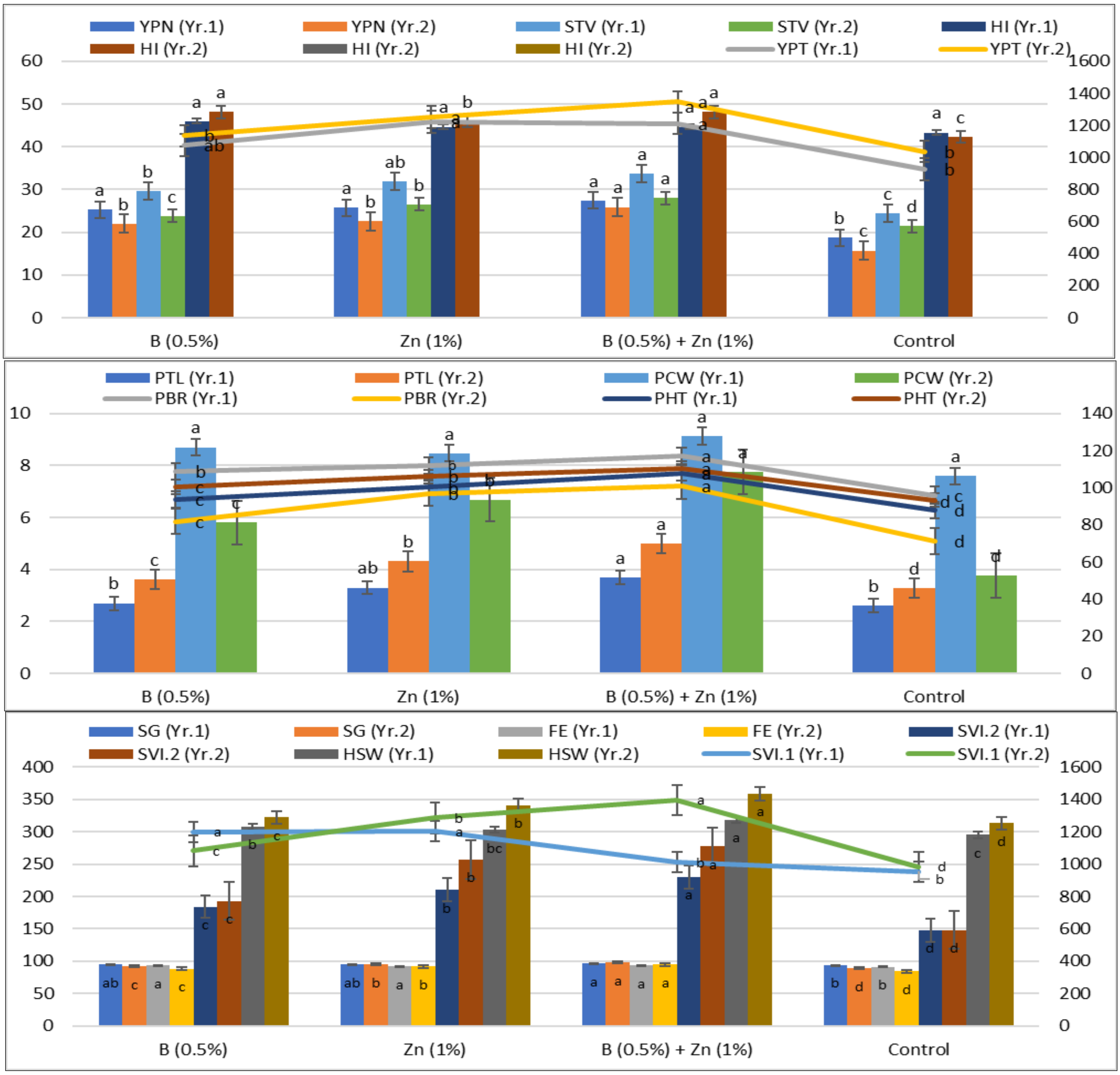

Fig. 1. Effect of B and Zn on plant growth, seed yield and quality traits in foxtail millet (cv. SiA3156) during post-rainy seasons of 2020-21 (Yr.1) and 2021-22 (Yr.2).

