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Effect of agronomic biofortification with zinc and iron on yield and economic returns of foxtail millet (*Setaria italica* L.)

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ABSTRACT

A field study was conducted during Rabi 2025-26 at the College of Agriculture, Bheemaranagudi, UAS, Raichur, to evaluate the effect of agronomic biofortification of zinc and iron on yield and economics of foxtail millet. The experiment was laid out in an Randomized Complete Block Design (RCBD) with nine treatments replicated thrice. Results showed that soil application of ZnSO₄ and FeSO₄ @ 5 kg ha⁻¹ each at sowing + foliar spray of ZnSO₄ and FeSO₄ @ 0.5 % each at 40 DAS along with RDF recorded significantly higher yield parameters viz., ear head length (19.9 cm), ear head weight plant⁻¹ (8.8 g), number of ear heads meter⁻¹ (36.0), number of productive tillers meter⁻¹ (45.9), grain yield (2047 kg ha⁻¹) and straw yield (5106 kg ha⁻¹), it was on par with soil application of ZnSO₄ and FeSO₄ @ 2.5 kg ha⁻¹ each at sowing + foliar spray of ZnSO₄ and FeSO₄ @ 0.25 % each at 40 DAS along with RDF (18 cm, 7.8 g, 34.7, 44.5, 1960 kg ha⁻¹ and 4829 kg ha⁻¹, respectively). Economic analysis revealed that soil application of ZnSO₄ and FeSO₄ @ 5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.5 % each at 40 DAS along with RDF resulted significantly higher net returns (₹ 39,622 ha⁻¹) and B:C (2.01) and it was found to be on par with soil application of ZnSO₄ and FeSO₄ @ 2.5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.25 % each at 40 DAS along with RDF (₹ 36,539 ha⁻¹ and 1.94, respectively).

Keywords: Agronomic biofortification, Foxtail millet, Foliar spray, Yield and yield parameters, Economics

Introduction

Millets are climate-resilient, nutrient-rich cereals well adapted to arid and semi-arid regions and low-input farming systems. Their short duration, low water requirement and adaptability to marginal soil and unfavourable environments make them important for sustainable food and nutritional security. They are rich in carbohydrates, protein, dietary fibre and essential minerals such as Fe, Zn, calcium and magnesium and are therefore recognized as “nutri-cereals” (Saleh *et al.*, 2013) [1]. Foxtail millet (*Setaria italica* L.) is an ancient, short-duration C₄ cereal with high photosynthetic efficiency and good adaptation to moisture-limited environments. In India, millets occupy about 12.19 million ha, producing 15.38 million tonnes with an average productivity of 1.26 t ha⁻¹ (Anon., 2024) [2]. In Karnataka, foxtail millet is cultivated on approximately 9,000 ha, producing 12,141 tonnes with a productivity of 1,349 kg ha⁻¹ (Anon., 2023) [3]. Despite its adaptability, its productivity remains relatively low, necessitating improved nutrient-management strategies. Zinc and Fe deficiencies are major contributors to global “hidden hunger”, affecting human growth, metabolism and overall health (Anon., 2013) [4]. Nearly half of the world’s cereal-growing soils have inadequate plant-available Zn, which can restrict crop productivity and grain Zn concentration (Cakmak, 2008) [5]. Similarly, Fe deficiency can impair chlorophyll formation, physiological activity and plant growth (Zhang *et al.*, 2008) [6].

Agronomic biofortification through fertilizers application provides a practical and relatively rapid approach to increase micronutrient concentration in edible plant parts. However, Zn and Fe availability is often restricted in alkaline and calcareous soils. Soil and foliar application of ZnSO₄ and FeSO₄ can improve nutrient availability, uptake and translocation to grain. Therefore, the present study was undertaken to evaluate Zn and Fe application strategies for improving yield, grain micronutrient accumulation and economic returns in foxtail millet and to identify an effective and economically feasible nutrient-management practice for sustainable production and nutritional security.

Material and methods

The experiment was conducted at the Experimental Block of College of Agriculture, Bheemaranagudi, (UAS, Raichur) which lies in the North Eastern Dry Zone of Karnataka (Zone-II). It is located at 16°15' N latitude, 77°21' E longitude and at an elevation of 389 meters above mean sea level.