◊ PTL: productive tillers per plant, PBR: primary branches per panicle, PCW: panicle dry weight (g), PHT: plant height (cm), YPN: yield per plant (g), YPT: yield per plot (g), STV: stover dry weight per plant (g), HI: harvest index (%), HSW: hundred seed weight (mg), SG: seed germination (%), FE: field emergence (%), SVI. 1: seedling vigor index-1, SVI. 2: seedling vigor index-2, Yr.1: year-1, Yr.2: year-2, B: B (0.5 %), Zn: Zn (1 %)

◊ *The mean data with different labels (a, b, etc.) indicate significant differences as per Tukeys HSD all pairwise comparison test.*

significance was observed only in the second year. These improvements indicate a synergistic effect of Zn and B, where Zn enhances auxin metabolism, enzymatic activity and inter-nodal elongation, while B contributes to cell wall integrity, carbohydrate transport and reproductive development (26, 27). Furthermore, Zn plays a role in hormone synthesis, which indirectly supports carbohydrate translocation and metabolism, thereby promoting overall crop growth (28). B similarly facilitates efficient translocation of assimilates, boosting plant development (29). Through its involvement in carbohydrate metabolism and nutrient uptake, B also enhances chlorophyll synthesis, photosynthesis and enzyme activation (30).

Foliar applications at both the PI and FL stages (S_3) demonstrated superior performance compared to single-stage applications (PI or FL) or soil application (SA). Across both years, the S_3 treatment (PI + FL) consistently recorded significantly higher values for PHT (112), PTL (4), PBR (108) and PCW (8) (Fig. 2). Pooled interaction data further confirmed that the application of both B and Zn at both stages ($M_3 \times S_3$) resulted better performance with PHT (118 cm), PTL (5), PBR (119) and PCW (10 g). Individual foliar applications of Zn (M_2) and B (M_1) at S_3 also showed significant improvements over the control (M_4), though they did not match the peak performance achieved under the combined M_3 treatment. These findings highlight the importance of the requirement of both Zn and B at critical growth stages to enhance vegetative vigor and yield potential. Zn, a key component in chloroplast development, promotes photosynthesis when available in optimal concentrations. It also activates essential enzymatic processes, serving as a cofactor for