The experiment design followed was RCBD with nine treatment combinations and three replications viz., T₁: Control, T₂: Soil application of ZnSO₄ @ 5 kg ha⁻¹, T₃: Soil application of FeSO₄ @ 5 kg ha⁻¹, T₄: Soil application of ZnSO₄ and FeSO₄ @ 5 kg ha⁻¹ each, T₅: Foliar spray of ZnSO₄ @ 0.5 % at 40 DAS, T₆: Foliar spray of FeSO₄ @ 0.5 % at 40 DAS, T₇: Foliar spray of ZnSO₄ and FeSO₄ @ 0.5 % each at 40 DAS, T₈: Soil application of ZnSO₄ and FeSO₄ @ 2.5 kg ha⁻¹ each + Foliar spray of ZnSO₄ and FeSO₄ @ 0.25 % each at 40 DAS, T₉: Soil application of ZnSO₄ and FeSO₄ @ 5 kg ha⁻¹ each + Foliar spray of ZnSO₄ and FeSO₄ @ 0.5 % each at 40 DAS.

Foxtail millet variety HN-46, recommended for Zones I–III of Karnataka, was sown at 30 × 10 cm spacing in gross and net plot sizes of 4.8 × 3.6 m and 3.6 × 3.2 m, respectively. The crop was sown on 5th November 2025 and harvested at physiological maturity on 28th January 2026. Recommended FYM (6 t ha⁻¹) and NPK (30:15:15 kg ha⁻¹) were applied, while ZnSO₄ and FeSO₄ were applied through soil and foliar methods as per the treatments. Soil application was done at sowing, whereas foliar sprays were applied at 40 DAS using a knapsack sprayer with 500 l ha⁻¹ spray volume. The FeSO₄ solution was appropriately neutralized before spraying to minimize leaf scorching. Standard agronomic practices, including protective irrigation, manual weeding and plant protection measures, were followed throughout the crop period. The experimental data were statistically analyzed following the procedure suggested by Panse *et al.* (1967) [7].

Results and discussion

Yield and yield parameters

Economic yield is the cumulative result of physiological and biochemical processes during crop growth, influenced by plant morphology, biomass accumulation and assimilate partitioning. Adequate and balanced availability of resources, particularly Zn and Fe, plays a vital role in improving yield attributes and overall crop productivity.

The results revealed significant differences among the treatments with respect to yield and yield attributes, namely ear head length (cm), ear head weight per plant (g), number of ear heads per meter, grain yield (kg ha⁻¹) and straw yield (kg ha⁻¹). These variations were brought about by effect of the agronomic biofortification of zinc and iron. The detailed results were presented in Table 1 and represented in fig. 1.

Length of ear head (cm)

The treatment receiving soil application of ZnSO₄ and FeSO₄ @ 5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.5 % each at 40 DAS recorded significantly higher ear head length (19.9 cm), which was statistically on par with soil application of ZnSO₄ and FeSO₄ @

2.5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.25 % each at 40 DAS (18.0 cm). Whereas, the control was recorded significantly lower ear head length (15.5 cm). The increased ear head length may be attributed to the synergistic effects of Zn and Fe in promoting auxin synthesis, enzyme activity, chlorophyll formation, photosynthesis and assimilate translocation, thereby enhancing reproductive development and ear head elongation. Similar results founded by Qureshi *et al.* (2021) [8] and Krupashree *et al.* (2022) [9].

Ear head weight (g plant⁻¹)

Among different treatments, the treatment soil application of ZnSO₄ and FeSO₄ @ 5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.5 % each at 40 DAS recorded significantly higher ear head weight (8.8 g plant⁻¹). While, the control recorded the significantly lower ear head weight (5.8 g plant⁻¹). Remaining treatments recorded intermediate values. Combined soil and foliar application of ZnSO₄ and FeSO₄ enhanced photosynthesis, assimilate production and translocation to developing ear heads.