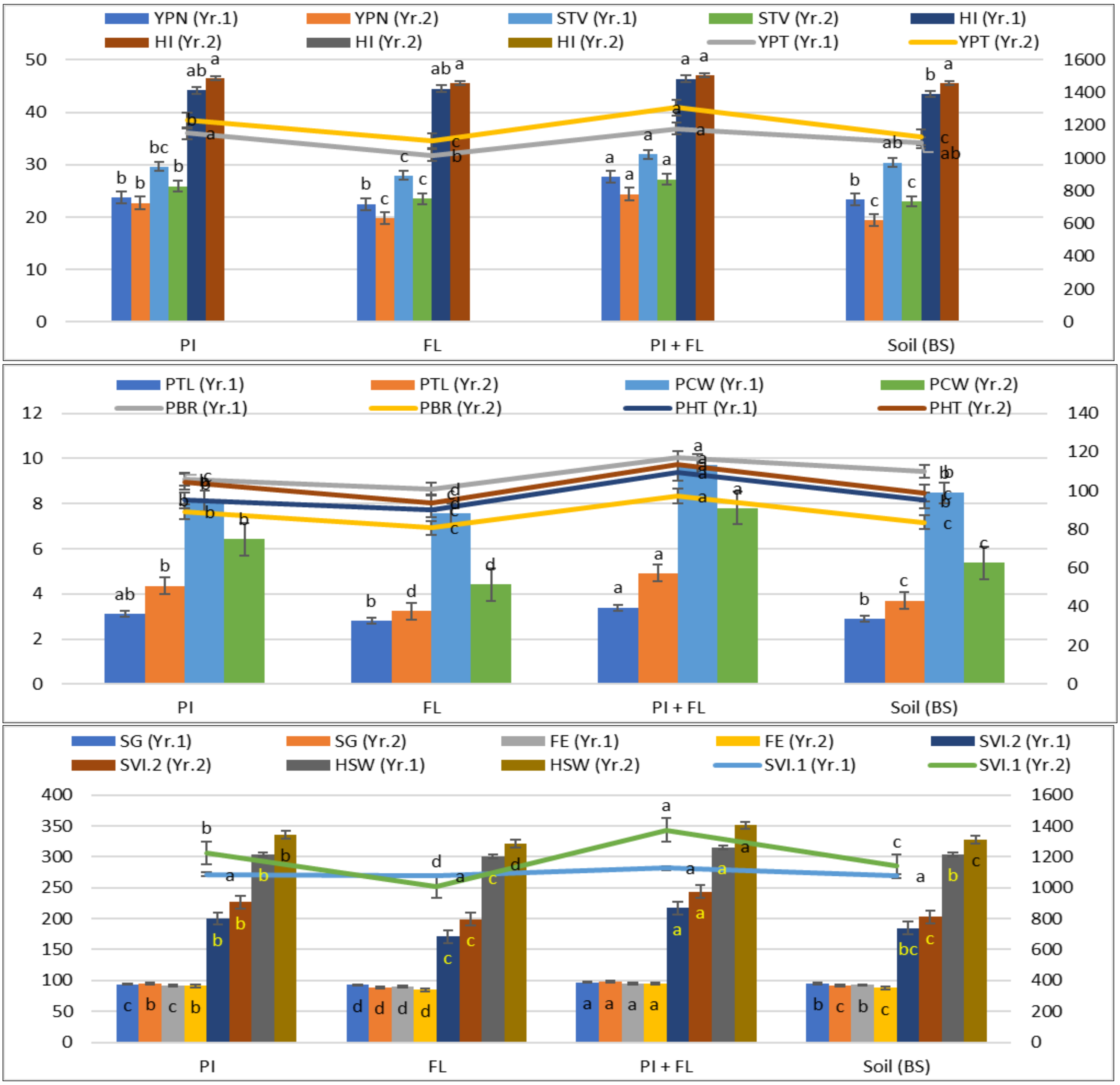

Fig. 2. Effect of different stages of foliar sprays and soil application of B and Zn on plant growth, seed yield and quality traits in foxtail millet (cv. SiA3156) during post-rainy seasons of 2020-21 (Yr.1) and 2021-22 (Yr.2).

◊ PTL: productive tillers per plant, PBR: primary branches per panicle, PCW: panicle dry weight (g), PHT: plant height (cm), YPN: yield per plant (g), YPT: yield per plot (g), STV: stover dry weight per plant (g), HI: harvest index (%), HSW: hundred seed weight (mg), SG: seed germination (%), FE: field emergence (%), SVI. 1: seedling vigor index-1, SVI. 2: seedling vigor index-2, Yr.1: year-1, Yr.2: year-2, PI: PI stage, Fl: flowering stage, Soil (BS): soil application before sowing.

◊ *The mean data with different labels (a, b, etc.) indicate significant differences as per Tukeys HSD all pairwise comparison test.*

numerous enzymes (31). Similar benefits due to foliar supplementation of Zn were observed with improved photosynthetic efficiency, growth and plant vigor in foxtail millet grown under marginal conditions (32). In finger millet as well, the foliar sprays of Zn and B significantly enhanced the plant growth and yield (33, 34).

Seed yield and attributes

Significant improvements in yield and yield-related attributes such as YPN, YPT, HSW, STV and HI were observed with the foliar application of B and Zn, applied individually or in combination. The combined treatment (M_3) consistently outperformed all other treatments across 2 years, recording the highest mean values for YPN and YPT with 30.1 % increase over the control (M_4). Substantial improvements were noted in STV (34 % increase), HSW (11.5 %) and HI (8.4 %) (Fig. 1). Similar synergistic effects on yield enhancement have been reported in finger millet (35). The physiological basis for these improvements lies in the complementary roles of Zn and B, where Zn enhances pollen viability, reduces sterility and increases grain number per panicle, while B supports efficient fertilization and reduces sterility by promoting pollen tube growth (36, 37). Optimal Zn availability improves nitrogen uptake, contributing to greater dry matter accumulation and ultimately higher seed yield (38).

Evaluation of application timings revealed that foliar spraying at both PI and 50 % FL significantly enhanced productivity, compared to other timings. Foliar application at S_3 stage (PI + FL) improved HSW, YPN and ultimately increased YPT by 11 % over soil application alone (S_4). The increase in STV due to S_3, reflected at the increase in HI by 46.7 % compared to S_4(Fig. 2). In contrast, foliar application at the FL stage alone failed to improve yield over pre-sowing soil application. This is likely because by the flowering stage, most macronutrient uptake has already occurred, limiting the effectiveness of foliar-applied nutrients in supporting key physiological processes. In contrast, application at PI aligns with a critical early reproductive window when metabolic activity and nutrient demand are high, enabling more effective support for growth and yield formation.

These findings emphasize the need to supply Zn and B during both early and mid-reproductive stages (PI + FL) to ensure sustained nutrient availability for spikelet initiation and seed filling. The combined foliar application of B + Zn at PI and FL ($M_3 \times S_3$) produced the highest two-year mean values for YPT, HSW, STV and HI. Separate applications of Zn and B at the same developmental stages also showed notable improvements. In contrast, the control treatment without any micronutrient supplementation consistently recorded the lowest values across all measured parameters (Fig. 3). The superiority of foliar sprays over soil application highlights the ability of foliar nutrition to bypass soil-related constraints such as micronutrient fixation, leaching and pH-induced unavailability. Foliar sprays deliver nutrients more efficiently during stages when root uptake may be limited (39). Similar positive effects of Zn and B foliar sprays on crop growth and yield were reported in finger millet and pearl millet (40, 41).