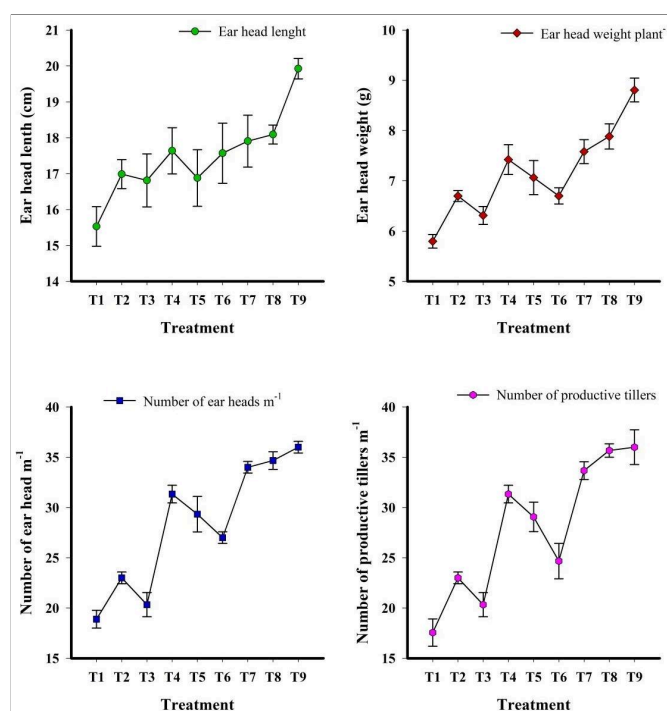


Figure 1. Yield parameters of foxtail millet as influenced by agronomic biofortification of zinc and iron

- RDF-30:15:15 kg N:P₂O₅:K₂O ha⁻¹; FYM @ 6 t ha⁻¹ is common for all the treatments.
- Half of N, entire P, K was applied as basal and remaining half of N was top dressed at 30 days after sowing.
- DAS: Days After Sowing.

Table 1. Yield and yield parameters of foxtail millet as influenced by agronomic biofortification of zinc and iron

Treatment	Length of ear head (cm)	Ear head weight (g plant ⁻¹)	Number of ear heads (m ⁻¹)	Number of productive tillers (m ⁻¹)	Grain yield (kg ha ⁻¹)	Straw yield (kg ha ⁻¹)
T ₁ : Control	15.5	5.8	18.9	21.8	1709	4290
T ₂ : Soil application of ZnSO ₄ @ 5 kg ha ⁻¹	16.9	6.7	23.0	28.7	1790	4311
T ₃ : Soil application of FeSO ₄ @ 5 kg ha ⁻¹	16.8	6.3	20.3	25.8	1764	4297
T ₄ : Soil application of ZnSO ₄ and FeSO ₄ @ 5 kg ha ⁻¹ each	17.6	7.4	31.3	37.9	1847	4582
T ₅ : Foliar spray of ZnSO ₄ @ 0.5 % at 40 DAS	16.8	7.1	29.3	36.6	1823	4628
T ₆ : Foliar spray of FeSO ₄ @ 0.5 % at 40 DAS	17.5	6.7	27.0	31.9	1798	4532

(continued on next page)

T ₇ : Foliar spray of ZnSO ₄ and FeSO ₄ @ 0.5 % each at 40 DAS	17.9	7.5	34.0	43.3	1864	4656
T ₈ : Soil application of ZnSO ₄ and FeSO ₄ @ 2.5 kg ha ⁻¹ each + Foliar spray of ZnSO ₄ and FeSO ₄ @ 0.25 % each at 40 DAS	18.0	7.8	34.7	44.5	1960	4829
T ₉ : Soil application of ZnSO ₄ and FeSO ₄ @ 5 kg ha ⁻¹ each + Foliar spray of ZnSO ₄ and FeSO ₄ @ 0.5 % each at 40 DAS	19.9	8.8	36.0	45.9	2047	5106
S.E.m.±	0.6	0.2	1.0	1.6	63	107
C.D. (P = 0.05)	1.91	0.7	2.9	4.8	191	322

Note: The synergistic roles of Zn in enzyme activity and reproductive development and Fe in chlorophyll synthesis and energy metabolism improved grain filling and source-sink balance, resulting in heavier ear heads. This is supported by the physiological mechanisms reported by White *et al.* (2009) [10].

Number of ear heads m⁻¹

Among different treatments, soil application of ZnSO₄ and FeSO₄ @ 5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.5 % each at 40 DAS recorded significantly higher number of ear heads (36.0 m⁻¹), while it remained statistically on par with soil application of ZnSO₄ and FeSO₄ @ 2.5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.25 % each at 40 DAS (34.7 m⁻¹) and foliar spray of ZnSO₄ and FeSO₄ @ 0.5 % each at 40 DAS (34.0 m⁻¹). Whereas, control was recorded significantly lower number of ear heads (18.9 m⁻¹). Combined Zn and Fe application enhanced tiller production, productive tiller survival and reproductive development, thereby increasing ear head formation. Improved enzyme activity, chlorophyll synthesis, photosynthesis and assimilate translocation under balanced Zn and Fe nutrition favoured ear head initiation and development. Similar improvements in foxtail millet growth and yield attributes under Zn and Fe nutrition were reported by White *et al.* (2009) [10], Qureshi *et al.* (2021) [8] and Krupashree *et al.* (2022) [9].