Seed physiological quality

Seed quality metrics were significantly improved through the combined foliar application of B + Zn (M_3). This treatment recorded the highest SG and FE along with substantial enhancement in seedling vigor. Two-year mean values of SVI. 1, SVI. 2 and seed test weight improved by 24.3 %, 71.6 % and 11.5 % respectively over the control (Fig. 1). Among the application stages, S_3 (PI + FL) recorded the highest SG, FE and SVI. 1 and SVI. 2 (Fig. 2). Application at FL alone (S_2) was less effective, reflecting similar trends observed in growth and yield attributes. This reinforces the importance of early-stage micronutrient availability for assimilating accumulation and embryo development. Interaction effects revealed that the combined foliar application of B + Zn at both PI and FL stages (S_3) was effective in enhancing final seed quality, especially seedling vigor. Individual applications of B (M_1) or Zn (M_2) at S_3 also improved seed traits relative to the control but remained inferior to the combined treatment. As expected, M_4 consistently recorded the lowest values across all parameters (Fig. 3). The improvements in seed vigor and emergence are attributable to Zn-mediated enzyme activation and carbohydrate metabolism, along with the role of B in cell division and assimilate translocation resulting in increased metabolic readiness and membrane stability during early germination (42 - 45). Similar enhancements in seed quality due to foliar Zn and B applications have been reported in finger millet and pearl millet (46-48).

Economic analysis

The economic analysis based on breeder seed price revealed that among the foliar spray treatments, Zn application at 1 % (M_2) consistently recorded the highest BC ratio (1.5) in both years, followed by the combined application of B + Zn (M_3). B alone (M_1) resulted in moderate profitability, while the control (M_4) remained the least profitable. Across growth stages, application at PI (S_1) and PI + FL (S_3) stages maintained slightly higher BC ratios followed by SA (S_4) compared to FL (S_2). The interaction effects highlighted the superiority of Zn at PI + FL stage ($M_2 \times S_3$), which consistently resulted the highest BC ratio (1.6), followed by Zn at PI (M2 × S1) and combined sprays at PI ($M_3 \times S_1$), indicating the significance of both nutrient source and timing in improving profitability of breeder seed production (Fig. 3). Similar findings were stated in maize on application of Zn and B (49). On the contrary, control treatments across all stages recorded lower BC ratio. Overall, our study revealed that foliar application of Zn at the PI + FL stages ($M_2 \times S_3$) provided the greatest economic benefit for breeder seed production. Although the combined application of B + Zn (M_3) at the same stages (S_3) resulted in the highest yield among all treatments, the increased input cost from applying both micronutrients diminished its economic advantage. In contrast, B applied alone offered only limited economic returns.

Conclusion

The findings of present study collectively highlight the effectiveness of foliar application of micronutrients particularly the combined use of Zinc (1 %) and Boron (0.5 %) at both panicle initiation and 50 % flowering stages ($M_3 \times S_3$) as an effective strategy for improving plant growth, seed yield and physiological seed quality in foxtail millet during the post-rainy season. This approach aligns with growing evidence that foliar feeding ensures rapid nutrient delivery during critical growth phases while bypassing soil-related limitations. Given that foxtail millet is a staple crop in rainfed regions often characterized by marginal soils, this nutrient management strategy presents a promising avenue for optimizing seed production protocols, boosting seed vigor and yield and promoting sustainable agriculture in micronutrient-deficient environments. Future research should focus on multi-location trials to validate these