Number of productive tillers (m⁻¹)

The combined soil and foliar treatments produced the higher conversion of tillers into productive tillers. Soil application of ZnSO₄ and FeSO₄ @ 5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.5 % each at 40 DAS recorded significantly higher number of productive tillers 45.9 m⁻¹, followed by soil application of ZnSO₄ and FeSO₄ @ 2.5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.25 % each at 40 DAS, 44.5 m⁻¹. Whereas, significantly lower productive tillers were recorded in control (21.8 m⁻¹). The balanced availability of Zn and Fe also enhances nutrient uptake and dry matter accumulation, resulting in a greater number of productive tillers. Similar improvement was reported in foxtail millet under Zn and Fe nutrition through enriched organics by Krupashree *et al.* (2022) [9].

Grain yield (kg ha⁻¹)

Among the different agronomic biofortification treatments, soil application of ZnSO₄ and FeSO₄ @ 5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.5 % each at 40 DAS recorded significantly higher grain yield (2047 kg ha⁻¹) and 19.8 % higher grain yield than the control. However it was found statistically on par with soil application of ZnSO₄ and FeSO₄ @ 2.5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.25 % each at 40 DAS (1960 kg ha⁻¹) and foliar spray of ZnSO₄ and FeSO₄ @ 0.5 % each at 40 DAS (1864 kg ha⁻¹). The lower grain yield was recorded in the control (1709 kg ha⁻¹).

Straw yield (kg ha⁻¹)

A similar trend was observed in straw yield as that of grain yield. The treatment receiving soil application of ZnSO₄ and FeSO₄ @ 5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.5 % each at 40 DAS recorded significantly higher straw yield (5106 kg ha⁻¹) and it was found statistically on par with soil application ZnSO₄ and FeSO₄ @ 2.5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.25 %

each at 40 DAS (4829 kg ha⁻¹). Whereas significantly lower straw yield was obtained in the control (4290 kg ha⁻¹).

The significant improvement in yield and yield attributes such as ear head length, ear head weight per plant, number of ear heads per meter, grain yield and straw yield under zinc and iron biofortification of foxtail millet may be attributed to the complementary physiological roles of these micronutrients in enhancing plant growth, photosynthetic efficiency, nutrient utilization and assimilate translocation. Zinc plays an important role in auxin synthesis, enzyme activation, protein metabolism and pollen development, whereas iron is indispensable for chlorophyll synthesis, electron transport and energy generation during photosynthesis. Adequate availability of both micronutrients promotes vigorous vegetative growth, efficient carbohydrate production and effective partitioning of assimilates towards reproductive sinks, thereby improving grain formation and final yield. Similar results quoted by White *et al.* (2009) [10], Yadav *et al.* (2011) [11], Sathisha *et al.* (2019) [12] and Krupashree *et al.* (2022) [9] in foxtail millet.

Economics

The results on cost of cultivation (₹ ha⁻¹), gross returns (₹ ha⁻¹), net returns (₹ ha⁻¹) and benefit cost ratio as influenced by agronomic biofortification of zinc and iron were furnished in Table 2 and depicted in Fig. 2.

Cost of cultivation (₹ ha⁻¹)

The cost of cultivation varied among the treatments depending on the method and level of zinc and iron application. The higher cost of cultivation was incurred with soil application of ZnSO₄ and FeSO₄ @ 5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.5 % each at 40 DAS, (₹ 39,171 ha⁻¹), followed by soil application of ZnSO₄ and FeSO₄ @ 2.5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.25 % each at 40 DAS (₹ 38,862 ha⁻¹). The control recorded lower cost of cultivation (₹ 36,493 ha⁻¹).

The higher cost of cultivation under zinc and iron biofortification treatments was primarily due to the additional expenditure incurred on ZnSO₄ and FeSO₄ fertilizers and their foliar application, including labour charges. Treatments involving both soil and foliar application recorded the highest cultivation cost because of the increased input requirement. However, the additional investment in micronutrient application contributed to improved crop growth, yield and grain micronutrient enrichment. Similar economic trends under agronomic biofortification of sorghum have been reported by Sudeep *et al.* (2025) [13].

Gross returns (₹ ha⁻¹)

Among different treatments, the treatment receiving soil application of ZnSO₄ and FeSO₄ @ 5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.5 % each at 40 DAS recorded significantly higher gross returns (₹ 78,793 ha⁻¹), which was statistically on par with soil application of ZnSO₄ and FeSO₄ @ 2.5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.25 % each at 40 DAS (₹ 75,401 ha⁻¹). The control recorded the significantly lower gross returns (₹ 65,825 ha⁻¹).

Table 2. Economics of foxtail millet as influenced by agronomic biofortification of zinc and iron

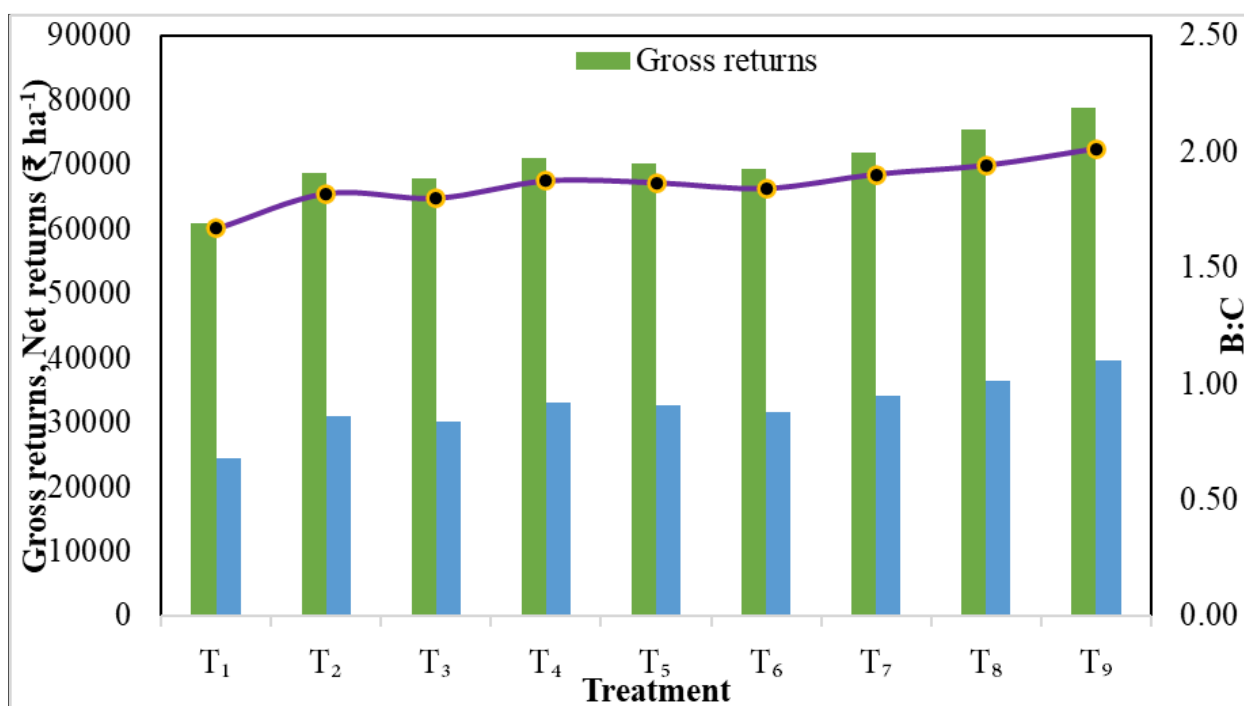
Treatment	Cost of cultivation (₹ ha ⁻¹)	Gross returns (₹ ha ⁻¹)	Net returns (₹ ha ⁻¹)	Benefit cost ratio
T ₁ : Control	36493	65825	29333	1.79
T ₂ : Soil application of ZnSO ₄ @ 5 kg ha ⁻¹	37780	68745	30965	1.82
T ₃ : Soil application of FeSO ₄ @ 5 kg ha ⁻¹	37677	67803	30126	1.80
T ₄ : Soil application of ZnSO ₄ and FeSO ₄ @ 5 kg ha ⁻¹ each	37935	71081	33146	1.87
T ₅ : Foliar spray of ZnSO ₄ @ 0.5 % at 40 DAS	37652	70251	32599	1.87
T ₆ : Foliar spray of FeSO ₄ @ 0.5 % at 40 DAS	37600	69244	31644	1.84
T ₇ : Foliar spray of ZnSO ₄ and FeSO ₄ @ 0.5 % each at 40 DAS	37729	71773	34044	1.90
T ₈ : Soil application of ZnSO ₄ and FeSO ₄ @ 2.5 kg ha ⁻¹ each + Foliar spray of ZnSO ₄ and FeSO ₄ @ 0.25 % each at 40 DAS	38862	75401	36539	1.94
T ₉ : Soil application of ZnSO ₄ and FeSO ₄ @ 5 kg ha ⁻¹ each + Foliar spray of ZnSO ₄ and FeSO ₄ @ 0.5 % at 40 DAS	39171	78793	39622	2.01
S.E.m.±	-	2282	2282	0.06
C.D. (P = 0.05)	-	6841	6841	0.18