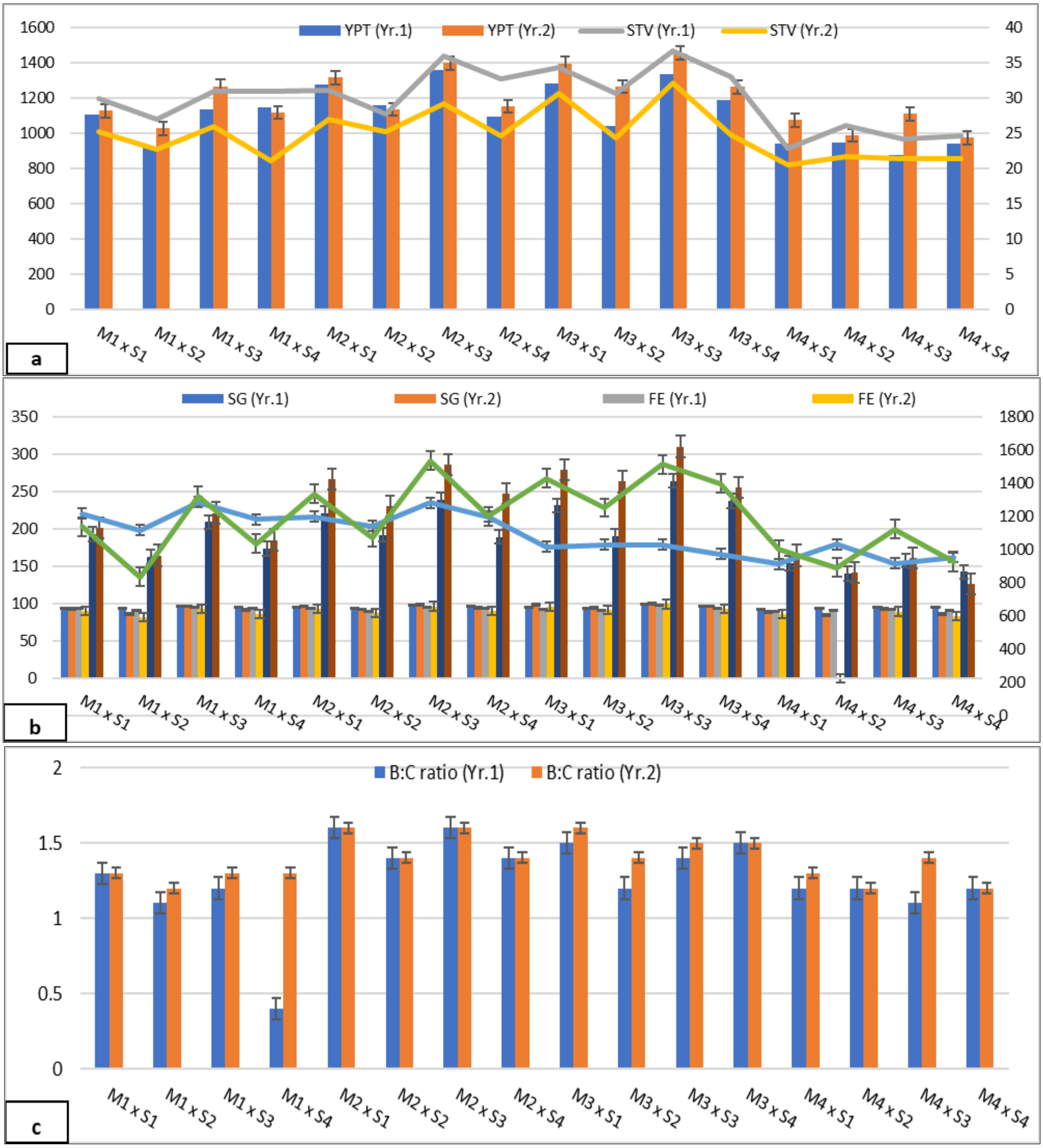

Fig. 3. Interaction effects of micronutrients (M) with stage (S) of application on **a.** seed yield; **b.** seed quality; **c.** Net benefit-cost ratio across treatments for breeder seed (BS) class @ Rs. 57/- per kg in foxtail millet (cv. SiA3156) during post-rainy seasons of 2020-21 (Yr.1) and 2021-22 (Yr.2).

◊ YPT: yield per plot (g), STV: stover dry weight per plant (g), SG: seed germination (%), FE: field emergence (%), SVI. 1: seedling vigor index-1, SVI. 2: seedling vigor index-2, Yr.1: year-1, Yr.2: year-2, M1 : B (0.5 %), M2 : Zn (1 %), M3 : B (0.5 %) + Zn (1 %), M4 : Control (Water spray) & no soil application, S1 : foliar spray PI (PI), S2 : foliar spray 50 % flowering (FL), S3 : foliar spray at PI + FFL and S4 : soil application before sowing.

◊ *The mean data with different labels (a, b, etc.) indicate significant differences as per Tukeys HSD all pairwise comparison test.*

results across diverse agro-ecological zones, to assess the residual and cumulative impacts of repeated foliar micronutrient applications on soil health and to explore their integration with bio-fortification and precision nutrient management strategies to optimize nutrient use efficiency and seed quality.

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Authors' contributions

GB, KN and HK conceptualized the research program and designed the experiments. KN and GB conducted the experiments. KN, GB, DIK, SR and NM analyzed the data and interpreted. KN, GB, NM, HK, SR, S and TSC prepared the manuscript. All authors read and approved of the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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