Note: Men and women labour @ ₹ 500 each, Bullock pair @ ₹ 1200 day⁻¹, Tractor hiring @ ₹ 1000 hr⁻¹, FYM @ ₹ 1100 t⁻¹, Urea @ ₹ 5.37 kg⁻¹, DAP @ ₹ 27 kg⁻¹, MoP @ ₹ 34 kg⁻¹, ZnSO₄ @ ₹ 50 kg⁻¹, FeSO₄ @ ₹ 30 kg⁻¹, Seeds @ ₹ 80 kg⁻¹, Foxtail millet grains @ ₹ 3600 q⁻¹, Straw @ ₹ 100 q⁻¹, Marketing charges @ 3% of the produce. **RDF** - 30:15:15 kg N:P₂O₅:K₂O ha⁻¹; FYM @ 6 t ha⁻¹ is common for all the treatments. Half of N, entire P, K was applied as basal and remaining half of N was top dressed at 30 days after sowing. **DAS**: Days After Sowing.

Net returns (₹ ha⁻¹)

The treatment receiving soil application of ZnSO₄ and FeSO₄ @ 5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.5 % each at 40 DAS recorded the significantly higher net returns (₹ 39,622 ha⁻¹), which was statistically on par with soil application of ZnSO₄ and

FeSO₄ @ 2.5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.25 % each at 40 DAS (₹ 36,539 ha⁻¹), foliar spray of ZnSO₄ and FeSO₄ @ 0.5 % each at 40 DAS (₹ 34,044 ha⁻¹) and soil application of ZnSO₄ and FeSO₄ @ 5 kg ha⁻¹ each (₹ 33,146 ha⁻¹). The control was recorded significantly lower net returns (₹ 29,333 ha⁻¹).

**Figure 2.** Gross returns and net returns and B:C of foxtail millet as influenced by agronomic biofortification of zinc and iron

Higher gross and net returns under Zn and Fe biofortification were primarily due to increased grain and straw yields, which compensated for the additional cost of micronutrient fertilizers and their application. Improved nutrient use and crop productivity consequently enhanced the profitability of foxtail millet cultivation. Similar findings have been reported in agronomic biofortification studies conducted on foxtail millet by Dinesh *et al.* (2017) [14], Krupashree *et al.* (2022) [9] and in sorghum by Sudeep *et al.* (2025) [13].

Benefit cost ratio (B:C)

Among different treatments, application of treatment receiving soil application of ZnSO₄ and FeSO₄ @ 5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.5 % each at 40 DAS recorded the significantly higher B:C (2.01), which was statistically on par with soil application of ZnSO₄ and FeSO₄ @ 2.5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.25 % each at 40 DAS (1.94), foliar spray of ZnSO₄ and FeSO₄ @ 0.5 % each at 40 DAS (1.90), soil application of ZnSO₄ and FeSO₄ @ 5 kg ha⁻¹ each (1.87) and foliar spray of ZnSO₄ @ 0.5 % (1.87). The control was recorded significantly lower

B:C (1.79). The increased benefit cost ratio under the combined basal and foliar zinc application treatment may be attributed to enhanced yield performance and higher gross returns over the cost of cultivation resulted in increased benefit cost ratio. Similar results were reported by Anilkumar *et al.* (2017) [15], Vinita *et al.* (2021) [16], Krupashree *et al.* (2022) [9] and Sudeep *et al.* (2025) [13].

Conclusion

Soil application of ZnSO₄ and FeSO₄ @ 5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.5 % each at 40 DAS along with RDF was found to be the most effective agronomic biofortification treatment for foxtail millet, recorded 19 % higher grain and straw yield over control along with maximum gross returns, net returns and B:C followed by soil application of ZnSO₄ and FeSO₄ @ 5 kg ha⁻¹ each + foliar spray of ZnSO₄ and FeSO₄ @ 0.5 % each at 40 DAS along with RDF.

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